268
5/15/80
PAS

SERI/TP-641-653
UC CATEGORY: UC-62 DR. 1193

CONF-800604--17

RELIABILITY AND DURABILITY STUDY OF A THERMAL RECEIVER UTILIZING ASI TYPE 316 STAINLESS STEEL IN CONTACT WITH MOLTEN ALUMINUM

JOHN D. WEBB
STEVEN L. POHLMAN

MARCH 1980

TO BE PRESENTED AT THE
AS/ISES 1980 ANNUAL MEETING
PHOENIX, ARIZONA; JUNE 2-6 1980

PREPARED UNDER TASK NO. 3141.00

Solar Energy Research Institute

1536 Cole Boulevard
Golden, Colorado 80401

A Division of Midwest Research Institute

Prepared for the
U.S. Department of Energy
Contract No. EG-77-C-01-4042

DISCLAIMER

Printed in the United States of America
Available from:
National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road
Springfield, VA 22161
Price:
Microfiche $3.00
Printed Copy $4.00

023 (EM-3-1)
p. 1

RELIABILITY AND DURABILITY STUDY OF A THERMAL RECEIVER UTILIZING ASI TYPE 316 STAINLESS STEEL IN CONTACT WITH MOLTEN ALUMINUM

John D. Webb and Steven L. Pohlman
Solar Energy Research Institute
1617 Cole Blvd.
Golden, CO 80401

ABSTRACT

Compatibility of ASI Type 316 stainless steel with molten aluminum was studied to determine probable lifetimes of unprotected steel components exposed to the liquid aluminum used for heat transfer and storage in a solar receiver supplied as a part of a commercial dish/electric solar generator. Steel samples immersed in molten aluminum showed rapid growth of hemispherical pits accompanied by an exponential increase in weight loss with time. A simple geometric model for the pitting process was developed that correlated well with the data collected on weight loss. Using this model, rate constants for the dissolution process were determined at 978, 1033, 1088, 1144, and 1200 K, and an activation energy of 17.5 kcal mole^{-1} was calculated.

An expression for the rate constant was developed enabling use of the pitting model to predict failure time envelopes for steel receiver components at a given temperature. Maximum lifetimes of the steam coil and wall were predicted to be 94 and 172 hours at 978 K, respectively. Mean predicted lifetimes and lifetimes predicted at higher temperature were shorter. The model accurately predicted actual lifetimes of field and laboratory tested components.

Since failure of the steam coil could lead to a receiver wall failure and cause uncontrolled and possibly violent release of molten aluminum, a recommendation was made that such receivers be operated only at temperatures well below the melting point of aluminum.

1. INTRODUCTION

Point-focus distributed solar concentrators normally employ a cavity-type receiver mounted at the focus of a parabolic reflector. The receiver was designed to operate at temperatures up to 1255 K in order to deliver high-pressure steam to a turboelectric generator.

Figure 1 is a cross-sectional view of a typical receiver. The steam coil and the receiver walls were constructed of ASI Type 316 stainless steel. The cavity is fabricated from Inconel™ 600 alloy. Solar radiation focused by the reflector into this cavity heats the primary heat-transfer fluid, which, in turn, heats the steam coil.

Aluminum has been suggested as a good heat-transfer and storage medium for such solar receivers because of its high heat of fusion, high thermal conductivity, relatively low melting point, and availability. However, because iron and ferrous alloys are extremely soluble in molten aluminum (1,2,3), the reliability of such receivers at temperatures above the melting point of aluminum was questioned. Work by Ueda et al. (4) showed that at 973 K, steel dissolution is controlled by convective

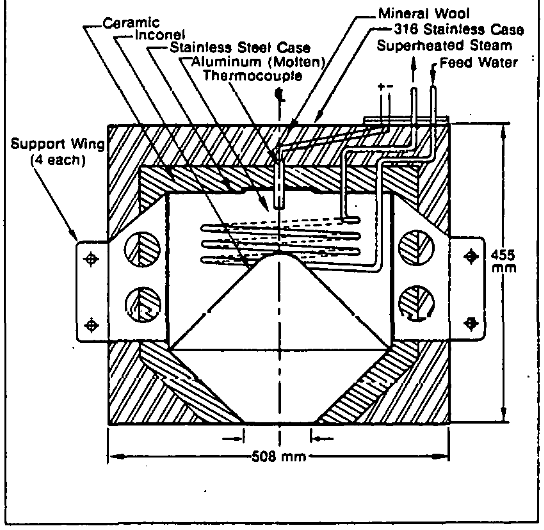

Fig. 1. Cross-sectional diagram of receiver tested

dissolution of iron into the molten aluminum, although at higher temperatures mass transfer or chemical reactions in the FeAl compound layer may be rate-controlling. If the chemical dissolution reaction controlled the rate of subsidence of the steel receiver surfaces, failure could be quite rapid and, under steam pressure, could present a serious safety hazard (5,6).

