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Technical Memo

ARGONNE NATIONAL LABORATORY
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Argonne, Illinois 60439

MASTER

ANL/EES-TM-135

ATMOSPHERIC CORROSION OF BATTEN AND
ENCLOSURE MATERIALS FOR FLAT-PLATE
SOLAR COLLECTORS

prepared by

ECA, Inc.
Woodridge, Illinois

for

Energy and Environmental Systems Division
Argonne National Laboratory
under Argonne Contract No. 31-109-38-5621

September 1980

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FOREWORD

This report is one of a series of reports prepared by the staff associated with Argonne National Laboratory's Solar Reliability and Materials Program (SRMP). The SRMP, a major activity of the Energy Supply and Utilization Section of the Argonne Energy and Environmental Systems Division, is managed by R.M. Wolosewicz. This report was prepared by a subcontractor, ECA, Inc., and the principal investigators were C.P. Chen and C. Cheng. The program is sponsored by the Department of Energy (DOE) Office of Solar Applications for Buildings, Active Heating and Cooling Division, Field Application Branch; R. Hassett is the DOE Program Manager.

P.S. Chopra, Director
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Energy and Environmental Systems Division

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ATMOSPHERIC CORROSION OF BATTEN AND
ENCLOSURE MATERIALS FOR FLAT-PLATE
SOLAR COLLECTORS

by ECA, Inc.

ABSTRACT

As part of the Solar Reliability and Materials Program at Argonne National Laboratory, the atmospheric-corrosion-monitoring project is to assess the materials used for battens and enclosures for flat-plate solar collectors. Sensors at nine test sites have provided atmospheric data. Other data have been obtained by analyzing corrosion samples that were exposed for varying periods of time. This interim report summarizes the results of the first test period.

1 INTRODUCTION

This report summarizes the results of tests of some metal batten and enclosure materials for flat-plate solar collectors. The performance of sample coupons exposed to various climates can indicate likely materials, from a cost/performance standpoint, for use in solar collectors.

Atmospheric-corrosion monitoring is part of the Solar Reliability and Materials Program at Argonne National Laboratory, and the specific tasks were documented in Ref. 1. Atmospheric-corrosion monitoring relies on the sensors and the data-acquisition equipment installed as part of the National Solar Data Network (NSDN). Data were collected for analysis from nine of the NSDN sites. In this report the data are analyzed, and the degradation of materials caused by atmospheric corrosion is evaluated.

2 APPROACH

Atmospheric corrosion of metal is a discontinuous process attributed to the synergistic effects of humidity, temperature, and atmospheric constituents. Metal corrosion or weight loss occurs only in the presence of electrolyte layers that can produce anodic and cathodic reactions. The total weight loss of a metal coupon is the sum of the weight losses that occur during separate corrosion periods (i.e., periods of wetness).

2.1 DATA ACQUISITION

Fifteen NSDN sites were selected initially for the atmospheric-corrosion study (see Fig. 1). Site selection was based on (1) climate, (2) availability of data-acquisition channels, and (3) contractor cooperation. For various reasons, six of the sites were dropped. Field data are currently being gathered from the remaining nine sites.

Collected data include relative humidity (RH), ambient temperature, and corrosion current. Corrosion-current data are obtained at each site by a specially designed atmospheric-corrosion monitor (ACM) developed by Rockwell International (Ref. 2). The ACM makes possible in-situ monitoring of time of wetness and corrosion behavior. The ACM consists of a stack of copper and zinc plates (see Fig. 2). The monitor is mounted parallel to the solar-collector panels (see Fig. 3). During a time of wetness, the difference in potential between the copper and the zinc plates generates a galvanic current. The current is amplified by signal-conditioning equipment (see Fig. 2) and recorded by the Site Data-Acquisition System (SDAS).

All sensor data are transmitted via the SDAS to the central NSDN data-processing facility at Vitro Laboratories in Silver Spring, Md. There, site data are converted into data-engineering units and forwarded to ANL.

2.2 MONITORING STRATEGY

2.2.1 Coupon Preparation

Four types of 22-gage specimens are being tested: aluminum (6061), galvanized steel (G90), aluminized steel, and polyester-painted steel. The galvanized and aluminized steel were manufactured by hot-dipping sheets of 1008 carbon steel. For the painted-steel specimens, 1008 carbon steel was first coated with a chromate primer and then painted with a white polyester produced by Hanna Chemical Coatings.

The steel sheets were cut into 4-in. x 6-in. coupons, which were then degreased. The edges were left in as-cut condition to permit evaluation of edge effects on the galvanized- and aluminized-steel coupons.

