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BIOFOULING AND CORROSION RESEARCH FOR MARINE HEAT EXCHANGERS*

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ABSTRACT

Experimental research on biofouling and corrosion of heat-exchanger materials in warm and cold seawater was carried out between 1977 and 1987 for the U.S. Department of Energy's Ocean Thermal Energy Conversion (OTEC) program. Major findings include the following: (1) there is negligible biofouling from deep (600 m) seawater; (2) biofouling from warm surface seawater can be controlled by intermittent chlorination at environmentally acceptable levels; (3) the uniform rate of corrosion for aluminum is acceptable in both warm and cold seawater with no pitting observed in warm seawater; (4) some aluminum alloys show good resistance to pitting in cold seawater; and (5) the use of claddings and other protective measures does not now appear to be cost effective. From these and other experiments, we conclude that marine heat exchangers need not be designed for cleaning by mechanical methods, and that aluminum-based materials can be considered for marine applications.

INTRODUCTION

An OTEC system derives power from the thermal energy stored in the ocean in the form of a temperature gradient [1]. This thermal gradient can be converted into electrical energy by using a heat engine. Since the temperature difference between warm and cold seawater is about 20°C, the heat exchangers must be large and efficient; it was initially estimated that these exchangers would represent up to one-half the total capital cost of an OTEC plant. The problem is compounded by the fact that copper-based materials -- traditionally used in marine heat exchangers because of their corrosion resistance and biocidal action against marine organisims -- are incompatible with ammonia, the preferred working fluid for closed-cycle OTEC. Exchangers made from titanium and certain stainless steel would be corrosion resistant but would be expensive to manufacture. Aluminum is relatively inexpensive and can be formed into configurations that are cheaper to build and more thermally efficient than are shell-and-tube designs, but aluminum has not previously been considered for seawater applications. Moreover, a major advantage of aluminum -- its suitability for manufacturing processes used in many innovative designs -- would be lost if mechanical cleaning is required. Despite these handicaps, it was deemed worthwhile to investigate various aluminum alloys and the means for keeping aluminum heat-exchangers clean by non-mechanical means.

EXPERIMENTAL PROGRAM

During the period 1977-1981, experimental measurements of the rates of corrosion and biofouling buildup were carried out by Argonne National Laboratory (ANL) under subcontract at sites along the U.S. east coast, in the Caribbean, and off Hawaii [2]. Although the results of these studies were encouraging, there were doubts as to their universality because of the wide variations in water quality between costal sites, and between coastal and open-ocean water. Moreover, none of the shore-based sites had access to deep ocean water. Because of the practical difficulties in conducting research on open-ocean buoys or barges, the need was evident for a shore-based facility with ample supplies of warm and cold seawater of open-ocean quality. To meet this need, a facility was designed and built at the Natural Energy Laboratory of Hawaii (NELH) under ANL direction, becoming operational in June of 1981. It is located at Keahole Point on the island of Hawaii, a site that was chosen because it has several natural and practical advantages.

The facility operated continuously until September of 1987. During these six years, the emphasis was on biofouling studies, biofouling control, and corrosion tests of various materials and configurations. The experimental facilities and the test program are described in detail elsewhere [3] and are summarized briefly here. Tests were conducted with warm seawater drawn from a point 100 m offshore at a depth of 12 m; because there are no major river systems on the west coast of Hawaii, the surface water is of open-ocean quality beyond the surf zone. Cold seawater is drawn from a point about 1500 m offshore at a depth of about 600 m. Twelve warm-water test loops and six cold-water test loops were installed. The original emphasis was on research in support of large OTEC plants. At that time, biofouling was considered to be a major problem. The initial test plan included a large number of titanium and high-alloy stainless-steel samples cleaned by various methods, as these materials were believed to have acceptable service lives in marine environments and good resistance to the abrasion caused by mechanical cleaning. Test specimens were smooth tubular sections, partly because this geometry is easier to clean by mechanical means, and partly because the shell-and-tube design was a leading candidate for OTEC exchangers. As expected, titanium and stainless steel showed excellent corrosion resistance and are cleanable with the same techniques successfully used on aluminum alloys. When the corrosion test data for aluminum alloys continued to be encouraging, there was a shift of emphasis to these materials. The primary goal, however, was to accumulate long-term data. Therefore, the list changed only moderately over the years. Test periods for these experiments varied from six months to 1700 days. Sample analysis was performed by the University of Hawaii.

