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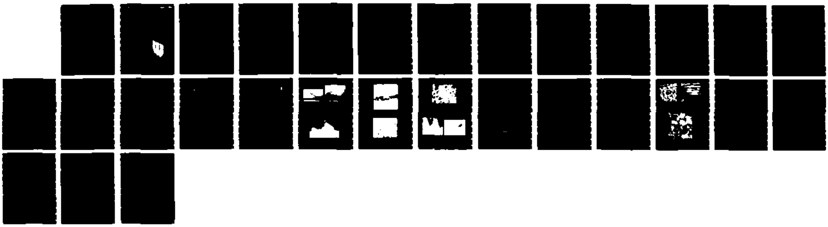

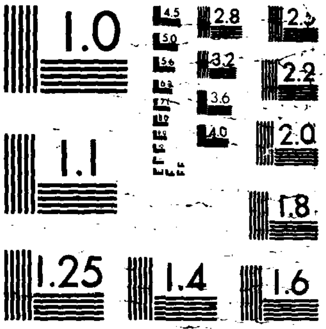
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US Army Corps of Engineers
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TECHNICAL REPORT M-86/17
September 1986
Underground Distribution Systems

Corrosion of Aluminum Jackets on Aboveground Heat Distribution Systems

by
Kirk E. Cooper
Ellen G. Segan

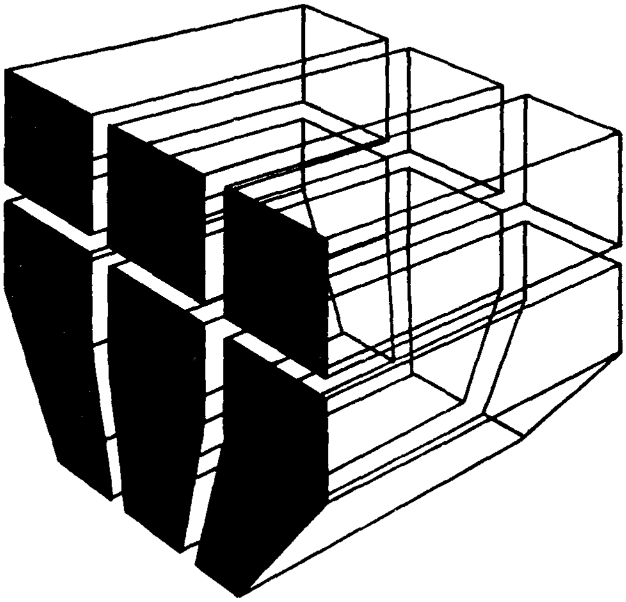
Severe corrosion of aluminum sheet used as a protective jacket on aboveground heat distribution systems has occurred at several military installations.

This study was conducted to determine the cause of this corrosion and to recommend revisions to guide specifications on the design, selection, and construction of insulation systems on aboveground systems.

Used and virgin materials were tested to determine the source of failure. It was concluded that the pitting corrosion of the aluminum resulted from leachable chloride ion in the insulation system. Heavy metal particles contributed to the attack by supplying additional cathode area.

A number of corrective measures were recommended to minimize corrosion in future construction:

1. Reduce the acceptable level of leachable chloride ion in the insulation components to 50 ppm,
2. Limit the amount of heavy metals in the insulation system,
3. Require a leaching test of insulation components to ensure that soluble binders have a pH of 6 to 7.5,
4. Design the insulation system to prevent excessive ingress of water from the outside and to prevent condensation of moisture on the inside of the aluminum jacket,
5. Design the vapor control system to prevent significant accumulation of water vapor, and
6. Avoid using a polyethylene coating on the aluminum jacket.



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4. Design the insulation system to prevent excessive ingress of water from the outside and to prevent condensation of moisture on the inside of the aluminum jacket.
5. Design the vapor control system to prevent significant accumulation of water vapor.
6. Avoid using a polyethylene coating on the aluminum jacket.

FOREWORD

This investigation was performed for the Office of the Chief of Engineers (OCE) under Operations and Maintenance, Army (O&MA), "Underground Heat Distribution Systems," FAD 86080017, January 1986. The work was performed by the Engineering and Materials Division (EM), U.S. Army Construction Engineering Research Laboratory (USA-CERL). The OCE Technical Monitor was Dale Otterness, DAEN-ECE-E.

Dr. R. Quattrone is Chief of USA-CERL-EM. COL Norman C. Hintz is Commander and Director of USA-CERL, and Dr. L. R. Shaffer is Technical Director.

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1 INTRODUCTION

Background

Severe corrosion problems have occurred at several military installations where new insulation and aluminum weather jackets were installed on aboveground heat distribution lines. In September 1982, insulation and jacketing on a section of line at the Naval Research Laboratory (NRL) were removed and replaced; within 10 days, corrosion blisters were observed on the weather jacket's exterior surface. Similarly, between June 1982 and October 1983, about 32 miles (51.2 km) of aboveground heat distribution line at the Redstone Arsenal were retrofitted with glass fiber insulation and aluminum alloy weather jacketing. The new insulation was placed directly over the old insulation and aluminum jacket. Three different configurations of insulation and vapor/moisture barrier were used. An inspection in October 1983 revealed corrosion blisters and pits in the aluminum jacket which subsequently perforated the jacket. Thus, it has become clear that there is a need for materials* and designs that will reduce this type of corrosion.

Objectives

The objectives of this investigation were to: (1) ascertain the cause of the observed corrosion of aluminum weather jackets, and (2) recommend revisions to applicable guide specifications governing the design, selection, and construction of insulation systems on aboveground systems.

Approach

Literature documenting other investigations of this problem was reviewed and analyzed. Used and virgin materials were then obtained from sites where there has been excessive corrosion and tested to determine the source of attack. Samples of pitted aluminum jacket were analyzed to determine residual aggressive elements, and insulation components from failed areas were analyzed for leachable chloride ion content. Based on the data obtained and the information documented in the literature, methods for mitigating this type of attack were recommended.

Mode of Technology Transfer

This study will impact the revision of Corps of Engineers Guide Specification (CEGS) 15705, *Underground Heat Distribution Systems;* Naval Facilities Engineering Guide Specification (NFGS) 15705, *Underground Heat Distribution Systems;* Air Force Pamphlet 88-44, *Underground Heat Distribution Systems;* and CEGS 15709, *Heat Distribution Systems Outside of Buildings–Concrete Shallow Trench Systems.* The information will also impact Federal Specifications (HH-B-100B, *Barrier Material Vapor (for Pipe, Duct and Equipment Thermal, Insulation),* and HH-I-515D, *Insulation Thermal (Loose Fill for Pneumatic or Poured Application): Cellulosic or Wood Fiber,* and Military Specifications MIL-I-24244A, *Insulation Materials, Thermal With Special Corrosion and Chloride Requirements,* and MIL-E-22344C, *Insulation, Pipe, Thermal, Fibrous Glass.*

2 LITERATURE REVIEW

The literature documents the results of several studies undertaken to address the problem of aluminum jacket corrosion. In an October 1983 investigation, NRL researchers removed several sections of corroded jacket to examine them and the underlying vapor barrier and fiberglass insulation.[1] Upon removal of the jackets, they noted a strong smell of acetic acid. The pitting observed was attributed to trapped moisture between the vapor barrier and the jacket interior.

A separate study of the same problem, conducted by Washington Testing, Inc., described results of corrosion tests that simulated service conditions of the aluminum jackets at NRL. It was concluded that the pitting attack was caused by moisture from the insulation system.[2] Both the insulation and the vapor

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*Materials specifications limiting impurities in insulation materials are addressed in Military Specification MIL-I-24244A, *Insulation Materials, Thermal, With Special Corrosion and Chloride Requirements* (Department of Defense [DOD] November 1976). Specifications for designing heat distribution systems are listed in the Appendix.

[1] A. J. Sedriks and R. A. Bayles, *Corrosion of Aluminum Alloy Jackets Surrounding Steam and Return Lines at NRL* (Naval Research Laboratory, October 1983).

