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SEAWATER CORROSION STUDIES OF SNAP-21 MATERIALS

U.S. NAVAL RADIOLOGICAL DEFENSE LABORATORY

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ADMINISTRATIVE INFORMATION

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ABSTRACT

The corrosion rates of several SNAP-21 materials measured in seawater at ambient room temperature and pressure (Hastelloy C, Hastelloy X, Titanium-621, Berylco-165) have been compared to those measured in 200°C seawater vapor (Hastelloy C, Hastelloy X), in seawater under a hydrostatic pressure of 7000 psi (Hastelloy C, Titanium-621, Berylco-165) (23°C) and in seawater in an ionizing radiation field of 2×10^5 r/hr (Hastelloy C, Hastelloy X) (30°C). Significant increases in corrosion rate were observed only for Hastelloy C and Hastelloy X in hot seawater vapor (approximately two orders of magnitude) and for Hastelloy C in seawater under high hydrostatic pressure (approximately an order of magnitude).

SUMMARY

The Problem

Radiological-safety consideration of the SNAP-21 radioisotopically-fueled power system (for marine environment use) requires that the corrosion behavior in seawater of the materials used in construction of the system be known in the event of accidental entry of seawater into the system. The corrosion environment one might expect in such a situation is that of hot seawater vapor, high hydrostatic pressure and ionizing radiation.

Findings

Experiments were conducted to determine the corrosion behavior in seawater of several SNAP-21 materials under conditions of hot seawater vapor (200°C), high hydrostatic pressure (7000 psi) or ionizing radiation (2×10^5 r/hr).

The results of these experiments indicated that the hot-seawater-vapor and high-hydrostatic-pressure environments increased the corrosion rate of Hastelloy C, the material of primary interest (Hastelloy C is the fuel-container material). The radioisotopic fuel, however, would still remain contained for a relatively long time compared to its half-life and would therefore not constitute a serious radiological hazard to man.

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I. INTRODUCTION

The SNAP-21 system has been designed and is presently being developed by the Minnesota Mining and Manufacturing Company (3M) under the sponsorship of the Division of Reactor Development and Technology of the United States Atomic Energy Commission. The system is a radioisotopically-fueled power source providing 10 watts of electrical energy through thermoelectric conversion of the radioisotopically generated heat energy.

The radioisotopic nature of the fuel material, strontium-90 titanate, dictates that utmost precautions be taken to insure that man will not be subjected to its radiological hazards under credible accident situations.

Under normal deployment conditions the outside pressure vessel, made of titanium 621 alloy (subsequently changed to Berylco-165, a beryllium-copper alloy), is the only part of the system exposed to the ocean environment. It is possible, however, that seawater may enter the interior of the system in the event of a severe accident situation.

Because of this consideration it is necessary to examine the corrosion behavior of the materials comprising the SNAP-21 system resulting from exposure to seawater.

A previous report has described electrochemical corrosion studies of galvanically coupled SNAP-21 materials in seawater.[1] The present report describes corrosion rate measurements on test specimens exposed to hot seawater vapor, high hydrostatic pressure or ionizing radiation. These conditions were chosen to simulate those which might exist in the interior of a broached SNAP-21. Corrosion rates obtained under standard conditions (i.e., ambient room temperature and pressure) were used as baseline values to which corrosion rates obtained under different conditions were compared.

Radioactive tracer techniques, in which radioactive test specimens are placed in seawater and the seawater assayed for radioactive corrosion products, and conventional analytical techniques were employed to obtain a measure of corrosion rates.

II. EXPERIMENTAL

A. TEST APPARATUS

Standard Tests

The exposure apparatus used to obtain corrosion rates of the radioactive test specimens under "standard" conditions consisted of a pyrex exposure vessel contained in a lead shield. A detailed description of the apparatus has been reported elsewhere.[2,3]

Hot-Vapor Exposure Apparatus

The apparatus used to expose test specimens to hot seawater vapor consisted of two vessels, one within the other (Fig. 1). The inner vessel, a sealed pyrex tube, held one test specimen and the test seawater; the outer vessel, made of stainless steel, held the pyrex vessel and some distilled water. The pyrex tube had a circumferential indentation on which the specimen rested, the seawater level being below this indentation. This arrangement insured that the specimen was not immersed in the seawater. The assembled exposure apparatus was placed in a cylindrical-type electrically heated oven (Hevi-Duty Electric Company, Milwaukee, Wisconsin) and heated to nominally 200°C. The temperature and pressure within the stainless steel vessel were monitored by a dial thermometer (Weston Instruments, Newark, N.J.) and a pressure gauge (Marsh Instrument Company, Skokie, Illinois), respectively. The exposure apparatus was designed to provide a very large pressure safety factor. The pyrex vessel which contained the radioactive specimen had nominal dimensions of 20 mm OD, 1.2 mm wall thickness and 12 cm length. The recommended maximum working pressure for a pyrex vessel of these dimensions is reported to be 500 psi.[4] The pyrex vessel, however, would not experience much of a pressure differential. The stainless steel vessel, with dimensions of 3.175 cm OD and 21.6 cm length, had a pressure rating of 10,000 psi at a working temperature of 200°C.* High-pressure stainless steel tubing and "Ermeto" fittings,

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*Private communication from Milton S. Frank Co., Inc., authorized representatives for Autoclave Engineers, Inc., dated 19 July 1966.

rated at 15,000 psi, were used to introduce the pressure gauge and thermometer stem to the interior of the stainless steel vessel. For minimization of the radiation hazard to personnel the entire apparatus was placed in a lead cave.

The experimental procedures used in making a run were as follows. The pyrex tube was filled up to just below the circumferential indentation with seawater, the radioactive specimen put into the pyrex tube, and the pyrex tube flame-sealed under vacuum. After cooling to room temperature the pyrex tube was inserted into the stainless-steel pressure vessel, distilled water added to partly fill the vessel, and the end cap screwed on. The cylindrical oven in which the pressure vessel was placed was oriented in the vertical position (Fig. 1). After an exposure period was completed the pressure vessel was removed from the oven and allowed to cool to room temperature. After cooling, the end cap of the pressure vessel was unscrewed, and the pyrex tube was removed and placed into a hole drilled in a lead block.

The pyrex tube was scratched with a file above the specimen position, the scratch was wet with water and the tip of a small diameter pyrex rod (heated white hot) was applied to one end of the scratch. This procedure produced a circumferential crack around the pyrex tube and allowed its top to be easily removed. This method of opening allowed minimum handling of the pyrex tube and avoided spilling of its contents during the opening operation.

After opening, the radioactive specimen was removed and placed into a new pyrex tube for the start of another exposure period. The seawater contained in the opened pyrex tube was then assayed for radioactivity.

High-Hydrostatic-Pressure Exposure Apparatus

The apparatus and procedure used to expose specimens to a high hydrostatic pressure (Fig. 2) was similar to that used for the hot-vapor experiment. The inner pyrex tube, which held the specimen, was completely filled with seawater and a thin,tight-fitting rubber finger (a finger cut from a surgeon's rubber glove) was slipped over the open top to seal it. The filled pyrex tube was then inserted into the stainless steel pressure vessel (the same type as used in the hot-vapor experiment), the pressure vessel filled completely with distilled water, and the hydrostatic pressure inside the pressure vessel raised to 7000 psi by means of an air-operated hydraulic power unit (Sprague Engineering, Model S-216 CR, Gardena, California). A 0-7500 psi pressure gauge (Autoclave Engineers, Inc., Erie, Pa.) was used to monitor the pressure. This hydrostatic pressure was transmitted to the interior of the pyrex tube via the thin rubber covering over the open end of the tube. This experiment was carried out at ambient room temperature(ca. 23°C).

Cobalt-60 Gamma-Ray Exposure Apparatus

The test specimen was placed in an exposure configuration such that one side of the specimen was in contact with seawater while the ionizing radiation from the cobalt-60 gamma ray source impinged on the dry (other) side. This exposure configuration was achieved by the specimen's being epoxied over a hole on the outside wall of a cylindrical pyrex jug (Fig. 3). Two tubulations on the top of the jug served as the inlet and outlet for the test gas, either air or nitrogen. The inlet tube had a fritted pyrex bubbler on the end that extended to the bottom of the pyrex jug. Stainless steel tubing was epoxied to the ends of the inlet and outlet tubulations and the tubing was routed out of the irradiation cavity of the cobalt-60 source through a hole in the bottom of the cavity. The exhaust tubing terminated just outside of the irradiation cavity while the inlet tubing was attached to the source of test gas. The inlet flow of the gas, either from an air or nitrogen tank, was controlled by a regulator valve and a flow meter, in that order. A third tubulation on the top of the pyrex jug served as a filling and sampling tube. It extended approximately 8 cm from the top of the jug.