FOULING TEST RESULTS

- Biofouling from deep cold water is negligibly small and for all practical purposes no routine biofouling control method is required (Fig. 1).

- For warm surface seawater, intermittent chlorination of 50 to 100 parts per billion (ppb) employed for 1 hr/day can maintain the biofouling resistance within acceptable limits for titanium, stainless steel and aluminum surfaces (Fig. 2).

- Biofouling control for moderately enhanced water-side surfaces is comparable to that required for smooth surfaces (Fig. 3). As with smooth surfaces, biofouling by cold water is also negligible for enhanced water-side surfaces.

FREE FOULING OF STAINLESS STEEL TEST SECTION IN COLD WATER

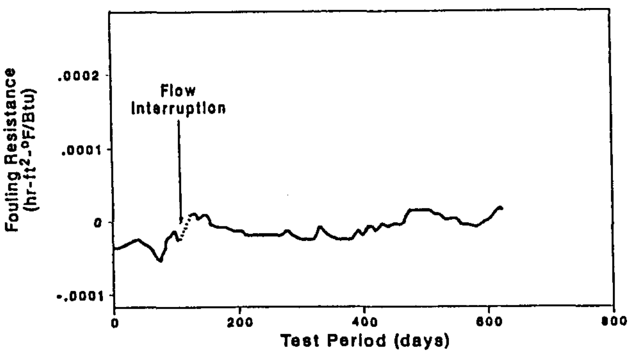

Figure 1. Free fouling of stainless steel in cold seawater.

BIOFOULING IN ENHANCED TUBES CAN BE CONTROLLED WITH LOW LEVEL CHLORINATION

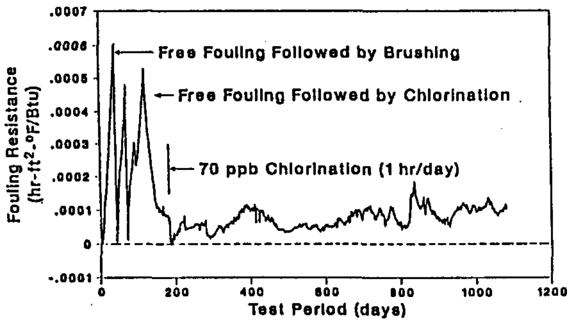

Figure 3. Prevention of biofouling on moderately enhanced surfaces.

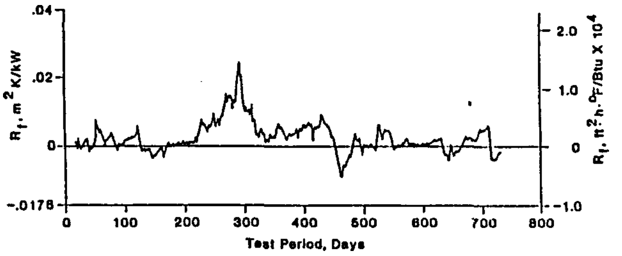

Figure 2. Prevention of biofouling buildup on smooth titanium surfaces by intermittent daily chlorination.

- Biofouling film can be effectively removed and the heat-transfer performance restored by intermittent or continuous chlorination at levels of 50-110 ppb (Fig. 4).

- A corrosion-fouling buildup occurred on aluminum surfaces after long-term exposure to cold seawater (Fig. 5). This phenomenon had not previously been observed. The buildup is first noticed after 12-18 months' exposure and eventually reaches a value of about 3 R_f units, at which point cleaning is required. (An R_f unit is a measure of fouling resistance to heat transfer and is equal to 0.0001 h-ft^2°F/Btu or 0.0176 m^{2}K/kW.) A similar phenomenon was observed with warm seawater, except that warm-water corrosion fouling has a more rapid initial rise and then levels off, whereas cold-water fouling has a lower rate but continues linearly (Fig. 6). The difference may be the result of the much greater oxygen concentration of the warm seawater.

- One hour's recirculation of 20% acetic acid will remove three years' accumulation of corrosion fouling from an Al 5052 tube exposed to cold seawater (Fig. 5).

