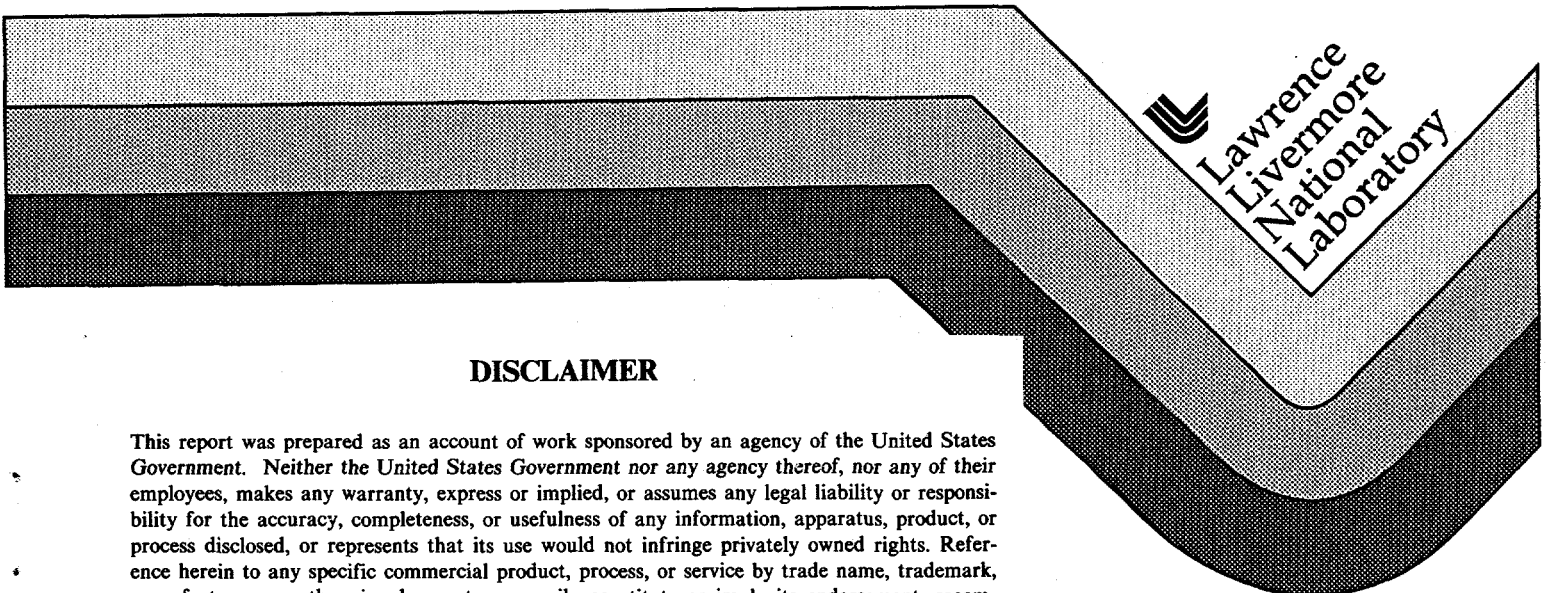


Survey of the Degradation Modes of Candidate Materials for High-Level Radioactive Waste Disposal Containers

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**Survey of the Degradation Modes of Candidate Materials
for High-Level Radioactive Waste Disposal Containers**

Nickel-Copper Alloys

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I. Introduction

One of the most significant factors impacting the performance of waste package container materials under repository relevant conditions is the thermal environment. This environment will be affected by the areal power density of the repository, which is dictated by facility design, and the dominant heat transfer mechanism at the site. The near-field environment will evolve as radioactive decay decreases the thermal output of each waste package. Recent calculations (Buscheck and Nitao, 1994) have addressed the importance of thermal loading conditions on waste package performance at the Yucca Mountain site. If a relatively low repository thermal loading design is employed, the temperature and relative humidity near the waste package may significantly affect the degradation of corrosion allowance barriers due to moist air oxidation and radiolytically enhanced corrosion.

An evolution of the waste package design effort has resulted in an increased emphasis on the performance of the engineered barrier system (EBS). The EBS includes the waste package and the near-field engineered repository environment. This evolution has prompted research and analysis related to the development of a multiple barrier Advanced Conceptual Design (ACD) for the waste package disposal container. The ACD systems currently under consideration consist of a multiple barrier design. The outer barrier will be fabricated from a corrosion allowance material, such as carbon steel. The inner barrier will employ a corrosion resistant material, such as Alloy 825. The thickness of each barrier is currently a variable in the container design process. The predicted long-term performance of each barrier material under repository relevant conditions will dictate the ultimate thicknesses of each barrier. Degradation modes surveys for Alloy 825 (Farmer, et al., 1988 and Gdowski, 1991) and carbon steel (Vinson, et al., 1995) have been completed previously.

A significant factor related to repository thermal performance that impacts the degradation of the container is the time period over which each container is predicted to remain dry. During this time period, a majority of the degradation of the container will occur due to simple moist air oxidation. However, current repository thermal designs include a lower thermal loading option which may result in container surface temperatures dropping below the boiling point of water in relatively short times following emplacement. This could result in a significantly more aggressive corrosion environment for the corrosion allowance material employed in the waste container. Various options addressing this potentially more aggressive environment are currently

being considered. These options may employ an additional outer barrier that is moderately corrosion resistant under expected low thermal loading repository conditions or replacement of the carbon steel corrosion allowance barrier with a more corrosion resistant material, such as a nickel-copper alloy (Monel 400).

The estimation of long-term container performance in a deep geologic repository environment, such as the proposed site at Yucca Mountain, requires the evaluation of relevant materials degradation data. These data are required for the completion of performance assessment modeling efforts. Previous degradation modes surveys (Farmer, et al., 1988) have been completed for the six candidate materials from the Yucca Mountain Site Characterization Plan (DOE, 1988). Additional reviews of the degradation of nickel-base alloys and carbon steel were also completed by Gdowski (1991) and Vinson, et al., (1995). These surveys have been employed to identify relevant failure mechanisms for the container materials under repository relevant conditions (Farmer, et al., 1991) and to provide a relative ranking of potential container materials based upon currently available data (Van Konynenburg, et al., 1993).

The purpose this report is to present a literature review of the potential degradation modes for moderately corrosion resistant nickel copper and nickel based candidate materials that may be applicable as alternate barriers for the ACD systems in the Yucca Mountain environment. This report presents a review of the corrosion of nickel-copper alloys, summaries of experimental evaluations of oxidation and atmospheric corrosion in nickel-copper alloys, views of experimental studies of aqueous corrosion in nickel copper alloys, a brief review of galvanic corrosion effects and a summary of stress corrosion cracking in these alloys.

II. Nickel-Copper Alloys

Monel is primarily a corrosion resistant alloy for handling acids, alkalies, brines, waters, food products, and for atmospheric exposure (The International Nickel Company, Inc.). Table 1 contains the compositions for the Monel nickel-copper alloys. The metal finds considerable use in elevated temperature applications. According to The International Nickel Company, Inc., it does not oxidize at a destructive rate below approximately 1000 °F. The oxide scale formed on Monel is adherent and does not spall.

Following is a summary of the characteristics of the Monel nickel-copper alloy metals compiled by Rosenberg (1968). Monel Alloy 400 gives excellent service in sea or brackish water under high-velocity conditions, as in propellers, impellers, and condenser tubes, where resistance to the effects of cavitation and erosion is important. Corrosion rates in strongly agitated and aerated sea water usually do not exceed 1 mil per year (mpy). Another important consideration in the use of the alloy in corrosion environments is its general freedom from stress-corrosion cracking.

The results of the ASTM 20-year atmospheric exposure tests of Monel Alloy 400 as reported by Rosenberg (1968) show that Alloy 400 is equally excellent in resisting the less corrosive atmospheres and is markedly superior to nickel in resistance to the industrial atmospheres of Altoona and New York City. According to Rosenberg, Monel Alloy 400 has very good resistance to oxidation at temperatures up to about 900 °F. From 900 to 1300 °F the surface scale is still thin and very adherent, but grain boundary penetration of oxide is evident. Above 1500 °F the bulk of the oxide grows rapidly, remains adherent and apparently quite dense, but is poorly protective.

According to Rosenberg (1968), the 70/30 Ni/Cu alloy has the best high-temperature strength of the straight nickel-copper alloys. This alloy also has the greatest resistance to creep. Monel Alloy 401 has a low temperature coefficient of electrical resistivity. It is used in the manufacture of wire-wound resistors. Monel Alloy 402 is used for fixtures in operations for pickling steel and copper alloys. It is resistant to hot sulfuric acid pickling solutions and to hydrogen embrittlement when it is galvanically coupled to steel.

In Monel Alloy 403, the nickel, iron, and manganese contents are so adjusted that the alloy remains nonmagnetic at the freezing point of sea water (27 °F). It was developed for use in mine-sweepers. Monel Alloy 404 is characterized by low magnetic permeability and excellent brazing characteristics. Residual elements are controlled at low levels to provide a clean wettable surface even after prolonged firing in wet hydrogen. Its permeability is not significantly affected by processing and fabrication.

Monel Alloy R-405 is very similar to Monel Alloy 400 in all respects except that a controlled amount of sulfur is added to improve machining characteristics. Monel Alloy

406 is particularly resistant to corrosion from mineral waters. Monel Alloy 474 is essentially free from nonmetallic inclusions, is nonmagnetic, and has low permeability. The alloy has good formability and superior brazing characteristics even in wet hydrogen atmospheres.

Monel Alloy K-500 has good mechanical properties over a wide temperature range (strength, ductility, and toughness). Monel Alloy 501 is similar to Alloy K-500, except that it has improved machining characteristics.

III. Oxidation and Atmospheric Corrosion

According to a summary of the corrosion resistance of nickel base alloys included in the ASM International *Handbook of Corrosion Data* (1989), corrosion of Monel is negligible in all types of atmospheres, although a patina will develop. Incoloy Alloy 825 develops a very thin and protective, passive oxide film that prevents even significant tarnishing. Mirror finishes on Incoloy Alloy 825 surfaces can be maintained after extended exposure to the atmosphere.

A 20 year atmospheric corrosion testing program evaluating the corrosion performance of non-ferrous metals and alloys has been completed by the American Society for Testing and Materials (ASTM) (Copson, 1955). Samples of Monel were exposed independently at Bayonne, New Jersey, and the results of these exposures were also considered. The testing program completed by ASTM consisted of 24 non-ferrous metals boldly exposed vertically at seven test locations. The testing at Bayonne, New Jersey, provided three conditions of exposure. These were sheltered vertical, exposed vertical, and exposed inclined. The results of these testing programs were reported by Copson (1955). Data for the Monel test specimens for ASTM tests can be found in Table 2 and for Bayonne exposures in Table 3. Results of the Monel exposures are summarized as follows.

In the ASTM testing program, Monel was exposed to seven environments (see Table 2). The locations are Altoona, Pennsylvania, New York, New York, Sandy Hook, New Jersey, Key West, Florida, La Jolla, California, State College, Pennsylvania, and

Phoenix, Arizona. The Altoona and New York sites are industrial locations with severe air pollution. The Sandy Hook site is an industrial marine location. Key West proved to be a comparatively mild marine location. La Jolla is a severe marine location. State College and Phoenix are rural locations, with Phoenix being quite dry. Monel was found to be quite resistant to general corrosion in marine and rural locations. At Sandy Hook, the corrosion rate of Monel increased to more than three times the corrosion rates of any of the rural or marine locations. The severe industrial locations of New York and Altoona proved to be the most corrosive environments to Monel, providing more than two times the general corrosion rate found at the industrial marine location of Sandy Hook.

Monel samples exposed to the sheltered vertical condition at Bayonne, New Jersey exhibited higher corrosion rates than those boldly exposed to the atmosphere (see Table 3). Also, Monel sheets exposed in the sheltered vertical position showed deeper pits than those boldly exposed in a vertical position. Inclined samples that were boldly exposed corroded at a lower rate than the sheltered vertical samples but at a higher rate than the boldly exposed vertical samples. The deleterious effects of sheltered exposures versus boldly exposed tests are well documented in the literature (Vinson, et al., 1995).

Southwell, et al. (1976) reported on the results of 16-year tests of materials exposed in coastal and inland atmospheres in a tropical environment. Data for atmospheric corrosion of Monel and for comparison metals are included in Table 4 and are summarized in Figures 1 and 2 for inland and coastal atmospheric exposure, respectively. Of the fifty-two different alloys included in this study, Monel (cold-rolled and hot-rolled) is of interest in this study. For comparison, data for a 70Cu-30Ni alloy, for Type 316 stainless steel, and for a structural carbon steel (0.25C-0.08Cu) are reported.

For atmospheric corrosion due to exposure in a tropical environment, the data suggest that the Monel alloy is superior to the 70Cu-30Ni alloy for exposures longer than 8 years and to the carbon steel specimens for all measurements (see Table 4). The Monel alloy lost approximately one half as much mass due to corrosion as did the 70Cu-30Ni alloy after eight and sixteen year exposures. The Monel alloy showed less than three percent of the mass loss realized by the carbon steel at all times. The Type 316 stainless steel had the best overall corrosion resistance, having zero mass loss over the duration of

the atmospheric exposure. It is worth noting that, with the exception of carbon steel, each of these metals exhibited some resistance to pitting. The pitting penetration of these metals was reported as being less than 5 mils.

Baker (1988) summarized the results of exposures in the natural marine atmosphere at Kure Beach, North Carolina, for a test duration of 45 years for some nickel base alloys (Incoloy Alloy 825 was exposed for only 28 years). Baker found that Monel Alloy 400, Monel Alloy K500, Nickel Alloy 200, and Incoloy Alloy 825 all exhibited long-term corrosion resistance to the marine atmosphere. Corrosion rates for these alloys were less than 1 $\mu\text{m}/\text{year}$ after their respective test durations. This study found that the nickel-base alloys generated a very thin oxide film that provided excellent resistance to corrosion. One test panel from Monel Alloy 400, Monel Alloy K500, and Nickel Alloy 200 was evaluated after 36 years. Baker reported corrosion rates of 0.3 $\mu\text{m}/\text{year}$, and a pit depth of 0.1 mm for the Monel Alloy 400 specimen. Monel Alloy K500 showed a corrosion rate of 0.2 $\mu\text{m}/\text{year}$ and a pit depth of 0.2 mm, maximum. A corrosion rate of 0.25 $\mu\text{m}/\text{year}$ and no pitting was found on the Nickel Alloy 200 specimen.

In a review of selected literature on the corrosion of metal in marine environments, Boyd and Fink (1975) state that Monel Alloy 400 and the cupro-nickels are all resistant to marine environments. The investigators report that Incoloy Alloy 825, Monel Alloy 400 and Monel Alloy K500 are resistant to marine environments, but may develop some pits at sites where sea water is stagnant. Hastelloy Alloy G (45Ni-21Cr-7Mo-20Fe-2Cu-2.5Co) was reported to have negligible crevice attack and good resistance to general attack in sea water. Further, Monel Alloy 400 was found to be susceptible to oxygen concentration-cell corrosion. Thus, this study suggests that crevices and other areas where sea-salt solutions may be trapped and set up local cells be avoided when using Alloy 400 in marine environments. It was noted that Incoloy Alloy 825, Monel Alloy 400, and Monel Alloy K500 exposed to a splash zone maintain passive surfaces due to the frequent splashing and well-aerated conditions as long as the surface is clean and free of deposits and pockets where sea water can collect.

In a series of atmospheric corrosion tests carried out in Birmingham, Alabama, eleven stainless steels and thirteen nickel alloys were exposed over a 10 year period (Evans, 1972). Compositions of the nickel alloys included in the tests are listed in Table 6.

