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Review
Overview of metallic materials for heat exchangers for ocean thermal energy conversion systems

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Candidate materials for use in ocean thermal energy conversion systems, OTECS, heat exchangers include aluminium, Cu–Ni, stainless steel and titanium alloys. These are considered in this review, and their advantages and disadvantages are highlighted and discussed. Aluminium alloys have shortcomings for the anticipated long life span of OTEC heat exchangers; however they may still offer an economic alternative in the form of short-life, disposable units of low initial capital cost. The long-term effects of exposure to ammonia and to erosion pose questions about the suitability of Cu–Ni alloys. Although stainless steel alloys provide a strong challenge for OTECS use, titanium exhibits better seawater performance, has good fabricability, and has an excellent service history in marine environments. These factors, together with current and projected developments promise major savings in materials usage, reduced OTECS structure sizes and increased efficiencies consequent on the use of titanium and its alloys.

1. Introduction
Ocean thermal energy conversion systems (OTECS) utilize naturally occurring temperature gradients existing between the warm surface layer and deep, cooler layers in tropical waters, to produce usable energy. Thus, they promise the nonpolluting generation of large amounts of energy from a renewable source. OTEC uses a Rankine cycle in which the warm surface water (typically around 25° C) is used to evaporate a working fluid which drives a turbine-generator, and is then condensed for re-use using cold water (around 4° C) brought up by a pipe from a depth of 500 to 1000 m. A schematic layout of an OTEC system is shown in Fig. 1. The electricity produced can be transmitted ashore or used on a plant ship to make products such as hydrogen, oxygen, ammonia and methanol.

In an OTEC plant the power system represents the area of highest metals usage, especially the heat exchanger. The efficiency of power plants is linked to temperature difference, and consequently OTEC plants will operate with a very low efficiency, of the order of 2.5%.

The performance of the heat exchangers is crucial to a system's efficiency, and since the efficiency is dependent on the temperature difference experienced by the working fluid, heat exchangers having the largest possible area in contact with two fluids have to be used. As a result the heat exchangers for an OTEC plant represent the single most important cost category, around 25% of the total capital costs [1].

The power system must be designed for long life (upto 30 years) with minimal maintenance. Therefore, the initial material and fabrication costs have to be balanced against their corrosion/wear performance during the material selection cycle. The most important elements in heat exchangers are the heat transfer surfaces and as a result the tubes in tube-and-shell units and plates in the plate-type units represent the areas of greatest concern. Condenser and evaporator water-side transfer effectiveness is one of the engineering variables having the greatest potential impact on total system cost [1], and tube material cost is cited as the cost-related variable having the greatest potential impact [1].

2. OTEC heat exchanger materials
Materials studies have mainly considered four basic alloy groups; namely aluminium alloys, copper–nickel alloys, stainless steel alloys, and titanium alloys.

2.1. Aluminium alloys
Aluminium is attractive because of its relatively low cost, but its corrosion resistance in seawater is poor so that protective measures and frequent maintenance and/or replacement are required.

Although there are detailed differences amongst aluminium alloys, they are considered here as a group in order to emphasize their broad differences from alternative groups of candidate materials. Where necessary individual alloys are singled out for attention. Aluminium alloys have not been qualified for OTECS because of information gaps in critical areas [2], such as corrosion and pitting resistance.

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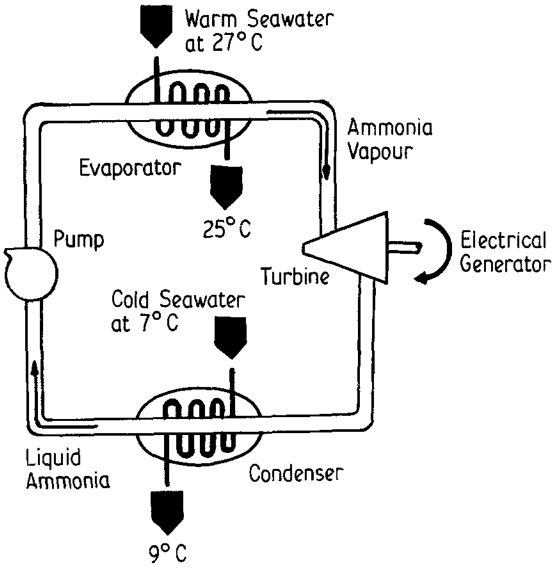

Figure 1 Principle of OTEC (approximate temperatures used).

Considering present information it is assumed that an OTEC plant built using aluminium alloys would have an expected life of 10 to 15 years [3], but because of the information gaps even such predictions are not considered reliable.

Currently Alcan (Canada) are installing a corrosion rig for OTEC work in Hawaii in an attempt to generate appropriate data for Al-alloy plant life predictions. However, aluminium alloys have been developed for specific use in marine applications [4]. Prime candidates for OTECS applications are alloys 5050 (0.4Si–0.1Mg), 5052 (0.45Si–0.1.Mg) and Alclad 6061 (0.4–0.8Si–0.15Mg), 6063 (0.2–0.6Si–0.1Mg). Aluminium does not possess the biocidal properties of copper, and as a result its surfaces rely on mechanical cleaning for the removal of biofouling films.

