Aluminum Alloy Performance Under Dry Cooling Tower Conditions

by
A. B. Johnson, Jr.
S. Begej
M. W. Martini
R. P. May

December 1977

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Battelle
Pacific Northwest Laboratories
Richland, Washington 99352

FOREWORD

The Dry Cooling Tower Development Program at Battelle, Pacific Northwest Laboratories was initiated with a program scope that included the following near-term and ultimate emphases.

Near-Term Objectives:

- Develop economic and performance models for cost optimization of total heat rejection systems using dry cooling.
- Analyses of, and dissemination of experience on, existing dry-cooled plant performance.
- Demonstrate certain features of existing technology equipment to provide confidence for specification by utilities.

Ultimate Objective:

- Promote water conservation through industry use of dry cooling by developing and demonstrating the reliability of lower-cost systems. The development of advanced wet/dry systems is also considered to be within this scope.

Over the past two years the following documents have been issued, reporting the results of the work toward these objectives.

Cost Optimization of Dry-Cooled Heat Rejection Systems:

A Review and Assessment of Engineering Economic Studies of Dry-Cooled Electrical Generating Plants. B. C. Fryer, BNWL-1976, March 1976.

Heat Transfer and Pressure Drop Characteristics of Dry Tower Extended Surfaces. Part I: Heat Transfer and Pressure Drop Data. PFR Engineering Systems, Inc., PFR-7-100, March 1976.

Heat Transfer and Pressure Drop Characteristics of Dry Tower Extended Surfaces. Part II: Data Analysis and Correlation. PFR Engineering Systems, Inc., PFR 7-102, June 1976.

Analysis of Performance of Existing Dry-Cooled Plants:

Dry Cooling Tower Program: Results of Industrial Contacts Through August 1974. BNWL-1878, November 1, 1974.

A Survey of Materials and Corrosion Performance in Dry Cooling Applications. A. B. Johnson, Jr., D. R. Pratt, and G. E. Zima, BNWL-1958, March 1976.

European Dry Cooling Tower Operating Experience. J. G. DeSteeese and K. Simhan, BNWL-1995, March 1976.

Mathematical and Experimental Investigations on Dispersion and Recirculation of Plumes from Dry Cooling Towers at Wyodak Power Plant in Wyoming. Y. Onishi and D. S. Trent, BNWL-1982, February 1976.

Aluminum Alloy Performance under Dry Cooling Tower Conditions, A. B. Johnson, Jr., S. Begej, M. W. Martini, and R. P. May, PNL-2292, December 1977.*

Advanced Dry (wet/dry) Cooled Systems:

Preliminary Evaluation of Wet/Dry Cooling Concepts for Power Plants. W. V. Loscutoff, BNWL-1969, July 1976.

Compatibility of Ammonia with Candidate Dry Cooling System Materials. D. R. Pratt, BNWL-1992, April 1976.

Scale Formation in Deluged Dry Cooling Systems. D. R. Pratt, BNWL-2060, March 1976.

Ammonia As An Intermediate Heat Exchange Fluid for Dry Cooled Towers. R. T. Allemann, B. M. Johnson, and G. C. Smith, BNWL-SA-5997, September 1976.

A group of recently issued reports serves the dual purpose of developing cost optimization models for dry cooling systems based on available technology and comparing the results of analyzing the costs of these systems with the projected cost of several advanced dry and wet/dry systems. Included in this group are:

An Engineering and Cost Comparison of Three Different All-Dry Cooling Systems. B. C. Fryer, D. W. Faletti, Dan J. Braun, David J. Braun, and L. E. Wiles, BNWL-2121, September 1976.

A Study of the Comparative Costs of Five Wet/Dry Cooling Tower Concepts. F. R. Zaloudek, R. T. Allemann, D. W. Faletti, B. M. Johnson, H. L. Parry, G. C. Smith, R. D. Tokarz, and R. A. Walter, BNWL-2122, September 1976.

*This report.

Dry Cooling of Power Generating Stations: A Summary of the Economic Evaluation of Several Advanced Concepts Via A Design Optimization Study and A Conceptual Design and Cost Estimate. B. M. Johnson, R. T. Allemann, D. W. Faletti, B. C. Fryer, and F. R. Zaloudek, BNWL-2120, September 1976.

Costs and Cost Algorithms for Dry Cooling Tower Systems. P. A. Ard, C. H. Henager, D. R. Pratt, and L. E. Wiles, BNWL-2123, September 1976.

A User's Manual for the BNW-I Optimization Code for Dry-Cooled Power Plants. David J. Braun, Dan J. Braun, Warren V. Demier, D. W. Faletti, and L. E. Wiles, BNWL-2180, January 1977.

A recent report considers the economic, legal, and water availability factors which will contribute to selection of dry and wet/dry cooling vis-a-vis other methods of cooling in the future and thus influence the projected market for these types of cooling systems in the next twenty years.

An Overview of Economic, Legal, and Water Availability Factors Affecting the Demand for Dry and Wet/Dry Cooling for Thermal Power Plants. Paul L. Hendrickson, BNWL-2268, June 1977.

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SUMMARY AND CONCLUSIONS

Aluminum alloys are important construction materials in air-cooled equipment. They have performed satisfactorily as fin materials in thousands of industrial air coolers. They also are utilized in several relatively large dry cooling towers for electrical generating stations, particularly in Europe. The prospects that additional dry-cooled power stations will be built in the U.S. over the next 20 years justifies development of a sound basis for material and site selection. Funding limits restricted this study to aluminum alloys, but other candidates also need a comprehensive assessment. In particular, the corrosion characteristics of galvanized steel, compared to aluminum alloys, are currently unknown. No conclusions can be drawn regarding the comparative merits of these two principal materials until a similar field survey and laboratory investigation are made of galvanized steel finned atmospheric heat exchangers.

The report draws on the following sources to define the scope of successful aluminum alloy performance and also to define problems which have developed:

- recent surveys of dry-cooled equipment performance in Europe⁽¹⁾ and the U.S.;⁽²⁾
- metallographic examination of aluminum fin specimens from several operating plants with dry-cooled equipment, sited in a variety of environments;
- metallographic examination of aluminum alloy 6063 finned-tube specimens placed at two Gulf Coast locations, including specimens exposed both at ambient and cooling tower temperatures.
- metallographic examination of aluminum alloy 1100 specimens subjected to selected contaminants in a laboratory study, including specimens exposed both at ambient and at dry cooling tower temperatures.

The results of the investigations are summarized below:

1. Aluminum alloys have performed satisfactorily in thousands of industrial air coolers, in exposures up to 28 years, principally at rural locations. Several aluminum-finned dry cooling towers in electrical generating plants also appear to be functioning well.
2. At a very small fraction of the sites, substantial corrosion of aluminum fins has occurred. Environments containing chlorides appear to be the most prevalent and consistent cause of corrosion on aluminum equipment. However, there is presently an incomplete basis for assessing the action of other contaminants.
3. Aluminum alloy finned-tube specimens were placed at two Gulf Coast industrial sites which use air-cooled equipment. Samples were cut from the specimens at the end of 1-year and 2-year exposures.
 - a. After one and two years, very little corrosion had occurred on heated (130°F, 56°C) specimens located at a rural location, approximately 6 miles (9.2 km) from the Gulf of Mexico. Ambient-temperature specimens mounted at a location away from the cooler were essentially free of corrosion; ambient-temperature specimens mounted under the cooler and subject to soap-laden spray during cooler cleaning operations showed substantial corrosion after two years. The effect of the soap is uncertain.
 - b. After one and two years at a location approximately 450 ft (137 meters) from the Gulf shore, aluminum alloy specimens exposed at approximately 120°F (50°C) had only minor evidence of corrosion attack. However, three specimens exposed only at ambient temperatures all showed advanced stages of corrosion. At the same location, failure of aluminum dry-cooled equipment occurred after 13 years. In addition to salt water, elemental sulfur was a potential contaminant, but its importance to the corrosion mechanism is not clear.