Upon inspection of the samples after exposure, Evans (1972) noted that Alloy 600 and Alloy DS suffered the least attack with weight losses in the range 2 to 6 mg/cm² and that the corrosion was mainly confined to shallow pitting beneath a continuous, thin film of corrosion product. Nickel Alloy 200 and Nickel Alloy 213 suffered more corrosion with weight losses of 50 to 60 mg/cm². These nickel alloys also exhibited shallow pitting beneath a thin film of corrosion product. Alloy 301 gave lower weight losses than Nickel Alloy 200, ca 20 mg/cm², but did not pit. The nickel-copper alloys, Monel Alloy 400 and Monel Alloy K500, exhibited weight losses similar to Alloy 301, but showed more extensive and deeper pitting, especially on the more sheltered, downward-facing samples. The cupro-nickels were inferior to the Monel alloys, exhibiting no pitting, but higher corrosion weight losses of 30 to 50 mg/cm² were observed.

The 1957 Test Program carried out by the American Society for Testing and Materials (ASTM 1959; 1961; 1962; 1966) included five nickel base alloys, Nickel Alloy 200, Incoloy Alloy 800, Inconel Alloy 600, Monel Alloy 400, and Incoloy Alloy 825, exposed to the atmosphere of four test sites. Compositions of these alloys are included in Table 7. Data summarizing the results of the test program through 7 years exposure may be found in Table 8. Actual 7-year exposure times varied at the three locations involved. Exposure times are listed in Table 9. Seven-year specimens at Port Reyes, California were vandalized so that no 7-year data is available from this test site. Included in this summary, however, is two year data for all four test sites including Kure Beach (25 meter lot), North Carolina, Newark, New Jersey, State Park, Pennsylvania, and the Port Reyes site.

Data from the 1957 Test Program were investigated by van Rooyen and Copson (1968). In this study, the nickel-chromium-iron alloy, Incoloy Alloy 825, showed lowest corrosion rates after both exposure times, while panels of Monel Alloy 400 and Nickel Alloy 200 were corroded more. Pit depths of all alloys considered were very small, all being less than 1 mil deep. The Incoloy alloys and the Inconel Alloy 600 exhibited marked decreases in corrosion rates at all sites between two- and seven-year measurements. The

Nickel Alloy 200 and the Monel Alloy 400 corroded at a nearly linear rate with time through 7 years.

The investigators make reference to previous work done by Wesley (1940) which they feel is consistent with the findings from the 1957 program data. This study also mentions measurements of the thickness of Monel Alloy 400 roofing sheets on the old Penn Station in New York City. After some 54 years, when the building was torn down, the sheets were measured. The sheets measured roughly 0.017 inches thick compared to an initial thickness of about 0.020 inches. This corresponds to a corrosion rate of 0.342 milligrams per square decimeter per day (mdd), which is in close agreement with New York City exposure data from the ASTM test program reported previously by Copson (1955). Copson found corrosion rates for Monel Alloy 400 to be 0.35 and 0.38 mdd for 10-year and 20-year exposure, respectively (see Table 2).

IV. Aqueous Corrosion

Southwell, et al. (1976) reported on the results of 16-year tests of materials exposed to sea and fresh water immersion and sea water mean tide in a tropical environment. Data for aqueous corrosion of Monel and for comparison metals are included in Table 5 and are summarized in Figures 3, 4, and 5 for sea water immersion, fresh water immersion, and sea water mean tide exposure, respectively. As was found in the atmospheric exposure data, carbon steel exhibited the worst corrosion resistance of the metals considered in this report. The Monel alloy showed less corrosion resistance than the 70Cu-30Ni alloy and the stainless steel. Monel displayed a susceptibility to pitting in all aqueous corrosion environments, although the cold rolled Monel showed slightly more resistance than the hot rolled version. Both Monels, however, pitted more than the 70Cu-30Ni alloy, which was more resistant than the stainless steel to pits.

In reviewing the results of the Southwell and Alexander data (1969), Boyd and Fink (1975) report that the nickel-copper alloys (Monel) and nickel-chromium-iron alloys (Incoloy Alloy 825) will become covered with marine fouling in the tide zone and below making passivity difficult to maintain. Table 5 summarizes the behavior of Monel Alloy

400 immersed in fresh water, immersed in sea water, and at mean tide level in the tropical environment of the Panama Canal Zone.

After 16 years exposure, Monel Alloy 400 (cold-rolled) showed a weight loss penetration of 0.17 mpy with a maximum pit depth of 21 mils. The investigators state that general experience indicates that the pit depth on Monel Alloy 400 rarely exceeds 50 mils in the tide zone. Further, they state that pits develop slowly and do not increase appreciably in depth after the eighth year. Cupro-nickels reportedly are more resistant in this environment and tend to show only slight pitting in the same exposures.

In a review of selected literature on the corrosion of metal in marine environments, Boyd and Fink (1975) found that in submerged high velocity applications, the nickel-copper alloys, as represented by Monel Alloy 400 and Monel Alloy K500, have excellent resistance to sea water. Their surfaces maintain passivity, and water motion tends to prevent fouling. Data provided by The International Nickel Company for high velocity sea water impingement test show corrosion rates of 0.3 mpy, 0.4 mpy, and 0.4 mpy, respectively, for Incoloy Alloy 825, Monel Alloy 400, and Monel Alloy K500. This test lasted for 30 days with a flow velocity of 135 fps. A cast iron and a medium-carbon steel were included in this test. The iron base alloys were greatly inferior to the nickel base alloys, exhibiting corrosion rates of 176 mpy and 600 mpy, respectively, for the medium-carbon steel and the cast iron.

In quiet sea water, Monel Alloy 400, Monel Alloy K500, and similar alloys tend to pit or to experience local attack at screened area (Boyd and Fink, 1975). This is supported by data in Table 5, which shows a weight-loss penetration of only 8.70 and 8.40 mils after 16 years but pits of up to 55 and 82 mils for cold-rolled and hot-rolled Monel panels, respectively. Boyd and Fink (1975) state that pitting of the copper-nickel alloys tends to progress rapidly during the first year, after which the pits tend to spread out rather than deepen.

Data for corrosion rates and depth of attack on Monel Alloy 400, Monel Alloy K500, and Incoloy Alloy 825 specimens exposed for 3 years in quiet sea water can be found in Table 10. The data show that Monel Alloy 400 and Monel Alloy K500 corrode at nearly equal rates with similar pit depths, ranging from 30 to 55 mils. The Monel alloys

experience numerous broad pits. Incoloy Alloy 825 shows greatly improved corrosion resistance. The weight loss of the alloy was found to be less than one percent of the weight loss experienced by either of the Monel alloys during the testing period. Further, Incoloy Alloy 825 had very shallow pit depths, ranging from 1 to 7 mils, but exhibited crevice corrosion beneath barnacles.

In testing the effect of material composition in high-temperature water corrosion, Roebuck (1955) reported on the general corrosion resistance of a carbon steel, a 70Cu-30Ni alloy, a Hastelloy alloy, and a Monel alloy exposed to water with a dissolved oxygen concentration of about 1 ml per liter at high temperatures. The testing temperatures ranged from 93 °C to 360 °C. Roebuck categorized corrosion resistance by assigning grades of A, B, or C, to each metal at each intermediate temperature. The grades were assigned based on the following:

- A) Highest Resistance: No apparent corrosion products; clean tarnish film. Less than 0.3 milligrams per square centimeter per month, or 1 milligram per square decimeter per day.
- B) Intermediate Resistance:
No apparent corrosion products; clean tarnish film. Greater than 0.3 milligrams per square centimeter per month.
or
Some apparent corrosion products on surface or moderate amount of pitting and spalling. Less than 0.3 milligrams per square centimeter per month.
- C) Low Resistance: Heavy deposit of corrosion products on surface, or general deep pitting and spalling. Greater than 0.3 milligrams per square centimeter per month.

Roebuck found that of the four metals listed above, the carbon steel and the Hastelloy alloy showed the least resistance to general corrosion in water. From 93 °C to 260 °C, Roebuck assigned a grade of B and a grade of C for temperatures ranging from 316 °C to 360 °C for the carbon steel. The Hastelloy alloy was assigned a grade of A at 93 °C, a grade of B at 149 °C, and a grade of C for temperatures ranging from 205 °C to 360 °C. Both the 70Cu-30Ni alloy and the Monel alloy received grades of A for temperatures from 93 °C to 260 °C, but the Monel alloy showed superior corrosion

resistance at 316 °C receiving a grade of B while the 70Cu-30Ni alloy received a C. Both alloys received a grade of C at 360 °C.

Jet impingement tests were carried out by the method described by May and DeVere Stackpoole to assess corrosion in moving sea-water (White, et al., 1966). These tests were carried out in the waters of the Mediterranean and the Dead Seas. Typical analysis of Mediterranean sea water and of water from the Dead Sea as used by White, et al. (1966) are given in Table 11. Among the materials tested were Cupro-nickel 70/30, Monel, an 18:8 stainless steel (7Ni-17.6Cr), and a mild steel (0.27Mn-0.11C). The 70/30 Cupro-nickel was included in all runs as reference standards. Data for the jet impingement tests are summarized in Figure 6. In addition to the jet impingement tests, static immersion tests were carried out by the investigators. Data for materials relevant to this survey are included in Tables 12, 13, and 14.

Results of the impingement tests and the total immersion test show that the stainless steel is superior to Monel, which was more resistant than the 70/30 cupro-nickel in all test conditions. Partial immersion test data, however, show that Monel is more resistant to the static sea water of the Dead Sea, while less resistant to the static sea water of the Mediterranean Sea. Both the stainless steel and Monel were greatly superior to the mild steel in all tests.

Eight materials were commonly used for engineering applications in the marine environment were exposed to chlorinated and unchlorinated sea-water under quiescent and flowing conditions for one year by Thomas, et al. (1988). The researchers suggested that the term "halogenation" be used to more accurately characterize the electrolytic addition of chlorine to sea-water. This convention will be used in this survey in a summary of their findings.

Thomas, et al. (1988) exposed engineering materials to natural sea water and halogenated sea water at concentrations of 1 and 4 mg/L for approximately one year (8900 hours). Materials of interest included in the study were a 70/30 Cupro-nickel, Monel Alloy 400, and Monel Alloy K500. The researchers found that the 70/30 Cupro-nickel and the K-Monel showed no differences between exposure in unhalogenated sea water and the 1 mg/L treatment, but a 300 percent increase corrosion rate was observed in

the 4 mg/L treatment. The Monel Alloy 400 samples showed an increased resistance to corrosion at 1 mg/L and no difference between the unhalogenated sea water and the 4 mg/L treatment.

Upon visual inspection of the coupon surfaces, the investigators noted that the Cupro-nickel showed some localized corrosion, especially at the edges and in crevices, and the extent of localized corrosion increased at both levels of halogenation. The Monel alloys exhibited pitting and showed edge and crevice corrosion at all conditions. The Monel Alloy K500 was affected by both levels of halogenation, while the Monel Alloy 400 showed a reduction in localized corrosion with halogenation.

Wheatfall (1967) reported on the corrosion of metals in deep ocean environments. Test specimens for general corrosion experiments in deep ocean environments, including AISI Type 304 stainless steel, 70/30 cupro-nickel, Monel Alloy 400, Monel Alloy K500, and Incoloy Alloy 825, were exposed at 5640 feet for 123 days and 751 days and at a depth just below the water surface for 386 days. Data for Type 304 stainless steel and 70/30 cupro-nickel at 5300 feet for 1064 days are also included. Rectangular metal plates (12 x 12 inches) were used in three deep-marine exposures. The samples were from 1/16 to 1/4 inches thick. The surface exposure samples were 12 x 3 inches and 1/16 inches thick. In all of these tests, a crevice of constant area existed on each specimen due to the contact area created by nonmetallic supporting fixtures. In addition, crevice corrosion experiments were carried out on specimens of Type 304 stainless steel (12 x 2 x 1/8 inches) and Monel Alloy 400 (12 x 2 x 1/16 inches). The crevice area was varied from 0 to 14 square inches on both faces of the specimens by means of tree-shaped nylon strips. The crevice corrosion samples had an additional 8 square inch crevice on each face of the alloy due to nylon strips used to secure samples to the steel rack. Data from the general corrosion experiments can be found in Table 15 and is summarized as follows.

Wheatfall (1967) found that, of the alloys considered in this survey, only the 30% cupro-nickel alloy showed a resistance to localized corrosion, but the general corrosion rates for this alloy were among the highest. Only the stainless steel exhibited higher general corrosion rates. The stainless steel also realized the susceptibility to localized corrosion. Incoloy Alloy 825 exhibited the greatest overall resistance to general

corrosion, but suffered severe pitting in the crevice created by the nylon strip used to secure the samples. Monel Alloy 400 was more resistant to corrosion in all test conditions than was Monel Alloy K500, but both Monel alloys suffered from localized corrosion inside and outside the crevice area.

The crevice corrosion experiments included Monel Alloy 400 and Type 304 stainless steel. Wheatfall found moderate crevice corrosion on Type 304 stainless steel at a depth of 2340 ft, but no attack was observed on Monel Alloy 400. No localized corrosion was detected on the boldly exposed surfaces of either material. In 6780 ft of water, more severe deterioration was noted for both alloys. Incipient crevice corrosion was evident on Monel Alloy 400, but no pits were present. Wheatfall attributes the increase in corrosion at this depth to an increase in oxygen content from 0.70ppm to 1.60 ppm as well as to a longer exposure time. Severe crevice corrosion and overall surface corrosion were quite pronounced in the shallow water investigation. Several perforations at the crevices and on the surfaces remote from the crevices were found on the stainless steel in the shallow water exposures. One of the Monel Alloy 400 samples was perforated at the crevice under these conditions. Wheatfall concluded that variations in oxygen content in the crevice-corrosion experiments was the most important factor in the behavior of Type 304 stainless steel and Monel Alloy 400.

Cramer, et al. (1983) reported on results of corrosion tests conducted in brine steam process streams produced by flash evaporation of wellhead brine from geothermal well Magmamax No. 1 at the Bureau of Mines geothermal test facility. Operating conditions for test packages averaged over the approximately 45 days of the study are given in Table 16. Figure 7 shows a block diagram of the facility and relative locations of the test packages for the corrosion tests. General and localized corrosion rates were gathered for nickel alloys including Nickel Alloy 201, Monel Alloy 400, Monel Alloy 404, Incoloy Alloy 825, and Hastelloy Alloy G after 15, 30, and 45 days exposure in brine and steam. The material composition of these alloys are given in Table 17. Data for general corrosion measurements are reported in Table 18 and are summarized in Figure 8.

The data show that Nickel Alloy 201 corrodes at substantially higher rates than the nickel alloys in brine and steam environments. Corrosion rates for Incoloy Alloy 825 in

the brine and steam environments were negligible when compared to those of the Monel alloys. Of the alloys considered, the Hastelloy Alloy G showed the greatest resistance to general corrosion. Monel 404 corroded more rapidly than Monel Alloy 400 in all separated steam environments. Highest corrosion rates were experienced in wellhead brine. Corrosion rates decreased with time for all nickel base alloys. The investigators suggest that much of the corrosion in the brine and steam environments occurred in the first 15 days and that the scale and corrosion product was protective, substantially retarding further corrosion. Investigators report that with the exception of Hastelloy Alloy G, which exhibited negligible corrosion, corrosion rates typically decreased with increasing exposure time for all of the alloys.

Cramer, et al. (1983) recorded maximum and average pit penetrations for nickel alloys including Monel Alloy 400, Monel Alloy 404, and Incoloy Alloy 825. Data collected is listed in Table 19 and are summarized in Figure 9. Average pitting rates for the Monel alloys varied from 260 to 430 $\mu\text{m}/\text{day}$ in 45-day tests in the brine environments. Average pitting rates for the Monel alloys varied from 210 to 330 $\mu\text{m}/\text{day}$ in 45-day tests in the steam environments. Very few pits were observed for Monel Alloy 400 and for Monel Alloy 404 in the wellhead brine. All alloys considered pitted at substantial rates in the steam environments. Monel Alloy 400 and the Hastelloy Alloy G showed more resistance to pitting in the steam environments than the other two alloys, with Hastelloy Alloy G showing greater resistance after the 15 day exposures. Pitting rates of all alloys decreased significantly between 15-day and 30-day exposures.