The painted-steel coupons were prepared according to ASTM specification D1654-74. A scribe mark along the long axis of the coupon was made on a jig, using a lathe cutting tool having an included angle of 60 degrees.

Fig. 1 Atmospheric-Corrosion-Monitoring Sites

Fig. 2 Atmospheric-Corrosion-Monitor System

Fig. 3 Solar-Collector Panels and Corrosion-Monitoring Apparatus

After preparation, coupons were stored in an argon-gas-filled drum for protection against atmospheric effects prior to distribution to exposure sites.

2.2.2 Rack Installation

At the nine selected solar-energy demonstration sites, the coupons were mounted on racks as shown in Fig. 4. The complete assembly is arranged so that the rack is parallel to the solar-collector panels and is along their midline, as shown in Fig. 3. Each vertical column on a rack contains six coupons of the same material. Each horizontal row holds four coupons, each of different material.

Coupon racks were installed at each of the nine sites indicated in Fig. 1. There is one rack for each site except the IL site, where there are four racks. Racks at each site face south. An exception is the rack at site FL; this rack faces skyward. Tilt angles, in degrees from the horizontal, are given in Table 1.

Fig. 4 Coupon-Rack Assembly

2.2.3 Coupon-Exchange Schedule

Corrosion coupons are replaced at approximately three-month intervals. The exchange schedule is shown in Table 2. Figure 5 presents the exposure period for every coupon. For each site, approximate exposure times of 3, 6, 9, and 12 months are indicated on the horizontal axis. A vertical line above the indicated exposure time means that coupons were exposed at that site for approximately that length of time. An exposed coupon is identified by number to the left of (or above) the appropriate vertical line and across from the date on which that coupon was withdrawn. The shaded portion of the figure indicates those periods during which NSDN data were sent for analysis to Rockwell International. The time remaining in the 24-month evaluation period for the metal coupons is shown in Fig. 6.

Table 1 Tilt Angles of Coupon Racks

Site	Tilt Angle (degrees from horizontal)
AL	30
CA	45
IR	30
FL	0
NC	45
IA	50
IL	45
MA	57
WI	50

Table 2 Coupon-Exchange Schedule

Site	Date of First Coupon Installation			Replacement or Withdrawal Date											
				3rd Month ^a			6th Month ^a			9th Month ^a			12th Month ^a		
	mo	d	yr	mo	d	yr	mo	d	yr	mo	d	yr	mo	d	yr
AL	3	9	1979	6	8	1979	9	11	1979	1	14	1980	3	17	1980
MA	3	22		8	15		9	21		1	10		4	25	
FL	4	18		8	6		12	11		2	29		4	17	
IL	7	11		10	10		1	10	1980	4	10				
WI	7	12		10	12		1	11		4	15				
IA	8	22		11	19		2	21		5	19				
IR	9	21		1	3	1980	3	24							
CA	9	24		1	3		3	20		6	12				
NC	10	10		1	10		4	18		7	8				

^aApproximately.

Fig. 5 Coupon-Exposure Diagram

Fig. 6 Schedule for Additional Exposure Time

2.2.4 Coupon Evaluation

To evaluate the atmospheric-exposure effects on the withdrawn coupons, the aluminum and galvanized-steel coupons were cleaned or descaled according to ASTM standard procedure G1-72. The painted-steel coupons were evaluated according to ASTM specification D1654-80.

Weight-loss data on galvanized steel and aluminum are presented in this report, and the evaluation results for painted steel are also included. However, descaling the aluminized-steel coupons was not completed because of time constraints. Results for these coupons will be included in the final report.

2.2.5 Methodology for Analysis

The Rockwell ACM made possible the correlation of galvanic current with time of wetness, relative humidity, and ambient temperature. These data can also be correlated with weight-loss data from test coupons exposed on the rack adjacent to the ACM. The combined results indicate the corrosion rates of various materials as functions of relative humidity, time of wetness, temperature, and atmospheric constituents at each site. The task of data analysis for the nine sites was subcontracted to Rockwell International.

3 RESULTS AND ANALYSIS

3.1 FIELD DATA

For sites AL, CA, IR, FL, MA, WI and IL, atmospheric-corrosion field data were available from December 1, 1979, to May 1, 1980; data were not available for site NC prior to March 1, 1980, or for site IA prior to January 1, 1980. The period within which tapes containing field data were available is indicated in Fig. 5 by shading. Figure 5 also includes the coupon-exposure periods; weight-loss data were available for these exposure periods. Comparing the availability of the weight-loss data and the availability of the field data makes it apparent that a direct full-scale data analysis is not possible at this time.