4. Investigation of a section from a European aluminum-finned cooling tower indicated that at locations where coal dust was caked onto the fins, severe corrosion of the aluminum had been initiated. Very little corrosion was evident on the fins where coal dust was absent. The tower had been on line approximately 8 years. Analysis of coal dust removed from the fins indicated a chloride concentration of approximately 1500 wt ppm. Both sulfur and chloride contaminants were identified in the corrosion products.
5. Laboratory studies on aluminum alloy 1100 specimens indicated that sodium chloride was consistently an aggressive agent; elemental sulfur or Na_2SO_3 alone did not cause observable corrosion, but combinations of sulfur and chloride showed some evidence of a synergistic enhancement of corrosion; however, the evidence is based on only one laboratory observation. European coal (1500 wt ppm Cl^-) and U.S. coal (28 wt ppm Cl^-) both initiated corrosion, but the attack caused by the European coal was notably more severe.

Laboratory specimens exposed perpetually at approximately 60°C generally had much less corrosion than specimens exposed perpetually at ambient conditions (approximately 20°C). Specimens cycled between 20 and 60°C had corrosion more nearly characteristic of ambient-temperature specimens.

In summary, the principal conclusions from the study are:

- Aluminum alloys can be expected to have lifetimes of 30 years or more at dry cooling tower temperatures in "clean" environments. Many industrial air coolers with aluminum alloy fins also have had extended operation in contaminated environments.
- Effects of specific contaminants are not well defined at cooling tower temperatures, but chloride is clearly an aggressive agent on aluminum components, in agreement with extensive published evidence.
- Corrosion is most severe at temperatures below the dew point, where moisture can participate in the attack; severe corrosion seldom

occurs at dry cooling tower temperatures, unless the plant is subject to considerable downtime; the implication is that high plant availabilities minimize corrosion; in aggressive environments, measures to minimize corrosion during extended outages may be desirable.

- The observation that caked coal dust promotes aluminum corrosion suggests that the relative siting of the cooling tower and the coal pile is an important consideration. The chloride content of the coal appears to be an important aspect of its corrosive character. Equally important may be the poultice effect of the coal contaminant. The particulate layer could trap impurities and might aid in establishing localized concentration cells.
- The importance of considering contaminants in material selection and siting of dry-cooled equipment is evident. For relatively small units, where 15- to 20-year lifetimes may be acceptable, aggressive environments may be tolerable for aluminum alloys, particularly if plant downtime is likely to be minimal. For large dry cooling tower installations, protection of the relatively large capital investment in the tower opts for requisite attention to plant siting, material selection, and possible application of corrosion control measures during plant outages. At potential power plant sites where corrosion characteristics of candidate metals are not well-defined, corrosion evaluations should be made as part of the site evaluation.
- Laboratory studies at dry cooling tower and ambient temperatures caused corrosion similar to corrosion on some plant specimens. Placement of prototypic specimens on and near dry cooling tower equipment also appears to offer a useful approach to evaluate corrosion under dry cooling tower operating conditions.
- The cooling tower temperatures are similar to temperatures on some types of solar equipment. Therefore, the results of this study provide some insights to corrosion on aluminum components in solar equipment as a function of environment.

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1.0 INTRODUCTION

The large scale use of water for cooling purposes by central power stations is becoming increasingly problematic because of environmental restrictions, increasing water costs and increasing demand for water for other uses. These factors may make dry cooling an attractive option before the end of this century in some areas of the United States.⁽³⁾

Battelle's Pacific Northwest Laboratories (PNL) is program manager for a Department of Energy (DOE), Division of Advanced Systems and Materials Production program to evaluate the feasibility of dry cooling utilization by the electric power generating industry. Corrosion was identified in an initial survey⁽⁴⁾ as a potentially costly factor which should be assessed in dry-cooled installations to minimize operating costs of future plants.

Previous reports^(1,2) have summarized materials performance in a cross-section of U.S. and foreign dry-cooled installations. This report supplements the previous reports with specific air-side corrosion data from operating dry-cooled installations and with corresponding laboratory studies. The report presents results of metallographic examinations on fin specimens taken from operating industrial air-cooled heat exchangers (dry coolers) and from dry cooling towers at power stations. The equipment operated in a variety of environments in the U.S. and Europe.

The previous surveys indicated that, in general, dry-cooled equipment operates with a minimum of operational problems. Therefore, it should be emphasized that the corrosion results reported here represent worst cases. For the most part, fin specimens were collected from coolers and towers that were known to have corrosion problems, though specimens from trouble-free plants also are shown. A major objective of this study has been to define environments which can be expected to cause corrosion; also to suggest possible causes of the corrosion. In general, corrosion has not been a frequent problem in dry-cooled equipment. Correct siting and materials selection will assure that corrosion problems are minimal in future installations. Aluminum is one of two predominant fin materials now used in dry-cooled power plants; the other principal material is galvanized steel. Both materials have performed

satisfactorily for long periods with few exceptions. This report examines the exceptions for aluminum equipment, with the objective of defining environments which should be avoided. No attempt is made to compare the two materials as there is not at this time a similar study for galvanized steel.

2.0 SUMMARY OF PREVIOUS SURVEYS ON PERFORMANCE OF DRY-COOLED PLANTS AND AIR-COOLED INDUSTRIAL EQUIPMENT

In a discussion of corrosion on dry-cooled equipment, it is important to provide a broad perspective, so the corrosion which is problematic at a few sites is not interpreted as a major industry-wide problem. The surveys cited earlier^(1,2) reflected successful dry-cooled equipment performance at the large majority of locations. Identification and characterization of sites which cause corrosion provide future selectors of plant sites for dry-cooled equipment with a basis for avoiding similar problems.

The following discussion briefly summarizes the results of the previous surveys.

2.1 EUROPEAN EXPERIENCE

The survey of European experience with dry-cooled electrical generating plants included reviews of five plants with aluminum fins and tubes and 13 plants with steel tubes and galvanized steel fins.⁽¹⁾ The corrosion performance of the plants was generally satisfactory. The cases where corrosion of aluminum components were a significant problem (Ibbenbüren and Rugeley) are discussed in some detail later in this report.

2.2 U.S. EXPERIENCE

The only aluminum-finned dry-cooling tower at a U.S. central generating station is a 3-MWe coal-fired unit at Wyodak, Wyoming. The unit began operation in 1962. Detailed examinations of aluminum components from Wyodak indicated that after ~10 years corrosion was not a problem.^(6,7) Other small dry-cooled power plants were identified in the survey, providing electricity for remote industrial plants. Aluminum alloy finned tubes also have operated satisfactorily in such units.

A coal-fired dry cooling tower having galvanized steel fins began operations at Wyodak in 1969. We have not performed metallographic exams on the fins, but we did participate in an on-site inspection in 1975, which suggested that the fins were performing satisfactorily in the dry, rural, coal-plant environment.

The survey of U.S. gas pipeline compressor engine coolers⁽²⁾ comprised responses from six pipeline companies, including some of the largest in the country, covering most of the geographic areas in the U.S., from California to Florida, and from Texas to New York and to the State of Washington. The coolers generally operate at 120 to 150°F (50 to 70°C). The scope of the survey is summarized in Table 1. Of the 219 stations covered in the survey, only two have experienced severe corrosion problems. One station is located within a few yards of the Gulf of Mexico. Corrosion at this site is discussed later as a part of this study. The other site is located ~30 miles from the Gulf. The corrosion occurred in ~1960 and details are not available.

Air-cooled equipment at some sites included in the survey has now exceeded thirty years of successful operation, generally at rural sites. At some industrial plants having highly corrosive environments, lifetimes of air-cooled equipment frequently are 15 years or less. However, with proper siting and operation, dry-cooled power stations should be able to avoid short tower lifetimes.