The goals of this study were to assess the rate and mechanism of attack of molten aluminum on Type 316 stainless steel; to predict useful lifetimes for the steel components of the receiver under exposure to molten aluminum through study of the temperature dependence of the attack rate; and to compare these predictions to data gathered from actual receiver tests.

2. PROCEDURE

The experimental work consisted of evaluating the resistance of Type 316 steel samples to molten aluminum as well as simulated and actual field testing of receiver assemblies. The steel samples were prepared as 25-mm square wafers 3 mm thick to simulate the receiver walls, or as U-bends, 2.5 cm I.D., of 0.635 cm (0.0) tubing to simulate the receiver steam coil. The wall thickness of the tested tubing was 0.124 cm; that of the tubing used in the receivers was 0.165 cm. The samples were weighted and then partially immersed in molten aluminum contained in aluminum crucibles placed in a muffle furnace. Exposure time and temperature were varied to yield data for the mechanistic and kinetic calculations. The samples were cleaned after testing by alternate immersion in strong NaOH and dilute HCl solutions, and reweighed to determine mass loss.

The first test series was conducted to determine the effect of wafer surface polishing on the initial attack rate. For this series, one side and one edge of three polished and three unpolished wafers were exposed to 30 g of molten aluminum at 1200 K for 0.50 hour.

The purpose of Test Series II was to determine the attack mechanism. One side and one edge of six polished wafers were exposed to 30 g of molten aluminum at 927 K for 1.16, 2.00, 2.92, and 4.09 hours. An attempt to remove the last two samples after 20 hour exposure was made, but the mass in these crucibles had solidified at 927 K.

Test Series III was performed to determine the temperature dependence of the attack rate. Pairs of polished wafers were exposed to 30 g of molten aluminum at 978, 1033, 1088, 1144, and 1200 K for 5.50 hours.

A fourth test series was performed to determine the effect of surface geometry on the attack mechanism. The curved portions of two tubing bends, as described above, were immersed in 100 g of molten aluminum at 978 K for 20.50 and 29.00 hours, respectively.

A limited failure analysis of actual hardware also was performed. To assess the extent of aluminum damage to a receiver field-tested on the point focus solar concentrator, 1 g samples were taken from two locations in a 2.7 kg solidified aluminum melt that leaked from the receiver during testing. The leak occurred at a weld failure in the receiver wall at the end of the second of two 3-hour test periods during which the temperature was maintained at 978 K. These samples were analyzed for iron content by means of atomic absorption spectrophotometry. A sample of cut aluminum similar to that used in the experimental series was also analyzed to provide a baseline.

As a parallel test, a direct assessment of dissolution damage was made through a visual inspection of a receiver subassembly tested between 6 and 12 hours at 1088 K. This hardware was tested in a diffusion furnace.

3. DISCUSSION OF EXPERIMENTAL RESULTS AND CORRELATION WITH MODEL ATTACK MECHANISM

Inspection of the steel test samples revealed that they were rapidly attacked by the molten aluminum. The extent of the damage was not evident until crystalline grey deposits observed at the iron-aluminum interface were washed off the cooled samples. The rapid dissolution of the deposits in the caustic wash, accompanied by rapid evolution of hydrogen gas, indicated that the deposits were high in aluminum and probably were similar to the iron-aluminum interfacial alloys described by Ueda et al. (6).

After removal of the alloy layer from the Test Series I coupons, small pits were observed on all exposed surfaces. No significant difference in initial weight loss between the polished and unpolished coupons was noted. All square coupons used in subsequent tests were polished.

In Test Series II, coupons were exposed to molten aluminum at 1200 K for up to 4 hours. Pitting was observed on all samples tested in this series. The pits were barely noticeable near the edges of the sample exposed for 1.16 hours. At 4.09 hours, the pits had nearly penetrated the 3-mm thick sample. In this test series, only one side and one edge were exposed to the aluminum.