Investigators found no stress corrosion cracking in either Monel alloys and Hastelloy Alloy G. Incoloy Alloy 825 was found to crack in wellhead brine. The Monel alloys exhibited severe uneven local corrosion in wellhead brine. Investigators found crevice corrosion in Incoloy Alloy 825 in the brine and steam environments P1 through P4. The Monel alloys exhibited no crevice corrosion in steam environments, but experienced slight crevice corrosion in the brine environment P2.

In a review of selected literature on corrosion of metals in marine environments, Boyd and Fink (1978) gathered data on corrosion of metals in sea water brine. Corrosion data for metals in normal sea water and sea water brine at cold and elevated temperatures

show that, in cold sea water (80°F, 8.2 pH, 8.5 ppm oxygen, salinity = 35 g/L), Monel exhibits a low corrosion rate (0.0003 inches per year (ipy)). In cold sea water, carbon steel, a 70/30 copper-nickel alloy, and Type 304 stainless steel corroded at rates of 0.029 ipy, 0.0015 ipy, and 0.0030 ipy, respectively. In hot sea water (187°F, 8.2, 7.8 ppm oxygen, salinity = 59.3 g/L) Monel corroded four times faster than Type 304 stainless steel (0.0004 ipy for Monel compared to 0.0001 ipy for stainless steel). The 70/30 copper-nickel alloy corroded more than 3 times faster than Monel and carbon steel corroded nearly 60 times faster than Monel. Of the alloys considered here, only Monel Alloy 400 showed an increased corrosion rate as the sea water temperature increased.

Results of corrosion tests in San Diego in deaerated sea water brine after 90 days show that Incoloy Alloy 825 is superior to Monel Alloy 400 in resistance to general corrosion (Boyd and Fink, 1978). Incoloy Alloy 825 exhibits crevice corrosion in all tests conditions, while Monel seemed to be immune to crevice attack. Type 316 stainless steel was superior to Monel Alloy 400 but exhibited more crevice attack than Incoloy Alloy 825. Monel Alloy 400 was, however, more resistant than a 70/30 copper-nickel, which was greatly superior to carbon steel.

In a report on the corrosion of metals in marine environments (Beavers, et al., 1986), it is reported that Monel Alloy 400 reaches a maximum weight loss in sea water at 30 °C, and the weight loss drops to very low values at 50 °C; whereas, in the same exposure, pit depths were reported to be greatest at 18 °C, decreasing to negligible values at 50 °C. Hastelloy Alloy G is reported to reach a maximum depth of crevice attack at 28 °C. In 30-day tests, it is reported that Hastelloy Alloy G exhibited an average crevice attack of 0.03 mm at 12 °C, 0.05 mm at 28 °C, and 0.0 mm at 50 °C. No crevice corrosion was observed after 31 weeks' exposure at 25 °C and 60 °C in Incoloy Alloy 825, but crevice corrosion was observed after 20 weeks' exposure at 100 °C.

V. Galvanic Corrosion

Pelensky, et al. (1978) reported on the progress of investigations being conducted at Panama Canal Zone, relative to the corrosion of dissimilar metal couples exposed in the

atmosphere, in the soil, and in sea water. Alloys included in the study were 6061-T6 and 7075-T6 aluminum, 360 brass, AZ31 magnesium, Monel Alloy 400, 4340 steel, Type 316 stainless steel and titanium 6A1-4V. Total (general, galvanic, crevice) corrosion rates, in mm/year, are given in Tables 20, 21, and 22, respectively, for atmospheric, soil, and aqueous exposures. The corrosion rates shown are of the alloy indicated, when coupled with various dissimilar metals. For comparison, the similar metal average corrosion rate is also indicated.

Atmospheric specimens used in the study were flat rectangular plates 0.55 by 2.54 by 3.81 centimeters. The plates were coupled using a stainless steel machine screw insulated from the faces of the specimens. These tests were carried out at the open field site at Fort Sherman, Panama Canal Zone. Atmospheric data for the 4340 steel indicates a high initial corrosion rate decreasing with exposure time, and a tendency toward leveling off after 8 months exposure (see Table 20). The greatest corrosion rates were observed when the 4340 steel is coupled with stainless steel and with Monel Alloy 400. The corrosion rates for Monel Alloy 400 and 316 stainless steel were essentially zero for all couples. Coupling of AZ31 magnesium with steel, stainless steel, and Monel resulted in the greatest attack on magnesium.

Soil and aqueous test specimens were 2.54 centimeters in diameter and 1.27 centimeter long. They were coupled using a steel screw but were separated by a plexiglass rod. The soil specimens were installed at the water table, buried at a depth of 1.2 meters below the soil surface, in an area adjacent to the open field test site. Investigators report that the 4340 steel shows a tendency toward slightly increased attack when coupled with brass and Monel and somewhat less when coupled with 6061-T6 aluminum (see Table 21). Appreciable sacrificial protection is indicated when coupled with magnesium. Corrosion rates of Type 316 stainless steel and Monel Alloy 400 when exposed in soil are considered slight or negligible.

Aqueous test specimens were completely immersed approximately 1.4 meters below the water surface at low tide and approximately 1.7 meters below the surface at high tide. They were exposed in Manzanillo Bay at the Coco Solo Naval Station, Panama Canal Zone. The Type 316 stainless steel exhibited crevice and pitting attack in the

stainless steel couple and in the dissimilar couple with Monel Alloy 400 (see Table 22). There was no evidence of corrosion when coupled with other dissimilar metals. Investigators noted that in some instances when stainless steel is coupled with Monel Alloy 400, that the stainless steel is not attacked, but Monel is attacked.

Analysis of 4340 steel found that increased attack in sea water when coupled with austenitic stainless steel, brass, Monel, and titanium alloys. The 4340 steel is protected by coupling with magnesium and aluminum alloys. The Monel Alloy 400 is protected when coupled with magnesium, steel, aluminum, and brass alloys; however, pitting of Monel occurs when coupled with titanium and also in similar Monel-Monel couple, as well as in some instances with austenitic stainless steel. Investigators rated the extent of attack in sea water from greatest to least as follows: magnesium alloy, steel, brass, austenitic stainless steel, aluminum alloys, Monel, and titanium. No attack on titanium was observed under any test conditions.

Southwell and Alexander (1969) reported on 16-year exposure data for bimetallic couples exposed to various waters and to various atmospheres at Panama Canal Zone. Results for corrosion penetration of the strip metal and the plate metal of galvanic couples exposed to aqueous environments are reported in Tables 23 and 24, respectively. In sea water, it was found that carbon steel is a highly effective anode for protecting Type 316 stainless steel, Nickel, Monel Alloy 400, and the 70/30 copper-nickel alloy. At mean tide, a high degree of anode protection was evident throughout the first 8 years. In all three aqueous environments, the Monel-bronze couple developed more severe galvanic corrosion than did the more noble 18:8 stainless steel-bronze couple. No significant protection of Monel was observed in fresh water and only to a slight degree at mean tide. In sea water, successful protection of Monel with bronze was achieved in about 50% of the specimens. Investigators concluded that in order to obtain effective cathodic protection of the nickel alloys, a higher potential will be needed than that supplied by anodes of bronze and copper. Data reveals that using a carbon steel anode on 70/30 copper-nickel plates resulted in almost complete protection of the copper-nickel alloy through eight years exposure, at the end of which, the steel anodes were depleted and corrosion of copper-nickel proceeded at its normal, uncoupled rate. Monel plates were

equally protected, and the anodes lasted for more than eight years. Investigators found that during the relatively long life of the anodes, highly effective protection was afforded the two nickel alloys. Weight loss was insignificant, and no crevice corrosion or underfouling corrosion was detected. Panels were entirely free of pitting during the protected period.

Results of galvanic couples exposed to atmospheric sites are reported in Table 25. A summary of the observations of Southwell, et al. (1976) follows. Two of the most noble metals in the atmospheric exposures, Type 316 stainless steel and Monel Alloy 400, reacted differently than when in sea water in which Monel caused slightly greater corrosion of more anodic metals. In the atmospheric exposures, Type 316 stainless steel caused a greater amount of anodic corrosion of steel than any other noble metal; almost double the amount caused by Monel cathodes. Investigators report that the extremely noble position of Type 316 stainless steel and the nickel-copper alloys in the galvanic series sometimes makes these materials hazardous for use in unfavorable area ratios with almost any other constructional metallic alloy. When used in structures, these metals are galvanically protected and can survive undamaged for years.

Southwell, et al. (1976) derived the following conclusions on the galvanic corrosion of metals in various environments. Carbon steel was a very effective anode for more noble metals. Strips of steel effectively protected bronzes, Monels, and austenitic stainless steels for periods in excess of 8 years in sea water, and through 16 years at mean tide. In fresh water, cathodic protection was not very effective. However, when the anodes were smaller than the cathodes, the anodes were significantly damaged by galvanic action in this medium. In the atmospheric exposures, the coastal marine atmosphere caused four to eight times more galvanic corrosion than the inland atmosphere.

VI. Stress Corrosion Cracking

An important consideration in the use of Monel Alloy 400 in corrosive environments is its general freedom from stress corrosion cracking. The limiting

temperatures for use of Monel Alloy 400 in various environments, according to Mudge (1948), are given in Table 26.

After 24 years of exposure at Kure Beach, North Carolina, Baker (1988) found that Monel Alloy K-500 continued to resist stress corrosion cracking. The test included a welded and a non-welded sample submitted to a two-point loaded bent beam stress corrosion test exposed for six months in sea water and then re-exposed in the marine atmosphere, 25 meters from the ocean. A stress of 96 ksi was introduced to the Monel alloy for the duration of the test. Some Monel Alloy K500 samples (welded and not welded) were tested for stress corrosion cracking after exposure to low velocity (5 m/s) sea water. Analysis of these samples revealed no failure between 548 to 964 day exposures.

Copson and Cheng (1956) reported the results of U-bend tests investigating the susceptibility of Monel to stress corrosion cracking when exposed to hydrofluoric acid vapor. In addition to Monel Alloy K500 and Monel Alloy 400, a special Monel containing 1 percent silicon and a high nickel Monel containing 85% nickel and 15% copper were included in the tests. Investigators found the Monel Alloy K500 to quickly develop a large number of closely spaced transcrystalline cracks penetrating deeply from the tension side of the U-bend. Reportedly, hot-rolled and age-hardened material behaved similarly. Monel Alloy 400 was found to crack in much the same manner as Monel Alloy K500. Cold-rolled material showed transcrystalline cracking, while annealed material exhibited cracking that was predominantly intergranular, with many short transcrystalline branches. Copson and Cheng report that in many instances, the cracks seemed to stop growing or to turn in a lengthwise direction after penetrating about half way through the specimens. The Monel plus 1 percent silicon behaved similarly to Monel Alloy 400, and the high nickel Monel cracked profusely. Investigators concluded that alloy additions of silicon, nickel, and aluminum to Monel have no major influence on susceptibility to cracking.

Copson and Cheng (1956) totally immersed U-bend specimens of Monel Alloy 400 and Monel Alloy K500 in 48% hydrofluoric acid, in 30% hydrofluosilicic acid, and in mixtures of these acids. In conditions where no vigorous aeration was present, corrosion rates were low, and the samples showed no sign of cracking for periods of up to 30 days.

In conditions where vigorous aeration was present, corrosion was greatly increased. Cracking was found in 15 days on Monel Alloy K500 totally immersed under these conditions. Investigators suggest stress relieving Monel by heating for 1 hour at 1100 °F to 1200 °F, and they recommend slow cooling.

Kolts and Sridhar (1985) completed a study concerned with the pitting and crevice corrosion resistance of nickel and nickel base alloys, including Hastelloy Alloy G, Hastelloy Alloy G3, and Incoloy Alloy 825. The compositions of the alloys are given in Table 27. Hastelloy Alloy G3 was found to be superior to Incoloy Alloy 825 in stress corrosion cracking resistance in concentrated chloride environments. In dilute chloride solutions, after 1 months' exposure, no localized attack was observed in Hastelloy Alloy G, with a general corrosion rate of less than 0.01 mm/yr, while Incoloy Alloy 825 exhibited pitting and crevice corrosion and a general corrosion rate of 0.03 mm/yr. Neither the Hastelloy Alloy G nor the Incoloy Alloy 825 showed any signs of stress corrosion cracking in the dilute chloride solution and the Hastelloy Alloy G3 was not tested in these conditions.

VII. Conclusions

The general corrosion data for Hastelloy G, Alloy 825, Monel 400 and carbon steel in steam environments suggest that the addition of chromium provides the greatest improvement in materials performance. Chromium-bearing Hastelloy G and Alloy 825 provided the greatest corrosion resistance while the Monel 400 was superior to carbon steel. The performance of the Hastelloy G was fundamentally the same as Alloy 825 in all environments with the Hastelloy G providing superior pitting resistance in steam environments

From the data identified in the literature, it appears that Alloy 825 provides superior pitting and aqueous corrosion performance when compared to Monel 400. Galvanic corrosion results are dependent upon the galvanic couple and aqueous media employed in the test. In general, the high-chromium alloys (Alloy 825 and Hastelloy G) are the least susceptible to galvanic corrosion. Monel 400 exhibited exceptional galvanic corrosion resistance in a majority of the corrosion couples, especially when coupled with carbon steel specimens

A ranking of the overall corrosion performance of the materials investigated in this study from most corrosion resistant to least corrosion resistant is provided below.

1. Alloy 825 and Hastelloy G
2. Monel 400
3. Carbon Steels and Low Alloy Steels

Since the materials to be employed in the Advanced Conceptual Design (ACD) waste package are considered to be somewhat corrosion resistant materials, the Monel alloys should not be precluded as candidates for the outer containment barrier in a wet repository environment. Based upon the corrosion data available for Monel, this material may be suitable for use in a moderately aggressive repository corrosion environment. However, care must be taken to evaluate all potential galvanic effects for specific waste package designs and applications.