Materials in small industrial air coolers include fins fabricated from aluminum alloys, copper alloys, galvanized mild steel and stainless steel. In some designs, the fins are wrapped onto or soldered to a tube which carries the stream to be cooled. A common combination in the pipeline coolers is aluminum fins wrapped onto Admiralty brass or copper-nickel tubes. At most locations, the combination has performed well. However, if conditions during outages permit moisture to accumulate in the aluminum/copper crevice formed by the wrap-on design, severe corrosion can result in three to five years, due to galvanic corrosion of the aluminum by the copper alloy. The resulting build-up of corrosion products in the crevice inhibits heat flow. When necessary, the crevice can be eliminated by the use of extruded fins or sealed with a coating of some sort as was done at Rugeley.⁽²⁾

The generally favorable corrosion performance of dry-cooled equipment relies to a major extent on the fact that it operates above the dewpoint, minimizing the action of moisture. The importance of time-of-wetness as a parameter in atmospheric corrosion defines the benefit of dry operation.⁽²⁾ Even in contaminated environments, corrosion at dry-cooling tower temperatures is much less than at ambient temperatures. Corrosion which occurs while the plant is not operating thus becomes a potentially important consideration.

TABLE 1. Compressor Engine Dry Cooler Summary⁽²⁾

<u>Company</u>	<u>A</u>	<u>B</u>	<u>C</u>	<u>D</u>	<u>E^{a)}</u>	<u>F</u>	<u>Total</u>
No. of Stations	60	22	36	52	40	9	219
No. of Coolers ^{b)}	~360	77	313	261	410	121	1542
Ave. Age, yr	20	15	17	22	20	17	
Max. Age, yr	26	19	25	25	28	>20	
Tube Materials ^{c)}	-	-	-	-	-	-	-
Fin Material ^{d)}	-	-	-	-	-	-	-
Locations:							
Rural	90%	90%	96%	98%	most	79%	
Urban	5%	5%	5%	0	ND	0	
Industrial	0	5%	0	2%	some	21%	
Marine	5%	0	0	0	0	0	
Temp. In, °C	50-80	80	ND	ND	50-105	ND	
Temp. Out, °C	45-55	50	ND	ND	45-75	ND	

ND = Not Determined

-
- a) Company E also uses dry coolers in other applications, including steam condensing and process cooling; the total number of coolers in their system is ~1000.
- b) As defined here, the number of coolers is approximately the same as the number of fans.
- c) Some units use an extruded aluminum alloy fin/tube configuration having a carbon steel tube liner which serves as the conduit for the coolant.
- d) A few pipeline coolers use copper fins.

3.0 ATMOSPHERIC CORROSION OF ALUMINUM

The nominal compositions of the aluminum alloys most commonly used in dry-cooled equipment are given in Table 2. The alloys used most frequently are 6061, 6063 and 1100. Common finned tube designs included extruded, plate and tension wound.⁽⁵⁾

TABLE 2. Aluminum Alloys Used as Fin Materials
for Dry-Cooled Heat Exchangers

Alloy Designation	Nominal Composition, Weight Percent (Remainder, Al)							
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti
1100	(1.0 total)		0.20	0.05	--	--	0.10	--
3003	0.6	0.7	0.20	1.2	--	--	0.10	--
5052	(0.45 total)		0.10	0.10	2.5	0.25	0.10	--
5454	(0.40 total)		0.10	0.8	2.75	0.1	0.25	0.20
6061	0.6	0.7	0.25	0.15	1.0	0.25	0.25	0.15
6063	0.4	0.35	0.10	0.10	0.7	0.10	0.10	0.10
7072	(0.7 total)		0.10	0.10	0.10	--	1.0	--

Alloy 7072 is sometimes used on selected alloys in atmospheric applications by cladding it onto an appropriate alloy substrate. This minimizes the substrate alloy perforation from pitting by limiting the depth of attack through the electrochemical protective action of the Zn in the 7072 alloy.

Atmospheric corrosion data at ambient temperatures are not an adequate basis for prediction of corrosion under dry-cooling tower conditions, for the reason indicated in the previous section. However, atmospheric corrosion data tend to represent worst-case conditions for dry-cooled equipment. Also, they are relevant to corrosion which occurs while the plant is off-line.

Atmospheric corrosion data for aluminum alloys, reported previously^(2,8,9) will be summarized here. Atmospheric corrosion of aluminum under average rural conditions is minimal. At industrial sites, atmospheric corrosion of aluminum alloys varies substantially, depending on specific environments. At one industrial site, the greatest corrosion occurred during the first two years, followed by low subsequent corrosion rate.⁽⁸⁾ However, atmospheric

corrosion of aluminum is sensitive to environmental conditions; air quality varies widely from one "industrial" area to another. Relatively high near-linear corrosion rates of aluminum have been observed at some industrial sites.^(8,9)

Marine industrial atmospheres tend to be the most corrosive to aluminum alloys. Marine atmospheres also may be corrosive to aluminum. The "marine" category includes a wide variation in local conditions (wind, salt deposition, periodic wetting, rain washing, etc.). Both marine and marine industrial atmospheres result in variations in aluminum corrosion which depend on local conditions. Conditions which cause acid chloride environments on aluminum surfaces are a significant factor in promoting intergranular attack on aluminum alloys at relatively low temperatures.

Atmospheric corrosion of aluminum alloys proceeds by attack at local anodic sites, developing a shallow, self-limiting oxide. The attack then develops at other anodic sites, gradually progressing over the entire surface and finally reaching a low steady-state rate.^(2,9) The low rate generally is reached after 2 to 3 years and continues unless the protective nature of the oxide is disturbed. Chloride ion is a common depassivator of aluminum,⁽¹⁰⁾ resulting in accelerated, often localized corrosion.

Preliminary data from aluminum fins collected from dry coolers at several locations in the U.S. indicated mild corrosion at most sites.⁽²⁾ However, severe intergranular attack occurred on Alloy 1100 aluminum fins exposed at a marine site which also was subjected to elemental sulfur. However, our laboratory studies do not clearly implicate elemental sulfur as a corrosive agent. Alloys of the 6XXX series (Mg + Si alloys) are known to be susceptible to intergranular corrosion. Intergranular corrosion can be caused by the precipitation of Mg_2Si along the grain boundaries, because this produces an anodic boundary that is more susceptible to corrosion. Alloys of the 2XXX are also susceptible to intergranular corrosion due to precipitation of $CuAl_2$ at the grain boundaries during age hardening;^(8,11) however, aluminum alloys of the 2XXX series are not generally used as fin material.

Intergranular corrosion has been produced experimentally in high-purity aluminum exposed to 4.7N HCl at room temperature⁽¹²⁾ or distilled water at 100-150°C.⁽¹³⁾ Aluminum alloys (Al-Mg-Si and Al-Cu) also corroded intergranularly under the influence of chloride ion.^(14,15) Under the conditions in our experiments, the chloride ion attack was transgranular but some intergranular attack occurred on industrial equipment where chloride was at least one participant in the attack. It has been postulated that if intergranular corrosion of pure aluminum is caused by stress in the grain boundaries, small amounts of impurity would tend to increase this stress factor and increase the susceptibility to intergranular attack.⁽¹²⁾

The influence of sulfur contamination on intergranular corrosion is largely unknown; sulfur is generally noncorrosive to aluminum in the elemental state, as evidenced by its wide use in the sulfur mining industry and in the handling of molten sulfur.⁽¹⁶⁾ Sulfur salts can be corrosive, and sulfuric acid will react with aluminum to form aluminum sulfate.⁽¹⁷⁾ Atmospheric sulfur, in the form of SO₂ and SO₃, seems to have no effect on aluminum unless moisture is also available.^(18,19)

Settled carbon particles, as in coal dust, will cathodically accelerate corrosion, but this effect is generally slight.⁽²⁰⁾ Potentially more important is the action of the coal-dust layer in providing a poultice, which traps impurities and may contribute to localized concentration cells.

4.0 EXPERIMENTAL - SPECIMEN EXAMINATIONS FROM OPERATING DRY-COOLED EQUIPMENT

Visits were made to several plants which use air-cooled heat exchangers (dry coolers) and operating dry-cooling towers sited in a variety of environments. Operating and historical data were collected, and, where possible, fin samples were taken for analysis. The results of this work are presented below, classified according to environment. Plant and company names are not identified in most cases for proprietary reasons.