The experimental procedure for the filling and sampling of seawater was the following. Seawater was introduced into the pyrex jug via a thin polyethylene tube inserted into the pyrex jug through the sampling tube. After introduction of 1 liter of seawater the polyethylene tube was withdrawn and the end of the sampling tube closed by heat-sealing. The cobalt-60 source was then lowered into the irradiation cavity. At the end of an exposure period the cobalt-60 source was removed and the sealed end of the sampling tube opened by heating and pulling of the softened pyrex until it was thin enough to break easily. The opening was then enlarged by heating of the edges of the opening. After the pyrex had cooled, a thin polyethylene tube was inserted into the jug via the sampling tube and all the seawater sucked out by vacuum into a pyrex suction flask. The jug was then refilled with fresh seawater, the sampling tube resealed and another exposure period started.

B. TEST SPECIMENS

The test specimens (unirradiated) received from the 3M Company were in the form of 1.4 in. squares 60 mil thick. Smaller specimens, required for the hot-vapor and high-hydrostatic-pressure experiments, were machine cut from the larger specimens.

Two sets of Berylco-165 specimens were tested. One set, designated "thin", had dimensions of 1.4 in. square by 60 mil thick while the other set, designated "thick", had nominal dimensions of 1.9 in. square by 220 mil thick. The difference between the two sets, other than size, was that the surfaces of the thick specimens had been milled by the vendor. The surfaces of the thin specimens were polished here, finishing with 0.5 μ aluminum powder. The surfaces of the other specimens were finished by 3M and no further polishing was performed here.

Table 1 shows the composition of the test specimens.

Each test specimen was cleaned in benzene, and then in absolute ethanol, in an ultrasonic cleaner.

Neutron Irradiation of Test Specimens

Specimens of Hastelloy C, Hastelloy X, and Titanium-621 alloy were made radioactive by thermal-neutron irradiation. A description of the apparatus and techniques used is given elsewhere.[2,3] As an example of the level of activation, the amount of cobalt-60 activity in specimens of Hastelloy C was approximately 40 mCi per specimen.

C. SEAWATER

Seawater for all experiments was collected on a biweekly schedule. Collection was made at least one mile from the nearest land mass (Farallon Islands off the northern coast of California) by dipfilling of the seawater into 5-gal polyethylene carboys. Prior to use the seawater was filtered through an 0.8 μ Millipore filter for removal of particulate matter.

D. EXPOSURE PROCEDURE

Standard (Baseline) Experiments*

Radioactive specimens of Hastelloy C, Hastelloy X and Titanium-621 alloy were immersed in seawater in exposure vessels described previously.[2,3] The seawater was either aerated (air purged) or deaerated (nitrogen purged). The experiment was carried out at an ambient temperature of approximately 20°C.

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*All new data, generated for this report.

TABLE 1

Composition of Test Specimens

Hastelloy C

Fe	5.0%	Mn	0.70
Cu	0.10	Mo	10.0
Ni	57.9	Si	0.20
Cr	20.0	V	0.30
Al	0.03	Mg	0.001
Co	1.8	Ti	0.002
		W	4.0

Hastelloy X

Fe	18.0%	Mn	0.70
Cu	0.10	Mo	16.0
Ni	47.9	Si	0.20
Cr	15.0	V	0.002
Al	0.02	Mg	0.001
Co	1.5	Ti	0.003
		W	0.60

Titanium-621

Fe	0.35%	Mo	0.70
Cu	0.001	Si	0.02
Ni	0.001	V	0.001
Cr	0.01	Mg	0.001
Al	6.00	Ca	0.0003
Pb	0.02	Ti	89.9
Sn	0.002	Nb	2.0
Co	< 0.001	Ta	1.0
		Mn	0.02

Berylco-165

Be	1.76%	Pb	0.004
Fe	0.09	Zn	0.027
Si	0.10	Ni	0.008
Al	0.07	Cr	0.003
Co	0.29	Mn	0.015
Sn	0.05	Ag	0.015
		Cu	97.6

At successive intervals of 32, 27, 29, 41 and 35 days (total elapsed exposure times of 32, 59, 88, 129 and 164 days) the seawater in each exposure vessel was drained and fresh seawater put in. Aliquots of the seawater from each exposure interval were analyzed for radioactive corrosion products.

Specimens of Berylco-165 (not radioactive) were immersed in 1 liter of seawater contained in a pyrex flask. The specimens were held in pyrex holders (Fig. 4). The conditions of exposure were the same as those for the radioactive specimens. At successive intervals of 9, 18, 31, 40, 37 and 48 days (total elapsed exposure times of 9, 27, 58, 98, 135 and 183 days) the seawater in which the thin Berylco-165 specimens had been immersed was removed from the pyrex flasks and replaced with fresh seawater. For the thick Berylco-165 specimens the sampling intervals were 40, 36 and 48 days(total elapsed exposure times of 40, 76 and 124 days). The seawater from each exposure interval was assayed[6] for copper content.

Two of the thick specimens were exposed in-situ at the NRDL test site at San Clemente Island for 4 months.

Hot-Seawater-Vapor Experiment

Radioactive specimens of Hastelloy C and Hastelloy X were placed in the exposure apparatus described above (Section IIA). The nominal temperature of the seawater vapor was 200°C.

At successive intervals of 14, 15, 17, 30, 41, 36 and 47 days (total elapsed exposure times of 14, 29, 46, 76, 117, 153 and 200 days) the specimens were removed and the seawater assayed for radioactive corrosion products. Fresh seawater was used for each exposure interval.

High-Hydrostatic-Pressure Experiment

Radioactive specimens of Hastelloy C and titanium-621 alloy and an inactive specimen of Berylco-165 were exposed to seawater under a hydrostatic pressure of nominally 7000 psi (apparatus described in Section IIA). The experiment was conducted at ambient room temperature (ca. 23°C). The specimens were removed and the seawater assayed for corrosion products at successive intervals of 18, 37 and 47 days (total elapsed exposure times of 18, 55 and 102 days). Fresh seawater was used for each exposure interval.

Cobalt-60 Gamma-Ray Experiment

Two radioactive specimens of Hastelloy C and two of Hastelloy X were exposed to seawater in an ionizing radiation field (apparatus described in Section IIA). The dose rate to the specimens was nominally

2×10^5 r/hr. The seawater was aerated (air purged) for one set of specimens and deaerated (nitrogen purged) for the other set. The ambient temperature in the cobalt-60 irradiation cavity was approximately 30°C. The seawater was removed and fresh seawater put into the exposure vessels at successive intervals of 22, 28, 27, 30 and 50 days (total elapsed exposure times of 22, 50, 77, 107 and 157 days). The seawater from each exposure interval was assayed for radioactive corrosion products.

E. CALIBRATIONS

Specific Activity

To obtain a corrosion rate from the amount of radioactive corrosion products released to the test seawater from the radioactive specimens, one must know the specific activity of each radionuclide of interest (e.g., cobalt-60 for Hastelloy C and X and tantalum-182 for titanium-621) expressed as cpm per µg of the alloy. The specific activities of Hastelloy C and Hastelloy X were determined on the basis of the specific activity of cobalt metal standards (irradiated together with the specimens) and the known cobalt content of these alloys(Table 1). The specific activity of the cobalt standard was determined by dissolution of an accurately weighed piece of the standard, dilution of the resulting solution to a known volume and assay of an aliquot of the resulting solution for cobalt-60 in a gamma pulse-height analyzer system. The specific activity of titanium-621 alloy was determined by dissolution of an accurately weighed piece of a radioactive specimen, dilution of the resulting solution to a known volume and assay of an aliquot of the resulting solution for tantalum-182 in a gamma pulse-height analyzer system.

Flux Profile

To make valid comparisons of the corrosion rates of the various radioactive specimens, one must make corrections for any differences in the neutron flux between the standards (e.g., pure cobalt metal) and each specimen due to neutron-flux attenuation by the specimens.

These corrections were obtained by comparison of the total activities (specimens counted in a high-pressure ionization chamber) of specimens of the same alloy placed at different positions within the specimen stack during irradiation. Results of these comparisons were used to normalize the specific activity of each alloy specimen to that of the standard (or to those of specimens which were used to determine the specific activity - see preceding section).

F. ANALYTICAL PROCEDURES

Hastelloy C, Hastelloy X

Cobalt-60 was used as the radioactive tracer for determination of the corrosion rates of Hastelloy C and Hastelloy X. Analysis for cobalt-60 was made by direct counting of the test seawater in a gamma pulse-height analyzer system. The amount of cobalt-60 present was determined by comparison with a series of standard samples containing known amounts of cobalt-60.

Titanium-621 Alloy

Determination of the amounts of titanium-621 alloy released to the test seawater was accomplished by direct counting of the seawater for tantalum-182 in a gamma pulse-height analyzer system. The amount of alloy present was determined via the specific activity of the alloy (Section E).