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Table 1. Nominal Compositions of Selected Monel Alloys (Rosenberg, 1968)

Designation	Nominal chemical composition -- weight percent									
	Ni	C	Mn	Fe	S	Si	Cu	Al	Ti	
Monel Alloy 400	66.0	0.12	0.90	1.35	0.005	0.15	31.5	...	...
Monel Alloy 401	44.5	0.03	1.70	0.20	0.005	0.01	53.0	...	...
Monel Alloy 402	58.0	0.12	0.90	1.20	0.005	0.10	40.0	...	...
Monel Alloy 403	57.5	0.12	1.80	0.50	0.005	0.25	40.0	...	...
Monel Alloy 404	55.0	0.06	0.01	0.05	0.005	0.02	44.0	0.02	...	
Monel Alloy R-405	66.0	0.18	0.90	1.35	0.050	0.15	31.5	...	...
Monel Alloy 406	84.0	0.12	0.90	1.35	0.005	0.15	13.0	...	...
Monel Alloy 474	54.0	0.01	trace	0.01	0.001	<0.01	46.0	trace	...	
Monel Alloy K-500	65.0	0.15	0.60	1.00	0.005	0.15	29.5	2.80	0.50	
Monel Alloy 501	65.0	0.23	0.60	1.00	0.005	0.15	29.5	2.80	0.50	

Table 2. Atmospheric Corrosion Data for Monel in ASTM Tests (Copson, 1955)

Location	Original Weight, g, avg	Loss in Weight				Corrosion Rate			
		g, avg		Per cent		mdd		mil per year	
		10 yr	20 yr	10 yr	20 yr	10 yr	20 yr	10 yr	20 yr
Altoona	550.99	17.31	47.99	3.1	8.8	0.37	0.46	0.0596	0.0756
New York	545.50	16.61	40.24	3.0	7.3	0.35	0.38	0.0564	0.0624
Sandy Hook	544.88	7.90		1.4		0.16		0.0266	
Key West	560.21	1.93	2.76	0.3	0.5	0.04	0.03	0.0065	0.0045
La Jolla	553.92	2.22	5.05	0.4	0.9	0.05	0.04	0.0077	0.0064
State College	547.16	1.48	4.26	0.3	0.8	0.03	0.04	0.0050	0.0067
Phoenix	550.84	0.48	1.24	0.1	0.2	0.01	0.01	0.0016	0.0020

Table 3. Atmospheric Corrosion Data for Monel at Bayonne, N. J. (Copson, 1955)

Form	Exposure Time, yr	Date Exposed	Corrosion Rate, mdd			Pit Depth, avg of deepest, mil	
			Sheltered Vertical	Exposed Vertical	Exposed Inclined	Sheltered Vertical	Exposed Vertical
Sheet	0.92	5/6/38	0.63	0.27			
Sheet	2.24	3/18/48			0.44		
Sheet	11.88	8/23/40	0.94	0.28		2.80	9.40
Screen (16 mesh, 0.009-in. wire)	5.00	8/19/40	2.15	1.15			

Table 4. Corrosion Damage Data for Selected Metals Exposed in Various Atmospheric Environments (Southwell, et al., 1976)

Metal Type [†]	Exposure Conditions ^{††}	General Corrosion					Final Steady State Rate ^{§§}			Pitting Penetration (mils)		
		Weight Loss (g/m ²)		Average Penetration (mils) [‡]			State Rate (mpy)			Average 20 Deepest Pits ^{†††}		
		1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr
Nickel (99.% Ni)	C	2	13	26	0.01	0.06	0.11	<0.01	<5	<5	<5	<5
	I	1	9	21	0.01	0.04	0.10	<0.01	<5	<5	<5	<5
Nickel - copper (Monel: 70Ni-30Cu, cold rolled)	C	10	26	49	0.04	0.12	0.22	0.01	<5	<5	<5	<5
	I	2	14	30	0.01	0.06	0.14	<0.01	<5	<5	<5	<5
Copper - nickel (70Cu-30Ni)	C	8	52	93	0.03	0.23	0.41	0.02	<5	<5	<5	<5
	I	4	30	62	0.02	0.13	0.28	0.02	<5	<5	<5	<5
Copper (99.9% Cu)	C	37	129	173	0.17	0.57	0.76	0.03	<5	<5	<5	<5
	I	18	43	60	0.08	0.19	0.26	0.01	<5	<5	<5	<5
316 Stainless Steel (18 - 13 plus Mo)	C	0	0	0	0.00	0.00	0.00	0.00	<5	<5	<5	<5
	I	0	0	0	0.00	0.00	0.00	0.00	<5	<5	<5	<5
Carbon Steel (0.24% C)	C	392	1352	2119	1.97	6.79	10.64	0.47	<5	14	18	39
	I	275	1005	1714	1.38	5.04	8.6	0.43	<5	14	19	26

† = All metals are in the as received condition, except the carbon steel, which was machined, and all metals were degreased before exposure.

†† = C = coastal marine atmosphere, and I = inland atmosphere.

‡ = Values calculated from weight loss data.

§ = Slope of linear portion of the time-corrosion curve, or if non-linear, the slope of the tangent at 16 years.

§§ = Determined from the five deepest pits on each surface of duplicate panels.

§§§ = The single deepest pit during the 16-year exposure.

§§§§ = Deep local-action pitting; average penetration values not appropriate.

§§§§§ = Value not Determined.

§§§§§§ = P = perforation.

Table 5. Corrosion Damage Data for Selected Metals Exposed in Various Aqueous Environments (Southwell, et al., 1976)

Metal Type [†]	Exposure Conditions ^{††}	General Corrosion				Final Steady State Rate [Ⓜ] (mpy)	Pitting Penetration (mils)				Deepest ^{‡‡} Pit
		Weight Loss (g/m ²)	Average Penetration (mils) [§]				Average	20 Deepest Pits [§]	8 yr	16 yr	
		1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	1 yr	8 yr	16 yr	
Nickel (99% Ni)	S	540	2840	4340	2.40 [§]	13.0 [§]	19.0 [§]	125	120	192	p ^{¶¶}
	M	80	580	990	0.4	2.6	4.4	<5	65	61	121
	L	0.0	0.0	10	0.0	0.0	0.0	<5	<5	<5	<5
Nickel - copper (Monel: 70Ni-30Cu, cold rolled)	S	370	1420	1950	1.6	6.3	8.7	17	40	34	55
	M	20	300	600	0.1	1.3	2.7	<5	14	14	24
	L	0.0	30	140	0.0	0.1	0.6	<5	12	17	53
Nickel - copper (Monel: 70Ni-30Cu, hot rolled)	S	470	1440	1870	2.1	6.4	8.4	43	50	56	82
	M	30	310	570	0.1	1.4	2.6	<5	17	24	36
	L	¶	¶	¶	¶	¶	¶	¶	¶	¶	¶
Copper - nickel (70Cu-30Ni)	S	120	340	510	0.5	1.5	2.3	<5	<5	<5	37
	M	20	100	170	0.1	0.4	0.8	<5	<5	<5	<5
	L	40	220	300	0.2	1.0	1.3	<5	<5	<5	<5
Copper (99.9% Cu)	S	270	1200	1360	1.2	5.3	6.0	20	28	31	57
	M	150	250	300	0.7	1.1	1.3	<5	10	<5	23
	L	50	190	230	0.2	0.8	1.0	<5	<5	<5	<5
316 Stainless Steel (18 - 13 plus Mo)	S	120	410	160	0.6 [§]	2.0 [§]	0.8 [§]	45p ^{¶¶¶}	156p ^{¶¶¶}	95	p ^{¶¶}
	M	10	40	20	0.1	0.2	0.1	5	16	13	36
	L	0.0	0.0	0.0	0.0	0.0	0.0	<5	<5	<5	<5
Carbon Steel (0.24% C)	S	1100	5390	9870	5.5	27.1	49.5	38	58	102	p ^{¶¶}
	M	2100	4950	8350	10.5	24.9	41.9	21	45	52	124
	L	1500	4030	4880	7.5	20.2	24.5	22	60	65	94

† = All metals are in the as received condition, except the carbon steel, which was machined, and all metals were degreased before exposure.

†† = S = sea continuous immersion, M = sea mean tide, L = lake, fresh water continuous immersion.

‡ = Values calculated from weight loss data.

‡‡ = Slope of linear portion of the time-corrosion curve, or if non-linear, the slope of the tangent at 16 years.

§ = Determined from the five deepest pits on each surface of duplicate panels.

§§ = The single deepest pit during the 16-year exposure.

§§§ = Deep local-action pitting; average penetration values not appropriate.

¶ = Value not Determined.

¶¶ = P = perforation.

Table 6. Compositions of Nickel Base Alloys Exposed to the Atmosphere of Birmingham, Alabama (Evans, 1972)

Material	Compositions of Materials, Weight Percent									
	C	Cr	Ni	Fe	Cu	Al	Si	Mn	S	P
Nickel 200	0.03	0.01	Bal.	0.2	<0.01	Undet.	0.14	<0.05	0.002	Undet.
Nickel 213	0.22	0.01	Bal.	0.2	0.02	Undet.	0.17	2.11	0.003	Undet.
Alloy 301	0.25	0.01	Bal.	0.1	<0.01	4.3	0.68	0.3	<0.002	Undet.
Alloy 600	0.09	14.5	Bal.	6.8	0.2	0.1	<.2	0.12	<0.002	Undet.
Alloy DS	0.08	18.5	36	Bal.	0.2	Undet.	2.36	1.15	0.007	Undet.
Alloy 400	0.14	0.04	Bal.	1.6	32.8	Undet.	0.06	1.1	0.006	Undet.
Alloy K500	0.14	<0.01	Bal.	0.3	34.2	Undet.	0.3	0.25	0.003	Undet.
55Cu/45Ni Alloy	0.007	0.01	41	0.2	Bal.	Undet.	0.1	0.83	0.004	Undet.
70/30 Copper-Nickel	0.024	<0.01	30.5	0.2	Bal.	Undet.	<0.05	0.5	0.004	0.004
80/20 Copper-Nickel	0.003	<0.01	20.5	0.2	Bal.	Undet.	<0.05	0.3	0.003	0.003

Table 7. Composition of Nickel Base Alloys Included in the ASTM 1957 Test Program (ASTM, 1959)

Alloy	Commercial Designation	Composition -- Weight Percent													
		Ni	Cr	C	Mn	Fe	S	Si	Cu	Al	Ti	Mg	B	Mo	Co
No. 48	Nickel Alloy 200	99.28	0.03	0.28	0.30	0.008	0.03	0.05	0.018	0.033
No. 49	Incoloy Alloy 800	32.80	21.08	0.06	0.83	44.58	0.007	0.38	0.24	0.420	0.480	.....	.....	.....
No. 50	Inconel Alloy 600	75.82	16.04	0.03	0.19	7.61	0.007	0.18	0.10	0.090	0.210	0.026	0.008	.....
No. 51	Monel Alloy 400	66.77	.....	0.10	0.86	1.34	0.010	0.14	30.76	0.007	0.009	0.051	.....	.....
No. 52	Incoloy Alloy 825	41.59	22.16	0.03	0.56	29.03	0.009	0.34	1.77	0.090	0.400	3.05	0.95

Table 8. Corrosion Data from the ASTM 1957 Test Program (ASTM, 1962; 1966)

Alloy	Commercial Designation	Site ^(a)	Corrosion Rate				Average 4 Deepest Pits		Maximum Pit Depth
			mg per dm per day		mg per yr		2 yr	7 yr	7 yr
			2 yr	7 yr	2 yr	7 yr	2 yr	7 yr	7 yr
No. 48	Nickel Alloy 200	A	0.0753	0.0590	0.0123	0.0095	0.9	0.7	1.4
		B	0.4840	0.4282	0.0790	0.0652	0.9	0.8	1.1
		C	0.0423	^(b)	0.0070	^(b)	0.6	^(b)	^(b)
		D	0.0700	0.0058	0.0117	0.0090	0.7	0.5	0.6
No. 49	Incoloy Alloy 800	A	0.0320	0.0131	0.0060	0.0023	0.9	0.5	1.3
		B	0.0220	0.0045	0.0040	0.0008	0.7	nil	nil
		C	0.0287	^(b)	0.0057	^(b)	0.9	^(b)	^(b)
		D	0.0210	0.0046	0.0004	0.0008	0.7	0.3	0.6
No. 50	Inconel Alloy 600	A	0.0310	0.0108	0.0050	0.0018	1.1	0.7	1.3
		B	0.0270	0.0064	0.0043	0.0013	0.9	0.4	0.7
		C	0.0270	^(b)	0.0043	^(b)	1.0	^(b)	^(b)
		D	0.0160	0.0053	0.0030	0.0008	0.6	0.2	0.3
No. 51	Monel Alloy 400	A	0.1057	0.0878	0.0057	0.0143	0.6	0.6	0.7
		B	0.2143	0.1957	0.0350	0.0318	0.9	0.9	1.4
		C	0.0690	^(b)	0.0110	^(b)	0.6	^(b)	^(b)
		D	0.0710	0.0505	0.0110	0.0082	0.5	0.6	0.8
No. 52	Incoloy Alloy 825	A	0.0340	0.0074	0.0060	0.0013	0.6	0.5	0.7
		B	0.0257	0.0043	0.0047	0.0007	0.5	0.3	0.4
		C	0.0400	^(b)	0.0067	^(b)	0.4	^(b)	^(b)
		D	0.0240	0.0046	0.0043	0.0008	0.4	0.3	0.5

^(a) A - Kure Beach (25-meter site), N.C., B - Newark, N.J., C - Point Reyes, Calif., D - State College, Pa.

^(b) Panels lost.

**Table 9. Exposure Time for 1957 Test Program
(ASTM, 1962;1966)**

Site	Exposure Time, days	
	2 year	7 year
A	730	2557
B	734	2558
C	726	....
D	735	2538

Table 10. Corrosion in Quiet Seawater After 3 Years Exposure (Boyd and Fink, 1975)

Material	Thickness, inch	Fouling Rate ^(a)	Weight Loss, grams	Corrosion Rate, mpy	Localized Attack, mils		Remarks
					Max	Ave ^(b)	
Monel Alloy 400	0.062	2	36.6	(c)	41	36	Numerous broad pits.
	0.062	2	34.2	(c)	52	48	Numerous broad pits, single perforation from opposing pits.
	0.125	2	33	(c)	39	30	Numerous broad pits, 5-8 mils; deeper attack in large areas on back side.
304 stainless steel	0.125	2	32.6	(c)	55	33	Crevice corrosion beneath barnacles and at sheared edges.
	0.125	2	16.8	(c)	Perforated		Crevice corrosion beneath barnacles and at sheared edges.
316 stainless steel	0.125	2	17.4	(c)	119	42	Crevice corrosion beneath barnacles and at sheared edges.
	0.125	2	4	(c)	72	50	Crevice corrosion beneath barnacles and at sheared edges.
	0.125	2	4.8	(c)	60	45	Crevice corrosion beneath barnacles and at sheared edges.
Incoloy Alloy 825	0.125	1	0.2	0.1	7	1	Crevice corrosion beneath barnacles.
	0.125	1	0.2	0.1	1	1	Crevice corrosion beneath barnacles.

Note - Specimen dimensions, 4 x 12 inches.

^(a) 10 = free of fouling, 0 = completely fouled. A values of 2 indicates that 80 percent of the sample surface was fouled.

^(b) Average five deepest pits.

^(c) Weight loss due to localized corrosion.

Table 11. Sea Water Analysis for Jet Impingement and Static Immersion Tests (g/L)
(White, et al., 1966)

Component	Na	K	Ca	Mg	Cl	SO ₄	Br
Mediterranean Sea	10.8	0.39	0.4	1.3	19.4	3	0.07
Dead Sea	33	6	13	36	181	1	4.5

Table 12. Corrosion Data for Impingement Test (White, et al., 1966)

Expt. No.	Exposure	Monel		70/30 Copper-nickel		Stainless steel (18:8)	
		Weight Loss (mg)	Pit Depth (μm)	Weight Loss (mg)	Pit Depth (μm)	Weight Loss (mg)	Pit Depth (μm)
12	Mediterranean Sea	91	5	198	105	10	3
13	Mediterranean Sea	135	5	150	50	(a)	(a)
10	Dead Sea	36	5	89	50	3	0
11	Dead Sea	18	10	75	20	3	0

(a) Value not determined.