4.1 RURAL, ARID ENVIRONMENT

4.1.1 Wyodak, Wyoming

The only operating dry-cooled central power plant in the U.S. is the Neil Simpson Station at Wyodak, Wyoming. This station consists of two units rated at 3 and 22 MWe that have been in service since 1962 and 1969, respectively. These are direct-cycle units; that is, the steam passes directly from the turbine to the dry cooling tower, where it condenses and returns to the boiler as condensate. The 3-MWe unit is cooled by a tower constructed by Griscom-Russel; it consists of wrapped-on aluminum fins, Admiralty brass tubes and steel headers. The 22-MWe unit was constructed by GEA and consists of galvanized steel fins on carbon steel tubes. A 330 Mwe unit, now under construction at Wyodak will be the world's largest single operating unit.

No fin samples were obtained from Wyodak; the results given here are based on examination of Wyodak components reported by others,^(7,9) indicating that aluminum component performance at Wyodak has been satisfactory after more than 10 years of service.

4.1.2 Columbia Basin, Washington

A pipeline company operates a natural gas compressor station in an arid, rural environment near the Columbia River in southeastern Washington (see Fig. 2 of Ref. 2). The jacket water from the compressor engines of this station is cooled by several air-cooled heat exchangers that have been

in service since 1956. The coolers consist of Admiralty brass tubes with solder-bonded aluminum fins. The inhibited glycol solutions from the compressor engines enter the coolers at about 175°F (79°C) and exits at about 120°F (49°C). No corrosion problems have occurred on these coolers in what is now 20 years of operation.

A fin specimen taken from the bottom row of tubes from one cooler is shown in Figure 1. About 70% of the fin area is covered by a thin layer of aluminum oxide; the darker areas toward the lower edge of the specimen are solder. No corrosion of the fin was associated with the solder. Maximum pit depth was about 0.3 mil (7.6 μm) (Fig. 2). Extrapolation of these results suggests that expectation of 30 years or more of useful life at this location appears reasonable.

4.2 RURAL, HUMID ENVIRONMENT

4.2.1 Inland Gulf Coast Area, Mississippi

A compressor station similar to that described above operates in a rural, humid environment approximately 6 miles (9.2 km) from the Mississippi Gulf Coast. This station has seven coolers, which consist of aluminum fins wrapped onto Admiralty brass tubes. The coolers have operated for 17 years with no air-side corrosion problems. Fouling of the fins by pollen, insects and dust occurs periodically. The fins are washed as needed with a detergent and with water or steam to remove this material (generally once per year).

Figure 3 shows a fin sample from the upper bank of tubes, which operate at about 130°F (54°C). The air cooler had been in service ~15 years when samples were taken. The amount of time at ambient temperatures over the life of the cooler is not clear, but in recent years the cooler has been at an elevated temperature approximately 80% of the time.

Figure 4 is a metallographic section of the fin shown in Figure 3. The aluminum oxide film thickness varies between 0.025 mil and 0.12 mil (0.64 to 3 μm) between the base and rim of the fin. Pit depths ranged from 0.02 to 0.14 mils (0.5 to 3.6 μm). Successful performance of aluminum alloy dry coolers in this environment for 30+ years appears to be a reasonable prospect.

Neg. No.
4K207B

2.2X

FIGURE 1. Aluminum Fin After 18 Years of Exposure to a Rural, Arid Environment. Fin Was Bonded to Tube by Solder (Dark, Finger-Like Areas Originating on Fin Lower Edge).

Neg. No.
4K207K

300X

FIGURE 2. Metallographic Cross-Section of Aluminum Alloy Fin Shown in Figure 1 Indicating Minor Corrosion. Maximum Pit Depth is 0.3 Mil ($\sim 8\mu\text{m}$).

Neg. No.
3F-1

FIGURE 3. Aluminum Fin Removed from a Gas Pipeline Compressor Engine Cooler after Exposure to Rural, Humid Environment Near the Gulf Coast for 15 Years - at about 130°F (~54°C). Surface Shows Little Corrosion.

Neg. No.
3F-2

1000X

FIGURE 4. Aluminum Fin Exposed to Rural, High Humidity Environment for 15 Years. 0.12 mil (3 μ m) Oxide Thickness Covering 0.14 Mil (3.6 μ m) Maximum Pit Depth.

Four one-foot finned tube specimens (Fig. 5) were placed in various locations at this station in July 1975. These samples consisted of steel tubes completely covered by extruded alloy 6063 aluminum fins. The specimens were mounted in the following locations:

- Tube #1 - In the hot (130°F, 54°C), flowing air above one cooler;
- Tube #2 - In the cool, incoming air below the cooler, not washed when the cooler was washed;
- Tube #3 - In the cool, incoming air below the cooler, washed when the cooler was washed;
- Tube #4 - On the site boundary fence.

Samples were taken after one year and again at two years. The most corroded and soiled specimens were those placed beneath the cooling coils in the cool incoming air (Fig. 6). The particular environment of each tube is summarized in Table 3.

TABLE 3. Summary of Environments and Specimens Placed at a Gas Compressor Station in a Rural, Humid Gulf Coast Location

<u>Tube Number</u>	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>
Location	Above Cooler	Below Cooler	Below Cooler	Site Fence
Temperature	130°F (54°C)	Ambient	Ambient	Ambient
Detergent Washing	Unknown	Not Intentionally	Yes	No (Rain Only)
In Flowing Air	Yes (Hot)	Yes (Cool)	Yes (Cool)	No
Contaminant Deposition	Slight	Mild	Mild	Slight
First Year Corrosion Evaluation	Slight	Minor	Mild	Slight
Second Year Corrosion Evaluation	Slight	Moderate	Severe	Minor

(Slight < Minor < Mild < Moderate < Severe)

FIGURE 5. Tube Specimen (Al Fins, Steel Tube) Similar to Specimens Installed at Two Gulf Coast Gas Compression Stations.

2X

FIGURE 6. Specimen Surface after Two Years of Exposure at Ambient Temperature in a Rural Humid Environment. Top and Bottom are Opposite Sides of Same Fin Showing Different Amounts of Contaminant on Rim.

A rim section of tube #1 is shown in Figure 7. The high temperature and small contaminant build-up has resulted in slight corrosion. Figure 8 shows a rim section of tube #4. This tube was not washed with detergent nor was it in flowing air. This has resulted in slight contaminant deposition build-up and slight-to-minor corrosion is visible. Note absence of corrosion in crevices presumably caused in forming operations. Where contaminant build-up has been facilitated by the tube being in flowing air and occasionally washed with detergent, then severe corrosion results at ambient temperature as shown in Figure 9. All second-year specimens were corroded more than first-year specimens. Corrosion on the upper surfaces had progressed substantially during the second year. On all specimens surface pitting was evident in places. Some sub-surface corrosion was noted, but only on the ambient-temperature specimens, subject to spray from cooler cleaning operations. However, participation of the detergent in the severe sub-surface corrosion is not verified. In fact, the specific causes of the corrosion on samples numbered 2 and 3 is not clear.

A SEM micrograph (Fig. 10) is shown of a specimen from tube number 3 after one year of exposure. The grain boundaries were high in silicon and sulfur content as determined by microprobe analysis. Surface contamination was also high in silicon and sulfur on the ambient-temperature specimen showing advanced corrosion. Sand and dirt may account for the silicon on the surface; but the source of sulfur contamination is unknown. Aluminum alloy 6063 is expected to have silicon at the grain boundaries as was detected by the SEM microprobe analysis. The X-ray fluorescence intensities are provided, and the peak heights are roughly proportional to the weight percent of the element, demonstrating a sulfur gradient though not identifying the sulfur species.