Efforts were made to process the NSDN data tapes to determine field-data trends separately for each site. However, it was found that only 70% of the needed information for the period Dec. 1, 1979, to May 1, 1980, was on the tapes. An example of the tape data is shown in Fig. 7 for site IR. There is a close relationship between RH and galvanic current. Monthly averages for the data are given in Table 3.

3.1.1 Galvanized-Steel Coupons

Two problems were encountered in evaluating the galvanized-steel coupons. A large amount of corrosion product accumulated on the exposed edges. The degree of edge corrosion was determined by gently polishing each of the four coupon edges. This corrosion accounted for 10-20% of the total weight loss for 60% of the coupons.

The other problem is that the top face of each coupon was exposed directly to rain and was thus subject to faster evaporation of moisture by the sun than was the bottom face. Therefore, the corrosion rates may not be the same for both sides.

Cleaning procedure G1-72 was followed to determine the amount of zinc lost as a result of exposure. The average amount of zinc coating before exposure was determined by dipping some coupons in hydrochloric acid; this showed that the average zinc coating weighed 4.42 g, about the same as ASTM-specified G90 galvanized coating from specification A525. The maximum zinc lost from atmospheric corrosion is 0.27 g, or 6%, for a 12-month coupon at site FL.

In Fig. 8, weight losses determined by cleaning the zinc surfaces are plotted with respect to the corresponding coupon-withdrawal dates for each of the nine sites. In Fig. 9, the data points are combined in one curve for each site, with the initial-installation date as the starting date. Each curve shows the general trend of weight loss typical of a given site. Results are quite scattered for some sites, probably due to seasonal climate changes; furthermore, steady-state corrosion was not reached at any of the sites.

Fig. 7 Field Data as Recorded Daily for Site IR

Table 3 Monthly Averages: Temperature, Relative Humidity, and Galvanic Current

Site	Quantity	1979	1980			
		Dec.	Jan.	Feb.	Mar.	Apr.
AL	Temp. (°F)	44.5	46.0	42.5	51.3	60.3
	RH (%)	60.1	64.8	58.0	62.0	58.5
	Current (μA)	2.50	4.46	4.15	6.54	6.35
CA	Temp. (°F)	51.7	51.2	56.3	53.3	57.8
	RH (%)	81.7	86.5	84.0	78.1	72.1
	Current (μA)	1.96	2.57	9.13	0.11	27.5
IR	Temp. (°F)	57.8	58.6	60.8	61.5	63.6
	RH (%)	64.8	83.0	87.7	82.4	76.5
	Current (μA)	5.41	18.7	23.5	93.3	7.81
FL	Temp. (°F)	63.4	62.7	57.3	68.7	71.9
	RH (%)	76.7	75.5	68.7	78.2	70.8
	Current (μA)	0.12	0.12	0.12	0.82	1.73
NC	Temp. (°F)	-	-	-	66.5	66.0
	RH (%)	-	-	-	72.2	72.9
	Current (μA)	-	-	-	21.1	23.1
IA	Temp. (°F)	-	20.3	20.3	32.0	48.6
	RH (%)	-	75.0	81.9	64.5	48.8
	Current (μA)	-	6.52	4.61	4.12	2.78
IL	Temp. (°F)	32.5	-	22.5	-	47.0
	RH (%)	81.8	-	85.0	-	65.0
	Current (μA)	3.85	-	2.33	-	4.12
MA	Temp. (°F)	32.7	29.9	24.2	33.6	46.1
	RH (%)	73.8	75.6	70.6	78.6	69.6
	Current (μA)	5.66	8.28	14.6	22.9	14.1
WI	Temp. (°F)	29.57	24.7	17.2	28.1	45.2
	RH (%)	84.27	90.8	89.2	84.3	74.7
	Current (μA)	3.91	5.79	3.44	3.80	2.90

Fig. 8 Weight-Loss Data for Individual Galvanized-Steel Coupons, by Site

Fig. 8 (Cont'd)

Fig. 8 (Cont'd)

Fig. 9 Combined Weight-Loss Data for Galvanized-Steel Coupons, by Site

Fig. 9 Cont'd

Fig. 9 Cont'd

Pitting was observed for most of the steel coupons at site FL. The pits were so deep that they penetrated the zinc coating and marked the steel coupon base (see Fig. 10). For these coupons, the number of pits ranged from two for the three-month coupons to five or six for the nine- and twelve-month coupons.