Berylco-165

Determination of the amount of this alloy released to seawater was accomplished by assay of the seawater for copper content. The analysis for copper was based on a spectrophotometric method described by Chow and Thompson.[6] The procedure, in brief, consisted of addition of a color-forming reagent, sodium diethyldithiocarbonate, to a seawater aliquot, extraction of the copper diethyldithiocarbonate in xylene and measurement of its absorbance at 436 mμ.

G. SURFACE PROFILE MEASUREMENT

Surface profile measurements were obtained by use of a Proficorder (Micrometrical Division, Bendix Corporation, Ann Arbor, Michigan). This instrument has the capability of measuring vertical surface irregularities as small as 0.5 microinches.

III. RESULTS AND DISCUSSION

Standard (Baseline) Experiments

Figure 5 shows the corrosion rates of Hastelloy C and Hastelloy X in aerated and deaerated seawater as a function of exposure time. It should be noted that the individual data points in Fig. 5, as in all of the figures to follow, represent not instantaneous corrosion rates but rather the average value over a particular exposure interval. All of the corrosion rates decreased to relatively constant values after about 100 days. There appears to be no significant difference between corrosion rates measured in aerated and those in deaerated seawater at the longer exposure times.

Figure 6 shows the corrosion rates of titanium-621 alloy in aerated and deaerated seawater as a function of exposure time. As in the case of the Hastelloy alloys, the corrosion rates decreased with time and there was no significant difference between the corrosion rate measured in aerated and that in deaerated seawater.

Figures 7 and 8 show the corrosion rates of the thin and thick Berylco-165 specimens in aerated and deaerated seawater, respectively, as a function of exposure time. There was a considerable difference in corrosion behavior between specimens immersed in aerated seawater and those immersed in deaerated seawater. In aerated seawater the area of the specimen which was in contact with the pyrex holder suffered relatively severe attack while the remaining areas not in contact with the holder corroded more uniformly. In deaerated seawater there was very little local attack at the pyrex-specimen interface; the entire area of the specimen corroded uniformly. Because of the non-uniformity of corrosion of the specimens in aerated seawater the corrosion rates in aerated seawater (Fig. 7) are not as meaningful as those in deaerated seawater (Fig. 8). (All corrosion rates reported here are calculated on the basis of uniform corrosion.) The initial "peak" in the corrosion rate of the thin Berylco-165 specimen shown in Fig. 7 very likely reflects the sharp increase in corrosion rate due to initiation of the severe attack shown in Fig. 9. The cause of the increased corrosion in aerated seawater is most likely due to the presence of carbonic acid (from the carbon dioxide in air) which dissolves the protective surface oxide film[5] followed by formation of oxidation cells between oxygen-rich and oxygen-deficient areas (crevices), the latter areas becoming anodic.

Figures 9 and 10 show photographs of the thin and thick Berylco-165 specimens, respectively, which had been immersed in aerated seawater (thin specimen - 183 days exposure, thick specimen - 124 days exposure). The presence of localized corrosion is evident in these photographs and the extent of corrosion is illustrated further in Figs. 11 and 12, which show the surface profiles of the areas of local corrosion (the arrows on the photographs indicate the approximate path of the proficorder sensing element). Figures 13 and 14 show a photograph and surface profile, respectively, of a representative area of the thick Berylco specimen which had been immersed in deaerated seawater for 124 days. The abrupt change in the profile in Fig. 14 is caused by a scale change on the proficorder. It is evident that the corrosion is much more uniform on this specimen.

Figures 15, 16 and 17 show photographs of the exposure configuration of the two thick Berylco-165 specimens which had been placed in the ocean at the NRDL Ocean Test Facility at San Clemente Island. These photographs were taken after 4 months exposure. The specimen holder was made entirely of plastic materials to avoid galvanic effects. Figure 18 shows the two specimens after they were removed from the holder. It is evident that the only severe corrosion occurred at the edges of the specimens where they were held between two pieces of Lucite plastic (Fig. 17).

Figure 19 shows a close-up photograph of the edge of one of the specimens. This photograph clearly shows the local attack on the edges. It is evident from the laboratory tests and from the <u>in-situ</u> ocean test that in aerated seawater local corrosive attack occurs at areas on the specimen surface which are relatively oxygen-deficient due to their being in contact with other surfaces.

Comparisons of the corrosion rates obtained under other conditions (discussed below) to those obtained in the baseline experiments are made at equivalent exposure times.

Hot-Seawater-Vapor Experiment

Figure 20 shows the corrosion rates of Hastelloy X and Hastelloy C in hot seawater vapor as a function of exposure time. The data points for several exposure periods are missing due to cracking of the pyrex vessel (and hence loss of the seawater sample) during these exposure periods. There appears to be no significant difference between the corrosion rates of Hastelloy C and Hastelloy X. The corrosion rates were relatively constant (within a factor of about two) during the duration of the experiment, the nominal value being about 5 x 10^{-4} mpy. This value is between one and two orders of magnitude greater than the values obtained in the baseline experiment (approximately 2 x 10^{-6} mpy for Hastelloy C and 1 x 10^{-5} mpy for Hastelloy X in deaerated seawater).

High-Hydrostatic-Pressure Experiment

Figure 21 shows the corrosion rates of Hastelloy C and titanium-621 alloy in seawater at a hydrostatic pressure of 7000 psi. The corrosion rate of both alloys decreased rapidly. The corrosion rate of titanium-621 at high pressure is about a factor of 3 higher than the baseline corrosion rate. The corrosion rate of Hastelloy C at high pressure is about an order of magnitude higher than the baseline value.

In an effort to determine whether any activity had diffused through the rubber membrane during an exposure period, a pyrex vessel containing 1.6 x 10^5 cpm of cesium-137 activity in seawater was subjected to the identical exposure procedure as the Hastelloy C, titanium-621 and Berylco-165 specimens. At the end of the exposure period no cesium-137 activity was detected in the distilled water in the stainless steel vessel. A recount of the seawater in the pyrex vessel indicated a loss of less than 2 percent of the initial cesium-137 activity. This 2 percent might have been lost through the rubber membrane; if so, the failure to detect it in the distilled water could have been due to adsorption on the stainless steel vessel wall.

Figure 22 shows the corrosion rate of Berylco-165 in seawater at a hydrostatic pressure of 7000 psi. The corrosion rate was relatively constant, being 5 x 10^{-2} mpy at the end of 103 days. This value can be compared to the value obtained on the thin Berylco-165 specimens, 9 x 10^{-2} mpy, in the baseline experiments (the smaller specimens used in the high-pressure experiment were cut from the thin Berylco-165 specimens). The deaerated seawater baseline value was used for comparison since it would be expected that the oxygen and/or carbon dioxide would become depleted in the relatively small volume of seawater (nominally 20 cc) in the pyrex vessel used for the high-pressure experiments. As an additional point of reference a specimen of Berylco-165 was run with the identical apparatus and procedure as was used in the high-pressure runs except that the seawater was not pressurized. This data point is shown in Fig. 22. It is evident that there is no significant effect of high hydrostatic pressure on the corrosion rate of Berylco-165 up to a pressure of 7000 psi.

Cobalt-60 Gamma-Ray Experiment

Figures 23 and 24 show the corrosion rates of Hastelloy C and Hastelloy X, respectively, in aerated and deaerated seawater in an ionizing radiation field. The corrosion rate of Hastelloy C in deaerated seawater is relatively constant, being nominally 1×10^{-5} mpy. This value is about twice the baseline value, 6×10^{-6} mpy. In aerated seawater the corrosion rate after 107 days was 3×10^{-6} mpy and decreasing. This value compares well with the baseline value of 2×10^{-6} mpy. The behavior of Hastelloy X is similar to that of Hastelloy C. In both environments there appears to be no significant effect of ionizing radiation on the corrosion rates of these alloys for the dose range used in these experiments.

IV. SUMMARY AND CONCLUSION

Table 2 summarizes the corrosion rates of the Hastelloy C, Hastelloy X, titanium-621 alloy and Berylco-165 alloy specimens in seawater under the various exposure conditions and compares them to their respective baseline values.

The results obtained on the Berylco-165 specimens indicate that crevices at the surface of the pressure vessel should be avoided. An undesirable situation, for example, would be one in which the SNAP-21 unit is lying directly on the ocean floor. The crevice formed at the interface of the pressure vessel and the ocean floor would promote localized corrosion.

The corrosion rate of the fuel container material, Hastelloy C, is of primary interest from a radiological safety standpoint in the event of an accident situation. Based on the results obtained, the corrosion rate of Hastelloy C will be approximately 7.4×10^{-4} mpy in an environment of hot seawater vapor and high hydrostatic pressure (assuming that their effects on the corrosion rate are additive). The effect of galvanic coupling of the various materials present in the interior of the SNAP-21 system is expected to be negligible[1] in a hot vapor environment since air would be excluded.

At a uniform corrosion rate of 7.4×10^{-4} mpy the Hastelloy C fuel container, being 0.25 in. thick, would remain intact for approximately 3.2×10^{5} years. This length of time, compared to the relatively short half-life of the radioisotopic fuel, 28 years, indicates that the SNAP-21 system can meet the requirement of not exposing man to the radiological hazards of the fuel.