In the samples taken the second year, the most corroded specimens were again those from tube #3, in the cool, incoming air below the cooler, washed when the cooler was washed with an industrial detergent. The effect of the washing is particularly evident in that the bottom edges of the fins are very corroded and far more soiled than the top surfaces. This could result from drainage of the detergent solution to the bottom of the fin. Whether or not the detergent is aggressive to the aluminum is unclear. Corrosion has completely

Neg. No.
4M1090A

200X

FIGURE 7. Aluminum Fin Exposed at Air Cooler Temperature (130°F, 54°C) for Two Years to a Rural-Humid Environment at a Gas Compressor Station in Mississippi, Near the Gulf Coast

Neg. No.
4M 1094A

200X

FIGURE 8. Aluminum Fin Exposed Only at Ambient Temperatures and Subjected Only to Rain Washing for Two Years at a Rural-Humid Environment

Neg. No.
4M 1092A

200X

FIGURE 9. Aluminum Fin Exposed Only at Ambient Temperatures - Subject to Spray from Cooler Cleaning Operations During Exposure for Two Years to a Rural-Humid Environment at a Gas Compressor Station in Mississippi Near the Gulf Coast

FIGURE 10. SEM Micrographs and Microprobe Analysis of an Al Alloy 6063 Fin Specimen Exposed One Year in a Rural Humid Environment.
a) General View of Area b) Specific Area where c) Analysis #1 of Surface Oxide and d) Analysis #2 of Internal Corrosion Product Were Taken

penetrated the bottom edge of the fin in places. The samples from the other two ambient temperature locations show very little corrosion after two years. The importance of this effect is that it serves to concentrate the soluble contaminants on the bottom edge of the fin and especially on the side away from the water source. The most troublesome contaminant, NaCl, may readily concentrate in this way, and could account, at least in part for the observed distribution and severity of corrosion.

4.3 INDUSTRIAL, ARID ENVIRONMENT

4.3.1 West Central Texas

A natural gas company in Texas employs dry coolers to cool compressor engine jacket water and oil cooling water in an industrial, arid environment. The station compresses so-called "sweet" natural gas; there is very little SO₂ or H₂S contamination in the plant area.

Fin specimens were taken from two operating coolers. The first had operated for about two years and consisted of aluminum fins wrapped onto 90/10 copper-nickel tubes. The surface of these fins was bright and corrosion-free. The second unit had been in operation for 22 years and was constructed of aluminum fins wrapped onto Admiralty brass tubing. The fins showed very little corrosion, principally some slight discoloration on the outer edges. A fin from the second unit (22 year) is shown in cross section in Figure 11; Figure 12 shows an oxide film thickness on the fin of about 0.05 mils. No pitting of these fins was observed, though some indents from mechanical damage are evident on Figure 11.

4.4 INDUSTRIAL, HUMID ENVIRONMENT

4.4.1 Ibbenbüren, Germany

The Preussag Power Plant at Ibbenbüren, Germany, is an indirect-cycle dry-cooled plant of the Heller-Forgo design. This design involves a carbon steel spray condenser with stainless steel nozzles, which inject cooled condensate into steam to condense it as it exits from the turbines. The condensate is pumped to the cooler to dissipate the heat absorbed from the steam. The tower has aluminum tubes and plate-type aluminum fins. The tubes are vertical and the fins are horizontal.⁽³⁾ A section of this tower is shown in Figure 13.

FIGURE 11. Aluminum Fins Wrapped on Admiralty Tubing Exposed for 22 Years to a Low SO_2 , Low S Atmosphere. 1) Metallographic Mounting Clip. 2) Outer Edge of Fin.

FIGURE 12. Oxide Thickness on Aluminum Fins Shown in Figure 11 is 0.05 Mil ($1.3 \mu\text{m}$). No pitting is evident.

The dry-cooled power station has serious fouling problems resulting from proximity to pulverized coal storage areas and wet cooling towers.⁽¹⁾ The situation is aggravated by the notched fins, which act as effective dirt traps. Since the aluminum Forgo-type fins cannot withstand cleaning by pressurized water, cleaning with pressurized air has been attempted several times with negligible effect. Removal of the bundles for cleaning may be necessary. The combination of fouling and corrosion has reduced the heat rejection capacity of the Ibbenbüren plant to 75% after eight years of operation.⁽²⁾ The fouling by coal dust is shown in Figures 14 and 15.

Examination of a fin/tube cross section reveals that severe corrosion has occurred, as shown in Figures 16, 17 and 18. However, corrosion occurred only under those regions covered by coal dust. Figure 16 shows that no corrosion occurred in the crevices between the fin + spacer, fin + tube, or spacer + tube (region A in micrograph).

Scanning electron microscopy and microprobe analysis (Figure 17) revealed a large variety of constituents in the coal dust. Chloride and sulfur appear to be potentially the most significant from the standpoint of corrosion. Sulfur and chlorine are found deep in the corrosion product, suggesting that they probably participated in the corrosion reaction.

The scale build-up on the water-side of the tube was 0.0007 in. (0.7 mil or 18 μm) (Figure 19), SEM microprobe analysis indicated that the scale has significant iron content, presumably due to corrosion product transport from the steel components in the circuit.

4.5 MARINE, MOIST ENVIRONMENT

4.5.1 Southern California Coast

Fin samples of 1100 series Aluminum were obtained from a compressor station on the southern coast of California. The fins had been in a moist marine environment up to 20 years. The rainfall is low (12 in./year, 30 cm/year), but the cooler is located ~1.4 km from the Pacific shoreland and is subject to frequent fogs and mists. The average humidity is 71 percent. The station operator reported that no corrosion problems were noted on the fins, but the steel supporting structures had corroded considerably. The air cooler is on line only about 25% of the time and is otherwise on cold stand-by.

Neg. No.
754693-13

SAMPLE 6A
PLANT: PREUSSAG AG POWER PLANT
LOCATION: IBBENBÜREN, GERMANY
SYSTEM TYPE: HELLER FORGO INDIRECT
TUBE FIN MATERIAL: ALUMINUM ALUMINUM
FIN TYPE: FORGO PLATE TYPE
COMMENTS: SERIOUS FOULING BY COAL DUST

0.32X

FIGURE 13. Section of Dry Cooling Tower from Ibbenbüren, Germany

Neg. No.
4K1042A

3.5X

FIGURE 14. Close-up of Coal Dust Fouling on Aluminum Plate-Type Fin.

Neg. No.
754693-3

FIGURE 15. Cooler Section Showing Alternate Layers of Al Plates and Spacers Stacked Around Al Tubes. Coal Dust fouling is evident.

Neg. No.
4K1042B

FIGURE 16. Metallographic Section Through Tube, Spacer, and Fin Plate on Section of Aluminum Cooling Tower. Note Severe Corrosion on Fins under Coal Dust and Lack of Corrosion on Inner Surfaces (Area A) Where No Coal Dust Was Present. For B, refer to Figure 17; for C, refer to Figure 18; and for D, refer to Figure 19.

FIGURE 17. a) SEM Micrograph Showing Locations of Microprobe Analysis (Area B of Figure 16). b) Analysis #1 of Fin Metal. c) Analysis #3 of Corrosion Product at Surface. d) Analysis #2 of Deep Corrosion Product

FIGURE 18. Close-up of Region C in Figure 16 Showing Severe Corrosion Under Coal Dust Deposit. Note: Etched View Shown in Figure 45.

FIGURE 19. Scale Build-up on Inner Wall (Water-Side) of Tube. Mean Thickness 0.7 mil (17.5 μm) (Region D of Figure 16).

Some paint was evident on the aluminum fins, presumably from overspray from painting of the steel supporting structures.

Corrosion was largely sub-surface (Fig. 20), resembling the corrosion found on other aluminum fins described in this report (e.g., Fig. 18). Corrosion of the fins appeared to be most severe near the tip. The amount of corrosion shown (Fig. 21) has not begun to noticeably influence cooler performance. However, whether the sub-surface corrosion is intergranular or transgranular has not been clearly established.