3.1.2 Aluminum Coupons

The problem of a possible difference in corrosion rates between the top and bottom faces, previously mentioned in connection with galvanized-steel coupons, also exists with aluminum coupons. However, edge effects do not exist with aluminum.

In Fig. 11, weight losses are plotted with respect to the corresponding coupon-withdrawal dates for each of the nine sites. The combined curves are shown in Fig. 12. Each curve shows the general trend of corrosion at a specific site. For aluminum, steady corrosion started at most of the sites after about four months. (This was not true for galvanized steel.)

An abnormally large corrosion rate was noted for aluminum coupons from site WI. Upon closer examination, it was found that the coupons were either chipped or abraded where they were held in place on the coupon rack by ceramic fasteners. The extent of mechanical wear was proportional to the time of exposure.

Pits were observed on most of the 12 coupons from site FL, but on only one out of five coupons from site IR and on one out of 32 coupons from site IL. At site FL there was an average of five pits for the three-month specimens, and more than ten pits were counted on the 12-month specimen. Pitting patterns on a nine-month corrosion coupon from site FL are shown in Fig. 13. Pitting was more extensive for aluminum coupons than for galvanized-steel coupons.

Fig. 10 Pitting on a Steel Coupon Base

Fig. 11 Weight-Loss Data for Individual Aluminum Coupons, by Site

Fig. 11 Cont'd

Fig. 11 Cont'd

Fig. 12 Combined Weight-Loss Data for Aluminum Coupons, by Site

Fig. 12 Cont'd

Fig. 12 Cont'd

Fig. 13 Pitting on a Nine-Month Aluminum Coupon at Site FL

In Florida, pitting was very extensive on aluminum coupons at site FL, but not at site NC. The difference is attributed to the fact that the coupons were horizontal at site FL.

On some coupons, the corrosion products -- presumably aluminum oxide -- could not be removed with chemical solutions. Subsequent rubbing with abrasive scouring powder was necessary to remove localized oxide spots. Consequently, additional error was introduced.

3.1.3 Painted-Steel Coupons

Table 4 gives, for painted-steel coupons, a rating scale based on the extent of paint loss (creepage) along the scribe. This table is derived from ASTM standard D1654 (1980). Table 5 shows the ratings for the painted-steel coupons from four sites. Three ratings are recorded for each coupon: one for minimum creepage, one for mean creepage, and one for maximum creepage. The table also indicates the number of isolated blister spots at the area of maximum creepage; if one or no blisters occurred, the distribution of less-serious discoloring is indicated.

Table 4 Rating Scale for Painted-Steel Coupons

Rating	Creepage	
	in mm	in mils
10	0-0.5	0-19.7
9	0.5-1.0	19.7-39.4
8	1.0-2.0	39.4-78.8
7	2.0-3.0	78.8-118.1
6	3.0-5.0	118.1-196.9
5	5.0-7.0	196.9-275.6
4	7.0-10.0	275.6-393.7
3	10.0-13.0	393.7-511.8
2	13.0-16.0	511.8-629.9
1	16.0+	630+

Information is available from all nine sites, but only the results for the scribed specimens from four sites are shown. They indicate that

Table 5 Corrosion Data for Painted-Steel Coupons from Four Sites

Site		Coupon Number ^a											
		01	02	03	04	05	06	07	08	09	10	11	12
	Creepage	Rating											
FL	min.	10	9	10	9	10	10	10	9	9	10	10	10
	mean	9	9	9	9	9	9	9	9	9	9	9	9
	max.	8	8	8	8	9	8	8	9	8	9	9	9
NC ^b	min.	10	10	9		10	10	10		9	10		
	mean	9	9	9		9	9	9		9	9		
	max.	8	8	7		8	8	9		8	8		
IA ^b	min.	10	10	10		10	10	10		10	10		
	mean	9	9	9		9	9	9		9	9		
	max.	8	9	9		9	9	9		9	9		
MA	min.	10	10	10	10	10	10	10	10	10	10	10	10
	mean	9	9	9	9	9	9	9	9	9	9	9	9
	max.	9	9	9	8	9	9	9	9	9	9	9	9
		Number of Blisters											
FL		11	12	0 ^c	10	12	15	23	19	32	4	3	0 ^d
NC ^b		37	32	25		44	41	5		29	52		
IA ^b		28	4	0 ^c		21	18	5		0 ^d	0 ^c		
MA		1 ^c	16	4	15	21	18	13	2	0 ^c	10	5	3

^aSee Fig. 5 for exposure period.

^bData for coupons 04, 08, 11, and 12 at this site not included in this report.

^cUniform discolored spots.