Table 13. Corrosion Data for Total Immersion Test (White, et al., 1966)

Exposure	Test Duration (days)	Average Rate of Penetration ($\mu\text{m}/\text{day}$)		
		Monel	70/30 Copper-nickel	Stainless Steel (18:8)
Mediterranean Sea	84		0.0048	
Mediterranean Sea	120	0.002		0.0015
Mediterranean Sea	165		0.0018	
Dead Sea	31		0.048	
Dead Sea	84		0.0384	
Dead Sea	120	0.0042		0.0131

Table 14. Corrosion Data for Partial Immersion Test (White, et al., 1966)

Exposure	Test Duration (days)	Rate of Loss in Weight (mg/day)		
		Monel	Stainless Steel (18:8)	Mild Carbon-steel
Mediterranean Sea	103			5.0, 5.1
Mediterranean Sea	120	0.05	0.016	
Dead Sea	103			1.4, 1.4
Dead Sea	120	0.075	0.17	

Table 15. Results of General Corrosion Rates of Metals in Deep-Ocean Environments (Wheatfall, 1967)

Alloy Designation	Exposure Depth	Exposure time, days	Corrosion Rate, mdd ^(a)	Comments	
				Surface Attack (outside crevice area)	Crevice Attack (maximum pit depth, mm)
AISI Type 304	5640 ft	123	5.91 ^(b)	No visible pits.	0.7874 - inside crevice.
	5640 ft	751	8.51 ^(b)	Scattered severe pitting and edge attack.	3.175 - inside crevice (perforated).
	5300 ft	1064	5.31 ^(b)	Scattered severe pitting and edge attack.	3.175 - inside crevice (perforated).
	Surface	386	3.15 ^(b)	Attack along all edges and scattered perforations (1.6 mm).	1.6 - inside crevice (perforated).
Cupro-Nickel 30%	5640 ft	123	6.27	Etched surface.	No attack.
	5640 ft	751	2.75	Etched and streaked surface.	Slight attack at crevice entrance.
	5300 ft	1064	3.08	Etched and streaked surface.	Slight attack at crevice entrance.
	Surface	386	1.42	Etched surface.	Slight attack at crevice entrance.
Monel Alloy 400	5640 ft	123	3.06	Etched, tarnished, and streaked surface.	Incipient - inside and at entrance of crevice.
	5640 ft	751	0.738 ^(b)	Etched, tarnished, and streaked surface.	0.33 - inside and at entrance of crevice.
	Surface	386	8.03 ^(b)	Severe surface pitting to 0.51 mm.	1.6 - inside and at entrance of crevice (perforated).
Monel Alloy K500	5640 ft	123	4.37 ^(b)	Etched surface.	0.28 - inside and at entrance of crevice.
	5640 ft	751	2.26 ^(b)	General surface pitting to 0.2032 mm.	1.6 - inside and at entrance of crevice (perforated).
	Surface	386	7.97 ^(b)	General surface pitting to 0.8382 mm.	1.6 - inside and at entrance of crevice (perforated).
Incoloy Alloy 825	5640 ft	123	0.634	No visible attack.	Incipient - inside crevice.
	5640 ft	751	2.31 ^(b)	Scattered pitting to 0.025 mm.	1.6 - inside crevice (perforated).
	Surface	386	0.218 ^(b)	Scattered pitting to 0.051 mm.	1.45 - inside crevice.

(a) mdd = milligrams per square decimeter per day.

(b) Weight loss attributed largely to localized corrosion.

Table 16. Operating Conditions for Corrosion Test Packages at a Geothermal Test Facility (see Figure 7) (Cramer, et al., 1983)

Corrosion test packages	Temp., °C	Absolute pressure, MPa	pH	[Cl ⁻], ppm
P1 and electrochemical package (wellhead brine)	215	2.00	5.3	115,000
P2 (brine from separator 1)	199	1.63	5.7	127,000
P3 (steam from separator 1)	199	1.63	6.2	8,100
P4 (brine from separator 2)	180	1.02	5.8	129,000
P5 (steam from separator 2)	180	1.02	6.9	1,700

Note -- Input flow rate = 130 L/min

Table 17. Composition in Weight Percent of Nickel-Base Alloys Exposed to Brine and Steam Systems (Cramer, et al., 1983)

Alloy	Ni	Cr	Fe	Cu	Mo	Mn	Other
Nickel 201	bal	---	---	---	---	---	---
Monel Alloy 400	bal	---	1.25	31.5	---	2.00 max	---
Monel Alloy 404	bal	---	0.5	44	---	---	---
Inconel Alloy 825	bal	21.5	30	2.25	3	---	0.9Ti
Hastelloy Alloy G	bal	21.7	19.1	1.84	6.8	1.42	1.22Co-2.15(Nb+Ta)-0.45Si-0.17W

Table 18. General Corrosion Rates for Nickel Alloys in Brine and in Steam, $\mu\text{m}/\text{yr}$ (Cramer, et al., 1983)

Alloy	Exposure, days		
	15 ^a	30	45
Wellhead brine (P1)			
Nickel 201	(b)	(b)	(b)
Monel 400	716	533	356
Monel 404	767	432	279
Incoloy 825	117	73.7	35.6
Hastelloy G	15.2	0.0	2.5
Brine 1 (P2)			
Nickel 201	(b)	302 ^(c)	(b)
Monel 400	209	112	91.4
Monel 404	343	190	152
Incoloy 825	7.6	10.2	2.5
Hastelloy G	0.0	0.0	0.0
Brine 2 (P4)			
Nickel 201	287 ^(c)	(b)	(b)
Monel 400	119	117	71.1
Monel 404	188	114	81.3
Incoloy 825	7.6	7.6	2.5
Hastelloy G	2.5	(b)	0.0
Steam 1 (P3)			
Nickel 201	(b)	(b)	251 ^(c)
Monel 400	394	248	191
Monel 404	538	305	216
Incoloy 825	22.9	30.5	17.8
Hastelloy G	2.5	0.0	0.0
Steam 2 (P5)			
Nickel 201	(b)	(b)	117 ^(c)
Monel 400	200	94	55.9
Monel 404	272	117	78.7
Incoloy 825	7.6	12.7	7.6
Hastelloy G	0.0	0.0	0.0

^a Average of results from four 15 - day tests.

^b No samples were exposed.

^c One sample.

Table 19. Maximum and Average Pit Penetration Rates for Nickel Alloys in Brine and in Steam, $\mu\text{m}/\text{yr}$ (Cramer, et al., 1983)

Alloy	Exposure, days					
	15 ^a		30		45	
	Max	Avg	Max	Avg	Max	Avg
Wellhead brine (P1)						
Monel 400	1480	(b)	450	(b)	350	(b)
Monel 404	2340	(b)	900	(b)	330	(b)
Incoloy 825	4510	1940	2160	1210	968	680
Hastelloy G	4880	1400	770	(b)	740	310
Brine 1 (P2)						
Monel 400	1550	870	740	(b)	740	430
Monel 404	1410	(b)	1330	740	520	310
Incoloy 825	5810	2290	1060	680	1150	740
Hastelloy G	2330	(b)	(c)	(c)	240	(b)
Brine 2 (P4)						
Monel 400	2350	930	610	420	410	260
Monel 404	2820	870	640	380	450	260
Incoloy 825	1870	900	990	920	720	450
Hastelloy G	2150	730	<320	(b)	850	390
Steam 1 (P3)						
Monel 400	1360	660	430	280	560	(b)
Monel 404	2160	820	930	400	390	210
Incoloy 825	3460	1420	1110	680	780	390
Hastelloy G	810	(b)	1150	(b)	400	(b)
Steam 2 (P5)						
Monel 400	1740	830	610	400	350	(b)
Monel 404	2410	970	480	350	500	330
Incoloy 825	2270	830	1570	900	800	370
Hastelloy G	(c)	(c)	800	<260	370	<170

^a Average of results from four 15 - day tests.

^b Less than five pits per coupon.

^c No pitting.

Table 20. Galvanic Corrosion Data for Atmospheric Exposure (Pelensky, et al., 1978)

Alloy	Exposure, months	Corrosion Rates, mm/year							
		AZ31 Magnesium	316 Stainless Steel	4340 Steel	6061-T6 Aluminum	7075-T6 Aluminum	360 Brass	400 Monel	
AZ31 Magnesium	2	0.031	0.076	0.096	0.047	0.047	0.074	0.092	
	4	0.037	0.079	0.089	0.050	0.040	0.066	0.077	
	8	0.034	0.057	0.064	0.048	0.048	0.064	0.059	
	15	0.025	0.045	0.049	0.036	0.037	0.048	0.052	
	24	0.028	0.061	0.076	0.040	0.039	0.051	0.049	
4340 Steel	2	0.033	0.071	0.069	0.069	0.061	0.068	0.074	
	4	0.018	0.050	0.055	0.055	0.050	0.050	0.050	
	8	0.014	0.036	0.037	0.038	0.036	0.036	0.036	
	15	0.013	0.047	0.046	0.030	0.031	0.038	0.044	
	24	0.011	0.049	0.048	0.026	0.025	0.037	0.049	
6061-T6 Aluminum	2	0.002	0.006	0.005	0.002	0.002	0.006	0.005	
	4	0.001	0.002	0.006	0.002	0	0.004	0.002	
	8	0.001	0.001	0.004	0.001	0.001	0.002	0.001	
	15	0	0.002	0.006	0.001	0.001	0.003	0.003	
	24	0	0.003	0.007	0.001	0.001	0.007	0.003	
7075-T6 Aluminum	2	0.003	0.007	0.009	0.005	0.003	0.010	0.007	
	4	0.002	0.005	0.005	0.002	0.003	0.004	0.003	
	8	0.001	0.003	0.004	0.001	0.001	0.003	0.003	
	15	0	0.003	0.016	0.002	0.001	0.005	0.003	
	24	0	0.003	0.012	0.002	0.001	0.010	0.003	
360 Brass	2	0.003	0.009	0.006	0.005	0.005	0.007	0.008	
	4	0.001	0.004	0.003	0.002	0.002	0.003	0.004	
	8	0.001	0.002	0.002	0.001	0.001	0.001	0.002	
	15	0.001	0.002	0.002	0.001	0.001	0.001	0.001	
	24	0	0.002	0.002	0.001	0.001	0.001	0.001	

Note -- Essentially zero corrosion rate for Type 316 stainless steel and 400 Monel specimens.

Table 21. Galvanic Corrosion Data for Soil Exposure (Pelensky, et al., 1978)

Alloy	Exposure, months	Corrosion Rates, mm/year							
		AZ31 Magnesium	316 Stainless Steel	4340 Steel	6061-T6 Aluminum	7075-T6 Aluminum	360 Brass	400 Monel	
AZ31 Magnesium	2	0.093	1.398	1.920	0.264	0.551	0.967	1.322	
	6	0.137	0.953	1.099	0.164	0.233	0.932	0.936	
	12	0.045	1.225	1.080	0.093	0.208	0.848	0.912	
	25	0.029	0.490	0.580	0.056	0.109	0.561	0.603	
4340 Steel	2	0.005	0.069	0.060	0.048	0.048	0.057	0.061	
	6	0.001	0.104	0.085	0.087	0.100	0.113	0.119	
	12	0.001	0.082	0.081	0.068	0.080	0.090	0.083	
	25	0.001	0.055	0.058	0.040	0.057	0.069	0.062	
6061-T6 Aluminum	2	0.067	0.003	0.003	0.003	0.003	0.004	0.007	
	6	0.017	0.008	0.001	0.005	0.009	0.011	0.013	
	12	0.009	0.008	0.006	0.002	0.001	0.010	0.011	
	25	0.003	0.006	0.003	0.001	0.005	0.007	0.008	
7075-T6 Aluminum	2	0.044	0.006	0.003	0.003	0.013	0.003	0.004	
	6	0.019	0.017	0.001	0.006	0.011	0.020	0.020	
	12	0.021	0.016	0.001	0.009	0.007	0.019	0.012	
	25	0.006	0.011	0.002	0.001	0.005	0.015	0.016	
360 Brass	2	0.004	0.016	0.006	0.006	0.005	0.005	0.005	
	6	0.001	0.015	0.001	0.001	0.001	0.007	0.014	
	12	0	0.012	0	0.001	0	0.005	0.009	
	25	0.001	0.007	0	0	0.001	0.004	0.008	
400 Monel	2	0	0.003	0.001	0.001	0.001	0.001	0.001	
	6	0.001	0.009	0	0.001	0.001	0.004	0.005	
	12	0	0.010	0	0.001	0	0.002	0.004	
	25	0	0.007	0	0	0	0.002	0.004	

Note -- Essentially zero corrosion rate for Type 316 stainless steel specimens.

Table 22. Galvanic Corrosion Data for Seawater Immersion (Pelensky, et al., 1978)

Alloy	Exposure, months	Corrosion Rates, mm/year						
		AZ31 Magnesium	316 Stainless	4340 Steel	6061-T6 Aluminum	7075-T6 Aluminum	360 Brass	400 Monel
AZ31 Magnesium	2	1.581	SM	SM	2.336	5.64	12.122	^(b)
	4	1.293	.....	.....	2.149	4.732	7.66	^(b)
	7	1.021	.....	.....	1.724	6.165	^(b)	6.281
	12	0.811	.....	.....	^(b)	^(b)	^(b)	^(b)
	18	SM ^(a)	.....	.....	1.628	.....	.....	^(b)
316 Stainless Steel	2	0	0.097 ^(c)	0	0	0	0	0.105 ^(c)
	4	0	0.034 ^(c)	0	0	0	0	0.033 ^(c)
	7	0	0.036 ^(c)	0	0	0	0	0.061 ^(c)
	12	0	0.013 ^(c)	0	0	0	0	0.028 ^(c)
	18	0.003	0.551 ^(c)	0	0	0	0	.....
4340 Steel	2	0.024	1.143	0.635	0.018	0.020	1.257	1.238
	4	0.093	0.831	0.468	0.004	0.006	0.802	0.813
	7	SM	0.770	0.612	0.012	0.014	0.921	0.922
	12	SM	0.436	0.289	0.005	0.004	0.542	0.453
	18	SM	0.596	0.338	0.005	0.004	0.504	0.535
6061-T6 Aluminum	2	0.449	0.378	0.252	0.043	0.073	0.437	0.385
	4	0.782	0.275	0.176	0.021	0.024	0.233	0.256
	7	0.864	0.302	0.189	0.017	0.017	0.288	0.288
	12	0.698	0.171	0.107	0.007	0.010	0.186	0.200
	18	0.645	0.139	0.081	0.006	0.031	0.118	0.148
7075-T6 Aluminum	2	5.143	0.465	0.340	0.013	0.040	0.411	0.490
	4	4.145	0.303	0.187	0.009	0.029	0.301	0.298
	7	3.563	0.297	0.253	0.016	0.023	0.275	0.229
	12	2.097	0.212	0.135	0.002	0.014	0.189	0.193
	18	1.445	0.086	0.113	0.002	0.049	0.142	0.172
360 Brass	2	0.009	0.339	0.006	0.007	0.005	0.124	0.293
	4	0.004	0.184	0.003	0.005	0.002	0.106	0.190
	7	0.004	0.159	0.008	0.022	0.008	0.190	0.223
	12	0.002	0.130	0.002	0.001	0.002	0.139	0.160
	18	0.001	0.110	0.001	0.001	0.001	0.115	0.146
400 Monel	2	0.001	0.011	0.001	0.001	0	0.002	0.034
	4	0.001	0.015	0.001	0.001	0	0.002	0.006
	7	0.001	0.009	0.002	0.001	0.001	0.002	0.008
	12	0.001	0.006	0.001	0	0.001	0.002	0.007
	18	0.001	0.015	0.001	0	0	0.001	0.027

^(a) SM = Specimens missing.

^(b) Total dissolution of magnesium presumed.

^(c) Stainless steel attack - crevice pitting.