[2] *Corrosion of Aluminum Jackets, Steam-Condensate Lines, NRL,* W. T. Project No. 83-5144-DC-2 (Washington Testing, Inc., January 1984).

barrier were found to contain leachable chloride ions, known to promote pitting of aluminum alloys.[3]

Washington testing then coordinated a field study at NRL[4] in which test sections of insulation, moisture barrier, and aluminum alloy jacket, in various configurations, were placed in service on steam and condensate return lines. Despite extensive sealing procedures, outside water entered the system. During shutdown, condensed and free water migrated by gravity to the inside bottom of the jacket. It was therefore concluded that the insulation degenerated upon becoming wet, as indicated by the loss of binders, and that corrosion would occur if water was present and the aluminum surface was not protected. However, this study did not determine the effect of the jacketing of aggressive binder constituents or the exact cause or mechanism of the pitting observed.

Energy-dispersive x-ray analysis (EDAX) of failed 1100 aluminum jacketing at Redstone Arsenal indicated large amounts of chlorine in the corrosion products.[5] Severe intergranular attack was attributed to the polyethylene moisture barrier on the inside of the jacketing which inhibited oxygen access and thus the formation of a protective oxide layer. Attack was enhanced by insoluble cathodic $FeAl_3$ particles present in the cold-worked structure. Leachates of insulation and corroded aluminum were mildly to strongly acidic, exhibiting sulfides and sulfides plus chlorides, respectively.

Laboratory reports indicated low chloride concentrations in the fiberglass insulation.[6] Less than 0.003 percent chloride was reported extracted from the insulation when it was boiled in water,[7] and extended x-ray absorbed edge fine structure (EXAFS) analysis of the corrosion product by the insulation manufacturer revealed no chlorine. Chemical analyses of leachates from samples of "New CT 500" fiberglass insulation, tested in accordance with ASTM C 871, MIL-I-24244A, and MIL-I-22344C[8] showed chloride ion concentrations at Redstone Arsenal to be less than 20 ppm in all samples tested. pH readings of the leachates were between 9.45 and 9.81.

Another report[9] concluded that moist alkaline conditions in the fiberglass were the initial cause of aluminum pitting. The residual corrosion product from inside the corroded jackets was analyzed and found to contain little or no known corrosive elements. Also, polarization studies indicated that distilled water at neutral pH and room temperature showed a tendency towards pitting corrosion. Thus, leachable constituents from the insulation were not required to produce corrosion, but they did enhance attack rates. It should be noted that the pH of the distilled water was adjusted by adding HCl or NaOH; however, the effect of the free chloride "ion" from the HCl–a strong acid which completely ionizes in water, resulting in an equal concentration of H^+ and Cl^-ions–was not accounted for in this work.

It is clear that the pitting corrosion observed in these systems would not have occurred unless trapped moisture served as an electrolyte. However, it must also be recognized that "immersed aluminum and its alloys have excellent resistance to attack by distilled or pure

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[3] *Corrosion, Volume 1: Metal/Environment Reactions,* L. L. Snrei, ed., 2nd ed. (Newnes-Butterworths, London, 1976); M. G. Fontana and N. D. Greene, *Corrosion Engineering,* 2nd ed. (McGraw-Hill, 1978). H. H. Uhlig, *Corrosion and Corrosion Control: An Introduction to Corrosion Science and Engineering* (John Wiley and Sons, 1967); G. A. W. Murray, "Artificial Pits for Quantitative Studies of Corrosion of Aluminum in Natural Waters," *Corrosion,* Vol 20, No. 10 (October 1964), p 329t; T. Hagyard and J. R. Santhiapillia, "Pitting Corrosion of Aluminum in Sodium Chloride Solutions," *J. Appl. Chem,* Vol 9 (June 1959); T. P. Hoar, *Discussions of the Faraday Society,* No. 1 (1947), p 299; M. A. Heine, D. S. Keir, and M. J. Prior, "The Scientific Effects of Chloride and Sulfate Ions on Oxide Covered Aluminum," *J. Electrochem. Soc.,* Vol 112, No. 1 (1965), p 24.

[4] *Report of Steam Pipe Insulation and Jacket Field Test Series–Naval Research Laboratory, Washington, DC,* W. T. Project No. 83-5144-DC-2 (Washington Testing, Inc., December 1984).

[5] *Metallurgical Investigation of Corrosion Found on Aluminum Jacketing Used to Cover the Insulation on Steam Piping* (Joseph D. Chodrow Metallurgical Services, December 1983).

[6] *"Results of Analysis" Report* (Schwarzkopf Analytical Laboratory, December 1983); Letter Report (CertainTeed Corporation, January 1984).

[7] *"Results of Analysis" Report.*

[8] "ASTM Standard C 871, "Chemical Analysis of Thermal Insulation Materials for Leachable Chloride, Silicate and Sodium Ions," *Annual Book of ASTM Standards,* Vol 04.06 (1983); Military Specification MIL-I-24244A; Military Specification MIL-I-22344C, *Insulation, Pipe, Thermal, Fibrous Glass* (DOD, 26 May 1981).

[9] *Final Report on Evaluation of Corrosion in Aluminum Steam Line Jackets,* Report No. 84-117-A (Metallurgical Consulting, Inc., September 1984).

condensate water . . ."[10] Several investigations[11] have shown that large amounts of chloride ions were present in the corroded systems. It is well known that chlorides in solution are a major cause of pitting corrosion in passive metals such as aluminum;[12] the chloride ions migrate to anodic sites where metal ions hydrolyze and form a protective oxide or hydroxide.[13] The deleterious effect of dissolved chlorides is enhanced by the presence of local galvanic cells resulting from metal particles or intermetallic phases. Figure 1 shows the mechanism of pitting involving these factors.

As suggested above, pH also plays a role in aluminum pitting. Mechanical defects in the protective oxide layer may act as sites for pit initiation in alkaline media.[14] Pits behave like occluded cells, in which pronounced decreases in pH and high chloride ion concentrations (often a seven to twelvefold increase over the bulk solution) are observed.[15]. In such a case, the potential inside the pit is in the active region (Figure 2), while most of the specimen may be in the passive region.

3 EXPERIMENTAL PROCEDURES

The U.S. Army Construction Engineering Research Laboratory (USA-CERL) performed tests on used and unused materials from NRL and Redstone Arsenal. These tests included microstructural examination, simulation of service conditions, determination of leachable ion concentrations in insulation components, and investigation of the effects of pH and chloride ion concentration on aluminum pitting.

Microstructure

Transverse sections of materials used in heat distribution lines at NRL and Redstone were mounted and polished through 0.05 micrometer Al_2O_3 to examine the microstructure and morphology of the pitting attack. An etching scheme[16] was used to identify the various phases.

Simulated Service Conditions

Unused materials from NRL were tested in simulated service conditions. Two samples of each of the following test materials were placed in beakers and immersed in about 200 mL of distilled water:

1. Sandwich of aluminum jacket (3000 m^2) between about 6-mm layers of fiberglass insulation.

2. Sandwich of aluminum jacket (3500 m^2), vapor barrier (Kraft paper toward jacket), and about a 6-mm thickness of fiberglass insulation.

All materials were handled with rubber gloves to prevent contamination. Samples were placed in distilled water and boiled for 5 minutes to ensure that the insulation was wetted completely. All beakers were covered and allowed to stand at room temperature for 3 weeks. At the end of this period, samples were removed, dried, and examined optically. These tests were repeated with lower water levels so that the aluminum was not submersed. By placing the specimens insulation-side down, wicking action of the insulation transported water up to the underside of the vapor barrier. These specimens were covered and kept at 60°C for 3 weeks.

Leachable Ion Concentrations

Tests to determine the concentrations of leachable ions in used and unused insulation and vapor barrier were conducted according to ASTM Standard C 871, except that solutions were boiled for 8 hours to ensure that all soluble ions were removed from the insulation and barrier samples.[17] Chicago Spectrographic Services (CSS) conducted additional tests of the vapor barrier. Samples were baked at 500°C, and spectrographic analyses were performed by CSS. Samples of used and unused aluminum jacket from both the Redstone Arsenal and NRL were also analyzed spectrographically.