There is, thus, concern over the possible erosion of protective layers that may be caused by such cleaning measures. In view of the thinness of walls of heat exchanger tubes, their prime requirement is resistance to penetration by pitting. Alclad appears to have an advantage in this respect, based on the ability of the cladding to arrest penetration of the core alloy, so long as a considerable area of cladding is able to survive. The effect of periodic cleaning on the cladding has to be established as yet, but some experimental results [4] show that Alclad materials with corrosion-susceptible core alloys exhibited good pitting resistance after 6 months' exposure at 713 m depth in the Pacific Ocean.

Corrosion testing programmes in Hawaii [5] and the Gulf of Mexico [6] have shown that there is a rapid initial build up of corrosion product (15 to 17 days of exposure) on the surface of 5052 alloy. After this period the film grows according to a parabolic law. The expected increase in resistance to heat transfer (fouling resistance R_f) has been observed with good correlation at both experimental sites.

Potential solutions for biofouling of aluminium surfaces other than mechanical cleaning have been put forward [4], involving use of an anodic oxide to serve as an anchor or substrate for application of materials which retard or prevent the formation of biofouling slime.

Although the possibility of reducing microfouling by impregnation of anodic oxides with biocides has the appeal of an innovating solution, it raises the questions of the effect of the anodic film on heat transfer. Also, in view of the high electrical resistance of anodic films, there could be a danger of accelerating localized corrosion at pores, cracks or other discontinuities in the films. Corrosion acceleration has been observed on anodized aluminium in connection with galvanic effects.

The danger of crevice corrosion has to be taken into account in connection with the use of aluminium, because there are ample opportunities for it to occur, for example at tube joints, tube supports or under occasional deposits. Crevice corrosion will be greater in plate heat exchangers, where crevices cannot be avoided, and in tube designs where seawater is outside the tubes. Aluminium is vulnerable to attack especially under water flow conditions since crevice corrosion is accelerated by movement of water.

Aluminium corrosion is accelerated by corrosion products of more noble metals, especially copper and iron. Aluminium corrosion is also subject to galvanic acceleration by other metals that may be considered for OTECS components, thus limiting the choices of materials for such components and possibly requiring more expensive materials for compatibility.

The relatively low corrosion-fatigue strength of aluminium suggests that aluminium tubing could be vulnerable to the effects of harmful vibrations, and its corrosion fatigue properties in seawater and seawater–ammonia mixtures should be determined. At the same time the necessary steps should be taken to control such vibrations.

Vibrations of heat exchanger tubes may result in wear or fretting corrosion at tube supports. Such damage has been experienced with aluminium tubes [2]. There should be no problem of stress-corrosion cracking (SCC) of aluminium in either seawater or ammonia.

Currently, ammonia is the preferred working fluid in OTEC heat exchangers. There have been limited tests in seawater with ammonia, but lower corrosion rates have been observed at ammonia concentrations that gave intolerably high rates in pure water [7]. Preliminary tests for evaluation of aluminium alloys and titanium under simulated OTEC conditions involving seawater–ammonia mixtures showed that CP (commercially pure) titanium exhibited negligible pit attack under 30° C with 8, 30, 80, 800 p.p.m. ammonia concentrations and simulated water leaks of 0, 0.1, 1.0, 2.5% seawater leak severity at 5° C condenser temperature.

On the other hand various degrees of pit attack were observed on aluminium alloys (severe at times) exposed in various combinations of temperature and ammonia concentrations in seawater. Negligible attack was observed in exposures to seawater concentrations in ammonia.

Calcareous deposits can form if there is leakage of ammonia into seawater. This process is associated with an increase of pH which in turn enhances calcium carbonate and magnesium hydroxide precipitate formation. Precipitates so formed may then nucleate and form scales on heat exchanger surfaces in a manner which will seriously impair heat transfer, and as a result a cleaning system is necessary to control the fouling/scale formation. Based on cursory results [8] a mechanical cleaning system is the preferred mechanism of fouling control for the aluminium alloys tested, whilst the performance of CP titanium appears independent of cleaning techniques employed.

Although efforts can be made to design OTEC heat exchangers that are leak-proof, means of ammonia leak detection, ability to repair leaks and provisions for removing water from the ammonia should be considered in early design stages.

In order to attain higher levels of heat transfer, tube configurations with extended surfaces or fins have been designed. Such configurations are achievable in aluminium tubes made by extrusion. It has already been mentioned that by employing a realistic approach aluminium heat exchangers could be designed for a 10 to 15 year life without tube failure. In order to achieve a 30 year life, the thickness of the tubes would have to be increased to a degree that would adversely affect the seawater flow and heat transfer. As such, aluminium as a heat exchanger material has to prove itself more economic after allowing for periodic replacement over a 30 year life span compared with stainless steel or titanium exchangers built for a 30 year expected life.