It must be kept in mind that it is difficult, if not impossible, to predict the corrosion environment due to an accident situation. For example, if the outer pressure vessel of the SNAP-21 unit is broached in such a manner that the seawater does not flow freely in and out of the unit, a hot vapor environment would probably prevail. On the other hand, if there is a flow of seawater through the unit a hot vapor environment would probably not exist. The corrosion environment would depend

TABLE 2

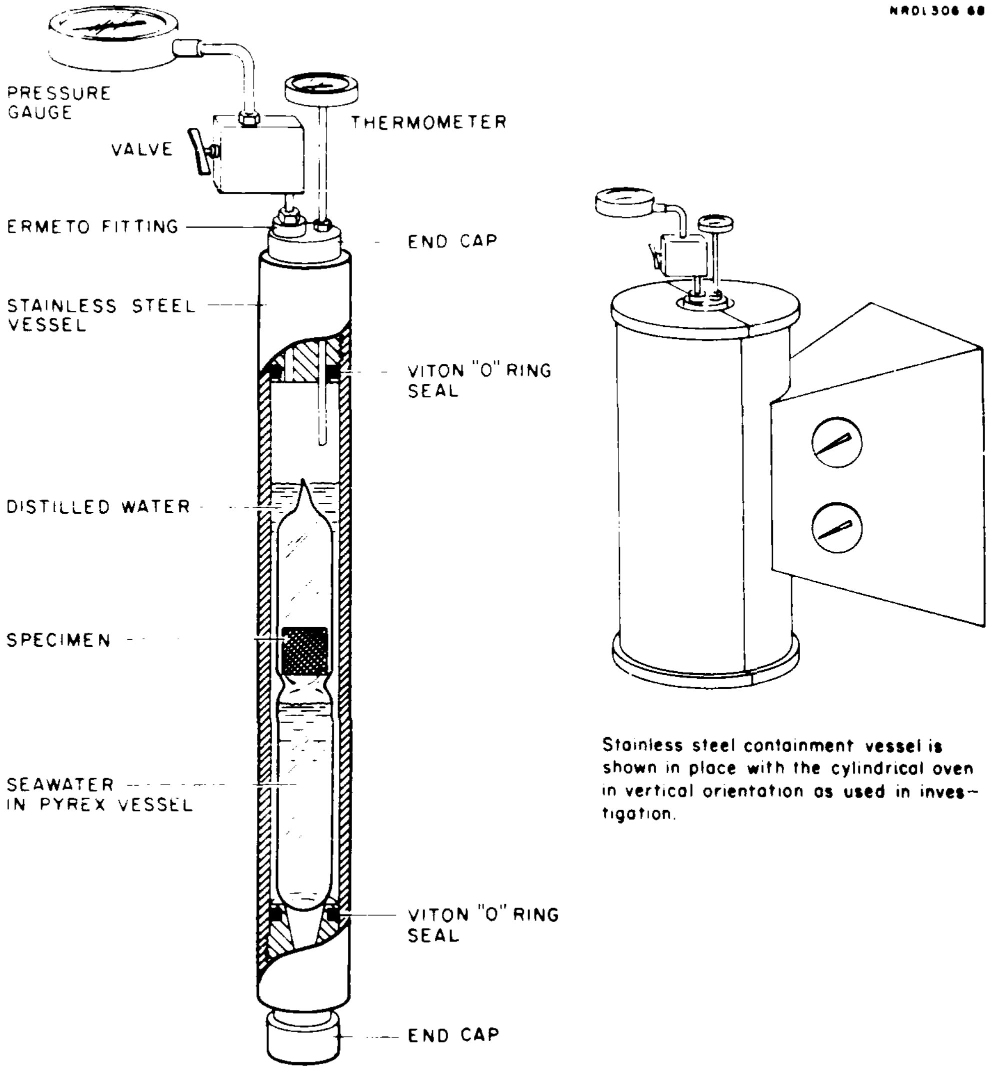
Nominal Corrosion Rate (mpy)*

Specimen	Hot Vapor	High Pressure	Cobalt-60
Hastelloy C	7×10^{-4} (D 2×10^{-6}) 200 days	4×10^{-5} (A 2×10^{-6}) 116 days (D 5×10^{-6})	A 3×10^{-6} (A 2×10^{-6}) D 9×10^{-6} (D 6×10^{-6}) 107 days
Hastelloy X	4×10^{-4} (D 8×10^{-6}) 160 days	--	A 8×10^{-6} (A 2×10^{-6}) D 7×10^{-6} (D 1×10^{-5}) 107 days
Titanium-621	--	7×10^{-6} (A 2×10^{-6}) 102 days (D 2×10^{-6})	--
Berylco-165	--	5×10^{-2} (D 9×10^{-2}) 103 days	--

*Values in parenthesis are baseline values taken from Figs. 5, 6 and 8. Comparison of corrosion rates between baseline values and values obtained under other exposure conditions was made at equivalent exposure times. A and D denotes aerated and deaerated seawater, respectively.

greatly upon the extent of seawater flow and the resulting thermal equilibrium of the unit.

The results obtained here are intended to provide indications of the corrosion behavior of the various SNAP 21 materials under several exposure environments which one might expect.



Stainless steel containment vessel is shown in place with the cylindrical oven in vertical orientation as used in investigation.

Fig. 1 Exposure Apparatus Used in Hot-Seawater-Vapor Experiment.

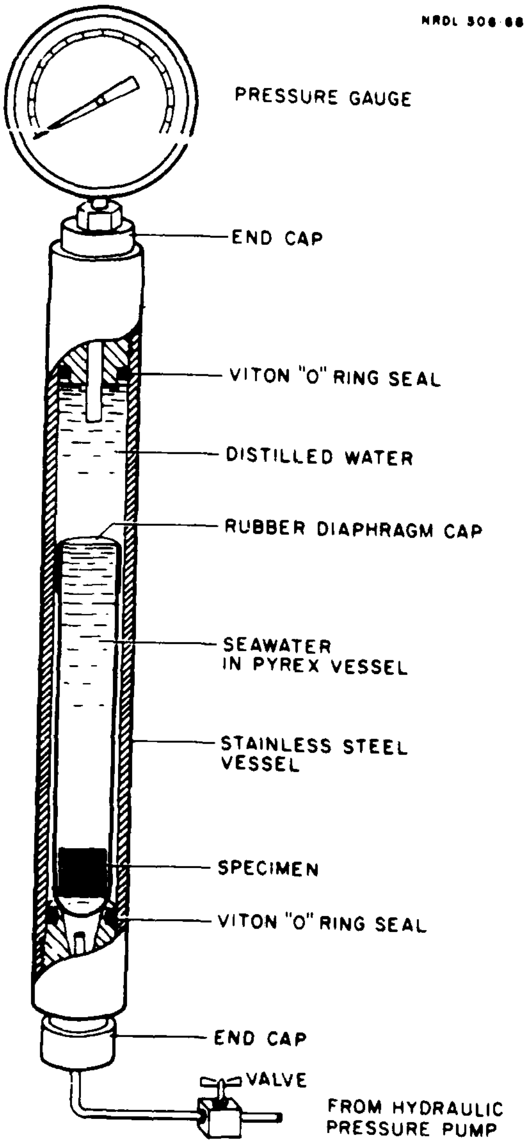


Fig. 2 Exposure Apparatus Used in High-Hydrostatic-Pressure Experiment.