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[10] *Corrosion, Volume I: Metal/Environment Reactions.*

[11] *Corrosion of Aluminum Jackets, Steam-Condensate Lines, NRL; Metallurgical Investigation of Corrosion Found on Aluminum Jacketing Used to Cover the Insulation on Steam Piping.*

[12] *Corrosion, Volume I: Metal/Environment Reactions;* M. G. Fontana; H. H. Uhlig; G. A. W. Murray; T. Hagyard; T. P. Hoar; M. A. Heine.

[13] T. P. Hoar.

[14] *Corrosion, Volume I: Metal/Environment Reactions.*

[15] T. Suzuki, M. Yamake, and Y. Kitamura, "Composition of Anolyte within a Pit Anode of Austenitic Stainless Steels in Chloride Solution," *Corrosion*, Vol 29, No. 1 (1973), p 18.

[16] G. L. Kehl, *The Principles of Metallographic Laboratory Practice* (McGraw-Hill, 1949).

[17] E. G. Segan, E. W. Blackmon, and C. Marsh, *The Effects of Minor Constituents in Calcium Silicate Insulation on the Corrosion of Underground Heat Distribution Systems,*" Technical Report M-346/A143378 (U.S. Army Construction Engineering Research Laboratory [USA-CERL], 1984), p 11.

Corroded specimens were examined with the scanning electron microscope (SEM) and EDAX. EDAX spectra were also taken of staples used to hold insulation together.

pH and Chlorides

The effects of pH and of chloride ions on the corrosion behavior of aluminum jacket material were investigated by immersing coupons for short times in solutions that varied in pH and chlorine ion concentrations and then examining them optically for attack.

4 RESULTS AND DISCUSSION

Figures 3 through 7 show the typical microstructures of the aluminum jacket materials. The large particles in Figure 3a were identified as Al-Cu-Fe-Mn particles. The structures in Figures 3a and 3b were found in material from both the Redstone Arsenal and NRL sites. The $FeAl_3$ particles present in the structure shown in Figure 3b were brought out by etching (Figure 4). Figures 5 through 7 show typical attack morphologies. Undercutting and blistering occurred in materials of both microstructures (Figures 5a and 5b). Figure 6 shows two pits that began at breaks in a 3/4-mil (0.019-mm) polyethylene coating. Crystallographic pitting of the aluminum layer of a vapor barrier is evident in Figure 7.

Both immersed samples containing the vapor barrier showed numerous pits of varying size and severity (Figure 8). The samples without the vapor barrier showed white deposits in discrete patches on the aluminum surface, but no apparent pitting. All coupons were stained or etched. Figure 9 shows a typical region of a nonsubmersed aluminum coupon following the test conducted with lower water levels. Here, preferential attack has occurred, likely following the grain structure of the aluminum.

Table 1 gives the results of tests to determine soluble ion concentrations and pH of leachates from the insulation and vapor barriers. Ion concentrations are reported in micrograms of ion per gram of sample (insulation or vapor barrier), or in weight (parts per million) of ion.

Spectrographic analysis of used and unused vapor barriers from NRL revealed large amounts (up to several atomic percent) of antimony, iron, zinc, and titanium. Trace amounts of other metals were also detected. Analyses of used and unused aluminum jackets (Table 2) identified alloys 1100, 3003, and 5005. These alloys, along with alloy 3105, are those most commonly used in insulation jacketing applications in heat distribution systems. Composition limits for several elements were exceeded on many of the jacket materials analyzed.

Figures 10a and 10b show typical samples of used jacket material; Figures 11a and 11b show the corresponding EDAX spectra. Figures 12 and 13 indicate other spectra demonstrating high chlorine concentrations in the corrosion products. Iron, titanium, and occasionally copper occurred near many corrosion pits. Corrosion product remaining on the aluminum-jacket side of the vapor barrier was high in chlorine (Figure 14). Figure 15 shows staples removed from the NRL system; their appearance and EDAX analyses suggest that carbon steel staples were used. CEGS-15709 requires insulation in shallow trench systems to be held in place with stainless steel straps.

Immersion tests in solutions of varoius pH and chloride ion concentration produced the following results:

1. Extensive pitting was observed in coupons immersed for short times in a 3.5 percent NaCl solution buffered to pH = 10. Little or no pitting was evident in the same solution buffered to pH = 4 (Figure 16).

2. Pitting attack occurred in distilled water buffered to pH = 10, but to a lesser degree than in the 3.5 percent NaCl solution (Figure 17). Incipient pitting and staining were present in coupons immersed in distilled water (pH = 9.2).

3. Coupons immersed for up to 120 hr in leachate from fiberglass insulation (pH = 8.3) showed no visible attack. This may be due to the inhibiting effect of sodium and silicate ions from the insulation.

4. Factory-applied condensate barriers on the aluminum surface were often loosened partially or fully after immersion for a short time. This was independent of pH or Cl^-.

These results suggest that excessive soluble chloride ion from insulation system components was the major source of the observed pitting corrosion in aboveground heat distribution systems. EDAX analyses of corroded specimens indicate that heavy metal deposits on the aluminum jackets supported the localized corrosion reaction. Large concentrations of chlorine were also frequently observed in EDAX spectra of corroded

Table 1

Results of Boiling Tests Showing pH and Chloride Ion Concentrations of Various Insulation System Components

Sample No.	Description	Soluble Cl^-(ppm)*	pH
1	Insulation from pitted region	222	8.55
2	Snap-on insulation from a cold line	224	8.91
3	Used insulation in a stained area	212	8.27
4	Used insulation from a badly pitted section	258	7.23
5	Vapor barrier from uncorroded section	496	5.27
6	Stained vapor barrier from corroded section	16500	3.89
7	Insulation from uncorroded section	87	6.16
8	Vapor barrier from a cold line	6800	5.53
9	Vapor barrier from heavily pitted section	4388	5.54
10	Insulation from heavily pitted section	230	8.52
11	Insulation from corroded elbow section	11410	7.38
12	Unused insulation	65	8.41
13	Unused insulation	588	6.8
14	Used insulation in a stained area	188	8.33
15	Used insulation in a stained area	11325	2.2
16	Unused vapor barrier	7200	5.62
17	Unused vapor barrier	643	—
18	Used vapor barrier from a stained area	10700	3.65
19	Used vapor barrier from a stained area	7975	-
20	Distilled water	3	5.22

*Chloride ion concentration.

Table 2

Compositions of Used and Unused Aluminum Jacket Materials

(Elemental concentrations are shown in weight percent.)

	Sample Number				
Element	No. 1	No. 2	No. 3	No. 4	No. 5
Silicon	0.10	0.19	0.29	0.34	0.28
Iron	0.70	0.53	0.60	0.70	0.39
Manganese	<0.05	0.46	0.73	0.46	0.20
Copper	0.07	0.12	0.23	0.32	0.22
Magnesium	<0.05	0.56	0.40	0.25	0.73
Zinc	<0.10	<0.10	<0.10	0.32	0.28
Titanium	<0.05	<0.05	0.08	<0.05	0.08
Lead	<0.05	<0.05	<0.05	<0.05	<0.05
Tin	<0.05	<0.05	<0.05	<0.05	<0.05
Nickel	<0.05	<0.05	<0.05	<0.05	<0.05
Chromium	<0.05	<0.05	<0.05	<0.05	<0.05

regions. The aluminum alloys used contained no unusual microstructural features or compositional anomalies that would reduce their resistance to pitting. Alkaline media also enhanced attack of the aluminum in a freely corroding situation (Figure 2).

One possible explanation of the observed corrosion is that water entrapped in the system became absorbed in the insulation. During passage of steam on high-temperature water through the carrier pipe, this moisture, carrying dissolved chlorides and heavy metals from the insulation, was driven out to the weather jacketing surrounding the system. Although soluble inhibitors such as sodium and silicate may mitigate corrosion of the aluminum initially, repeated cycles of wetting and drying can appreciably concentrate aggressive species on the inside aluminum surface and render inhibitors ineffective. In the presence of moisture that contains these concentrated aggressive species, rapid localized attack causes perforation of the jacket at certain sites.