2.2. Copper–nickel alloys

Copper–nickel alloys are widely used in power plants and have exhibited good performance in seawater condensers. For OTEC applications the prime candidate is alloy CA 706 (Cu–10 Ni–1.4Fe) which, however, is not yet qualified for OTEC use because of two questions relating to its performance in OTEC environments. The first involves the ability of CA 706 to tolerate ammonia, and although its ability to tolerate seawater contaminated by small amounts of ammonia might be underestimated [3], there are no available data on the alloy's ability to withstand ammonia containing small amounts of water.

A proposed way for circumventing corrosion problems of CA 706 in seawater–ammonia mixtures is the use of a duplex material, Cu–Ni clad steel. It appears that the technology is well developed and both duplex tubing and plate can be fabricated [3]. Cu–Ni alloy CA 706 is not subject to stress corrosion cracking in seawater [3].

The second question concerns the corrosion-erosion resistance of CA 706. It is recognized that certain plate-type heat exchanger configurations currently under consideration for OTEC, produce turbulence which may prove too severe for CA 706. If this proves to be the case, another chromium-containing candidate CA 722 (Cu–15Ni–0.5Cr) has been proposed, possessing the erosion resistance of CA 715 (70Cu–30Ni) and retaining the antifouling characteristics of copper.

The CA 706 alloy has been extensively used for condenser tubes on ships and in coastal power plants. The alloy has maintained design heat transfer efficiency for long periods without water treatment or the mechanical cleaning considered necessary for other materials in OTEC service.

The antifouling properties of CA 706, particularly with respect to bacterial slimes are backed by the results of the Gulf of Mexico study of biofouling on OTEC candidate alloys [6].

Although the Cu–Ni pipes exhibited the greatest initial loss in efficiency [6] due to initial film formation, the subsequent fouling resistance value was lower than for the other materials, and no organisms were found on the CA 706 samples. The overall effect of these relative fouling resistance behaviours was a better heat-exchange efficiency with the Cu–Ni samples after an initial "settling down" period. The Hawaii [5] study, due to various problems, provided inconclusive results on CA 706.

As a result Cu–Ni alloys are not as yet serious contenders for OTEC heat exchangers in spite of their appealing biocidal qualities.

2.3. Stainless steels

The specific alloy that has been qualified for OTEC heat exchanger applications is AL–6X (2Cr–25Ni–6Mo), based on short-term and long-term laboratory tests and, more importantly its performance in numerous power plants using seawater for cooling [3]. This and other stainless steel alloys have comparable performance with titanium alloys, and potential savings in fabrication costs against titanium make such alloys attractive.

The austenitic stainless steels perform well in seawater when their surface is clean and free of deposits, but once crevices form, attack can be very rapid.

The main problems associated with stainless steels in OTEC environments are marine fouling and localized corrosion attack (chloride pitting and crevice corrosion).

The passive surface of stainless steel has little or no toxic effect on marine biological deposits. In service such deposits produce crevices and lead to corrosion. These steels have good resistance to mechanical cleaning and such cleaning has been shown to be effective when used regularly [9]. The AL–6X alloy also has the advantage of tolerating chlorination.

Type 316 stainless steel is susceptible to crevice corrosion in seawater, and the degree of corrosion appears related to chloride concentrations and severity of crevices [10]. Conventional stainless steels have been rated high in resistance to general corrosion, erosion-corrosion, high water velocity inlet end erosion, steam erosion and ammonia attack. They are rated low in resistance to pitting, chloride attack and chloride stress corrosion. However, chloride stress corrosion only occurs in high temperature processes.

Alloy AL–6X was designed to improve chloride pitting and crevice attack resistance. Tests conducted for crevice attack on this alloy over a 6 year period [11] showed that tubes under unrestricted flow conditions exhibited no attack, while partially restricted AL–6X tubes showed light attack, never close to penetrating the tube wall. A study on the effect of mechanical biofouling control systems on tube material (AL–6X) indicated severe crevice attack [12], resulting from flow restriction due to local fouling in difficult locations not reached by the mechanical cleaning systems.

Stress corrosion cracking of complex stainless steel is not anticipated. Vibration of heat exchanger tubes may result in failure from corrosion fatigue. Service experience with AL–6X shows no reported vibration problems when this alloy has replaced copper alloys, if the location of tube supports are related properly to the characteristics of stainless steel tube.

The Gulf of Mexico [6] and the Hawaii Keyhole Point [5] studies on OTEC heat exchanger materials have shown that AL–6X exhibited excellent corrosion resistance in flowing seawater, and no detectable change in surface morphology including areas containing deposits of inorganic material. AL–6X attained the highest value of fouling resistance (R_f) [6] but it was found that the samples possessed the roughest and most irregular surface among the materials tested, and fouling growth may have been enhanced by this surface feature.