4.6 MARINE, HUMID, INDUSTRIAL ENVIRONMENT

4.6.1 Gulf Coast Area of Louisiana

A natural gas compressor station similar to that described in Section 4.1.2 is operated in a marine, humid, industrial atmosphere along the Louisiana Gulf Coast. A sulfur mine, processing plant and shipping dock are located about 3.5 miles (5.6 km) to the south; the prevailing wind blows northward from the sulfur plant to the compressor station. Oyster shells are used as a ground cover. Dust from the shells is present in the atmosphere, particularly during dry weather.

4.6.1.1 Corrosion of Original Dry Coolers

Four coolers of the unitized design were originally installed at this site, two in 1961 and two in 1963. Tubes were Admiralty, fins were aluminum, (1130 type aluminum alloy) solder-bonded to the tubes. These four units developed cooling problems starting about three years after installation, due to fin deterioration caused by corrosion. The fins on the lower banks of tubes came loose from the tubes. The corrosion was not restricted to the base but was sufficiently concentrated near the base that fin detachment occurred. However, solder did not appear to participate in the corrosion attack.

Figure 22 shows the appearance of the cooling fins on the top and bottom bank of tubes after 13 years of service. Gross corrosion is evident: the fins on the lower tube detached completely from the tube. Note that corrosion was much more severe on the lower tube bank which may have acted like filters in the induced draft.

Neg. No.
19-6

100X

FIGURE 20. Aluminum Alloy 1100 Fins Exposed for 20 Years in a Moist Marine Environment. Sub-surface corrosion is similar to corrosion found on other samples (e.g., Figure 18)

Neg. No.
19-1

100X

FIGURE 21. Sub-surface Corrosion, Concentrated Near the Tip of the Fin Shown in Figure 20

Figure 23 shows substantial corrosive attack near the solder joint, though evidently not involving the solder itself.* A close-up of the corrosion is shown in Figure 24 and Figure 25 is an etched view of a fin, showing the intergranular nature of the corrosion.

Scanning electron microscopy and microprobe analysis indicated that sulfur and lead were the major impurities at the grain boundary locations in the fins from the upper tube bank, while sulfur, lead, and calcium were present in the lower tube fins (Fig. 26).

A unit with extruded aluminum fins on Admiralty brass tubing has operated for nine years with the result that the Al fins underwent intergranular type corrosive attack at the outer periphery (see Fig. 27). Approximately 20% of the fin surface area was covered by corrosion products, predominantly at the outer edge of the fin.

Two units with wrap-on type fins on Admiralty tubing were operated for 4 and 5.9 years with the inlet/outlet temperatures at 125°F/115°F (52°C/46°C). Fins from both these units underwent severe intergranular type attack, with complete fin penetration in some areas. The attack was somewhat more intense at the base of the fin near the tube than at the outer periphery. Sixty to seventy percent of the fin surface area of the units was covered with corrosion patches, predominantly at the outer periphery (Figure 28).

4.6.1.2 Corrosion of Aluminum Finned Tube Specimens Placed at Site Discussed in Section 4.6.1

Four tube specimens were placed at the compressor station discussed in the preceding section. These tubes were extruded Al 6063 alloy fins on carbon steel tubes, of the same type shown in Figure 5 on page 14. These specimens were mounted in the following locations.

- Tube #1 - In the hot, flowing air above the engine cooling tubes
- Tube #2 - Below the cooling coils in the cool incoming air

* 80% Pb, 20% Sn solder alloy

Neg. No.
752079-1

.25X

FIGURE 22. Aluminum Fins after Exposure for 13 Years to a Humid Marine Environment (CaCO_3 , Cl and S Contamination). Fins detached from lower tube.

Neg. No.
4K 468A

8X

FIGURE 23. Metallographic Section Through a Tube from the Upper Bank, Refer to Figure 22. Shows corrosion along the length of the fin and not associated with the solder. 1. Tube. 2. Fin. 3. Solder. Area A is enlarged in Figure 24.

Neg. No.
4K 468F

FIGURE 24. Enlargement of
Region A in Figure 23
Showing Severe Attack
After 13-Year Ex-
posure to a Humid
Marine Environment

150X

Neg. No.
4K 473I

FIGURE 25. An Etched View of a Fin
in Figure 23 Showing
Intergranular Nature
of Corrosion

Etched Fin.
Etchant: Keller's Etch
Etch Time: 10 Sec Immersion

Admiralty Tube Metal

250X

FIGURE 26. SEM Micrograph and Microprobe Analysis of an Aluminum Fin Exposed for 13 Years to a Humid Marine Environment.
a) Micrograph Showing Analysis Areas. b) Analysis #1 of a Salt/Sulfur Crystal. c) Analysis #2 of a Sand Particle. d) Full Area Analysis. (Refer to Figures 22-25)

Neg. No.
4K 1037F

250X

FIGURE 27. Outer Edge of Fin Exposed for 9 Years to a Humid Marine-Environment. Note that Crevice Corrosion Did Not Develop in Extrusion Cracks at the Fin Tip.

Neg. No.
3C-1, -2

1X

FIGURE 28. Micrographs Showing Opposite Sides (Left and Right) of the Same Two Fins. Note Rim Build-up (Heavier on Left) and Corrosion at the Base of the Fin.

- Tube #3 - In the cool incoming air below the cooling coils of cooler closest to salt spray from Gulf of Mexico
- Tube #4 - Attached to plant headquarters building - control specimen at ambient temperature.

Specimens taken from the tubes after one year were examined metallographically and again after two years (Fig. 29 and 30).

The most discolored fins were those found beneath the coolers in the cold air stream (Fig. 31 and 33). These fins had the most salt, dirt, and particulate matter deposits. The lower coils would effectively act as filters in the updraft. Insufficient or ineffective washing, despite the 50 inches of rainfall, would allow a rapid deposit buildup. The more soiled fins also showed the most corrosion, perhaps due to poultice induced corrosion. These test specimens appeared very similar to those discussed in Section 4.2.1.

The corrosion was sub-surface, resembling the intergranular corrosion found on fins from the compressor station air coolers (Fig. 22-28). This is not surprising because the 6063 alloy is known to undergo intergranular corrosion with precipitation of silicon along the grain boundaries.⁽¹¹⁾ Scanning electron microscopy and microprobe analysis revealed that the salt-like surface deposits contained significant sulfur; sulfur was also present with silicon at the grain boundaries (Fig. 33). However, the chemical state of the sulfur is not clear. Silicon (probably sand) was also found on the surface. Chlorine was detected on the surface and in the corrosion products on the fin.

4.6.2 Rugeley, England

The central power station at Rugeley, England, includes an indirect-cycle dry-cooled, 120-MWe plant of the Heller-Forgo design, similar to the plant at Ibbenbüren.

The Rugeley plant has experienced serious air-side corrosion. The station is located at the site of a coal mine and is also adjacent to an ash sintering plant which makes light weight aggregate from the plant ash. Also, the dry tower is in close proximity to four evaporative towers and is subject to drift and spray from them. Within a short time after startup, serious

Neg. No.
4M 1150A

2X

FIGURE 29. Aluminum Alloy 6063 Fins Exposed for 2 Years to a Humid Marine Industrial Environment. Top Fin at Dry Cooling Tower Temperature Still Has Some Luster. Bottom Fin at Ambient Temperature in the Cooling Incoming Air is Heavily Contaminated.

Neg. No.
17DB

200X

FIGURE 30. Aluminum Fin Placed in a Humid-Marine Environment under an Atmospheric Cooler. Shows sub-surface corrosion after one year. Figure 33 is a close-up of Region A.

Neg. No.
4M 1147D

200X

a. Upper Fin Edge

Neg. No.
4M 1148A

200X

b. Lower Fin Edge

FIGURE 31. Aluminum Alloy 6063 Fins Exposed for Two Years to a Humid, Marine Industrial Environment. Both fin sections are from same tube (#3); a) fin edge from top of tube; b) fin edge from bottom of tube, showing greater corrosion caused by higher contaminant concentration on lower edge of fins.

Neg. No.
4M 1145A

200X

a. Operated at $\sim 115-125^{\circ}\text{F}$ ($46-52^{\circ}\text{C}$)

Neg. No.