5 RECOMMENDED GUIDANCE REVISIONS

Based on the data obtained in this study, several changes to MIL-I-24244A, MIL-I-22344C, and CEGS 15705 and 15709 are recommended to help reduce corrosion of aluminum jacketing in aboveground heat distribution systems.

Soluble Chloride Ion Content of Insulation Materials

In the proper environment, little or no chloride ion is needed to cause aluminum pitting. The only guidance which addresses the question of chloride content is MIL-I-24244A, which plots acceptable and unacceptable analyses on the basis of chloride versus sodium and silicate concentrations according to ASTM C 871. However, this specification is intended for insulation of stainless steel components and addresses primarily the problem of stress-corrosion cracking of these materials. Thus, its applicability to pitting in aluminum is questionable.

It is difficult to specify a minimum level of chloride ion so that no perforating pits will occur during condensation cycles and concentrate the chlorides. However, it is recommended that the guidance require a letter of certification from all suppliers of insulation and associated materials (vapor barriers, adhesives, etc.) stating that their products contain less than 50 ppm chlorides.

Boiling Times for Insulation

MIL-I-24244A and ASTM C 871 specify a 30-minute boiling period to leach unwanted constituents such as chlorides from insulation. However, an earlier investigation[18] found that chloride concentrations in the leachate of calcium silicate insulation increased with boiling time up to about 8 hours. A minimum boiling time of 8 hours should therefore be specified when testing for leachable constituents.

Heavy Metal Content

Any soluble heavy metals in a wet insulation system will cause problems with galvanic effects on aluminum. The letter of certification should include a statement that the materials supplied have a maximum heavy metal content of 10 ppm.

Vapor Barrier Staple Material

Monel, stainless steel, and carbon steel staples have been used or are recommended for fastening joints in vapor barriers. However, serious corrosion problems may arise if these are coupled galvanically with aluminum. There are potential differences of 1 V or more between aluminum and 304 stainless steel or Monel in an NaCl solution of pH = 10. Therefore, it is recommended that the guidance require aluminum staples. An alternative should be to require a self-sealing lap, which avoids the use of staples; this is already available on some products.

Selection of Jacket Material

Grades 1100, 3003, 3105, and 5005 aluminum are all rated as excellent in resisting corrosion. These materials are used almost exclusively in insulation weather jacket applications. Variations in the temper could have some effect on corrosion resistance, but is probably of minimal importance in the problems encountered to date. Guidance should require clear identification of each lot of jacketing, as well as a sample chemical analysis of that lot.

Design Considerations

Guidance should require a detailed calculation of the proper insulation thickness for each application, taking into account factors such as the emissivity of the weather jacketing to be used, operating and ambient temperatures, and thermal conductivity of the insulation. A step-by-step solution is included in the *Thermal Insulation Handbook*.[19] Moisture condensation on the

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[18] F. G. Segan, F. W. Blackmon, and C. Marsh.

[19] W. C. Turner and J. F. Malloy, *Thermal Insulation Handbook* (Krieger/McGraw-Hill, 1981).

jacket can be especially prevalent when a line is shut down for any length of time.

Severe corrosion occurs from galvanic coupling of aluminum weatherproofing sheet with steel supports or hangers.[20] Because the insulation becomes wet enough to act as a medium for ionic transport, guidance should therefore require isolation of the aluminum from the steel to avoid this type of attack.

Fiberglass insulation produced from soda glass can cause pitting under conditions of alkali leaching[21] (e.g., by condensation). Guidance should require use of fiberglass produced from borosilicate glass (Pyrex).

Completely eliminating water from the system is not possible. MIL-I-22344C requires that the pH of leachate from the insulation be not less than 7.5 nor more than 12. However, alkaline conditions are aggressive toward aluminum. Guidance should therefore require leaching tests of all insulation components which demonstrate that the leachate is neutral to weakly acidic (pH between 6 and 7.5) and does not exceed the limits of soluble chlorides and metals recommended above.

Insulation and vapor barrier materials should be selected on the basis of conformity to applicable guide specifications and site-specific installation and application requirements. A standard reference such as the *Thermal Insulation Handbook* can be helpful for insulation system design and materials selection.

6 CONCLUSIONS AND RECOMMENDATIONS

Pitting attack on the aluminum jacket resulted from high chloride ion concentrations in water within the insulation system. Attack was aggravated by the deposition of cathodic heavy metal ions.

Both the insulation and vapor barrier contained large amounts of leachable chlorides. Excessive amounts of heavy metals occurred in the vapor barrier.

Chlorine and heavy metals occurred in corrosion products.

Staples used on vapor barriers were rusted, indicating that carbon steel was used instead of the required stainless steel. Iron cations from these staples could deposit on the aluminum jacket interior, thus enhancing corrosion at these sites.

Based on the information obtained in this study, the following procedures are recommended to correct the observed corrosion problems:

1. Chloride ion levels, which might initially be low, can concentrate appreciably through a series of condensation/evaporation cycles and lead to rapid localized attack of aluminum alloys. Significant reduction of soluble chloride levels is therefore mandatory for the materials used in this application. This can be done by reducing the acceptable level of leachable chloride ion in the insulation and vapor barrier to an upper limit of 50 ppm.

2. Require a leaching test of insulation components to ensure that soluble binders have a pH of 6 to 7.5.

3. Set limits on the levels of heavy metals allowed in the insulation and vapor barrier, and require the manufacturer to submit chemical analyses for leachable chloride and metal concentrations for each lot supplied.

4. Ensure that material used to seal joints on the aluminum weather jacketing will prevent intrusion of water from the outside while allowing vapor from inside to escape. This will decrease condensation of water from wet insulation on the interior of the aluminum jacket.

5. Consider designing the vapor control system to use the flow-through principle, as outlined in ASTM Standard C 755.[22] The flow-through principle allows water vapor in the insulation system to pass through without significant accumulation. An alternate design is based on the moisture-storage principle, which permits accumulation of vapor in the system but at a rate designed to prevent any adverse effects. Evaluate material choices in light of the principle selected.

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[20] W. W. Binger, E. H. Hollingsworth, and D. O. Sprowls, "Resistance to Corrosion and Stress-Corrosion," *Aluminum, Volume 1: Properties, Physical Metallurgy, and Phase Diagrams*, K. R. Van Horn, ed. (American Society for Metals, 1967), p 255.

[21] *Corrosion, Volume 1. Metal/Environment Reactions.*

[22] ASTM Standard C 755, "Selection of Vapor Barriers for Thermal Insulations," *Annual Book of ASTM Standards*, Vol 04.06 (1983).

6. Avoid use of a polyethylene coating on the aluminum jacket, since this can contribute to accelerated corrosion rates at flaws in the coating.

7. It has been suggested that condensate barriers, which keep moisture in the system from condensing on the interior surface of the jacketing, be used in place of a vapor barrier, which merely retards the migration of water vapor to the lower vapor-pressure region. This is not recommended, since very concentrated attack can occur at imperfections and points where the condensate barrier has disbonded from the jacket. Also, oxygen depletion under this type of barrier can lead to accelerated corrosion rates once corrosion has begun.

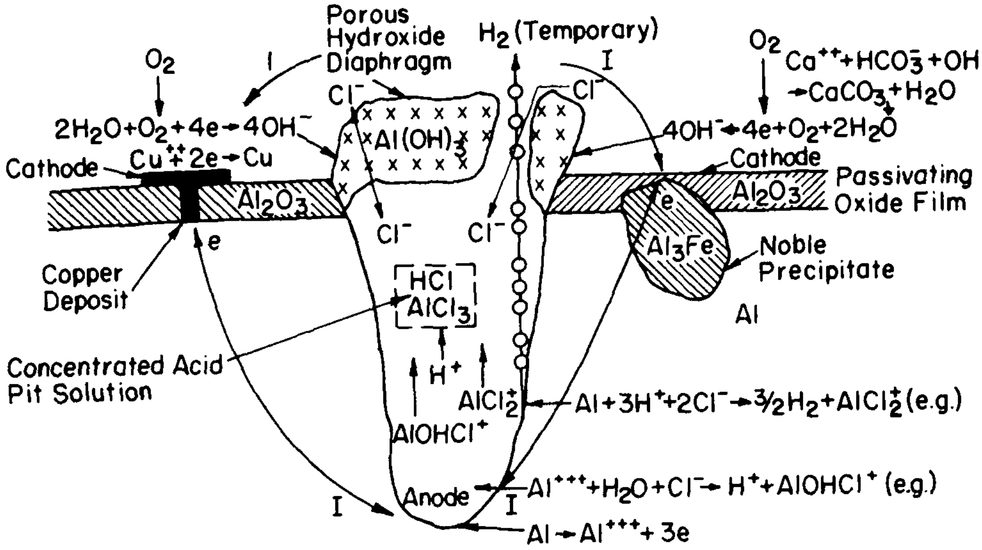


Figure 1. Typical reactions within an aluminum pit. (From *Corrosion, Volume 1: Metal/Environment Reactions*, L. L. Shreir, ed., 2nd ed. [Newnes-Butterworths, London, 1976]).