The ferritic stainless steels are also strong candidates due to their lower cost (low nickel content) and excellent resistance to pitting and crevice corrosion. Leading candidates include Fe–29Cr–4Mo and 26Cr–3Mo–2Ni. However, there is only limited service information on the performance of ferritic grades in seawater [12], in which no attack was reported upto 9 months of service. Test quantities of 29-4 condenser tubing have been placed in service to obtain information.

The AL–6X and the 29-4 stainless steels are strong candidates for OTEC heat exchanger use and in cost terms are around 20 and 40% more economical than titanium tubing of equal gauge.

These steels are more "noble" than most common construction metals and this can lead to possible galvanic problems, therefore compatibility with other materials and protection where necessary are important.

2.4. Titanium alloys

Titanium has emerged as the leading candidate for OTEC heat exchangers due to its outstanding seawater corrosion resistance and its service history in seawater condenser applications. Although the initial cost of the material is high, maintenance and replacement costs are minimized, resulting in an overall cost competitive with other candidates. Titanium and stainless steels (AL–6X and 29-4) present the least performance risk and, based on a 30-year plant life, have an acceptable cost. As a result, two successful OTEC development systems, the Mini-OTEC designed to produce 50 kW of power and OTEC-1 demonstration plant 1 MW power, used titanium heat exchange surfaces.

The Mini-OTEC utilized plate type heat exchangers composed of formed titanium plates assembled by mechanical fasteners with elastomeric gaskets as seals [4]. For the OTEC-1 the exchangers tested were of the shell-and-tube type, enhanced on the ammonia side only and fabricated from titanium. (Efficiency enhancement of heat exchangers is accomplished by increasing the effective area for heat transfer by attaching a thin layer of thermally conducting material to the outside of the tubes, or by having roughened or fluted tubes.) Typical dimensions were shells of 15 m in length, 3 m in diameter containing 6000 tubes of 25 mm diameter and 0.7 mm wall thickness. The tubes were roller expanded and welded to an explosively clad titanium tube sheet. Both of these types of construction generate crevices in the heat-exchanger assembly. Nevertheless, these heat exchangers operated satisfactorily and allowed the OTEC concept to be verified by the Mini-OTEC and OTEC-1 programmes. In particular, the heat transfer efficiencies of the heat exchangers exceeded the designers' expectations throughout operation. Therefore, current studies are aimed at large-scale plants, of the order of 10 to 40 MWe, with both shell-and-tube and plate-type heat exchangers being considered.

2.4.1. Titanium alloys for OTEC

The OTEC candidate from this family is commercially pure or unalloyed titanium, which is basically 99.0 to 99.2% titanium with a variety of impurity elements (Ti–50A, ASTM Grade 2). Other unalloyed or commercially pure titanium (ASTM Grades 1, 3 and 4) are available if better formability or higher strength are required. There is an overlap in specification requirements for these grades, and since ductility is considered an important property for the fabrication of plate-type heat exchangers and expansion of the tube at the tube sheet, preference is given to the low end of the Grade 2 specification.

Ti–6Al–4V (Grade 5) is a general purpose alloy offering higher strength, and although it has somewhat inferior corrosion resistance to unalloyed Grades, still offers excellent corrosion resistance in marine environments.

Ti–Pd alloy (Grade 7), offers better corrosion resistance than commercially pure grades and Ti-Code-12 alloy (Grade 12), containing 0.8% Ni and 0.3% Mo, is a low-cost alternative to Grade 7 for better crevice corrosion.

Heat exchanger tubing is most readily available in Ti–50A, Ti-Code 12 and Ti–Pd alloys.

2.4.2. Corrosion resistance of titanium

Titanium has now accumulated two decades of trouble-free service in seawater environments. This performance stems from the tenacious oxide film that forms immediately upon exposure to air or moisture. Breaking the oxide film does not induce corrosion in seawater, the film simply repairs itself. Although very thin, the film is very stable and is attacked by few substances, most notably reducing acids. Numerous studies demonstrate extremely low corrosion rates of titanium and its alloys. No corrosion evidence is present on titanium surfaces exposed to seawater, and marine atmospheres [5, 6, 15].

Pitting is totally absent, even where marine deposits form. Immersion tests with titanium and its alloys have never shown pitting or crevice corrosion in

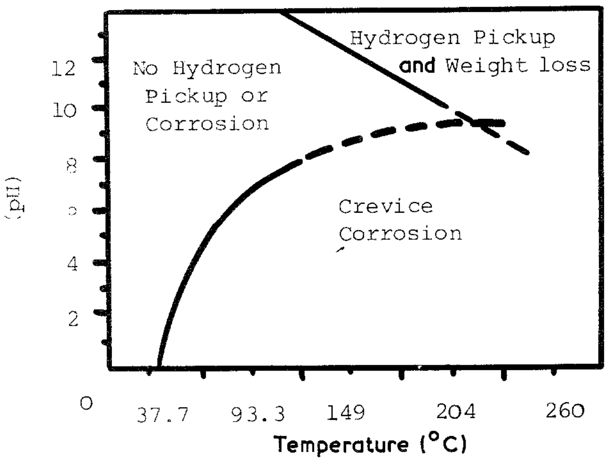

Figure 2 Effect of temperature and pH on crevice corrosion of Ti–50 in saturated NaCl brine.