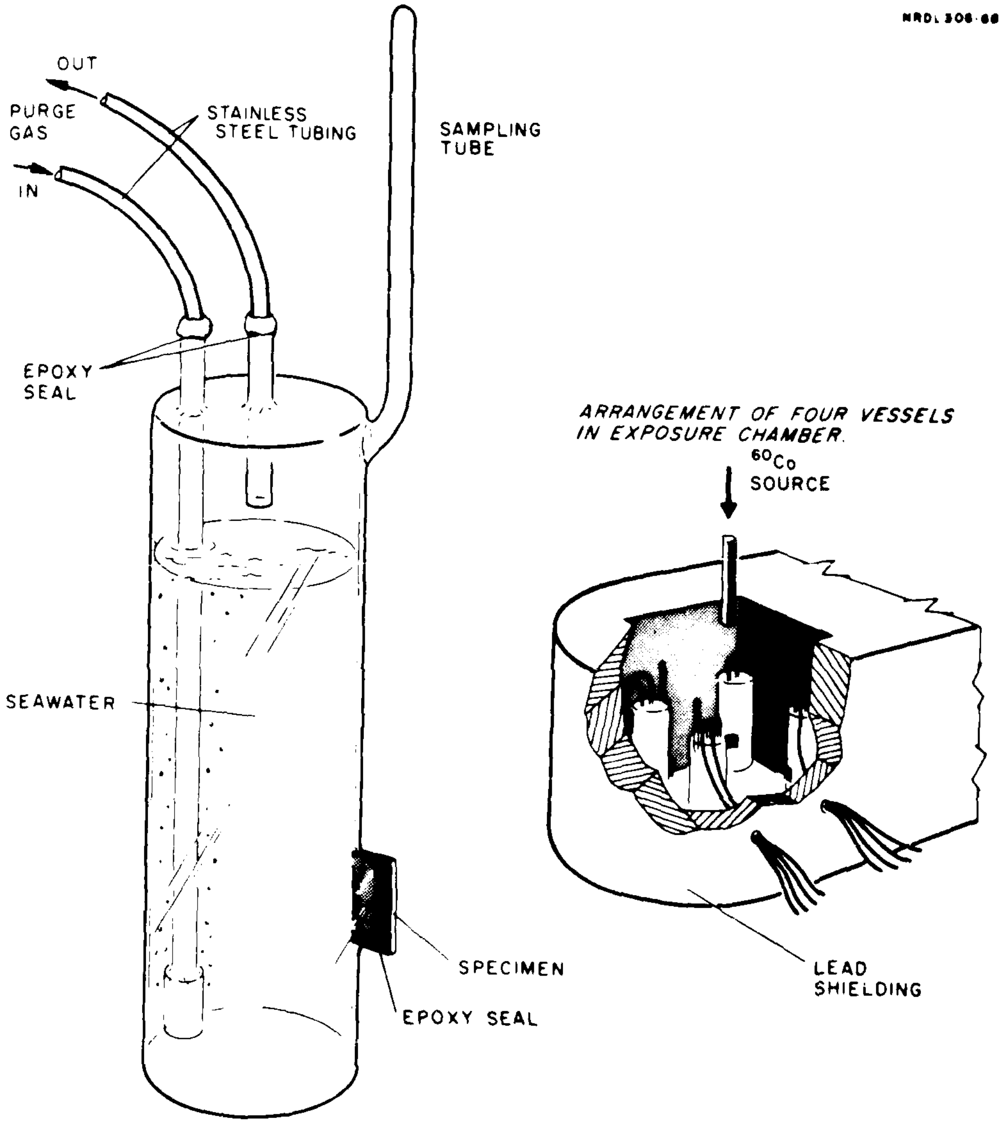


Fig. 3 Exposure Apparatus Used in Cobalt-60 Gamma-Ray Experiment.

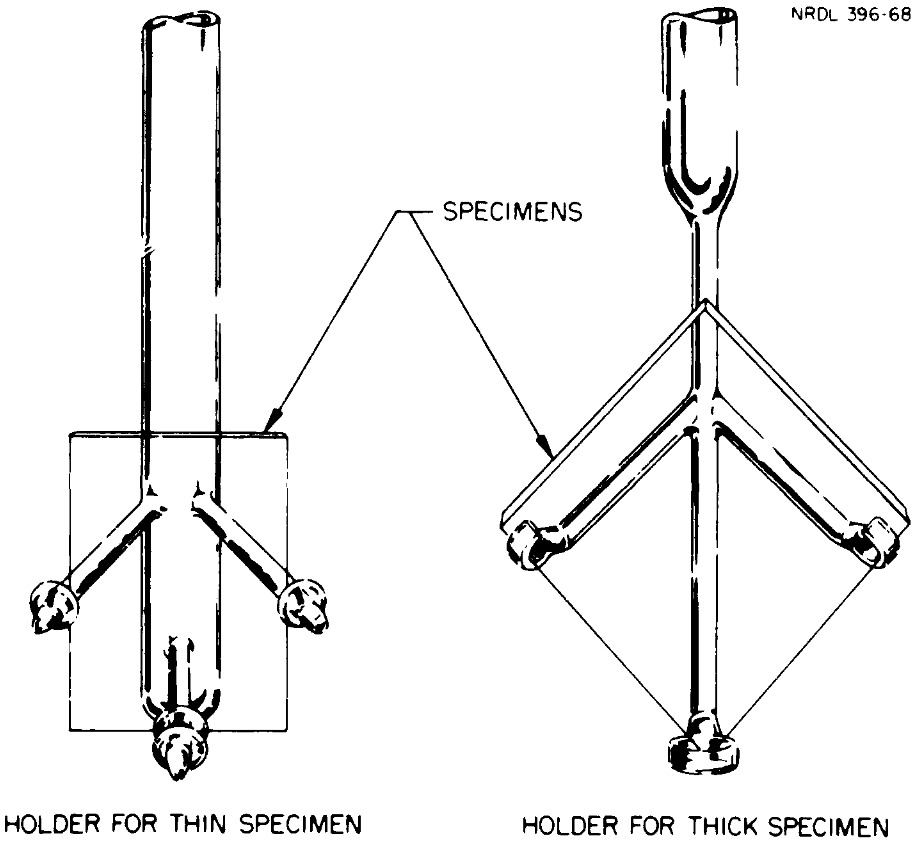


Fig. 4 Pyrex Holders for Thin and Thick Berylco-165 Specimens.

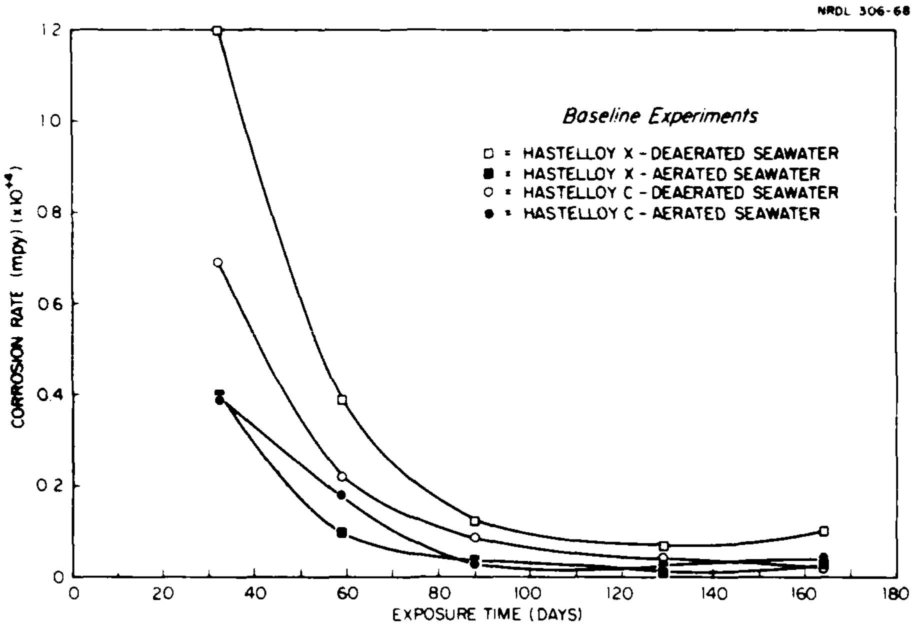


Fig. 5 Corrosion Rates of Hastelloy X and Hastelloy C in Seawater - Baseline Values.

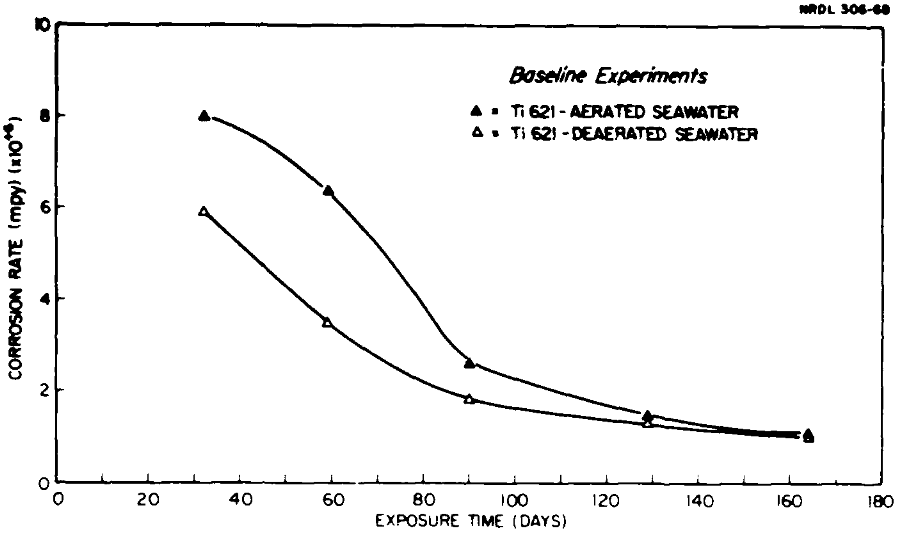


Fig. 6 Corrosion Rates of Titanium-621 Alloy in Seawater - Baseline Values.