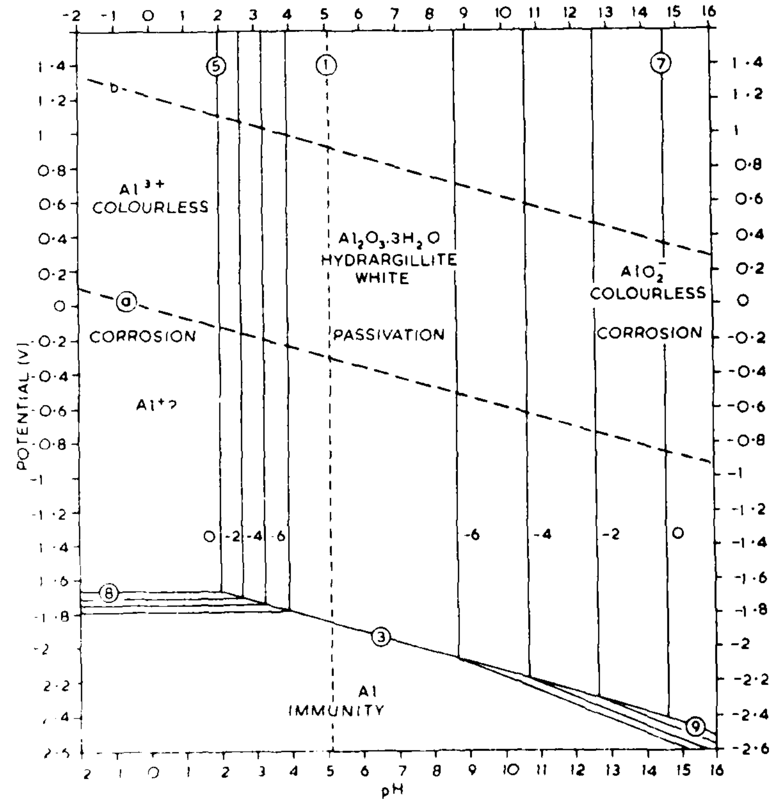


Figure 2. Potential versus pH diagram for Al/H$_2$O system at 25°C. (From *Corrosion, Volume 1: Metal/Evironment Reactions*, L. L. Shreir, ed., 2nd ed. [Newnes-Butterworths, London, 1976]).

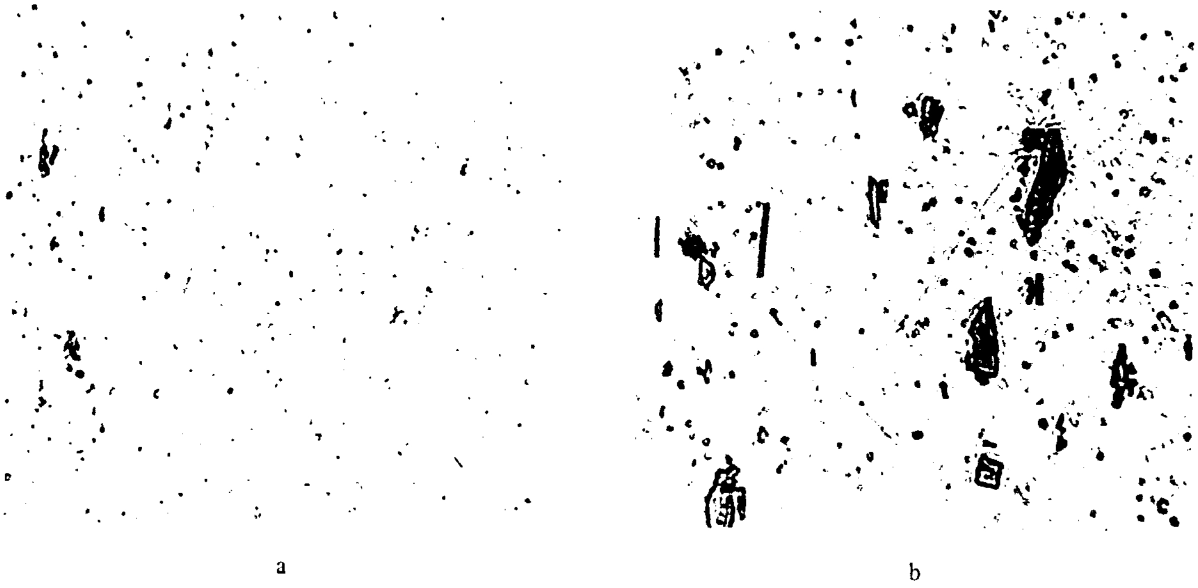


Figure 3. Two typical unetched microstructures in the aluminum jacketing (800 X).

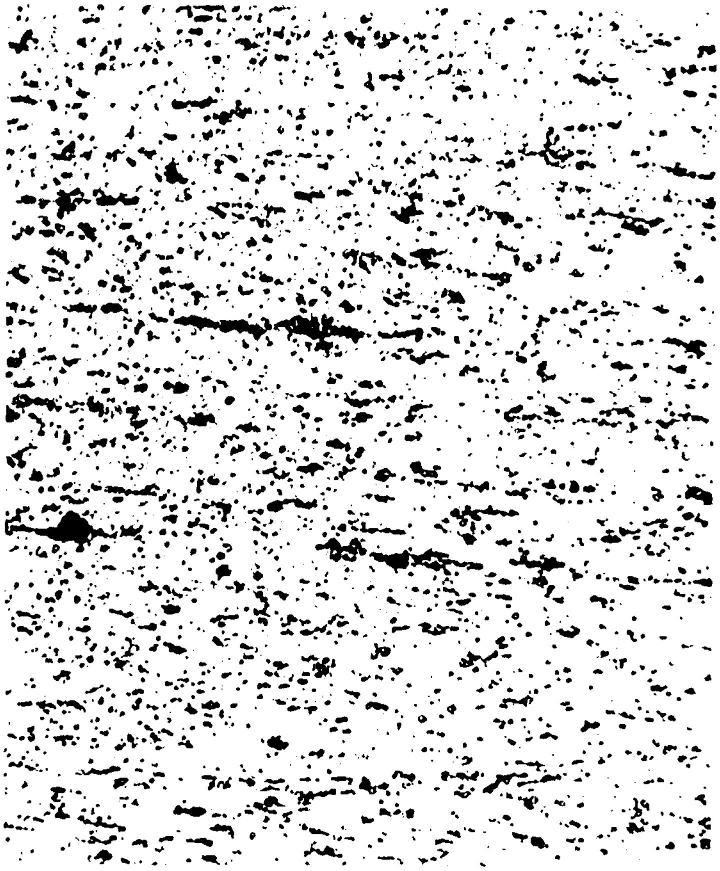
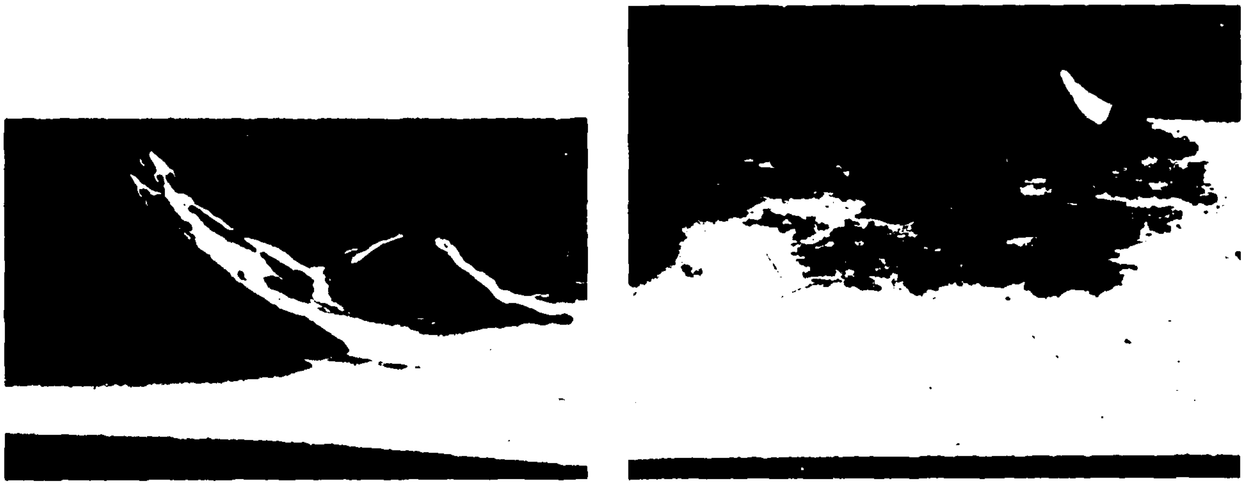