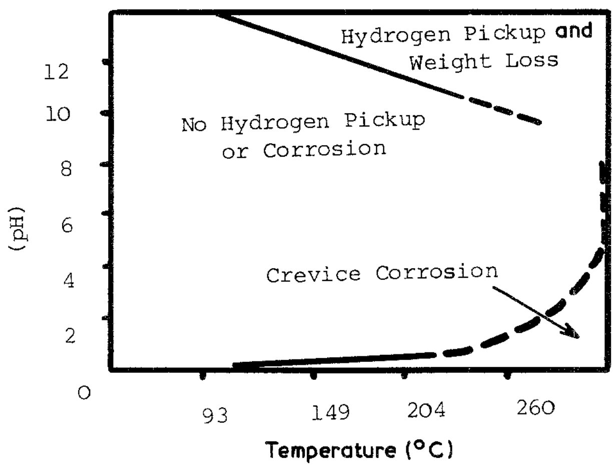

Figure 4 Effect of temperature and pH on crevice corrosion of Ti–Pd in saturated NaCl brine.

ambient seawater. Elevated temperature crevice corrosion of titanium has been reported, but unalloyed Ti–50A offers complete seawater corrosion resistance at temperatures anticipated for OTEC. However, if there is concern about unalloyed titanium, alloys such as Grades 7 and 12 offer complete resistance to neutral seawater at temperatures in excess of 260° C. Figs 2, 3 and 4 show the effect of temperature and pH on crevice corrosion of Ti–50A, Ti–Pd and Ti–Code 12 in saturated NaCl brine [16].

It can be seen from the figures that alloying combats the effects of increasing temperature and decreasing pH that can cause corrosion of one type or another. Palladium is an expensive alloy addition when used in massive structures, therefore for cost effectiveness clad construction should be considered, or use of Ti-Code 12, which is only moderately more expensive than unalloyed titanium. Since Ti-Code 12 is substantially stronger, it could be possible to reduce the weight of structures, and in effect offset the material cost differential. Galvanic couples are to be avoided or suppressed to ensure that free hydrogen does not form on the titanium. At ambient temperature, hydrogen causes little trouble, but above about 120° C the solubility of hydrogen increases markedly such that hydrides readily precipitate during cooling cycles [17]. Since hydrides cause embrittlement, such situations are to be avoided. Hydrogen is also quite mobile in titanium and distributes itself along thermal or stress gradients. Titanium is more tolerant of hydrogen than most metals; nevertheless, hydrogen is usually limited by specification to 150 p.p.m. in the metal.

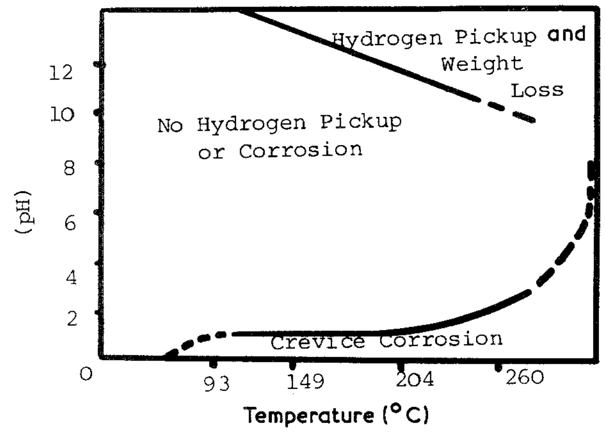

Figure 3 Effect of temperature and pH on crevice corrosion of Ti-code 12 in saturated NaCl brine.

It has been observed that the rate of hydrogen uptake is sensitive to the surface condition of titanium and that treatments which thicken and perfect the natural surface oxide film on the metal have a powerful inhibiting effect on hydrogen uptake in the short term (3 months). Long term tests [17] (3 years) show that the benefit does not last. The maximum of 150 p.p.m. was reached after 2 years, but subsequent metallographic study showed that the hydrogen taken up remained mainly at the surface and that the bulk hydrogen level of the titanium remained well below that limit.

Hydrogen absorption by titanium tubes for use in heat exchangers has been reported [18] and the cause was considered to be galvanic contact of titanium tubes with unprotected mild steel components.

It is common practice to refurbish in titanium, condensers originally tubed with copper alloys or stainless steels, by re-using existing tube and support plates in order to reduce both plant down-time and cost of replacement. In such cases attention should be focused on the special techniques required [19]. Whether in a new or refurbished system, choice of materials compatible with titanium for tube plates, water boxes and sometimes shells, together with associated protective measures, is of critical importance in avoiding galvanic corrosion problems in service.