^dFew discolored spots.

polyester-painted steel would be very good material for outdoor use. Although areas near the scribe marks were covered with brown iron oxides, adhesion of the paint to the steel substrate was very good.

Little or no creepage was observed except on coupons from the two Florida sites (FL and NC). Maximum creepage for most sites ranged from 0 to 19.6 mils from the scribe mark. For nearly all of the painted coupons except those from the two sites in Florida, the rating numbers are 10, 9, and 9. Coupons from site NC showed the most creepage, with maximums of 39-78 mils. Since more data are needed to compare the behavior at all sites, only a general comparison can be made.

3.2 DATA ANALYSIS

Weight-loss results for galvanized steel and aluminum, together with a copy of all the field-sensor data tapes, were sent to Rockwell International Science Center for data analysis. To date, Rockwell International has not completed the analysis. Therefore, only a tentative analysis based on weight-loss data has been made.

The following comparisons are based on the data for aluminum, galvanized-steel, and painted-steel coupons. A rank was determined for each material at each site by using the nine-month weight-loss data (available for most sites), as shown in Fig. 14; a uniform corrosion rate was assumed. The ranks are shown in Table 6. The set of ranks assigned to each test material cannot be used for comparing the materials; a judgement of the relative suitability of each material, based on corrosion data, is expressed in Sec. 4.

Painted steel appears to be satisfactory (rank 9, or 0-20 mils creepage) for 75% of the sites. Only at the Florida sites was it unsatisfactory (rank 1-2, or 40-80 mils creepage). Also, the ambient temperature appears to have more effect than the relative humidity on painted steel.

Similarly, the galvanized steel appears to be acceptable (rank 6-9, or 0.013-0.2 mil metal loss) for 75% of the sites. Again, at the Florida sites it is unsatisfactory. However, the data are insufficient to indicate how the uniform corrosion rates for galvanized-steel coupons are affected by site climatic conditions.

Aluminum is satisfactory only at site CA in California (rank 9, or 0.004-mil metal loss). At the remaining sites it is not as good. Again, the data do not indicate how relative humidity and ambient temperature affect the uniform corrosion rate. In general, salty sea air probably increases both the uniform corrosion rate and/or the pitting rate for all three materials tested.

Fig. 14 Determination of Rank for Aluminum and Galvanized-Steel Coupons

Table 6 Coupon Rank and Climatic Conditions

Site	Rank, by Material			Climatic Conditions ^a	
	Painted Steel ^b	Galvanized Steel ^c	Aluminum ^c	RH (%)	Temp. (°F)
CA	9	9	9	81	54
IA	9	8	5	68	30
AL	9	7	4	61	49
WI	9	7	--d	85	29
IL	9	6	5	77	34
MA	8	7	3	74	33
FL	2	1 ^e	1 ^e	74	65
NC	1	--f	2	73	66

^a Average from Dec. to Apr. (see Table 4).

^b Rank 9 = Rating 10-9-9, or 0-1.0 mm creepage; Rank 1 = Rating 9-9-7, or 0.5-3 mm creepage (see Table 5).

^c See Fig. 14.

^d Coupons abraded.

^e Pitting observed.

^f Data incomplete.

4 CONCLUSIONS AND RECOMMENDATIONS

- The field data revealed a close relationship between relative humidity and galvanic current. Detailed analysis of atmospheric-corrosion monitoring will be included in the final report.
- In general, the data are not sufficient to indicate how the corrosivity indexes of the three types of coupons (indicated by rank) are affected by climatic conditions, including the relative humidity and/or the ambient temperature.
- In general, both painted steel and galvanized steel appeared satisfactory for 75% of the sites, while aluminum appears better at the CA site than at any of the other sites. Comparing the three types of materials, it appears that polyester-painted steel is the best; the nine-month coupons have creepage of 0-40 mils paint loss along the scribe. Second best is the aluminum, with metal loss of 0.004-0.012 mil, followed by the galvanized steel, with zinc loss of 0.013-0.039 mil. Data on aluminized steel will be included in the final report.
- For aluminum coupons, steady corrosion started at most of the sites after about four months. However, steady-state corrosion was not reached at any of the sites for galvanized-steel coupons.
- It is recommended that we complete the evaluation on the corrosion behavior of metal coupons for 24 months at every site.
- It is recommended that more sites be included in the atmospheric-corrosion program, in order to cover different climatic conditions.

REFERENCES

- 1 *ANL Solar Data Project Plan*, ANL/SDP-TM-78-1 (Sept. 1978).
- 2 Mansfeld, Florian, Rockwell International, unpublished information (June 1979).