Figure 4. Microstructure (Figure 3b) after etching with Keller's reagent for 20 sec; FeAl particles are evident (800 X).



a

b

Figure 5. Blistering and undercutting associated with pitting of jacketing materials (a: 65X; b: 160 X).

Figure 6. Pits initiated at breaks in a polyethylene film on an elbow section. The position of the film is marked for clarity (365 X).

Figure 7. Crystallographic pits in the aluminum layer of a used vapor barrier (800 X).

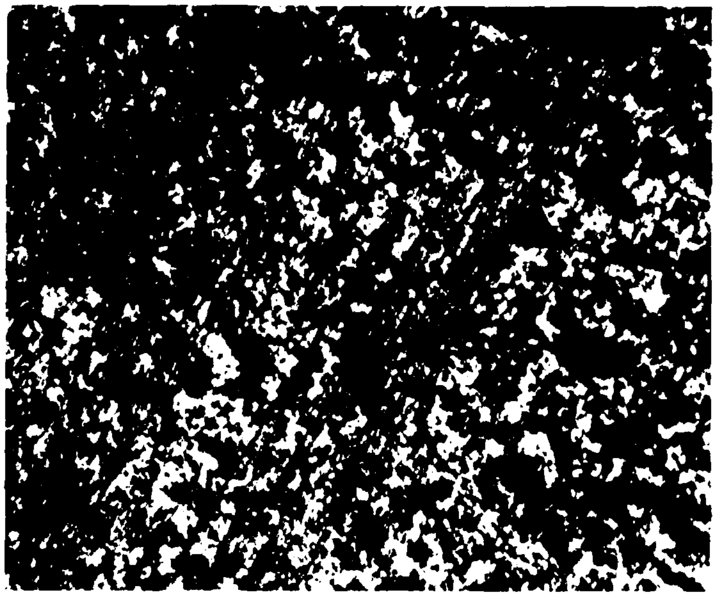


Figure 8. Pits present after 3 weeks submersion in distilled water. Sample was sandwiched next to vapor barrier and insulation (125 X).

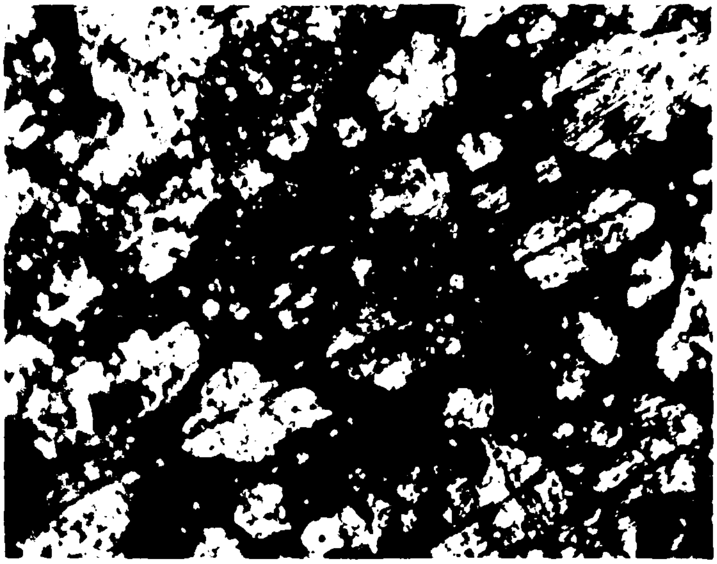
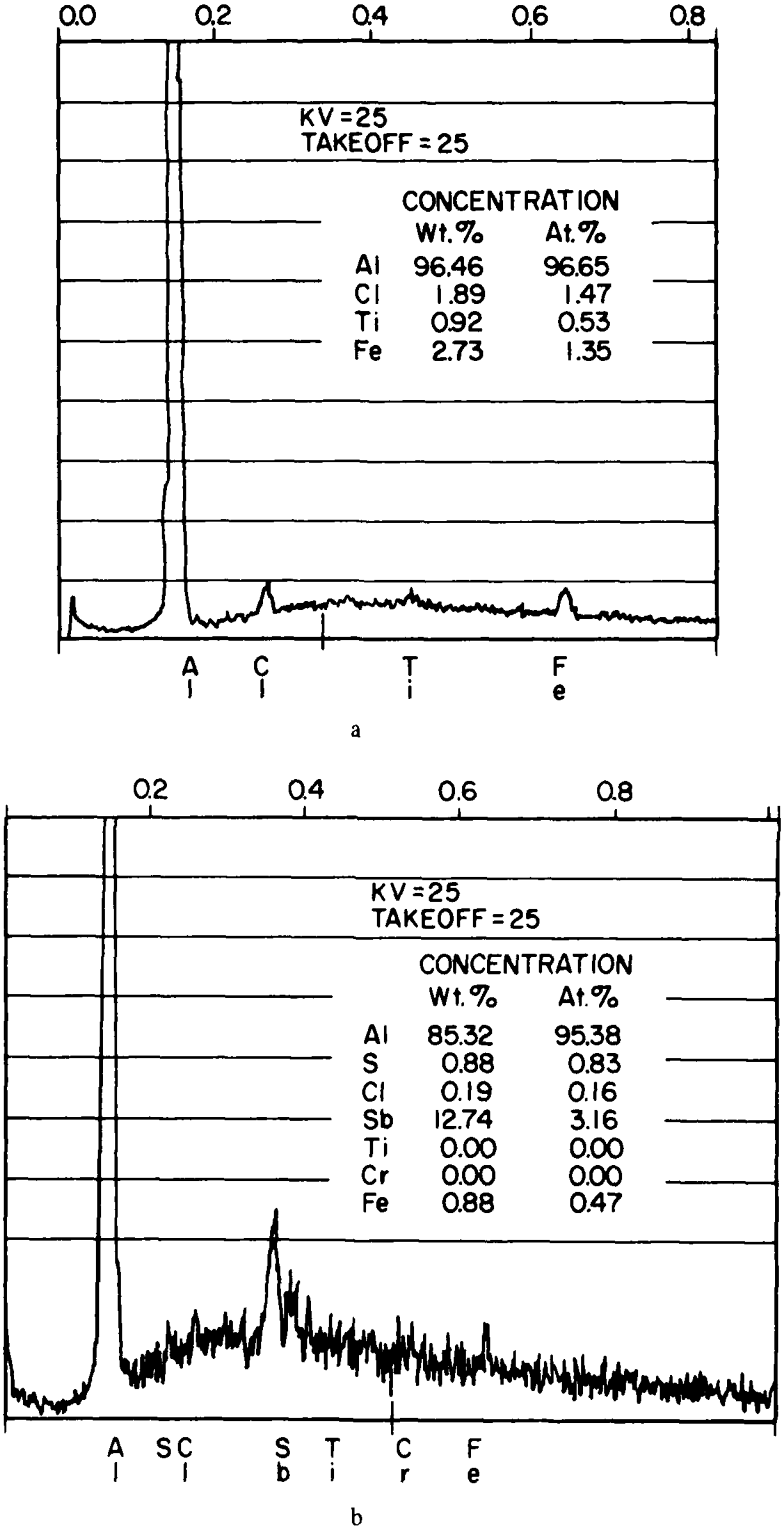