2.4.3. Velocity effects

An excessive velocity will by itself scour away the protective film on metals. The ability of titanium to resist seawater erosion has long been recognized. Seawater velocities of upto 10 m sec^{-1} have only a minor effect on corrosion rate. Velocities upto 36 m sec^{-1} were investigated for unalloyed titanium and Ti–6Al–4V [15], and although corrosion rates increased at high velocities they were still low, and no localized effects were observed.

Abrasive action of suspended particles in seawater combined with general corrosion can result in high attack rates in some metals. Data [20] show that titanium is very resistant to conditions that cause severe corrosion on cupro–nickel or aluminium. However, high flow rates coupled with large volumes of abrasive particles can break the titanium oxide film and cause high corrosion rates.

2.4.4. Vibration fatigue

The most common cause of failure is vibrations leading to fatigue and titanium is more likely to be affected because of its thin gauge and low modulus of elasticity. There have been vibration failures reported when relatively thin walled tubes were used to replace heavier copper alloys. Spacing of existing tube supports for copper alloys is not appropriate for replacement titanium tubes, and fatigue should and can be avoided by utilizing the proper support plate spacing. In OTEC heat exchangers designed to use titanium, location of tube supports would be properly related to the physical properties and dimensions of the tubes.

2.4.5. Stress corrosion

Neither titanium nor Cu–Ni alloys are susceptible to stress corrosion. Unalloyed titanium (Grade 2) is essentially immune to stress corrosion cracking. Other unalloyed grades with higher oxygen and iron contents and more beta phase in the microstructure may be susceptible to SCC under some conditions. However, titanium alloys may be susceptible to SCC if a crack is already present, and that crack may extend under static or cyclic loads. Ti–8Al–1Mo–1V is notorious in this regard, Ti–6Al–4V ELI (extra-low-impurity) is more resistant than Ti–6Al–4V, and Grades 1 and 2 are quite resistant to crack extension.

2.4.6. Resistance to ammonia

Anhydrous ammonia is proposed as the most efficient working fluid for OTEC heat exchangers. Although data concerning titanium in this environment are few, applicable data [21] strongly indicate that titanium does offer excellent resistance. Titanium resists corrosion by liquid anhydrous ammonia at room temperature and shows low corrosion rates at 40° C. Although titanium resists gaseous ammonia to temperatures above 150° C, ammonia decomposes to hydrogen and nitrogen and under these circumstances titanium could, over a long service period, absorb hydrogen and become embrittled. Titanium resistance to ammonium hydroxide, a product which may form if water and ammonia mix in on OTEC heat exchanger, has also been shown. Titanium offers excellent resistance to concentrated solutions (upto 70% NH_4OH) at boiling temperatures. Formation of ammonium chloride may result in crevice corrosion of Ti–50A at boiling temperatures but Ti-Code 12 and Ti–Pd alloys are totally resistant under these conditions.

2.4.7. Biofouling

All tube materials are subject to fouling by scale, slime, and various marine organisms.

The formation of scale is largely a function of seawater temperature and concentration rather than of tube material, and the slimes and marine organisms are dependent on plant location, type of seawater intake and degree of seawater purification. Unlike copper, titanium is nontoxic to marine and other organisms, and as a result, unless treated with chlorine or by mechanical means, organisms can grow inside titanium tubes.

Marine fouling on titanium heat exchanger surfaces can be minimized by maintaining water velocities in excess of $1.2\,\mathrm{m\,sec^{-1}}$. Seawater velocities above $2.7\,\mathrm{m\,sec^{-1}}$ killed small barnacles. As indicated earlier, high water velocity is not detrimental to titanium performance. Titanium is highly resistant to corrosion by chlorine and hypochlorite solutions and therefore compatible with chlorination as a biofouling control method. Chlorination has no detrimental effects on titanium other than formation of a brown surface film. The possible effects of repeated chlorination, and particularly if there are a number of OTEC plants each discharging chlorinated waters on marine life are not clear. This could present a problem in enclosed areas like the Gulf of Mexico, where restricted water circulation exists, and is considered as an important area for further studies.

The use of mechanical cleaning methods are compatible with the ability of titanium to resist erosion. The main methods in this category are: Amertrap recirculating rubber balls, helically twisted inserts, MAN flow-driven brushes and water jet cleaning. The possibility of abrasive particles injected into seawater contacting titanium surfaces is another possibility relying on the titanium's resistance to erosion-corrosion.

Since the degree of fouling at potential OTEC sites [22, 23] and the long-term effects of OTEC's themselves and associated pollutants on the establishment of fouling communities in the open ocean are unknown, both preventive and cleaning capabilities incorporated into first generation OTEC plant designs are recommended.

2.4.8. Heat transfer efficiency

The principal trend affecting cost is the use of even thinner wall titanium tubing than currently in wide use. In power and desalination plant 0.5 and 0.6 mm thick welded titanium tubes are being specified where 0.7 mm has been previously common. In new plant with freedom of design 0.3 and 0.4 mm thicknesses are being proposed for desalination projects. Fig. 5 demonstrates the material benefit of using thinner wall titanium tubes; use of thinner walls also influences efficiency, through improved heat transfer.