Close inspection of the attacked samples revealed that the pits were roughly hemispherical, especially during the early stages of attack, and that virtually no attack occurred between pits. These observations indicate the presence of discrete initiation sites for attack on the steel surface.

Results of Test Series III indicate that the rate of attack was strongly dependent on temperature. Evidently, the resistance of the interfacial boundary layer to diffusion was negligible, and the rate of steel dissolution was controlled only by temperature and by the area available for attack (7). The dissolution model developed by Webb et al. (8), correlating the growth of n spherical pits to total sample weight loss, therefore, was applicable to the data collected.

$$W_T^{1/3} = n^{1/3} K_2 t \qquad (1)$$

Data on weight loss for the Series II wafers dissolved at constant temperature in molten aluminum were fit to the above equation by performing a linear regression. A value for $n^{1/3} K_2$ of 0.278 $g^{1/3} h^{-1}$ was determined from this set of data. This result was used to generate the sample weight loss curve that appears as Fig. 2. The exactness of fit is a strong indication of the validity of the pitting model when applied to predict initial attack rates.

To obtain an exact value for K_2, values for n were obtained by a visual count of initiation sites on the various types of sample surfaces. A summary of these results is given in Table 1.

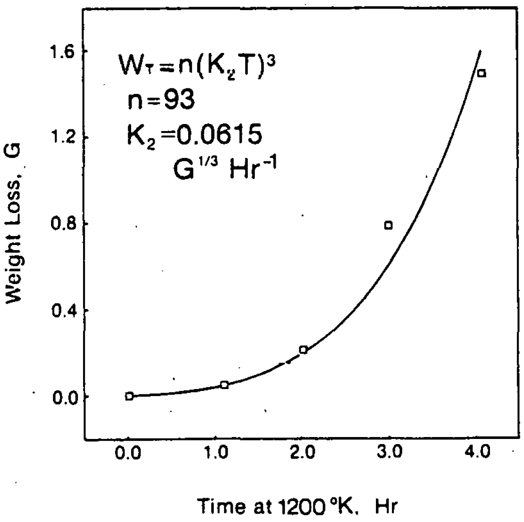

Fig. 2. Fit of pitting rate model to steel coupon weight loss data (correlation coefficient of linearized data = 0.99)

Table 1. INITIATION SITE DENSITY FOR VARIOUS SURFACE TYPES

Steel Surface Type	Site Density, n cm^{-2}
Polished, flat	10.5
Outer surface, close return tubing bend	24.0
Machine-cut edge	36.0

These results, and the weight-loss data gathered from Test Series II and III, were used in Eq. 1 to determine K_2 at 978, 1033, 1088, 1144, and 1200 K. Figure 3 is an Arrhenius plot of the ordered pairs (1/T, ln K_2), where T is temperature in Kelvin. From the intercept and slope of this line, the values for the pre-exponential factor A, 82.2 $g^{1/3}$ h^{-1}, and the activation energy E, 17.5 kcal mole^{-1}, in the Arrhenius expression for the rate constant K_2 were obtained. The value of 17.5 kcal mole^{-1} is consistent with other values reported (7) for chemically controlled reactions at a solid/liquid metal interface.

A general expression for K_2 can thus be written:

$$K_2 = 82.2 \exp^{-17,500/RT} \ (g^{1/3} h^{-1}) \qquad (2)$$

Much of the scatter in the points plotted in Fig. 3 can probably be attributed to the fairly large variations in the number of attack sites (n) on the individual test samples. However, the correlation coefficient for the fit is quite high, a strong indication that the assumption of linearity is correct. Solutions for Eq. 2 at the test temperatures are presented in Table 2.