Figure 9. Attack morphology after three weeks in an unsubmersed sample (320 X).

a

b

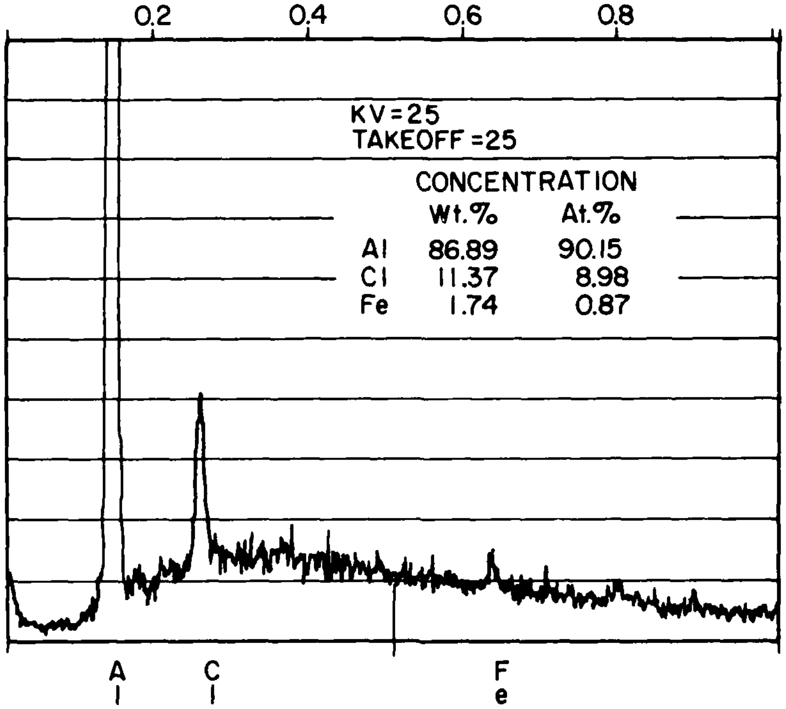
Figure 10. Pits and associated stains from a slightly pitted area of a cold line. a: Sample taken from a cold line, at 120 degrees from the top–slightly pitted area (0.64 X). b: Magnified view of pits and associated stains on sample shown in Figure 10a (3.2 X).



CONCENTRATION	Wt.%	At.%
Al	96.46	96.65
Cl	1.89	1.47
Ti	0.92	0.53
Fe	2.73	1.35

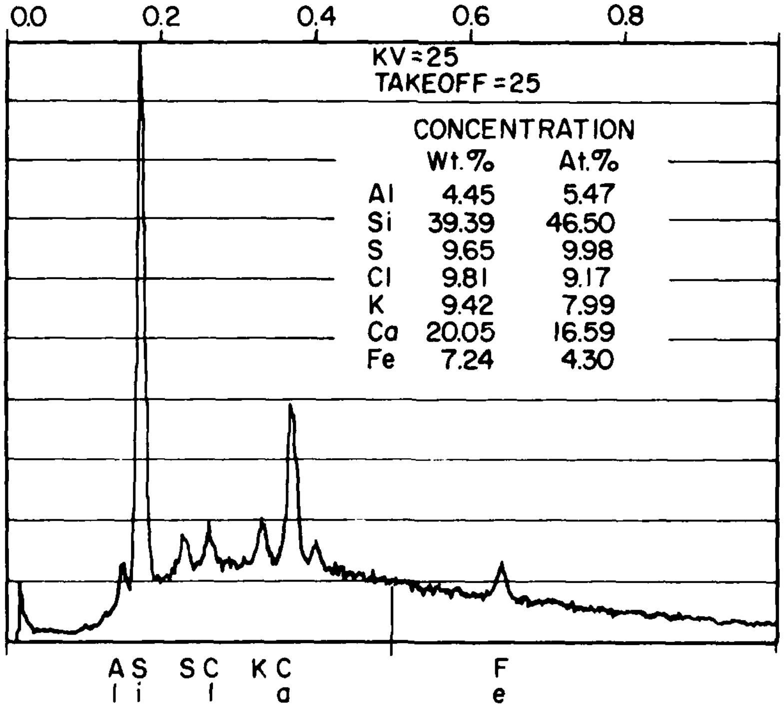
CONCENTRATION	Wt.%	At.%
Al	85.32	95.38
S	0.88	0.83
Cl	0.19	0.16
Sb	12.74	3.16
Ti	0.00	0.00
Cr	0.00	0.00
Fe	0.88	0.47

Figure 11. EDAX spot spectra. a: EDAX spot spectrum (1000 X) on the white deposit shown in Figure 10a. Elemental concentrations are shown in the inset. b: Spectrum (1000 X) on corrosion product around the pit shown in Figure 10b. The peak marked as antimony may be calcium.



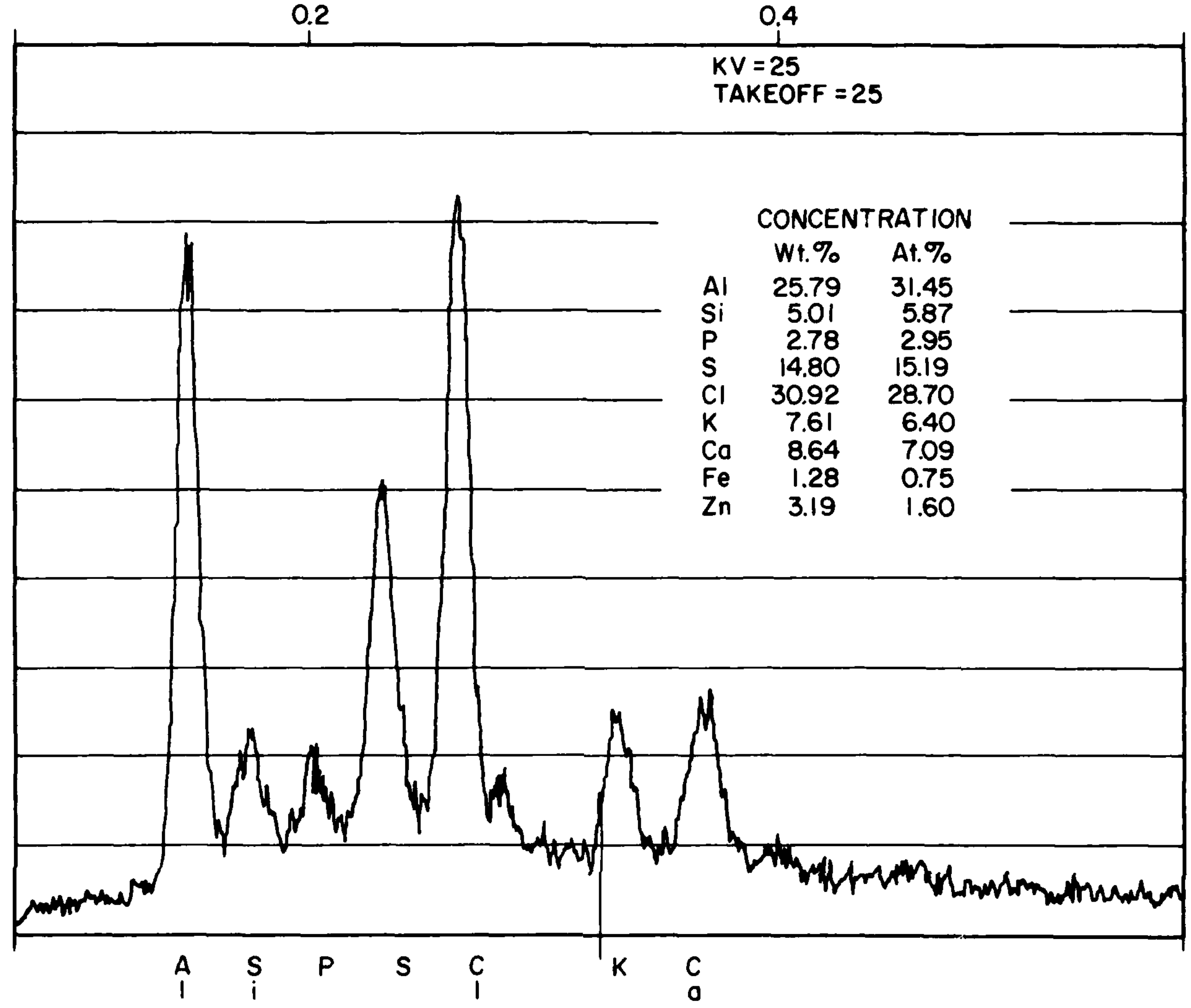
CONCENTRATION	Wt.%	At.%
Al	86.89	90.15
Cl	11.37	8.98
Fe	1.74	0.87