Fatigue properties under vibration of thin wall titanium tubes have been tested in a method simulating their use in a condenser [24] the results showing that 0.3, 0.4 and 0.5 mm thick titanium tubes can be used in the same way as conventional wall thickness (0.7 mm) if appropriate support spacing is applied to account for lower rigidity due to thinning.

Thinner wall titanium tubes are also considered to possess sufficient buckling strength [24], and use of 0.3 and 0.4 mm tubes in an evaporator [24] has shown no problems concerning strength.

A 15-year experimental operation of 0.3 mm thick titanium tubes [25] installed on an operational steam

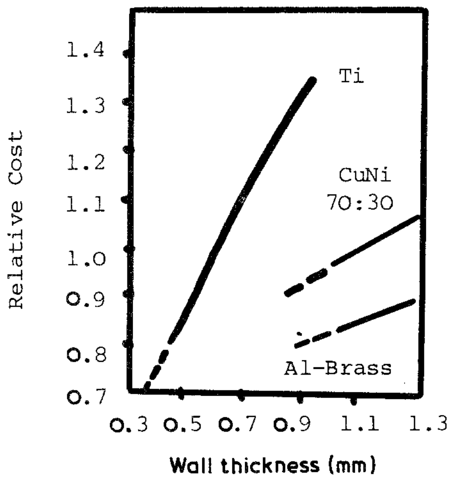

Figure 5 Relative costs per unit length for 25.4 mm o.d. condenser tube (mid-1984 basis).

turbine condenser has shown no erosion, no corrosion, no discrepancies including fretting damage and minor cracks, no degradation of mechanical properties, no problem due to hydrogen absorption, negligible reduction in the rate of overall heat transfer coefficient, negligible scale deposits and no marine biofouling.

In addition to the higher overall heat transfer coefficient of thin wall titanium tubes, there are major advantages to be gained by their use in terms of cost-savings. It has been estimated [26] that the tube price per unit length of titanium (0.5 mm wall-thickness) is cheaper than 70/30 Cu–Ni (1.245 mm), that titanium (0.4 mm) is nearly equal to 90/10 Cu–Ni (1.245 mm) and titanium (0.3 mm) is cheaper than 90/10 Cu–Ni (1.245 mm), showing the good economic competitiveness of Ti-alloy tubes. The point that the economic viability of OTEC plants depends on achieving high heat exchanger efficiency at the lowest cost has already been made. Increasing cooling water flow rates [19] and/or the use of advanced geometry tubes [26] may, potentially, have a major impact on efficiency. The excellent erosion and impingement resistance of titanium alloys in seawater is compatible with higher flow-rates subject to pressure drop constraints related to available pumping power (Fig. 6). The use of extended surfaces compensates for low heat transfer by increasing the surface area available. The provision of this additional surface requires either additional material or removal of existing material, and, therefore, the decision must be taken as a compromise between heat transfer requirements and economic constraints.

Enhancement techniques successfully used on titanium tubing include finning, fluting and coating. Finned tubing is being considered for OTEC condenser use for the horizontal heat exchanger design. The fins can be formed by cold forming techniques or by machining. Flutes can be formed in the strip prior to tube forming or after tube manufacturing. Fluted tubes are candidates for vertical evaporators and condensers.

Various proprietary coatings can be applied to the tube's outer surface to enhance shell-side boiling by nucleating bubbles at lower temperature. Enhancement can result in higher heat transfer coefficients, fewer or shorter tubes, smaller heat exchanger size and, as a result, a smaller platform size. These benefits are obtained at the price of increased tube costs. However, as manufacturing techniques improve and demand increases, it is expected the costs will be reduced. Roped tubes evaluated for use in OTEC plant evaporators and condensers have been shown to yield a 15% overall capital cost saving compared with plain tubes of the same thickness at optimum design.

Titanium low-fin tubes (LFT) have already been used in various kinds of heat exchangers in many industrial fields [27]. The finning method and finning tool are similar to the ones used for forming conventional copper alloy LFT, but inherently more difficult to carry out [26].

The heat transfer coefficient of titanium LFT is found to be about twice that of smooth-surfaced tube [24] (Fig. 7).

The corrosion of titanium low-fin tubes manufactured by cold working has been investigated [27] and it was found that LFTs have an improved corrosion resistance compared to smooth tubes.