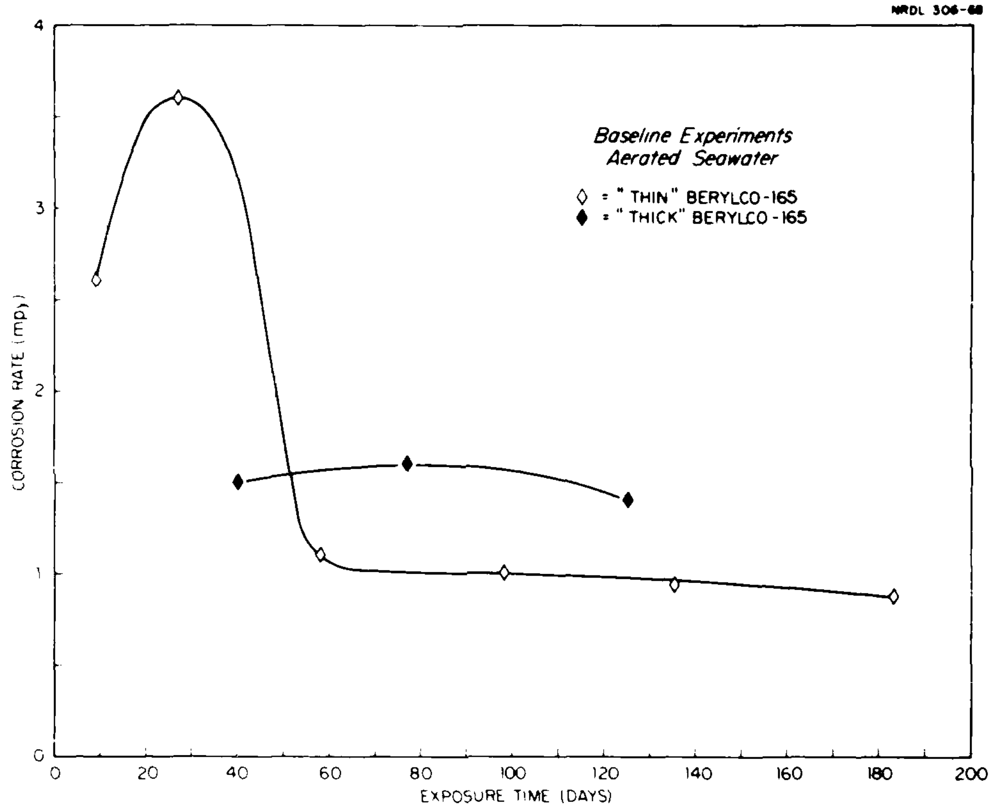


Fig. 7 Corrosion Rates of Berylco-165 Alloy in Aerated Seawater - Baseline Values.

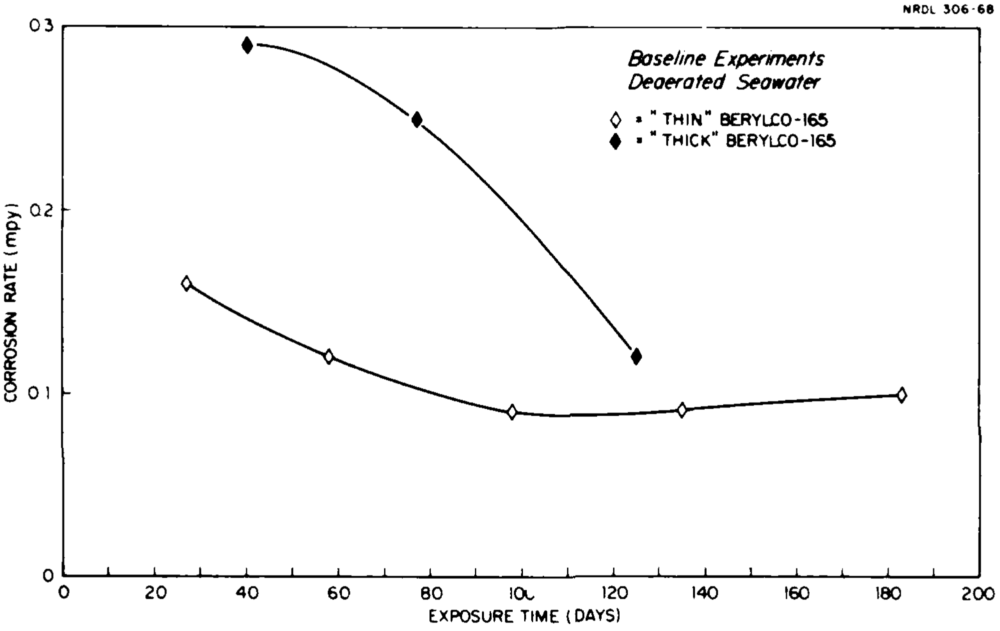


Fig. 8 Corrosion Rates of Berylco-165 Alloy in Deaerated Seawater - Baseline Values.

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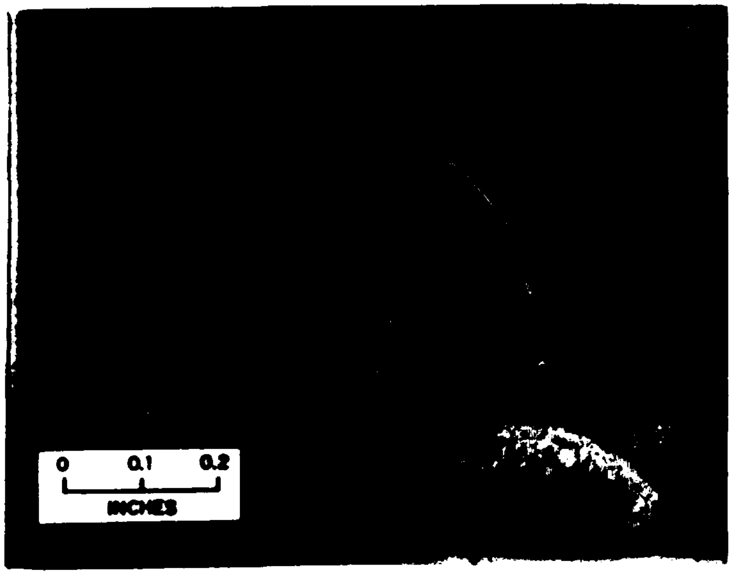

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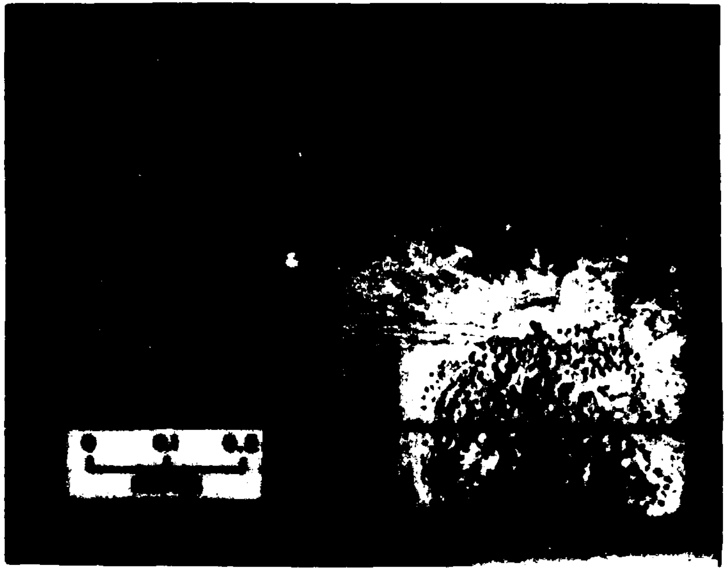

Fig. 9 Local Corrosion on Thin Berylco-165 Specimen After Immersion in Aerated Seawater. Arrow denotes path of surface profile measurement.

Fig. 10 Local Corrosion on Thick Berylco-165 Specimen After Immersion in Aerated Seawater. Arrow denotes path of surface profile measurement.

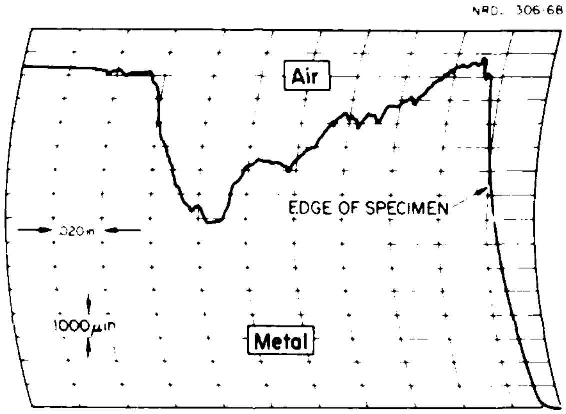

Fig. 11 Surface Profile of Local Corrosion on the Thin Berylco-165 Specimen Shown in Fig. 9.