Table 23. Corrosion Penetration for Strip Metal of Galvanic Couples Exposed to Various Waters in the Panama Canal Zone for Periods of up to 16 Years (Southwell & Alexander, 1976)

Strip (2x9x1/4 in)	Plate (9x9x1/4 in)	Strip Metal Average Penetration (µm)											
		Sea Water				Mean Tide				Fresh Water			
		1	8	16	16*	1	8	16	16*	1	8	16	16*
Carbon Steel (0.24% C)	Carbon Steel (0.24% C)	190.5	670.6	1270.0	1221.7	198.1	398.8	1198.9	1148.1	215.9	510.5	657.9	660.4
316 Stainless Steel	316 Stainless Steel	0	7.6	78.7	50.8	0	2.5	2.5	5.1	0	0	0	0
316 Stainless Steel	Carbon Steel (0.24% C)	0.0	0.0	2.5	50.80	2.5	0.0	2.5	5.08	0.0	0.0	0.0	0.0
Nickel (99%)	Carbon Steel (0.24% C)	0.0	0.0	2.5	490.2	0.0	0.0	2.5	111.8	0.0	0.0	0.0	0.0
Monel (70Ni-30Cu, cold-rolled)	Carbon Steel (0.24% C)	0.0	0.0	2.5	221.0	0.0	0.0	2.5	68.6	0.0	0.0	0.0	15.2
70Cu-30Ni Alloy	Carbon Steel (0.24% C)	0.0	0.0	2.5	58.4	0.0	0.0	2.5	20.3	0.0	0.0	2.5	33.0
Copper (99%)	Carbon Steel (0.24% C)	50.8	76.2	177.8	152.4	50.8	76.2	152.4	33.0	0.0	25.4	76.2	25.4
Carbon Steel (0.24% C)	Copper (99%)	927.1	4864.1	M	647.7a	447.0	2138.7	M	589.3a	360.7	1430.0	1973.6	660.4
Carbon Steel (0.24% C)	70Cu-30Ni Alloy	952.5	4287.5	M	647.7a	589.3	2456.2	M	589.3a	353.1	1270.0	1742.4	660.4
Carbon Steel (0.24% C)	Monel (70Ni-30Cu, cold-rolled)	868.7	4005.6	M	647.7a	591.8	2341.9	4864.1	1148.1	322.6	1016.0	1546.9	711.2
Carbon Steel (0.24% C)	Nickel (99%)	1003.3	4447.5	M	647.7a	515.6	2194.6	4693.9	1148.1	299.7	1219.2	1811.0	660.4
Carbon Steel (0.24% C)	316 Stainless Steel	881.4	3571.2	M	647.7a	574.0	2080.3	4455.2	1148.1	266.7	845.8	1127.8	660.4
Zinc (99.5%)	Carbon Steel (0.24% C)	800.1	3761.7	4968.2	378.5	947.4	2603.5	4932.7	335.3	68.6	614.7	1094.7	200.7
Phosphor Bronze (4Sn-0.25P)	Carbon Steel (0.24% C)	2.5	5.1	10.2	139.7	5.1	2.5	10.2	88.9	2.5	2.5	2.5	17.8
Phosphor Bronze (4Sn-0.25P)	70Cu-30Ni Alloy	40.6	83.8	116.8	139.7	17.8	33.0	40.6	88.9	2.5	10.2	12.7	17.8
Phosphor Bronze (4Sn-0.25P)	70Ni-30Cu (cold Rolled)	68.6	1684.0	1823.7	139.7	43.2	378.5	482.6	88.9	40.6	223.5	358.1	17.8

M indicates that strips were missing -- probably completely corroded away.

* Values listed represent the normal uncoupled corrosion loss.

a indicates that the value for normal uncoupled corrosion loss has been taken from 8 year corrosion data.

Table 24. Corrosion Penetration for Plate Metal of Galvanic Couples Exposed to Various Waters in the Panama Canal Zone for Periods of up to 16 Years (Southwell & Alexander, 1976)

Strip (2x9x1/4 in)	Plate (9x9x1/4 in)	Plate Metal Average Penetration (µm)											
		Sea Water				Mean Tide				Fresh Water			
		1	8	16	16*	1	8	16	16*	1	8	16	16*
Carbon Steel (0.24% C)	Carbon Steel (0.24% C)	172.7	609.6	1117.6	1221.7	248.9	454.7	1071.9	1148.1	213.4	520.7	670.6	660.4
316 Stainless Steel	316 Stainless Steel	0	15.2	33.0	50.8	0	0	25.4	5.1	0	0	0	0
316 Stainless Steel	Carbon Steel (0.24% C)	200.7	718.8	1257.3	1221.7	309.9	627.4	1110.0	1148.1	203.2	637.5	823.0	660.4
Nickel (99%)	Carbon Steel (0.24% C)	195.6	759.5	1290.3	1221.7	304.8	543.6	1074.4	1148.1	195.6	602.0	739.1	660.4
Monel (70Ni-30Cu, cold-rolled)	Carbon Steel (0.24% C)	203.2	706.1	1300.5	1221.7	266.7	584.2	1087.1	1148.1	200.7	591.8	675.6	660.4
70Cu-30Ni Alloy	Carbon Steel (0.24% C)	193.0	756.9	1280.2	1221.7	312.4	533.4	1346.2	1148.1	200.7	579.1	756.9	660.4
Copper (99%)	Carbon Steel (0.24% C)	193.0	749.3	1394.5	1221.7	302.3	584.2	1084.6	1148.1	198.1	607.1	777.2	660.4
Carbon Steel (0.24% C)	Copper (99%)	2.5	2.5	73.7	152.4	2.5	2.5	12.7	33.0	2.5	2.5	5.1	25.4
Carbon Steel (0.24% C)	70Cu-30Ni Alloy	0.0	2.5	40.6	58.4	0.0	2.5	2.5	20.3	0.0	5.1	7.6	33.0
Carbon Steel (0.24% C)	Monel (70Ni-30Cu, cold-rolled)	0.0	2.5	61.0	221.0	0.0	2.5	2.5	68.6	0.0	0.0	0.0	15.2
Carbon Steel (0.24% C)	Nickel (99%)	0.0	0.0	121.9	482.6	0.0	2.5	7.6	111.8	0.0	0.0	5.1	0.0
Carbon Steel (0.24% C)	316 Stainless Steel	0.0	0.0	0.0	50.8	0.0	0.0	0.0	2.5	0.0	0.0	0.0	0.0
Zinc (99.5%)	Carbon Steel (0.24% C)	17.8	22.9	393.7	1221.7	27.9	22.9	50.8	1148.1	177.8	452.1	505.5	660.4
Phosphor Bronze (4Sn-0.25P)	Carbon Steel (0.24% C)	190.5	751.8	1399.5	1221.7	287.0	566.4	1178.6	1148.1	221.0	622.3	734.1	660.4
Phosphor Bronze (4Sn-0.25P)	70Cu-30Ni Alloy	15.2	50.8	96.5	58.4	2.5	15.2	25.4	20.3	5.1	25.4	33.0	33.0
Phosphor Bronze (4Sn-0.25P)	Monel (70Ni-30Cu, cold-rolled)	7.6	50.8	177.8	221.0	2.5	25.4	55.9	68.6	0.0	10.2	20.3	15.2

M indicates that strips were missing -- probably completely corroded away.

* Values listed represent the normal uncoupled corrosion loss.

a indicates that the value for normal uncoupled corrosion loss has been taken from 8 year corrosion data.

Table 25. Corrosion Damage Data for Bimetallic Coupled Discs Exposed to Various Atmospheres in the Panama Canal Zone for Periods of up to 16 Years (Southwell & Alexander, 1976)

Couple ^(a)		Metal A (g/m ²)						Metal B (g/m ²)					
		Coastal			Inland			Coastal			Inland		
Metal A	Metal B	1	4	16	1	4	16	1	4	16	1	4	16
70Ni-30Cu (cold Rolled) Carbon steel (0.24% C) 316 Stainless steel	70Ni-30Cu (cold Rolled) Carbon steel (0.24% C) 316 Stainless steel	12	23	48	3	10	66	15	51	92	3	9	50
		631	1543	3393	306	691	1716	535	1438	3072	278	637	1626
		1	7	54	0	0	35	1	4	66	0	0	50
70Ni-30Cu (cold Rolled) 70Ni-30Cu (cold Rolled) 316 Stainless steel Nickel (99% Ni) 70Cu-30Ni Alloy	Phosphor Bronze (4Sn-0.25P) Carbon steel (0.24% C) Carbon steel (0.24% C) Carbon steel (0.24% C) Carbon steel (0.24% C)	16	38	92	4	14	53	86	192	638	15	63	187
		15	23	88	4	9	46	977	2127	4547	358	802	2026
		14	92	98	2	1	53	1521	3051	7298	364	819	2295
		13	35	77	2	8	35	1087	2029	5204	315	759	1854
		20	45	160	14	34	136	935	1904	3921	347	793	1944
70Cu-30Ni Alloy Copper (99%)	Phosphor Bronze (4Sn-0.25P) Carbon steel (0.24% C)	21	65	191	12	47	182	106	194	480	9	49	101
		67	134	292	37	65	225	942	2042	4051	413	971	2387

^(a) Couples consisted of metal discs of Metal A and of Metal B with approximately equal exposed areas of 0.54 in².

Table 26. Limiting Temperatures for Some Nickel Base Alloys (Mudge, 1948)

Material	Sulfur-Free Atmospheres						Sulfurous Atmospheres									
	Oxidizing			Reducing H ₂			Reducing CO			Temp. Below Which These Materials May Be Used(a)			Temp. Above Which These Materials Cannot Be Used			
	°C		°F	°C		°F	°C		°F	°C		°F	°C		°F	
	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F	°C	°F		
Nickel (99.4%)	1050	1900	1250	2300	1250	2300	425-475	800-900	315	600	250	500	540	1000	375	700
Monel 400	540	1000	1100	2000	815	1500(b)	375-425	700-800	315	600	250	500(c)	540	1000	340	650

(a) These materials should not be used above the recommended minimum temperatures without consulting supplier.

(b) Estimated.

(c) Not recommended for use in contact with crude oils containing sulfur at temperatures above 500 °F.

Table 27. Nominal Composition in Weight Percent of Alloys Exposed to Chloride Solutions (Kolts and Sridhar, 1985)

Alloy	Ni	Co	Cr	Mo	W	Fe	C	Ti	Cu	Other
Hastelloy Alloy G	bal	2.5	22	6.5	1	19.5	0.05	---	2	2.0(Cb+Ta)
Hastelloy Alloy G3	bal	5	22	7	1.5	19.5	0.015	---	2	0.8Cb
Incoloy Alloy 825	bal	2	21.5	3	---	29	0.05	1	2	---

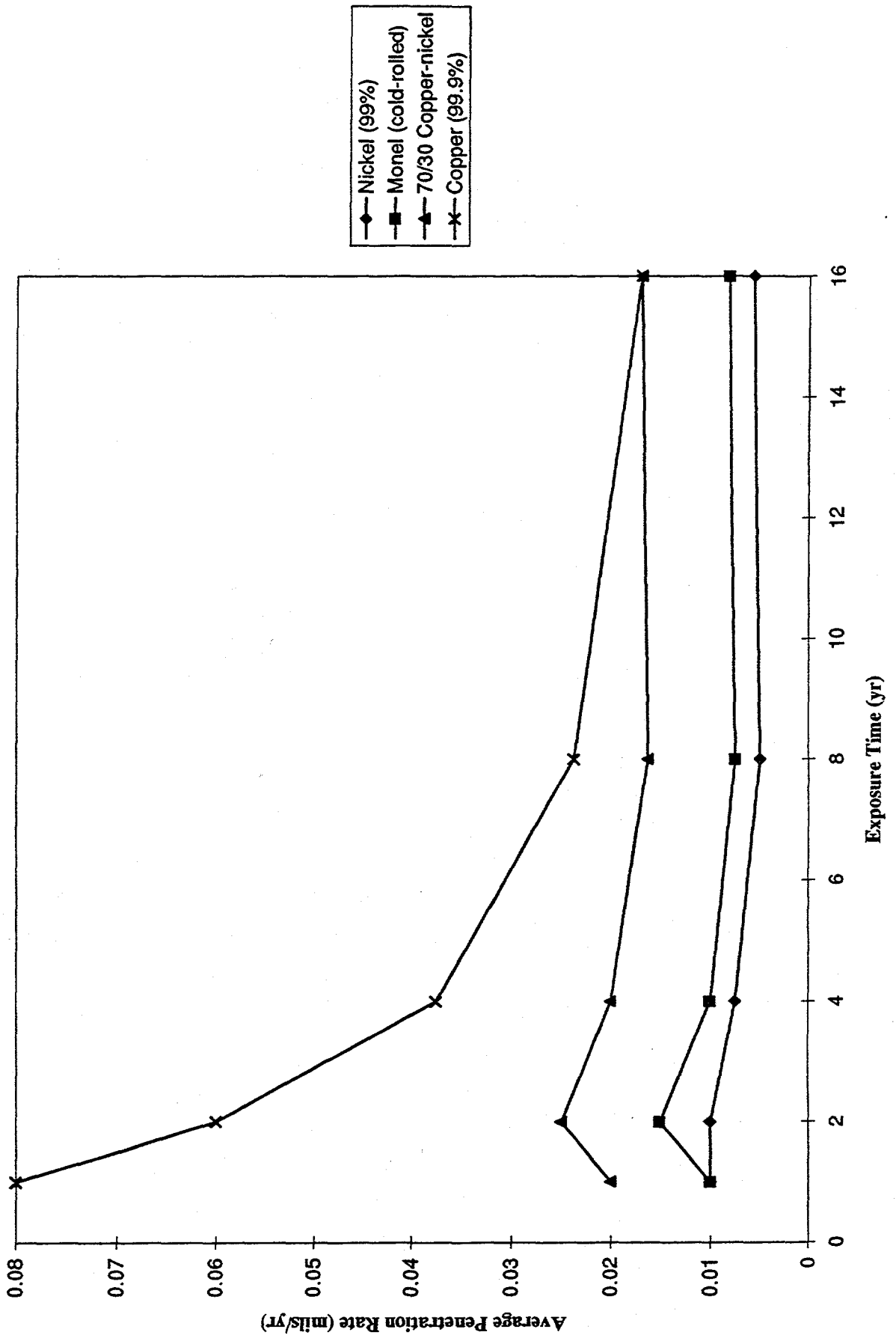


Figure 1. Average penetration rates for nickel-copper alloys exposed for 16 years in an inland location at Panama Canal Zone (Southwell and Alexander, 1969).

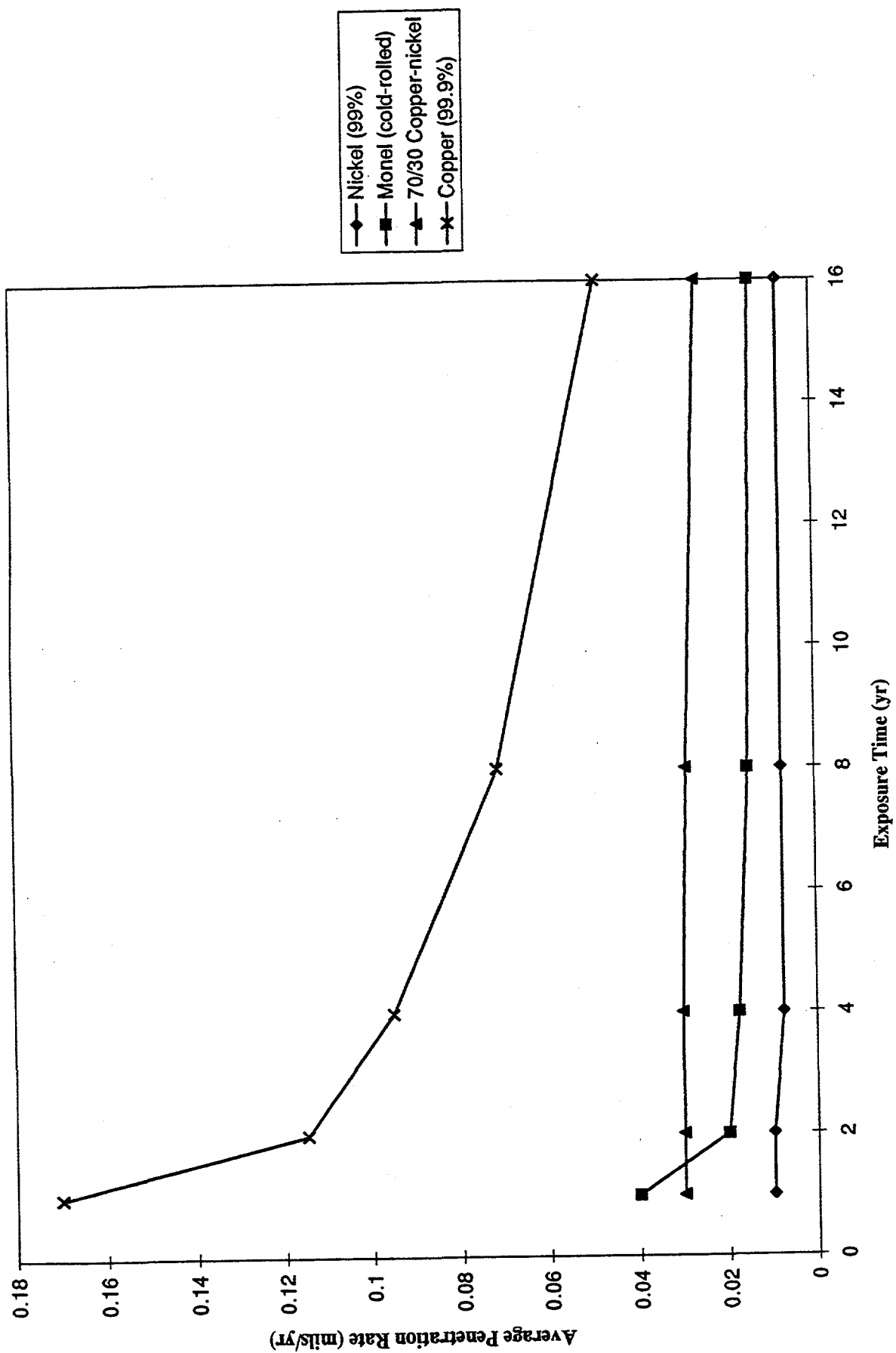


Figure 2. Average penetration rates for nickel-copper alloys exposed for 16 years in a coastal location at Panama Canal Zone (Southwell and Alexander, 1969).