On the other hand problems with finning of titanium-

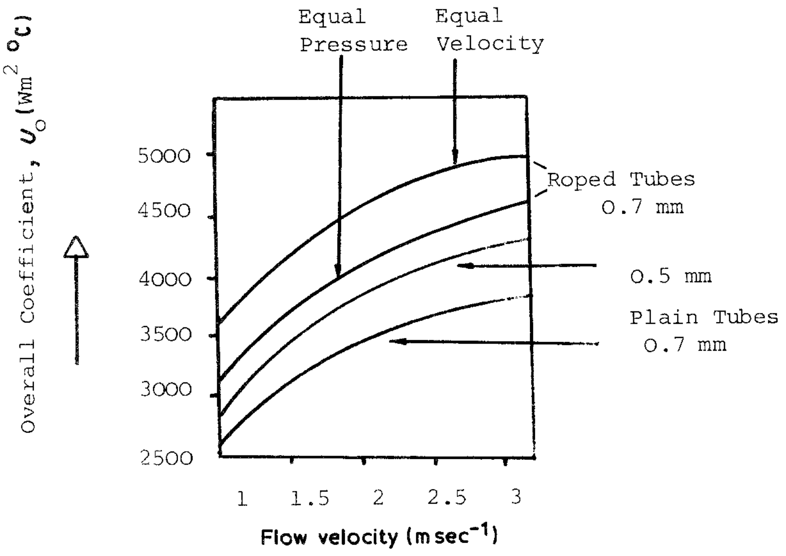

Figure 6 Typical overall heat transfer coefficients for titanium plain and roped tubes. Steam condensing tube diameter 25.4 mm, rope profile 0.3 mm groove depth and 5 mm pitch.

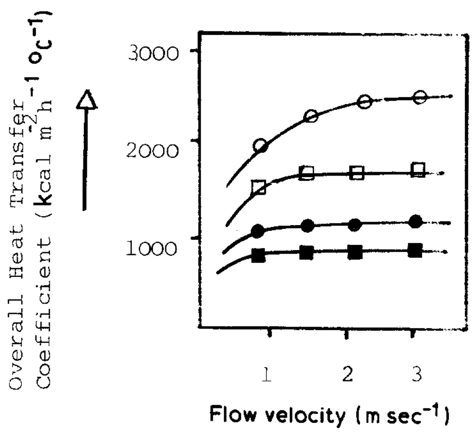

Figure 7 Condensing heat transfer characteristics of low-finned titanium tube. (■ ●) Ti plain tube, (□ ○) Ti LFT tube, (○ ●) 90 kg h^{-1} refrigerant flow, (■ □) 45 kg h^{-1} refrigerant flow.

tubes have been reported [26] and the possibility of resulting surface microcracks, that could be only marginally detectable by NDT methods, growing to critical sizes in service should not be underestimated.

In the OTEC1 construction, the shell and tube heat exchangers used were enhanced only on the ammonia side, in order to avoid the promotion of biofouling that might have arisen from the presence of a rough surface on the seawater side.

3. Future trends

Plate type heat exchangers are constructed usually by stacking preformed sheets in order to form alternate passages for the seawater and the working fluid. Joining can be accomplished by mechanical fastening, as in the Mini-OTEC, welding, brazing or adhesive bonding. The pattern in the individual sheets or plates increases the heat transfer area leading to more compact units and also stiffens the plate allowing the use of thinner gauges. The three major problems to be overcome are leak tightness, the development of a practical cleaning system to prevent biofouling, and resistance to crevice corrosion on the seawater side. The design must additionally allow for efficient and practical manifolding.

The mechanically joined designs have the capability of being disassembled on-site for cleaning and repairs, but may prove prone to leaks. The welded and brazed designs could be leak tight but must allow for in-position cleaning. Adhesive bonding has not been demonstrated reliably in ammonia for long term service and titanium and stainless steel alloys are difficult to bond. The patterns formed on the individual sheets can be cold formed, assuming that the required deformation is not severe. More severe deformations require hot forming for titanium. The superplasticity exhibited by some titanium alloys allows deep draws and complicated patterns to be imparted on the sheet.

Current thinking [28] concerning the design of a 10 MW floating OTEC pilot plant suggest that it should utilize three self-contained 5 MW power pods, two for routine production and one for development. The heat exchangers for the production pods should be conventional shell and tube design while the third pod should be a plate–fin design. This would allow the development heat-exchanger to experiment with the advantage of the superplastic-diffusion bonding properties of titanium and to this end work needs to be carried out on the following points:

1. nature of two phase flow in plate–fin heat exchangers
2. performance of titanium–“other-metal” sandwich for superplastic forming and diffusion bonding
3. optimization of heat transfer rates/pressure drop to enable selection of geometry for water and working fluid paths
4. further comparison of candidate materials in terms of more sophisticated economic assessment methods.

Although plastic heat-exchangers have not been covered in this review, they are used for desalination [29], and have been proposed for OTECS use [30]. In the future, metallic materials may have to bear scrutiny against this developing competition.

Summary

The major contender alloys for use in OTEC heat exchanger tubing have been discussed, and their advantages and disadvantages highlighted. It appears that titanium alloys are the leading candidates with a strong challenge from the stainless steel alloys suitable for OTEC use. Titanium's excellent seawater performance, its ability to be fabricated into the required shapes by existing technology, its successful service history and the current and projected developments exhibiting sound economics with major savings in material usage and reduced OTEC structure sizes, coupled with increased efficiencies make it the leading material for OTEC tubing.

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