Figure 12. High chlorine concentration in a section of corroded jacket. (Spectrum taken at 50 X).



CONCENTRATION	Wt.%	At.%
Al	4.45	5.47
Si	39.39	46.50
S	9.65	9.98
Cl	9.81	9.17
K	9.42	7.99
Ca	20.05	16.59
Fe	7.24	4.30

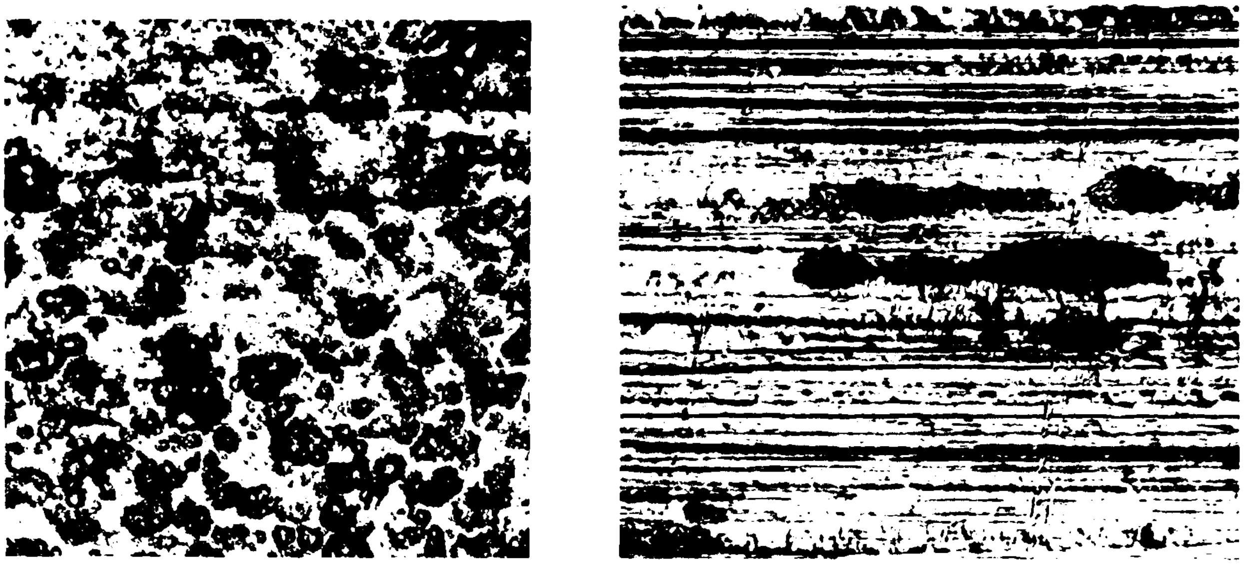
Figure 13. Spectrum (50 X) from a metallic-looking deposit on the paper side of corroded aluminum jacket. Note the high chlorine concentration.



	CONCENTRATION	
	Wt.%	At.%
Al	25.79	31.45
Si	5.01	5.87
P	2.78	2.95
S	14.80	15.19
Cl	30.92	28.70
K	7.61	6.40
Ca	8.64	7.09
Fe	1.28	0.75
Zn	3.19	1.60

Figure 14. EDAX spectrum of white corrosion product present on vapor barrier.

Figure 15. Staples taken from used vapor barrier (1.4 X). The presence of rust indicates that carbon steel staples were probably used. (Paper clip used to indicate size of staples.)



a b

Figure 16. Attack of aluminum jacket coupon after 20-hr immersion in 3.5 percent NaCl solution (400 X) a: pH = 10; b: pH = 4.

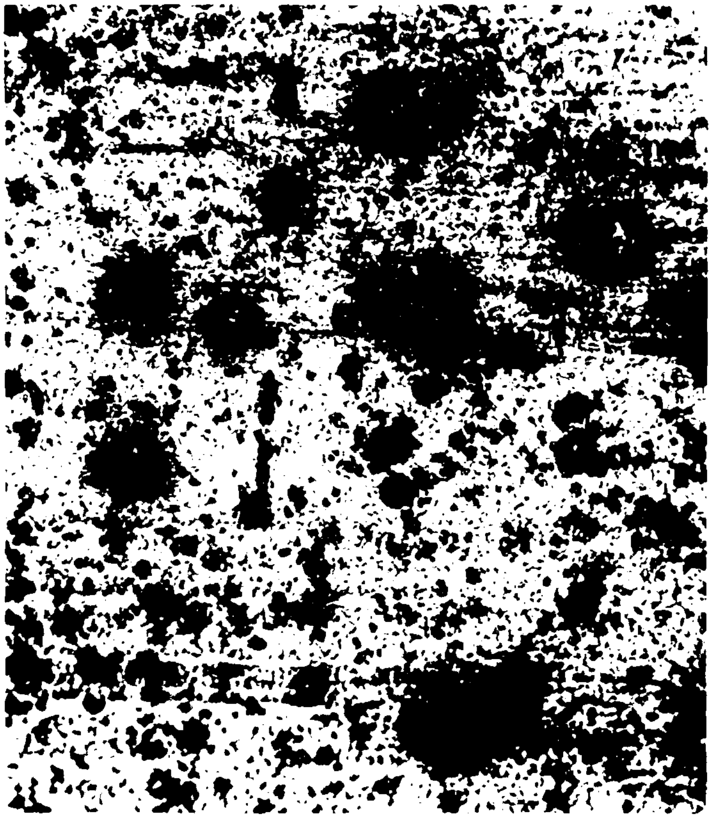


Figure 17. Attack of aluminum coupon after 16-hr immersion in distilled water of pH = 10 (400 X).

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APPENDIX:

APPLICABLE GUIDE SPECIFICATIONS

HH-I-515D, *Insulation Thermal (Loose Fill for Pneumatic or Poured Application): Cellulosic or Wood Fiber,* June 1978.

HH-I-558B, *Insulation Blocks, Boards, Blankets, Felts, Sleeving (Pipe and Tube Covering), and Pipe Fitting Covering, Thermal (Mineral Fiber, Industrial Type),* August 1976.

HH-B-100B, *Barrier Material Vapor (for Pipe, Duct and Equipment Thermal, Insulation),* September 1973.

MIL-I-24244A, *Insulation Materials, Thermal, With Special Corrosion and Chloride Requirements,* November 1976.

MIL-I-22344C, *Insulation, Pipe, Thermal, Fibrous Glass,* May 1981.

ASTM Standard C 871, "Chemical Analysis of Thermal Insulation Materials for Leachable Chloride, Silicate and Sodium Ions," 1983.

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MOGS-02750, *Heat Distribution Systems Outside of Buildings,* June 1983.

CEGS-15705, *Underground Heat Distribution Systems,* August 1984.

CEGS-15709, *Heat Distribution Systems Outside of Buildings–Concrete Shallow Trench Systems,* November 1983.

NFGS-15705, *Underground Heat Distribution Systems,* February 1984.

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