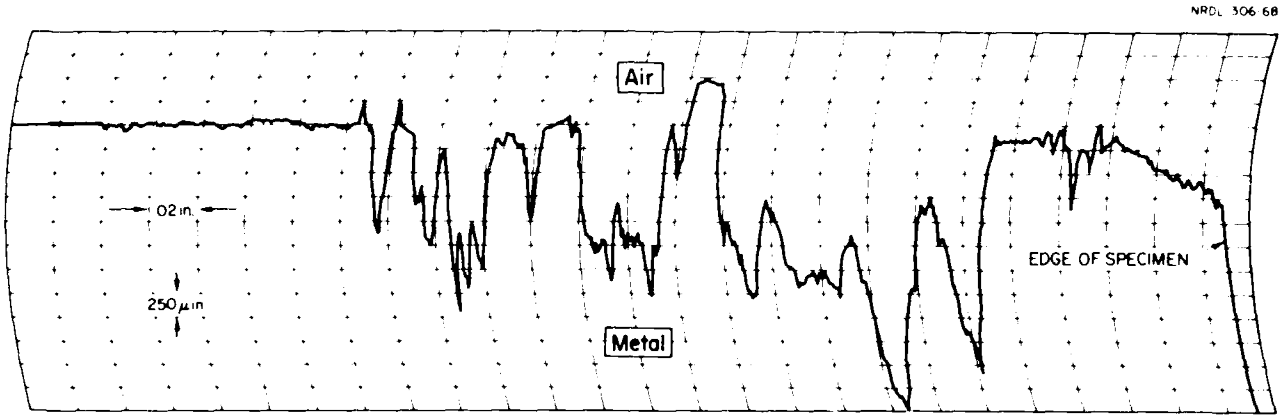

Fig. 12 Surface Profile of Local Corrosion on the Thick Berylco-165 Specimen Shown in Fig. 10.

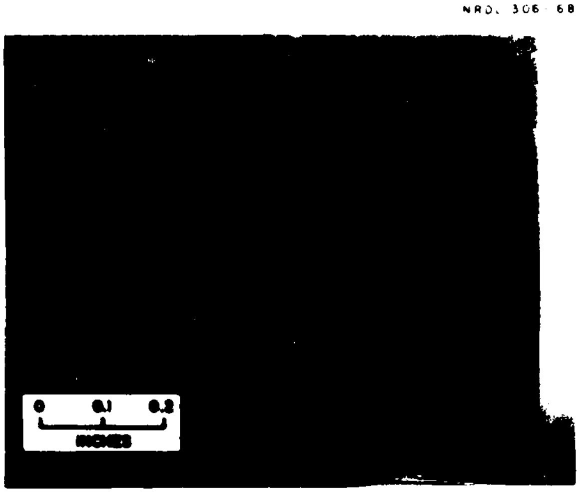

Fig. 13 Surface of Thick Berylco-165 Specimen After Immersion in Deaerated Seawater.

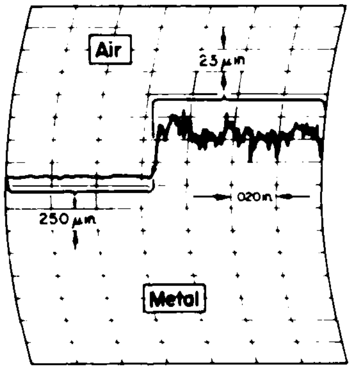

Fig. 14 Surface Profile of Thick Berylco-165 Specimen Shown in Fig. 13.

Fig. 15 Lucite Exposure Vessel (after ocean exposure) Which Contains Two Thick Berylco-165 Specimens.

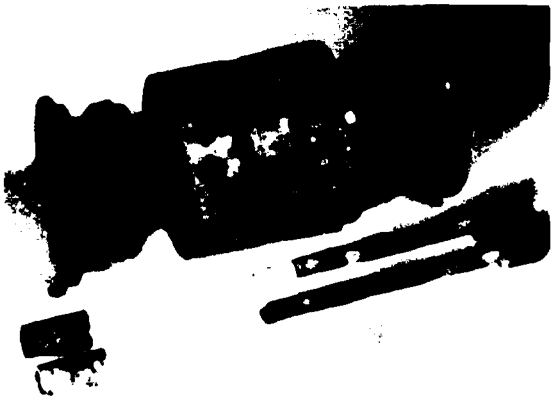

Fig. 16 Construction of the Lucite Vessel (after ocean exposure).

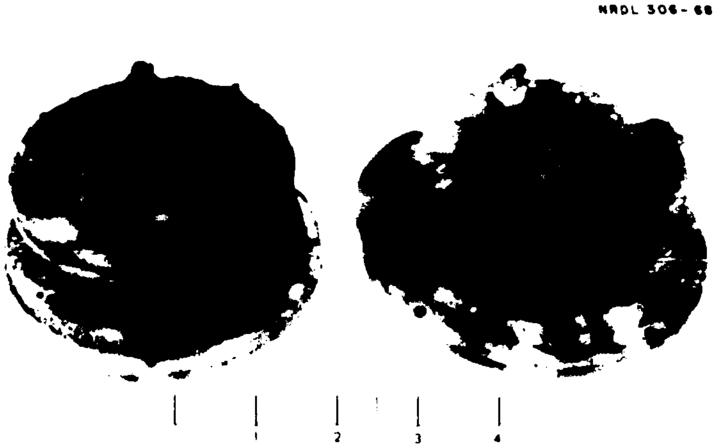

Fig. 17 The Two Berylco-165 Specimens in Their Lucite Holders (after ocean exposure).

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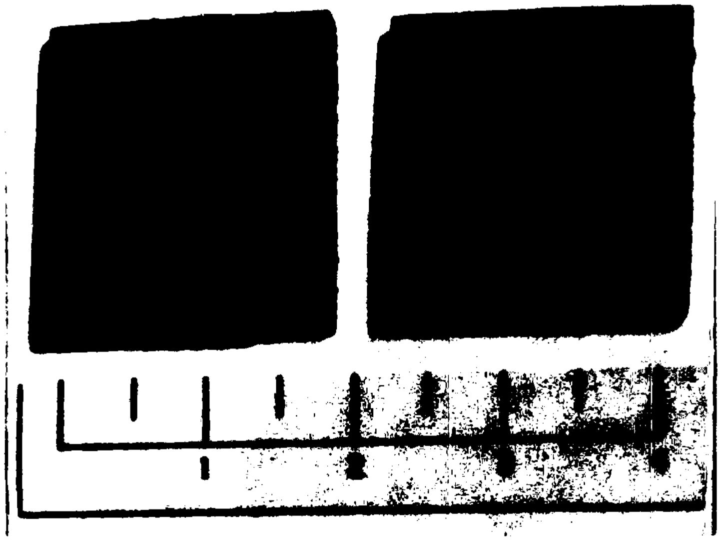

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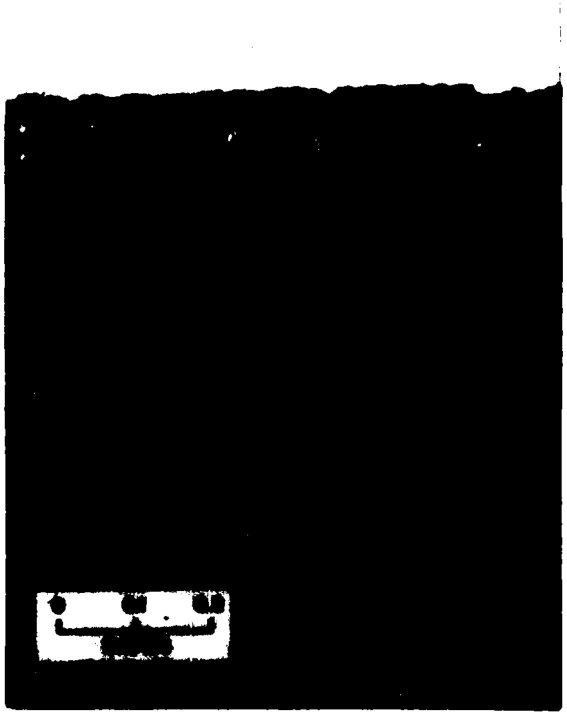

Fig. 18 The Berylco-165 Specimens After Ocean Exposure in Lucite Holders.

Fig. 19 Local Corrosion on One of the Berylco-165 Specimens After a 4-Month Ocean Exposure.