The confidence limits for K_2 presented above can be used to estimate the failure envelope for various steel receiver components. A conservative assumption that failure occurs as a result of unidirectional attack when pit depth r equals component thickness x was made. The equation giving the depth of a single pit (7) is:

$$r = K_2 t [3/(2\pi\rho)]^{1/3} \qquad (3)$$

where ρ is the density of the solute in gm cm^{-3}. Substituting x for r in Eq. 3, and solving for t, which is now the estimated time to failure of a steel component immersed in molten aluminum, gives the following result:

$$t = x\{[3/(2\pi\rho)]^{1/3} K_2\}^{-1} \qquad (4)$$

Solutions of this equation using the values for K_2 in Table 2 above are presented in Table 3. These solutions represent the estimated failure envelope of each receiver component tested. Actual failure times found in Test Series IV and in tests of actual receiver modules are presented for comparison. Correlation between actual and predicted failure times was generally good. In the receiver modules tested, pitting attack occurred only on the steel surfaces. The Inconel™ 600 surfaces exposed to molten aluminum showed uniform attack. Analysis of the aluminum leaked from the receiver tested on the point-focus reflector showed amounts of iron consistent with model predictions based on the time duration and temperature for which the test was conducted and the area and type of the internal steel surfaces of the receiver.

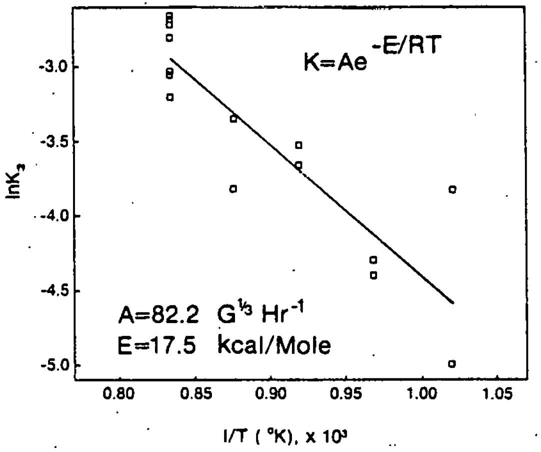

Fig. 3. Arrhenius plot showing dependence of the pitting rate constant K_2 on temperature (correlation coefficient = 0.89)

4. CONCLUSIONS

From the results presented above, it was concluded that aluminum-filled steel receivers are not safe to operate above the melting point of the aluminum heat-transfer medium. At temperatures slightly above the melting point of aluminum, dissolution is predicted to cause the receiver to fail within 100 operating hours. Mean time to failure will be much less. The calculated activation energy is moderately high (17.5 kcal $mole^{-1}$), and therefore each 55 K increase in operating temperature over the range 978-1200 K reduces predicted component lifetimes by about 40%. The accuracy of the model in predicting actual failure events reinforces these conclusions.

Since the growth of individual pits proceeds regardless of the number of attack sites present, it is considered unlikely by the authors that any coating will be found which would give complete protection over the wide variations in temperature encountered during receiver operation. Therefore, it is recommended that this type of receiver be operated only at temperatures below the melting point of aluminum.

5. ACKNOWLEDGMENT

Proof testing of thermal receivers was performed by the SERI Field Testing Team at the SERI Interim Field Testing Site. The support and cooperation of the team members, particularly Mark Bohn, Charles Benham, and Dean Stansbury, is gratefully acknowledged by the authors.

6. REFERENCES

(1) Ec Cent de Lyon, Ecully. MEM. SCI. REV. METALL, 72(11), 815-22 (1975).

(2) Fegel-Farnholz, O. et al. "Behavior of Carbon and Alloy Steels in Contact with Molten Aluminum," ALUMINUM, 5(8), 496-998 (1969).

(3) Lelby, Clare C.; Ryan, Thomas C. Thermophysical Properties of Thermal Energy Storage Materials - Aluminum, Air Force Cambridge Research Laboratories, (1973).

(4) Ueda, Y. et al. "Dissolution of Ferrous Alloys into Molten Aluminum," J. JPN. INST. MET. 42, 549-55 (1978).

(5) Rengstorff, G. W. P. et al. Review of Knowledge on Explosions Between Molten Aluminum and Water. Batelle Institute, (1969).

(6) Hess, Paul D.; Brondyke, Kenneth J. "Molten Aluminum-Water Explosions," MET. PROG., 93-100 (1969).

(7) Habashi, Fathi. "Extractive Metallurgy," 1, 143 (1969).

(8) Webb, John D.; Pohlman, Steven L. Reliability and Durability Study of a Thermal Receiver Utilizing ASI Type 316 Stainless Steel in Contact with Molten Aluminum, SERI/TR-31-338, Solar Energy Research Institute, Golden, Co, (1979).