200X

b. Operated at Ambient Temperature

FIGURE 32. Aluminum Alloy 6063 Fins Exposed for 2 Years to a Humid, Marine, Industrial Environment. a) Fin Held at Dry Cooling Tower Temperature. b) Control Fin Sample: at Ambient Temperature on Site but Away from Cooling System. Demonstrates Protection Provided by Operation at Dry Cooling Tower Temperatures.

a. SEM Micrograph

b. SEM Analysis #1

c. SEM Analysis #2

FIGURE 33. SEM Micrograph and Microprobe Analysis. a) Close-up of Region A in Figure 30. b) SEM Analysis #1 Metallic Area of Aluminum Fin. c) SEM Analysis #2 of Corrosion Product.

corrosion occurred in crevices between the cooling coil fins and the spacer collars. This corrosion eventually resulted in perforation of the tubes, resulting in air leaks to the steam condensate system. The problem is attributed to high humidity, evaporative tower drift and atmospheric pollutants, the principal active contaminants being moisture and chlorides. Despite the tight mechanical joints between the fins and spacer collars, moisture containing chlorides penetrated the minute crevices and set up active corrosion cells behind the collars, causing pitting and finally perforation of the aluminum tube walls. Moisture kept these cells active, and the bulky corrosion products distorted the tubes locally. The corrosion eventually became widespread on the weatherside tubes (outer tubes of bundles), particularly in coolers that had been out of service for a period.

Attempting to solve the Rugeley corrosion problem, an epoxy coating was selected as the best method to protect the coolers from air-side corrosion. At the present time, all of the cooling coils at the Rugeley Station have been treated with the epoxy coating. However, air-side corrosion of the cooling coils is still continuing; the more recent problems are attributed to a difference in coil design which introduced a collar which prevented adequate coverage by the epoxy coating, leaving a thinly-coated local area which remained vulnerable to air-side corrosion. A method has been developed for sealing the leaks at a very low cost; the procedure does not involve dismantling or down time.⁽¹⁾

Figure 34 shows a section of the Rugeley dry cooling tower. Figure 35 shows the spacing collar described above.

The scope of this investigation of aluminum as a dry cooling tower material is summarized in Table 4.

Neg. No.
754693-11

SAMPLE 5A
PLANT: CEBG RUGELEY STATION
LOCATION: RUGELEY, ENGLAND
SYSTEM TYPE: HELLER INDIRECT
TUBE/FIN MATERIAL: ALUMINUM/EPOXY-COATED ALUMINUM
FIN TYPE: FORGO (PLATE TYPE)
COMMENTS: PIN-HOLE LEAKAGE DUE TO CORROSION
RESULTING FROM CHLORIDE CONTAMINATION

0.36X

FIGURE 34. Section of Cooler from Rugeley, England, Removed for Examination. Unit is Epoxy-Coated.

Neg. No.
754693-2

Vulnerable
to Pitting

FIGURE 35. Close-up of Crevice Locations where Pinhole Leaks were Reported to Have Initiated.

TABLE 4. Scope of Dry Cooling Tower Materials Investigation^(a)

Environment	Rural		Industrial		Marine	
	Dry	Wet	Dry	Wet	Moist	Wet
Location	Washington Columbia Basin	Mississippi near Gulf Coast	Texas West-Central	Ibbenbüren, Germany	Southern California Coast	Louisiana Gulf Coast
Extent of Corrosion ^(a)	Mild	Mild	Mild	Moderate	Moderate	Severe
Alloy	(c)	Probably 1100 Al ^(b)	(c)	(c)	1100 Al	1100 Al
Type of Corrosion	Shallow Pitting	Intergranular	Shallow Pitting	Transgranular	(d)	Intergranular
Other Factors Involved	--	--	--	Coal Dust	--	Sulfur

- (a) Specimens were obtained from operating dry-cooled equipment at each location for aluminum fin metallurgical evaluation of corrosion.
- (b) Analysis revealed 0.3% Mg but otherwise was consistent with 1100 series alloys composition.
- (c) Unknown.
- (d) Sub-surface corrosion occurred; not clear whether attack is intergranular or transgranular.

5.0 LABORATORY EXPERIMENTS UNDER SIMULATED DRY-COOLED AND AMBIENT CONDITIONS

The morphology and relative amounts of corrosion caused by contaminants actually encountered in industrial use were studied under laboratory conditions. This was an effort to evaluate the relative effects of several selected contaminants in a controlled environment. Corrosion tests were conducted at both ambient and elevated temperatures.

Contaminants were tested singly and in pairs.

5.1 EXPERIMENTAL

5.1.1 Materials

A series of specimen coupons, 3/4" square and 1/16" thick, were cut from a sheet of Alcoa 1100-H14 series aluminum. Alloy composition is given as follows.

Wt Percent, Composition of Al Alloy 1100-H14			
<u>(Si + Fe)</u>	<u>Mn</u>	<u>Mg</u>	<u>Zn</u>
1.0	0.05	0.05	0.10

5.1.2 Environment

Nine of the coupons were held at a temperature above the dewpoint (58°C to 68°C). Five specimens were held at room temperature (~20°C), and the remaining five specimens were cycled between room temperature and operating temperature. All specimens were in covered petri dishes under a hood, which provided flowing laboratory air. The petri dish lids were raised sufficiently to allow a gap for air circulation. Maximum, mean and minimum average relative humidities for the duration of the experiment (June 1976 to August 1977) are tabulated below for Richland, Washington, where the laboratory experiment was conducted:

	<u>Maximum</u>	<u>Mean</u>	<u>Minimum</u>
Average of Monthly Relative Humidities (June 1976 to July 1977)	93	52	18

The Richland area is classified as desert, with average rainfalls of 6-8 in. per year. However, sprinkler irrigation and proximity to the Columbia River have some influence on the local humidity.

Ibbenbüren (Germany) coal (dusted from a specimen from an actual dry cooling tower section), sulfur, and NaCl; were the principal industrial contaminants selected for the laboratory test. These contaminants were discussed in an earlier section of this report (Section 3.0). About half of the coupons were tested with only a single contaminant. The remaining specimens were contaminated with NaCl and either a coal or sulfur. Other contaminants that were used in only a few specimens and tested only at the elevated temperature were NaSO₄ and Salinas, Utah coal. The contaminant(s) and environment(s) for each coupon are presented in Table 5. The relative severity of the corrosion is shown by the numbers, with zero indicating absence of corrosion.

TABLE 5. Environments, Contaminants and Relative Severity of Observed Corrosion on Aluminum Alloy 1100

<u>Contaminant</u>	<u>Elevated Temperature (~60°C)</u>	<u>Room Temp. (~20°C)</u>	<u>Cycled (20°→60°C)</u>
Blank (No Contaminant)	0	--	--
Salinas, Utah Coal	1	--	--
Ibbenbüren Coal	2	2	3
Na ₂ SO ₄	1	--	--
Sulfur	0	0	0
NaCl	3	7	2
NaCl and Salinas, Utah Coal	0	--	--
NaCl and Ibbenbüren Coal	4	1	9
NaCl and Sulfur	1	10	5

5.1.3 Results of Specimen Examination

After 405 days of testing, the specimens were mounted and examined metallographically. A relative evaluation of the amount of corrosion was made and is represented by the numbers given in Table 5. This is a visual subjective ranking of the corrosion observed on metallographic sections of the samples. The scale is from zero to 10. Zeros indicated that no corrosion was observed on metallographic samples at magnifications up to 1000X, and 10 is assigned to the sample which evidenced the most corrosion.

Chloride (NaCl) appears to be the primary cause of corrosion and this is not unexpected.⁽¹⁰⁾ Figures 36 and 37 show the effect of NaCl on aluminum in several environments. Elemental sulfur does not seem to be corrosive by itself (Fig. 38). The sulfur compound Na_2SO_4 caused only slight corrosion at the elevated temperature. Corrosion on specimens due to chloride when both S and Cl^- are present is illustrated in Figures 38 and 39, suggesting the possibility of a synergistic interaction.