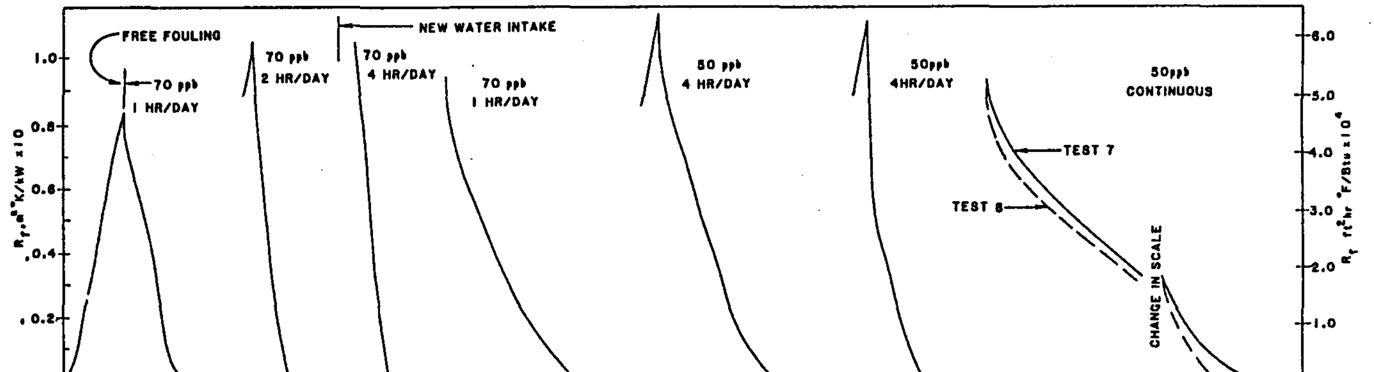

Figure 4. Removal of biofouling film by chlorination.

CORROSION FOULING OF ALUMINUM IN COLD WATER

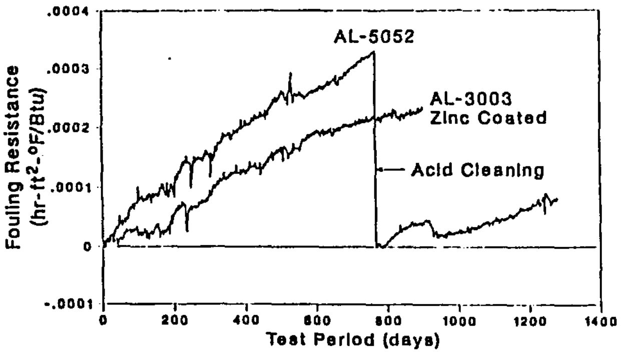

Figure 5. Corrosion fouling of aluminum in cold seawater.

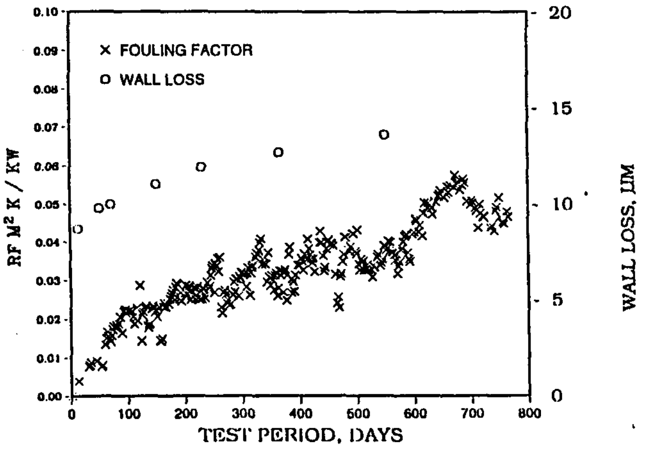

Figure 6. Corrosion fouling of aluminum in warm seawater.

WARM-WATER ALUMINUM-3003 CORROSION IS COMPATIBLE WITH LONG COMPONENT LIFE

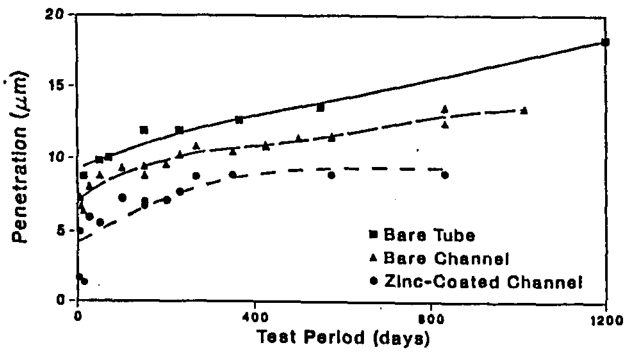

Figure 7. Corrosion of Al-3003 in warm seawater.