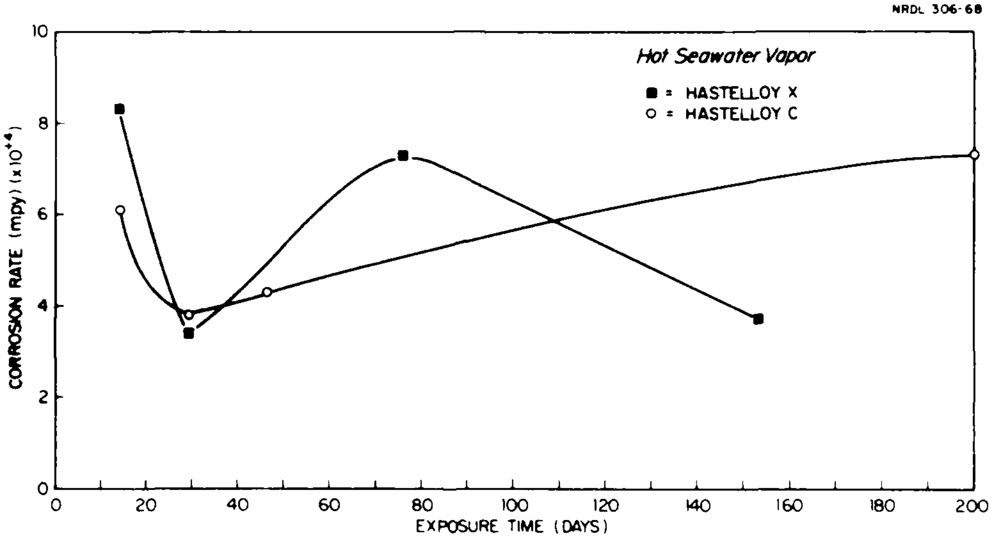

Fig. 20 Corrosion Rates of Hastelloy X and Hastelloy C in a Hot-Seawater-Vapor Environment.

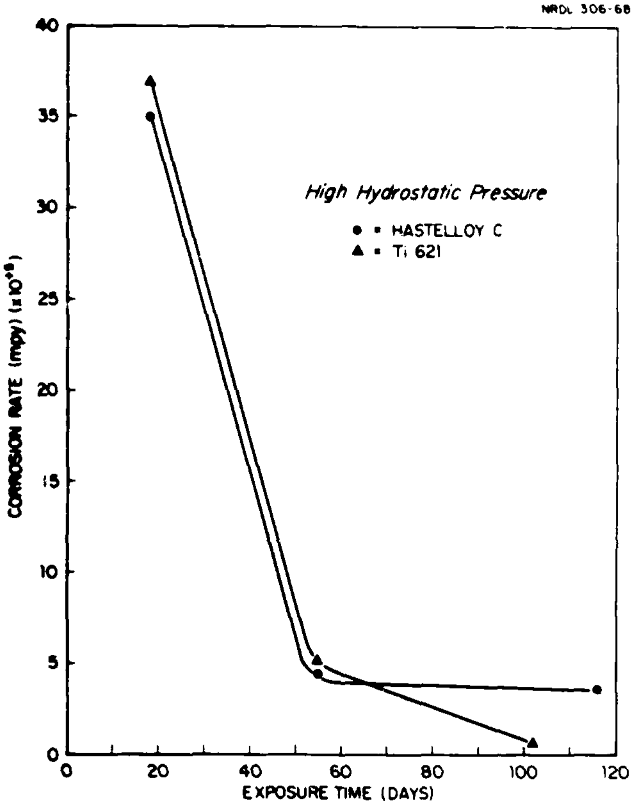

Fig. 21 Corrosion Rates of Hastelloy C and Titanium-621 Alloy in Seawater Under High Hydrostatic Pressure.

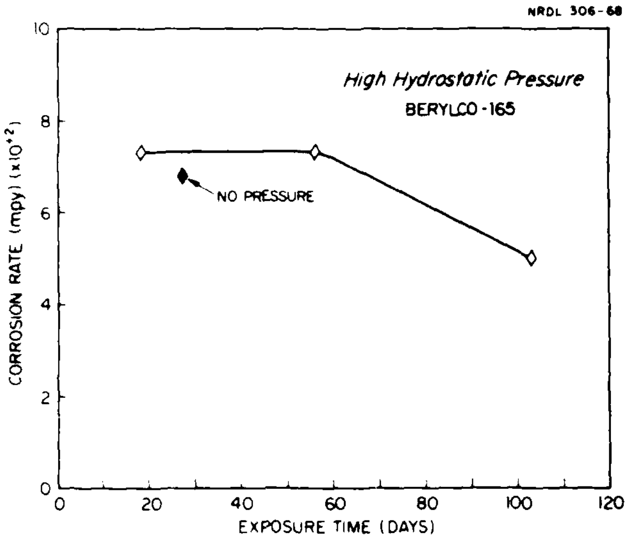

Fig. 22 Corrosion Rate of a Thin Berylco-165 Specimen in Seawater Under High Hydrostatic Pressure.

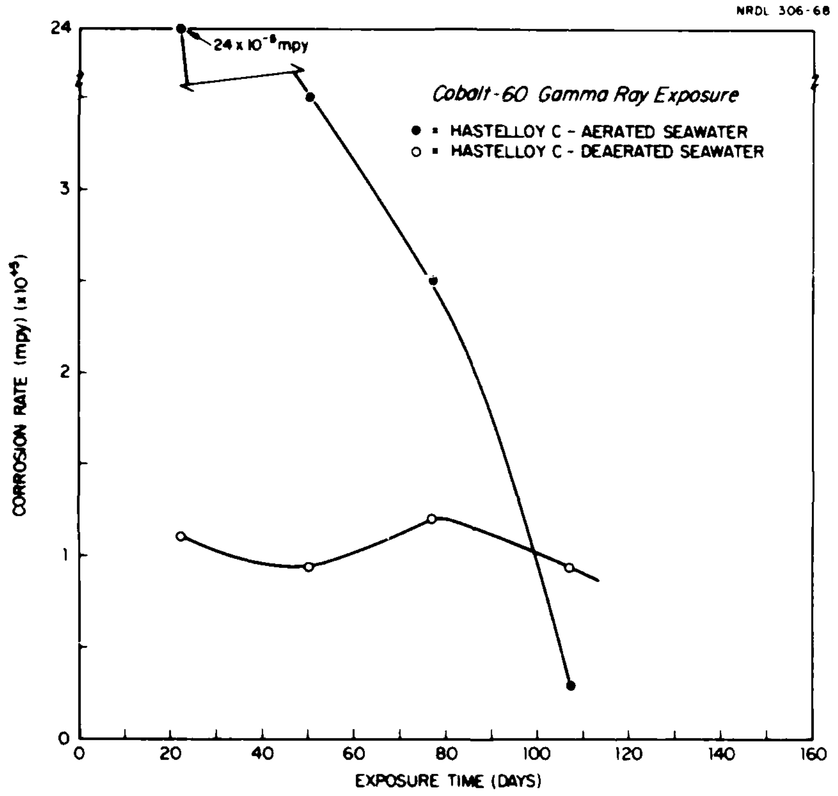

Fig. 23 Corrosion Rates of Hastelloy C in Seawater in an Ionizing Radiation Field.

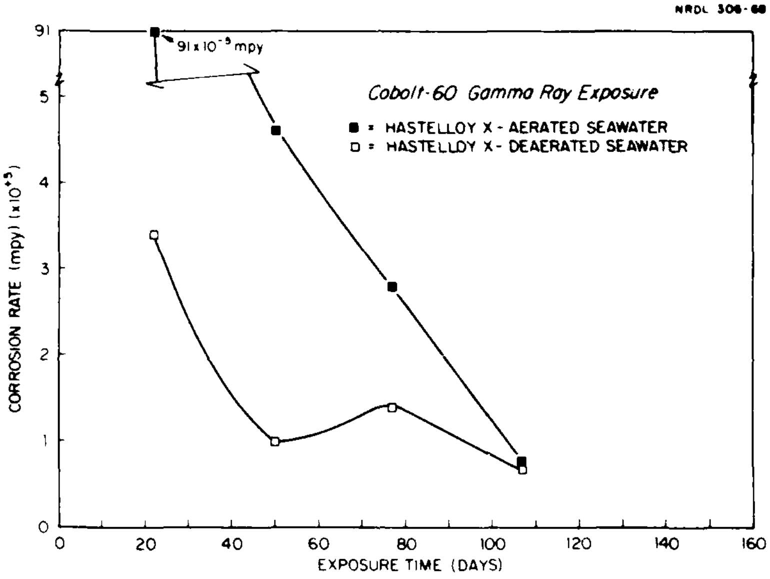

Fig. 24 Corrosion Rates of Hastelloy X in Seawater in an Ionizing Radiation Field.

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13. ABSTRACT

The corrosion rates of several SNAP-21 materials measured in seawater at ambient room temperature and pressure (Hastelloy C, Hastelloy X, Titanium-621, Berylco-165) have been compared to those measured in 200°C seawater vapor (Hastelloy C, Hastelloy X), in seawater under a hydrostatic pressure of 7000 psi (Hastelloy C, Titanium-621, Berylco-165) (23°C) and in seawater in an ionizing radiation field of 2×10^5 r/hr (Hastelloy C, Hastelloy X) (30°C). Significant increases in corrosion rate were observed only for Hastelloy C and Hastelloy X in hot seawater vapor (approximately two orders of magnitude) and for Hastelloy C in seawater under high hydrostatic pressure (approximately an order of magnitude).

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