Table 2. DISSOLUTION RATE CONSTANTS PREDICTED BY REGRESSION ANALYSIS AS A FUNCTION OF TEMPERATURE, WITH 95% CONFIDENCE LIMITS

Temperature (K)	Predicted K_2 $(g^{1/3}\ h^{-1})^2$	Upper Confidence Limit of K_2	Lower Confidence Limit of K_2
978 (1300°F)	1.00×10^{-2}	2.31×10^{-2}	4.47×10^{-3}
1033 (1400°F)	1.61×10^{-2}	3.47×10^{-2}	7.45×10^{-3}
1088 (1500°F)	2.47×10^{-2}	5.23×10^{-2}	1.18×10^{-2}
1144 (1600°F)	3.69×10^{-2}	7.81×10^{-2}	1.74×10^{-2}
1200 (1700°F)	5.28×10^{-2}	1.13×10^{-1}	2.47×10^{-2}

Table 3. FAILURE ENVELOPES FOR THREE STEEL RECEIVER COMPONENT TYPES PREDICTED AT THE 95% CONFIDENCE LEVEL

	Failure Time (h)											
	Tubing[a]				Tubing[b]				Receiver Wall[c]			
Temperature (K)	Max.	Min.	Mean	Actual	Max.	Min.	Mean	Actual	Max.	Min.	Mean	Actual
978 (1300°F)	71	14	32	29	94	18	42		172	33	77	6[d]
1033 (1400°F)	43	9	20		57	12	26		103	22	48	
1088 (1500°F)	27	6	13		36	8	17	12	65	15	31	
1144 (1600°F)	18	4	9		24	5	11		44	10	21	
1200 (1700°F)	13	3	6		17	4	8		31	7	15	

[a] As used in lab testing (Test Series IV); wall thickness = 0.124 cm

[b] As used in the receiver; wall thickness = 0.165 cm

[c] Wall thickness = 0.3 cm

[d] Failure appeared to be primarily stress-related.

Document Control Page	1. SERI Report No. TP-641-653	2. NTIS Accession No.	3. Recipient's Accession No.

4. Title and Subtitle Reliability and Durability Study of a Thermal Receiver Utilizing ASI Type 316 Stainless Steel in Contact with Molten Aluminum	5. Publication Date March 1980
	6.
7. Author(s) John Webb, Steve Pohlman	8. Performing Organization Rept. No.
9. Performing Organization Name and Address Solar Energy Research Institute 1617 Cole Boulevard Golden, Colorado 80401	10. Project/Task/Work Unit No. 3141.00
	11. Contract (C) or Grant (G) No. (C) (G)
12. Sponsoring Organization Name and Address	13. Type of Report & Period Covered Technical Report
	14.

15. Supplementary Notes

16. Abstract (Limit: 200 words)

Compatibility of ASI Type 316 stainless steel with molten aluminum was studied to determine probable lifetimes of unprotected steel components exposed to the liquid aluminum used for heat transfer and storage in a solar receiver supplied as a part of a commercial dish/electric solar generator. Steel samples immersed in molten aluminum showed rapid growth of hemispherical pits accompanied by an exponential increase in weight loss with time. A simple geometric model for the pitting process was developed that correlated well with the data collected on weight loss. Using this model, rate constants for the dissolution process were determined at 705, 760, 816, 871, and 927°C and an activation energy of 17.5 kcal/mole was calculated. An expression for the rate constant was developed enabling use of the pitting model to predict failure time envelopes for the steel receiver components at a given temperature. Maximum lifetimes of the steam coil and wall were predicted to be 94 and 172 hr at 705°C, respectively. Mean predicted lifetimes and lifetimes predicted at higher temperatures were shorter. The model accurately predicted actual lifetimes of field and laboratory tested components. Since failure of the steam coil could lead to a receiver wall failure and cause uncontrolled and possibly violent release of molten aluminum, a recommendation was made that the receiver be operated only at temperatures well below the melting point of aluminum.

17. Document Analysis

a. Descriptors Central Receivers; Stainless Steel-316; Stainless Steels; Inconel 600; Aluminum; Components; Heat Transfer Fluids; Testing; Dissolution; Pitting (Corrosion); Pitting Tests

b. Identifiers/Open-Ended Terms

c. UC Categories

62

18. Availability Statement National Technical Information Service U. S. Department of Commerce 5285 Port Royal Road Springfield, Virginia 22161	19. No. of Pages 7
	20. Price 4.00

Form No. 8200-13 (6-79)