In the generic sense, "coal" seems to have a corrosive effect on aluminum (Fig. 40). The amount of corrosion is expected to depend upon the chemical composition of the coal as well as the environmental conditions (Fig. 41). Again, chloride appears to enhance the corrosive effect when mixed with coal contaminants, particularly when the environment is cycled between elevated and ambient temperatures, allowing periodic moisture adsorption, judging from the Ibbenbüren coal samples shown in Figures 42 and 43 SEM microanalysis of the most corroded specimen ($\text{NaCl} + \text{S}$), indicated that there is a definite chloride gradient from the contaminant and increasing toward the corrosion interface. Sulfur was also detected deep in the corrosion zone through the species is not known. This is in keeping with previous observations that sulfur may be synergistic with chloride. Microprobe analysis are presented in Figure 44. The corrosion appears to be transgranular (Fig. 45).

Comparison of analyses for Ibbenbüren coal and Salinas, Utah coal, (Table 6), demonstrates the potential importance of chloride. Ibbenbüren coal has the higher chloride content and also causes greater corrosion.

Neg. No.
4M 1052B

250X

a. No Contaminants - Held at 60°C

Neg. No.
4M 1040C

250X

b. NaCl Contaminant - Held at 60°C

FIGURE 36. Aluminum Alloy 1100 Coupons Held at 60°C with (a) No Contaminants and (b) NaCl Contaminant after 405 Days

Neg. No.
4M 1042B

250X

a. Held at $\sim 20^{\circ}\text{C}$ - NaCl Contaminant

Neg. No.
4M 1041C

250X

b. Cycled between ~ 20 and $\sim 60^{\circ}\text{C}$ - NaCl Contaminant

FIGURE 37. Aluminum Alloy 1100 Coupons Contaminated with NaCl and (a) Held at $\sim 20^{\circ}\text{C}$, (b) Periodically Cycled Between $\sim 20^{\circ}\text{C}$ and $\sim 60^{\circ}\text{C}$, after 405 Days.

Neg. No.
4M 1034B

250X

a. Sulfur Contaminant Only - Held at 60°C

Neg. No.
4M 1044C

250X

b. Sulfur and NaCl Contaminant - Held at 60°C

FIGURE 38. Aluminum Alloy 1100 Coupons Held at 60°C and Contaminated with (a) Elemental Sulfur Only, and (b) Sulfur and NaCl after 405 Days.

Neg. No.
4M 1046B

250X

a. Held at $\sim 20^{\circ}\text{C}$ - Sulfur and NaCl Contaminant

Neg. No.
4M 1045B

250X

b. Cycled between ~ 20 and $\sim 60^{\circ}\text{C}$ - Sulfur and NaCl Contaminant

FIGURE 39. Aluminum Alloy 1100 Coupons Contaminated with Elemental Sulfur and NaCl and (a) Held at $\sim 20^{\circ}\text{C}$, (b) Periodically Cycled between $\sim 20^{\circ}\text{C}$ and $\sim 60^{\circ}\text{C}$ after 405 Days.

Neg. No.
4M 1034C

500X

a. Low Cl^- Coal - Held at 60°C

Neg. No.
4M 1037B

500X

b. High Cl^- Coal - Held at 60°C

FIGURE 40. Aluminum Alloy 1100 Coupons Held at $\sim 60^\circ\text{C}$ and Contaminated with Coal from (a) Salinas, Utah (Low Cl^-) (b) Ibbenbüren, Germany (High Cl^-) after 405 Days.

Neg. No.
4M 1047C

250X

a. Held at $\sim 60^{\circ}\text{C}$ - NaCl and Coal Contaminant

Neg. No.
4M 1049C

250X

b. Held at $\sim 20^{\circ}\text{C}$ - NaCl and Coal Contaminant

FIGURE 41. Aluminum Alloy 1100 Coupons Contaminated with NaCl and Coal from Ibbenbüren, Germany. a) Held at $\sim 60^{\circ}\text{C}$. b) Held at $\sim 20^{\circ}\text{C}$.

Neg. No.
4M 1039C

500X

a. Held at $\sim 20^{\circ}\text{C}$ - High Cl^{-} Coal Contaminant

Neg. No.
4M 1038B

500X

b. Periodically Cycled Between $\sim 20^{\circ}\text{C}$ and 60°C - High Cl^{-} Coal Contaminant

FIGURE 42. Aluminum Alloy 1100 Coupons Contaminated with High Cl^{-} Coal from Germany and a) Held at $\sim 20^{\circ}\text{C}$ for 405 Days, b) Periodically Cycled between $\sim 20^{\circ}\text{C}$ and 60°C for 405 Days

Neg. No.
4M 1048B

250X

a. Unetched

Neg. No.
4M 1048C

Etchant:
Keller's Etch

Etch Time:
10 sec immersion

250X

b. Etched

FIGURE 43. a) Unetched and b) Grain Boundary Etched View of an Aluminum Alloy 1100 Coupon Contaminated with NaCl and Coal from Ibbenbüren, Germany and Periodically Cycled Between $\sim 20^{\circ}\text{C}$ and $\sim 60^{\circ}\text{C}$ after 405 Days.

FIGURE 44. Aluminum Alloy 1100 Coupon Contaminated with S + NaCl and Held at $\sim 20^{\circ}\text{C}$. a) SEM Micrograph Showing where Analyses were Taken. b) Microprobe Analysis of Contaminant (Area 1). c) Microprobe Analysis of Corrosion Product (Area 2).

Neg. No.
4M 1048E

a. Grain
Boundary
Etch
(Keller's)

250X

Neg. No.
4M 1167B

b. Grain
Boundary
Etch
(Keller's)

250X

FIGURE 45. Comparison of Corrosion Observed on Aluminum. a) Laboratory Sample (NaCl + Ibbenbüren Coal, 405 Days Periodic Cycling between $\sim 20^{\circ}\text{C}$ and $\sim 60^{\circ}\text{C}$) b) Fin Section from Ibbenbüren, Germany Dry Cooling Tower. Corrosion Appears to be Transgranular in both Cases.

However, the relative amounts of other potentially corrosive species, such as sulfur compounds are not known. Figures 36-38 indicate the lesser importance of sulfur, unless it occurs in conjunction with chloride. Table 6 shows the sulfur analysis of the two coals.

TABLE 6. Analysis of Salinas, Utah and Ibbenbüren, Germany, Coals

	<u>Salinas, Utah Coal</u>	<u>Ibbenbüren Coal</u>
S	0.8%	<2%
Cl ⁻	0.0028%	0.15%
F ⁻	0.00349%	0.37%

5.2 CONCLUSIONS-LABORATORY EXPERIMENT

The laboratory experiment confirmed that aluminum fins exposed at dry cooling tower temperatures are far less prone to corrosion than identical materials exposed at ambient temperatures. Aluminum dry cooling tower materials are susceptible to corrosion in any environment which provides chlorides. The most obvious environment fitting this classification is the marine environment. But the Ibbenbüren coal analyses have shown that chlorides can also occur where coal dust is present. However, comparisons of two coals indicated large differences in chloride content.

The coal with the higher chloride content was also more corrosive to aluminum. Of major significance with regard to the aggressiveness of the corrosion is the amount of time that the system is off line. The corrosive effect of chloride is largely inhibited when moisture is not available. This would correspond to the system being on line and at a temperature above the dewpoint. Obviously, a constant source of moisture similar to that found in a marine environment (for example, wet cooling towers near the dry tower) would contribute to corrosion of the plant materials during periods when the plant is off line.

The laboratory studies suggested that elemental sulfur is not aggressive to aluminum, but combined with chloride, it appeared to act synergistically to accelerate corrosion. However, further work would be required to confirm the synergism.

The laboratory studies suggested that for some contaminants (Table 5) cycling between ambient and operating conditions may enhance corrosion.

The results of the laboratory test suggests that useful insights to dry cooling tower materials performance can be generated by this approach.

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