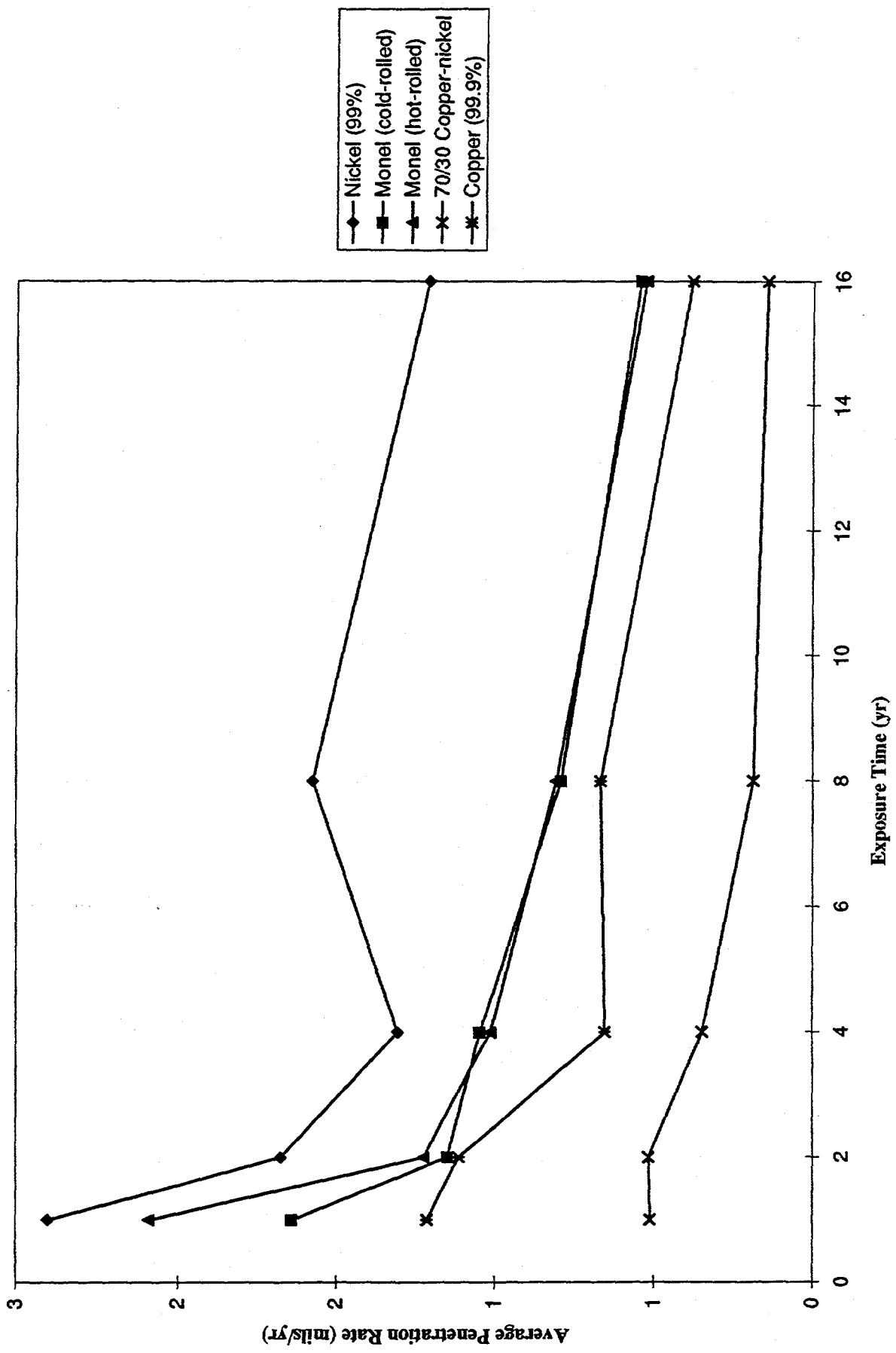


Figure 3. Average penetration rates for nickel-copper alloys exposed for 16 years in the sea water of Panama Canal Zone (Southwell and Alexander, 1969).

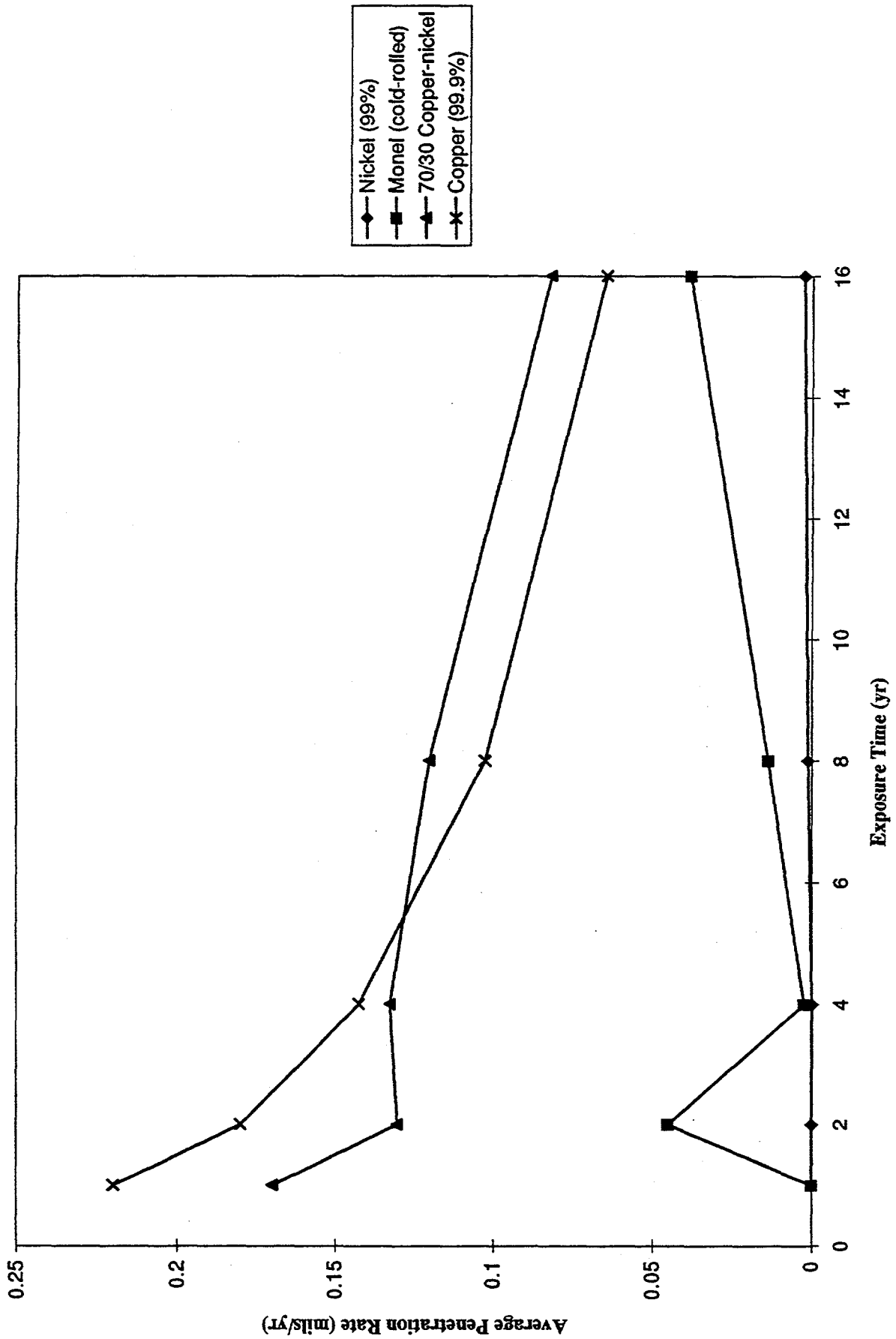


Figure 4. Average penetration rates for nickel-copper alloys exposed for 16 years in fresh water (Southwell and Alexander, 1969).

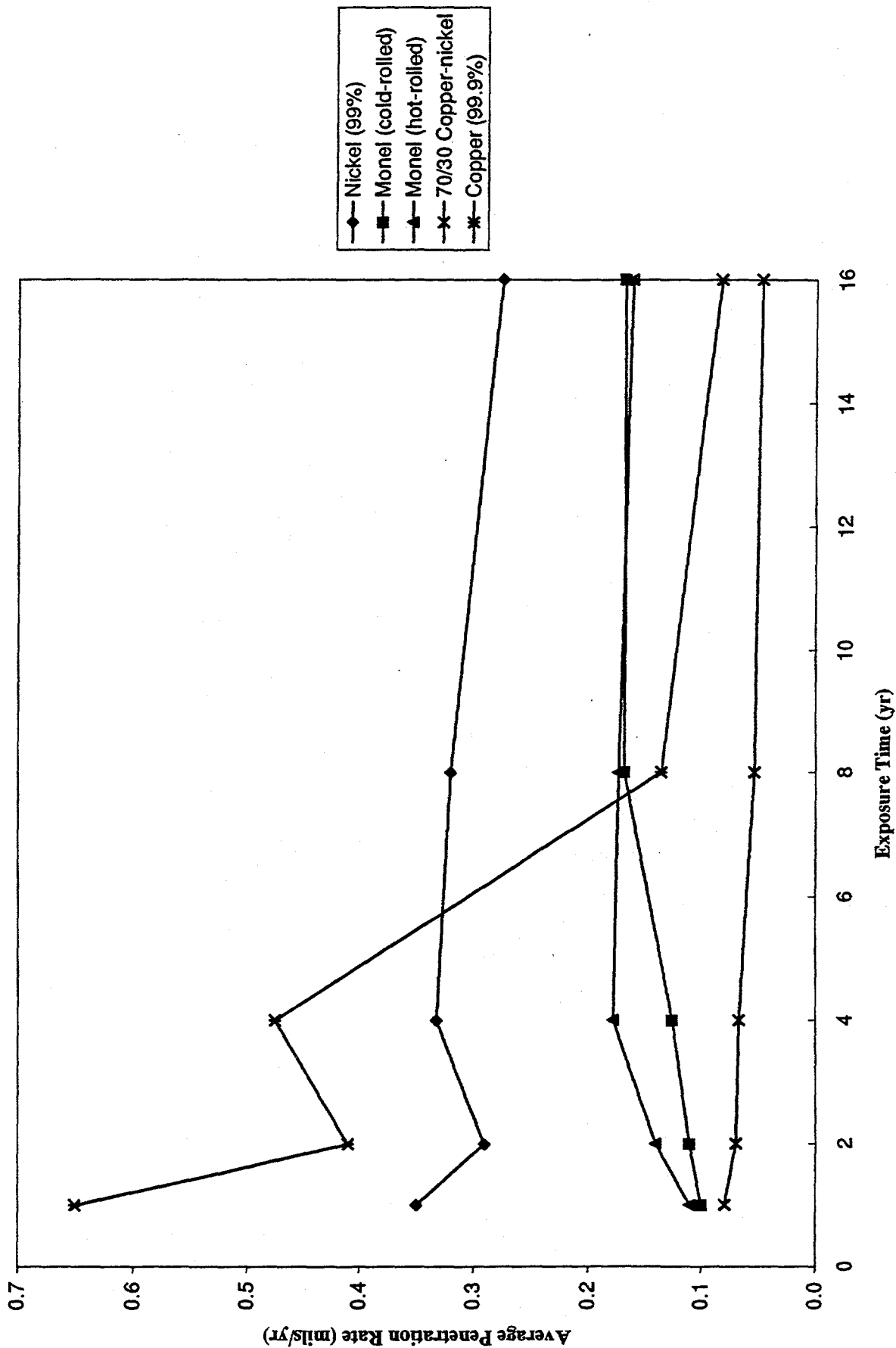


Figure 5. Average penetration rates for nickel-copper alloys exposed for 16 years at mean tide of Panama Canal Zone (Southwell and Alexander, 1969).

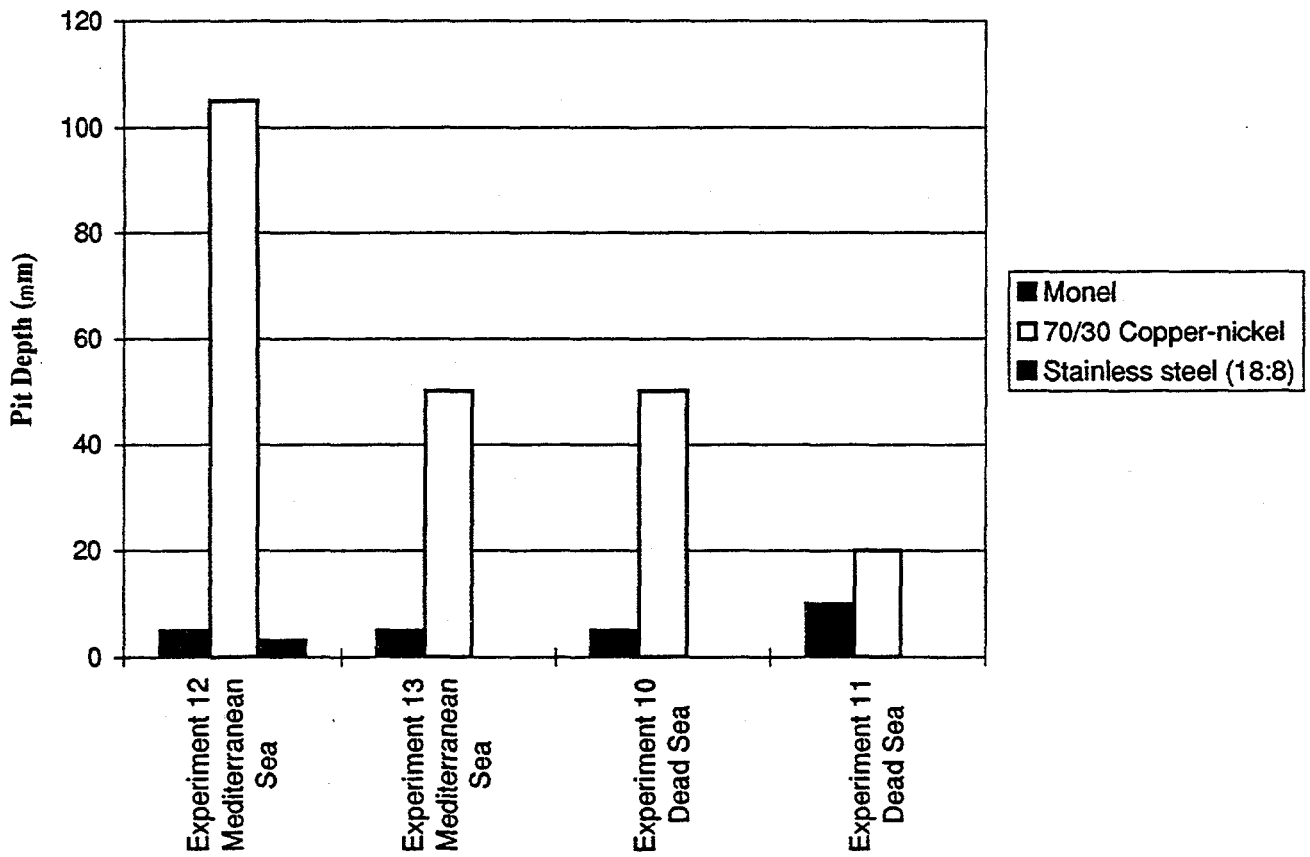


Figure 6. Pit depth of metals exposed for 15 days in jet impingement tests (White, et al., 1966).

