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THE CORROSION RESISTANCE OF METALLIC SOLAR ABSORBER MATERIALS IN A RANGE OF HEAT TRANSFER FLUIDS

By
A. J. Brock
E. F. Smith, III

Work Performed Under Contract No. AC04-81AL16222

Olin-Metals Research Laboratory
New Haven, Connecticut

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Foreward

This Final Technical Report covers the work performed on DOE contract, DE-AC04-81AL16222 for the period of 16 Feb. 1981 to 31 July 1983.

The work done under this contract was performed at the Metals Research Laboratory, (Brass Division, Olin Corporation) in New Haven. The work was under the technical direction of A. J. Brock and E. F. Smith III. Other Olin personnel contributing to the success of this program include, E. Finger, P. Lavin, R. Barth. The authors also wish to thank the DOE technical advisor, Mr. John Avery of Los Alamos National Laboratory, for both his assistance in defining the scope of the program and his efforts to provide field service correlation for the laboratory data contained in this report.

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INTRODUCTION

The majority of solar energy systems which have been installed throughout the country are based on flat plate collectors. Corrosion of the channels in such collectors by the heat transfer fluid looms as a potential problem, especially when the fluid properties have been degraded by extended use or by stagnation at high temperatures. Several types of corrosion such as pitting, pinholing, erosion corrosion, crevice corrosion, and galvanic corrosion, have been identified in actual collector units. Failure analysis suggests that these problems arose due to the use of improper heat transfer fluids, poor component design, improper installation practice, lack of proper maintenance, or poor system design. Corrosive attack can also be aggravated by the presence of dissimilar metals. Accelerated corrosion may be due to direct galvanic contact or to dissolution of a more noble metal at one location in the system coupled with redeposition on a more active metal at another location. A successful heat transfer fluid for use in these systems must have among its properties an ability to inhibit corrosion of the total system over prolonged periods.

The actual service conditions for the fluid are strongly influenced by the system design. For example, in self-draining systems, potable water is used as the heat exchange fluid in the collector loop. Freeze protection, where required, is provided by solenoid valves, which open and drain the water into storage when a preset low temperature is reached or when power failure occurs. In such systems, control of corrosion depends on appropriate selection of components to ensure compatibility with the local water supply.

Draindown systems utilize a separate heat transfer liquid in the collector loop. The liquid drains into the storage tank by gravity whenever the collector loop pump is inactive. Water may be used as the heat transfer fluid for copper collectors, or an inhibited aqueous formulation for other metals such as aluminum or low carbon steel. Double walled heat exchangers are utilized when nonpotable additives are included in the collector loop fluid. For these systems, corrosion control is provided by proper selection of both the heat transfer fluid and the individual wetted components.

Closed loop fluid paths are utilized in nondraindown systems. In areas where freezing is a potential problem, these systems often circulate a low freezing point fluid between the collectors and a heat exchanger immersed in the storage tank. Fluids offered on the market for such systems include hydrocarbons, silicons and aqueous solutions of propylene or ethylene glycol (sold either with or without specific corrosion inhibitors). Under conditions of stagnation (absence of fluid flow), these fluids remain in the collector and therefore may undergo exposure to temperatures as high as 400°F. Under such extreme conditions, thermal degradation may significantly alter the structure, formulation, or chemical stability of these fluids.

There is little published information regarding the mutual compatibility of typical construction materials and available solar heat transfer fluids. Until recently, there were no standardized tests specifically designed for the solar industry. Corrosion data that has been available to the solar community is usually taken from a standardized test developed for another industry (i.e. - automotive antifreeze testing). However, because of variations in service conditions, it is unlikely that the data will accurately predict fluid-metal interactions typical of solar applications.

A test designed to provide a relative measure of material compatibility for solar applications should closely approximate the thermal and environmental conditions typical of an actual operating system. One of the more important factors in such a test is the time base. In many mature industries where the most prevalent forms of corrosive attack have been identified, tests have been developed to accelerate the time base for this attack. Accordingly, laboratory screening tests can be accomplished in relatively short times. Unfortunately, these accelerated tests have not been developed for solar applications because of lack of pertinent correlation data between field and laboratory performance.

In the late 1970's a test procedure was developed at Olin to provide relative corrosion ranking under controlled, reproducible conditions. The program was intended to screen commercial heat transfer fluids with the two metals (Cu and Al) used in the fabrication of Olin Rollbond absorber panels. The experimental program was designed to provide a range of exposure conditions that were likely to be encountered in actual operating systems. Provisions were included to test for daily thermal cycling, simulated stagnation exposure, mixed or multi-metal systems, crevices in contact with the test fluid, simulated fluid flow, and a moderately long term exposure time of six months. Data from this program has predicted that specific fluid metal combinations can result in short term, catastrophic failure.