WARM-WATER CORROSION

- Aluminum alloys show a high potential for service lifetimes of 15-20 years for heat exchangers operating under OTEC conditions. After an initial conditioning period of one to two months, uniform corrosion rates of less than 0.02 mm per year were recorded for all alloys tested. Pitting appears to be of minor importance in warm seawater. These data are based on exposure times of up to 1700 days (Fig. 7).

- Alloys tested were 3003, 5052, 5086, and 6063. All had acceptable weight loss and displayed adequate pitting resistance. Of these, Al 3003 is of special interest because of its wide availability, good workability, and excellent corrosion resistance in warm seawater.

- Contrary to expectations, clad aluminum alloys did not show any superiority to unclad materials. Moreover, some test specimens lost large patches of cladding (believed to be caused by the cladding application). Because of the discouraging test results and the added expense of using the clad alloys, we cannot recommend further consideration of these materials for OTEC heat exchangers.

- Test results for zinc-diffused coatings on Al 3003 extrusions are promising but inconclusive. This process has the potential for increasing service lifetimes to 30 years through periodic reapplication of the coating. More testing is required.

- Brazed joints in fabricated channels performed well in limited initial experiments, but the data are too limited to be conclusive. Quality control of the brazing process may be crucial. More testing is required before a definite conclusion can be reached.

COLD-WATER CORROSION

- The uniform corrosion rate (about 0.02 mm per year) is comparable to that for warm seawater (Fig. 8).

- Alloys 3003, 5052, and 5086 were tested with exposure times of 600-1500 days. All performed

ALUMINUM CORROSION RATE IN COLD WATER

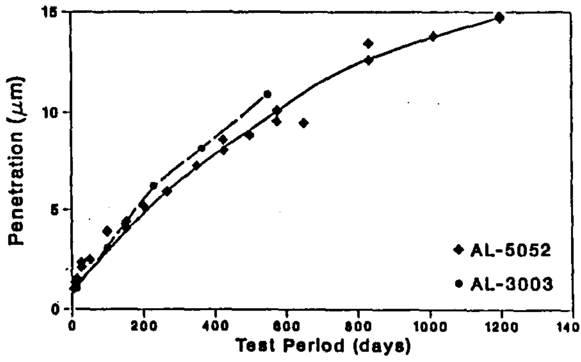

Figure 8. Uniform corrosion of aluminum in cold seawater.

well with only minimum pitting observed over the test period. Some initial pitting was observed during startup; samples taken later indicated a decreased pitting rate. The best results were obtained with Al 5052. Because of the poor forming characteristics of Al 5052, however, it would be desirable to have more data on Al 3003 and other easily worked alloys in order to qualify more completely one of them for cold-seawater service.

- Limited test data on enhanced aluminum surfaces indicate no significant increase in pitting or uniform corrosion rates in cold seawater as a result of the enhancements. The test data, however, are not extensive and do not permit a general conclusion. The samples tested were spirally fluted tubes.

- Alclad specimens tested showed the same sporadic gross loss of cladding as was observed in the warm-water tests, and which may be even more severe in cold seawater. The Alclad process as it now exists cannot be recommended for OTEC service.

- Cold seawater tests with zinc coatings were inconclusive, partly because of the difficulty in obtaining good test data with cold seawater. We consider this process potentially promising as a backup for the base alloys, especially for long-time exposure to seawater.

- Cold-water corrosion for brazed and welded joints was more severe than for warm water. Good quality control for the brazing process appears to be essential.

RECOMMENDATIONS FOR FUTURE TEST PROGRAMS

Although much has been learned, there are gaps in the data base that should be filled in order to give designers and builders confidence in their products. Such gaps can be filled by test programs of a much lower scope than that of the NELH experiments of 1981-1987. These tests would be fewer in number, require less equipment and instrumentation, and could mostly be automated and require a minimum of personnel. Most would be conducted with cold water and all would be of long duration (18-24 months). Some examples:

- Cold-seawater fouling-film chemistry should be studied and accurate weight-loss measurements made on promising aluminum alloys. These tests would supplement previous test data and yield a base for predicting the corrosion and life-cycle phenomena of aluminum alloys in marine environments.

- Additional tests of joining techniques -- especially brazing -- should be conducted, with special care taken with quality control of the joining techniques and materials.

- Additional testing of zinc-diffused coatings -- including detailed film analysis -- on aluminum surfaces is desirable. These tests may demonstrate that this technique will increase the service lifetimes of marine heat exchangers.

ACKNOWLEDGMENTS

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