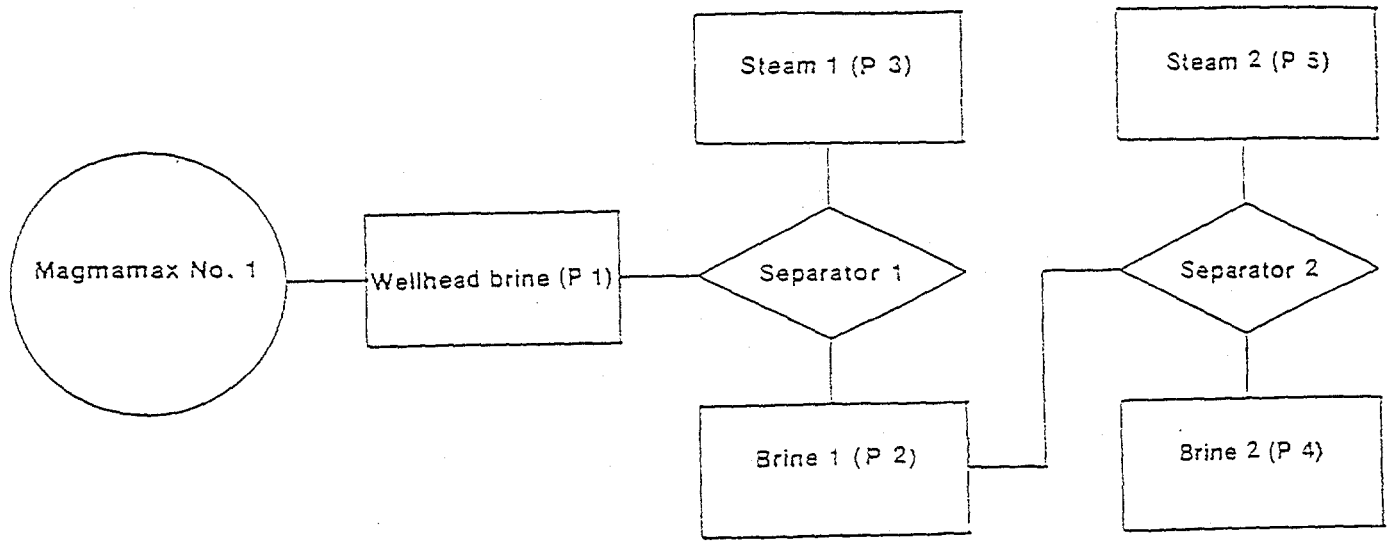


Figure 7: Block diagram of the Bureau of Mines geothermal test facility showing the relative locations of the corrosion test packages (Cramer, et al., 1983).

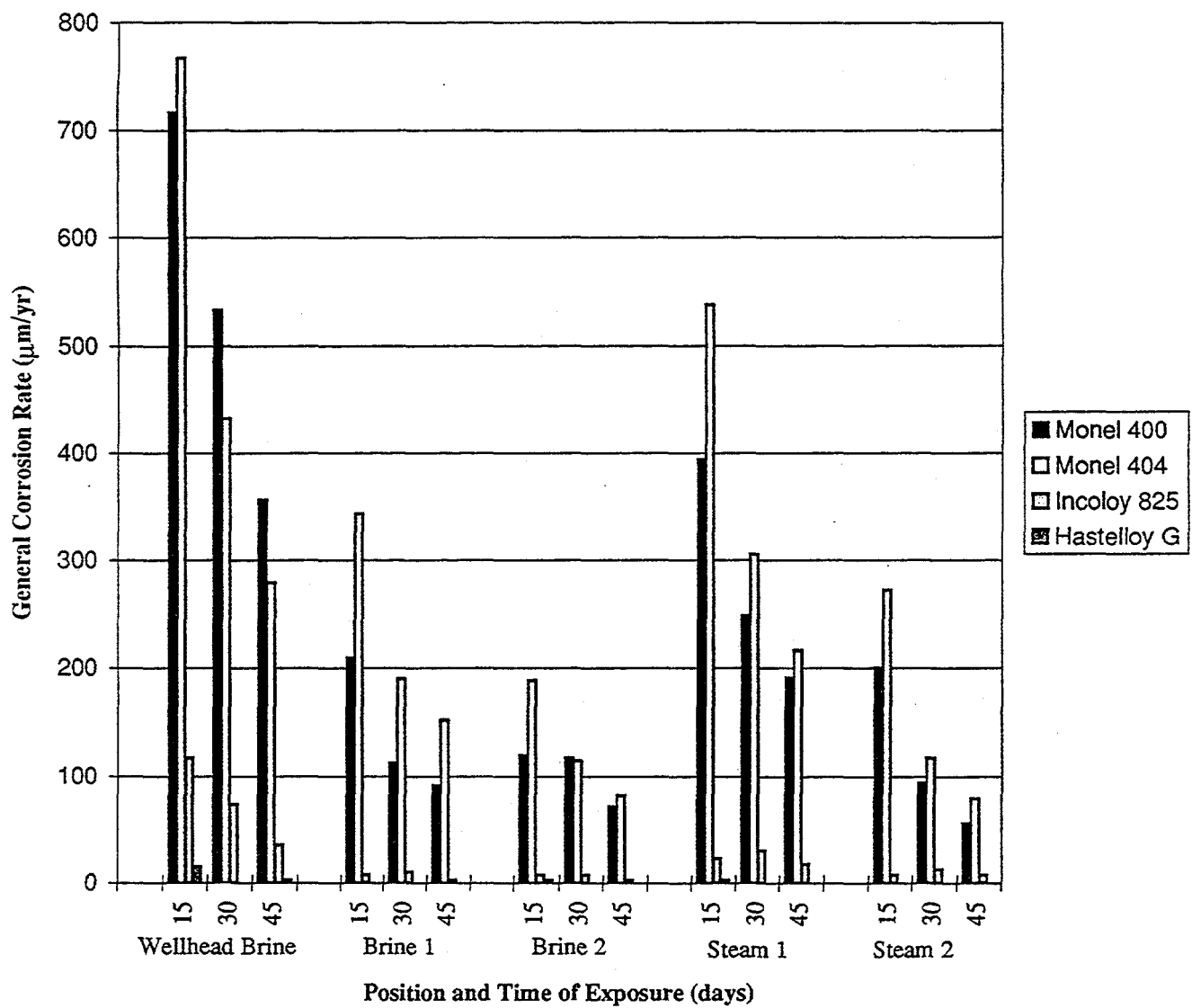


Figure 8. General corrosion rates for nickel alloys in brine and steam (Cramer, et al., 1983).

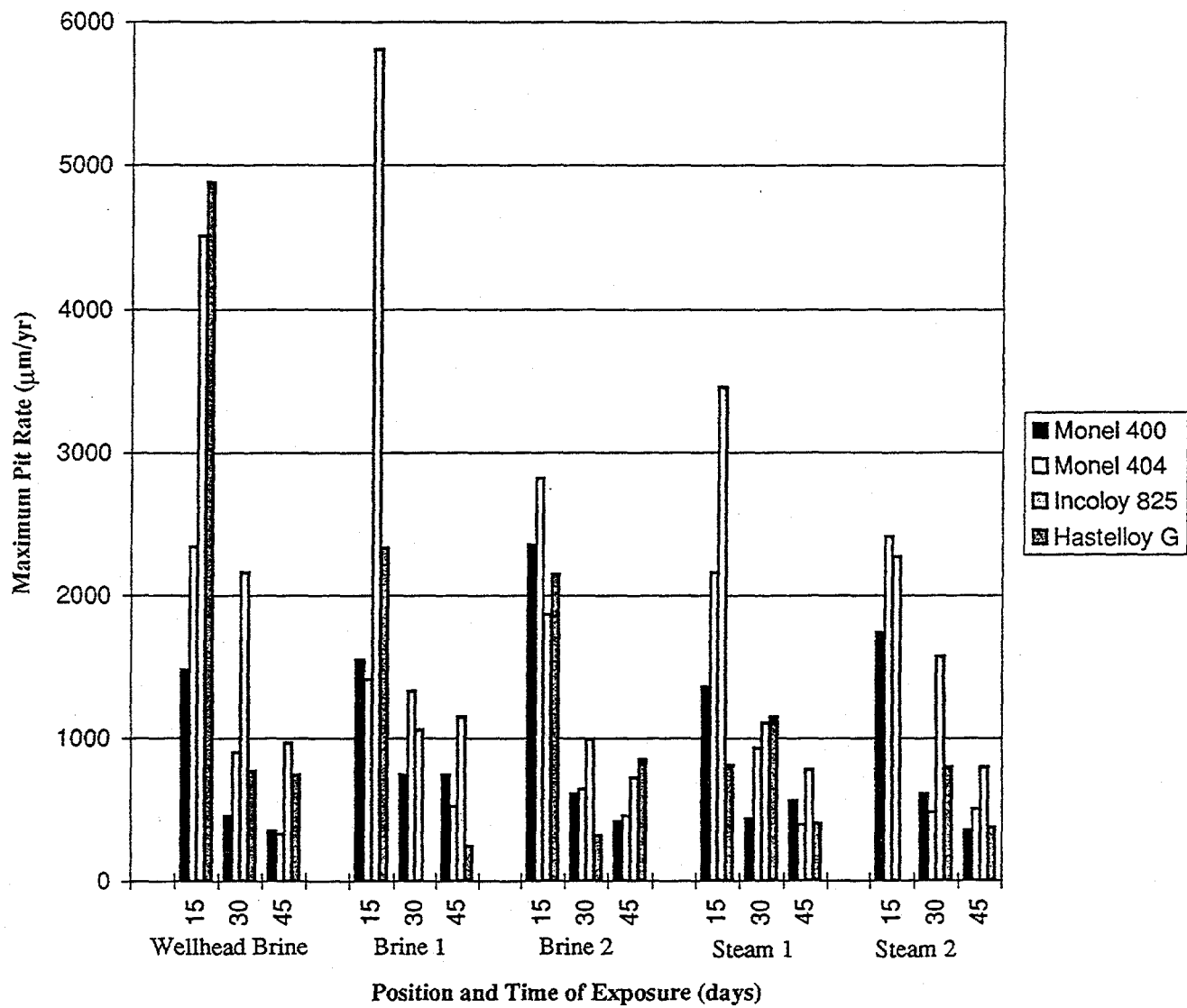
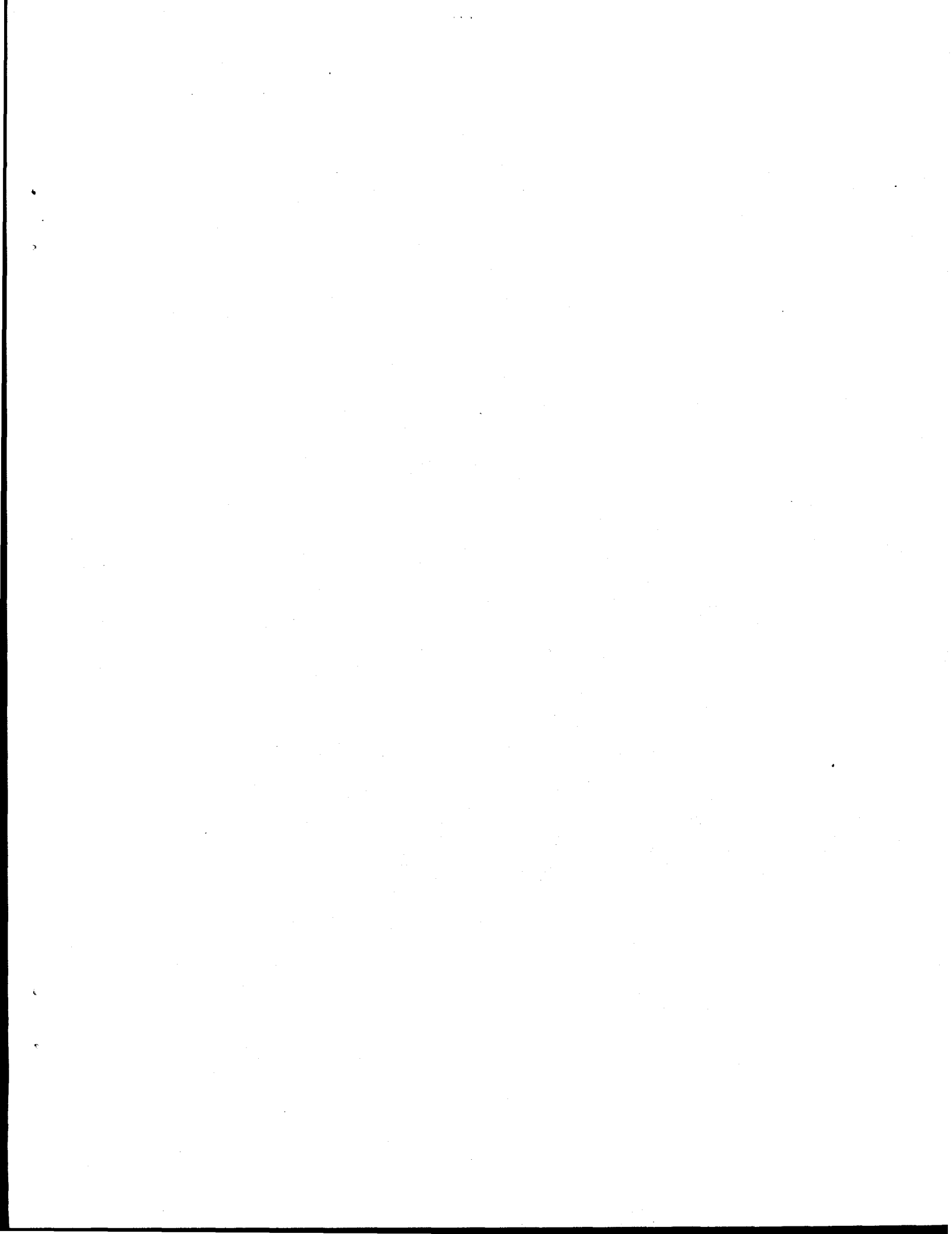


Figure 9. Maximum pit penetration rates for nickel alloys in brine and steam (Cramer, et al., 1983).





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