Additionally, analysis of the data also demonstrated dramatic long term changes in the corrosive nature of some fluids known to be used in solar applications. The data also indicated that the observed shift from initial low corrosion rates to potentially catastrophic levels was limited to specific metal-fluid combinations.

The present study described the results of similar tests conducted for a variety of potential solar heat transfer fluids in combination with four metals proposed as candidate materials for absorber fabrication. These are Al, Cu, low carbon steel, and a ferritic stainless steel. As with the original work the program utilized exposure of the metals as coupons under conditions intended to simulate the thermal cycles and fluid flow rates typical of flat plate collectors.

Generally, all four metals were exposed to each fluid under test. Galvanic effects were examined by including bimetal samples formed by bonding two metal samples together. Samples were withdrawn after periods of 1, 2, 3, and 6 months and cleaned by appropriate techniques. The amount of corrosion was determined from sample weight loss measurements and by examination of the metal surfaces by optical microscopy. The latter permitted determination of the extent of localized corrosion such as pitting, crevice corrosion, or intergranular corrosion which is not necessarily reflected in weight loss data. Where appropriate, some measurements were made of the properties of the heat transfer fluids. Thus, for aqueous fluids the change in pH with testing time was monitored, and for glycol-water based systems, changes in the freezing point of the solutions were measured. These measurements were intended as an initial monitor of fluid degradation.

Another potential application of solar energy collector units is in heating swimming pool water. Accordingly, testing of Cu and stainless steel samples was also conducted in a separate test where water, containing high levels of chloride (500, 1000, and 1500 ppm) flowed over them in an open trough at a rate of 3 ft/sec. In this test the water temperature was only 104°F(40°C) as opposed to 200°F in the previously described test.

The work described in this report is intended to provide manufacturers, designers, and installers with reliable corrosion compatibility data, meaningful maintenance schedule, and confidence in durability and performance of solar collector units.

SUMMARY

The corrosion behavior of Cu alloy 122, Al alloy 1100, mild steel 1010, and a ferritic stainless steel (alloy 444) was determined in a variety of potential solar heat transfer fluids. The fluids included potable waters, water glycol solutions, and four non-aqueous fluids. The test apparatus cycled the temperatures of the fluids through those typical of an operating solar energy collector unit. The 444 stainless steel was the most corrosion resistant material and in uninhibited solutions demonstrated only extremely shallow pits during the 180 day test. The use of inhibited solutions generally prevented pits from forming. Cu alloy 122 showed quite low corrosion rates in uninhibited solutions although the presence of excess solder flux promoted some crevice corrosion. In such solutions, uniform, corrosive attack produced general surface roughening along with a protective surface oxide. The overall corrosion rate of the alloy was generally lower in inhibited glycol solutions although pitting within the crevice region occurred in limited cases. Exposure in the non-aqueous fluids resulted in extremely low corrosion rates with little evidence of localized attack.

Aluminum alloy 1100 and mild steel 1010 demonstrated high corrosion rates in uninhibited solutions. The aluminum alloy pitted heavily while the mild steel usually dissolved uniformly at extremely high rates. In uninhibited glycol solutions these rates were sufficient to cause sample fragmentation after 90 days testing. In addition, the corrosion rates of the mild steel were further accelerated in uninhibited solutions by galvanic contact with the copper alloy or stainless steel. The corrosion rates of the Al alloy and mild steel were significantly reduced by the presence of the various inhibitors. For both of these metals however, none of these solutions could completely prevent some small amount of localized corrosion from occurring. In the non-aqueous solutions the overall corrosion rates of the alloys were extremely low. However, only in one instance, (Al alloy 1100 in Dow Corning 200), was localized corrosion not observed.

Measurement of solution pH, freezing point, and reserve akalinity during the test demonstrated that the inhibited glycol solutions were gradually degraded.

Corrosion testing of Cu alloy 122 in simulated swimming pool water, with thermal cycling to temperatures typical of a swimming pool showed that the alloy had corrosion rates much lower than 1 mpy. The highest rate was observed with an intermediate chloride ion content of 1000 ppm. The alloy corroded in a general manner with surface roughening although some crevice corrosion was observed. In the same test the ferritic steel demonstrated an excellent resistance to corrosion.

EXPERIMENTAL

1. Materials

The materials used in the present study were CDA alloy 122, aluminum alloy 1100, 1010 mild steel and type 444 ferritic stainless steel. The stainless steel was provided as sheets 0.02" thick. The other materials were in the form of sheets 0.030" thick. The nominal composition of the metals are shown below:

Cu Alloy 122: 99.9%Cu, 0.02%P

1010 Steel: .08-.13%C, .03-.06%Mn, balance Fe

444 Ferritic Steel: .020%C, .4%Mn, .3%Si, 18.5%Cr, 2.0%Mo, .8%(max)Ti+Nb, .02%N, .01%S, .025%P, balance Fe

Al Alloy 1100: 0.2%Cu, 0.05%Mn, 0.1%Zn, 1.0%(Si+Fe), balance Fe

2. Sample Preparation

Test specimens were sheared from the sheets and 3/32" diameter holes were punched in them according to the schematic shown in Figure 1. The edges of the samples were abraded lightly to remove burrs. Identifying code numbers were stamped on each sample. They were all thoroughly degreased by rinsing in benzene. The benzene was removed by immersion in 12(wt)%H_2SO_4 at 122°F for 15 seconds followed by thorough rinsing in distilled water. Aluminum samples were etched in N.[1] NaOH solution at room temperature for 5 minutes followed by a desmut of 1 second in 50% HNO_3 at 85°C.

This treatment provides a clean surface characterized by shallow depressions or scallops on a microscale. The mild steel and stainless steel samples were used in the as-received plus degreased condition.

In addition, bimetallic samples of copper-stainless steel, copper-mild steel, and stainless steel-mild steel were also prepared using a roll bonding technique. The starting materials, cut to 2.5 x 6 ins strips, were annealed in argon as follows:

122 Alloy: 600°C - 1 hour
444 Stainless: 800°C - 30 min.
1010 Mild Steel: 800°C - 30 min.

The strips were then vapor degreased, cleaned in a non-etch detergent, rinsed, and dried. One side of each strip was wire brushed and spot welded to its bimetallic partner along the leading edges. Bonding was achieved by cold rolling using the following single pass reductions:

122 Alloy/1010 Mild Steel: 67%
122 Alloy/444 Ferritic: 46%
1010 Mild Steel/444 Ferritic: 45%

Test samples similar to those described above was sheared out and prepared by abrasion using 400 silicon carbide paper. In an effort to prevent selective attack, no chemical cleaning was used on the bimetallic coupons. All samples were thoroughly degreased in benzene, washed with acetone, and dried prior to testing.

3. Heat Transfer Solution Preparation

The heat transfer solutions were prepared according to the manufacturer's specifications. New Haven potable water (NHPW) was used as a solvent in aqueous formulations. Table 1 shows a list of the fluids evaluated including the manufacturer, the type and the test concentration. Additionally, the table includes information as to whether the fluid is likely to be used in an aqueous draindown, aqueous nondraindown, or nonaqueous nondraindown system.

In addition to the commercially formulated fluid, other test solutions were included primarily as reference cases. Among these were reagent grade ethylene and propylene glycol solutions diluted with 50 volume % potable water. A second 50% solution of propylene glycol and water was autoclaved at 355^{o}F for 120 h. prior to testing. The intention of this was to thermally degrade the glycol by forming some organic acids during the heating cycle. The degraded solution was used in three different conditions. In the first it was used as degraded. In the second test, the reserve alkalinity was adjusted to 10 by the addition of disodium hydrogen phosphate. Measurement of reserve alkalinity were made by pipetting 10 mls of the sample into a 25 ml beaker and diluting to 100 mls with distilled water. The pH of the mixture was then monitored as 0.100N HCl was slowly added from a burette. The endpoint of the titration was the point where the solution pH was 5.5. The reserve alkalinity is then defined as the number of mls of 0.100N HCl required for this pH adjustment.

The third degraded propylene glycol solution also had its reserve alkalinity adjusted to 10. However, in this case the reserve alkalinity was monitored every 14 days and adjusted back to a value of 10 by the addition of Na_2HPO_4.

Another solution incorporated in the test was ASTM water which was prepared by the addition of 100 ppm each of Cl^-, $So_4^=$, and $HCO_3^=$ added as their calcium salts. Three other solutions were included which had been extracted from operating solar energy collector systems monitored by Los Alamos National Laboratory personnel.

The solution for the swimming pool water simulation was prepared from New Haven tap water and USP grade sodium chloride. The salt was added to give chloride contents of 500, 1000, adn 1500 ppm. These high chloride levels were intended to simulate the residuals from the various sanitizers used to treat the water (most of these products are based on hypochlorite, which produces soluble chloride as a reaction byproduct).

4. Test Apparatus

A photograph of the assembled test cell is shown in Figure 2. Each cell contained 2800 mls of solution. Samples, weighed to the nearest 0.01 mg, were attached to slots machined in 1" diameter Macor holders using glass pins. Glass pins were also used to fix the ceramic holders onto a titanium shaft. Generally, the test vessel contained eight samples of each metal with one sample of each bimetallic couple. However, in some solutions the alloy mix was modified to agree with specific field exposure conditions. These solutions, and the samples, were:

1. New Haven tap water, -24 Cu, 8 stainless steel.
2. New Haven tap water/excess solder flux, -16Cu, 8 soldered Cu samples 8 stainless steel.
3. Dowfrost, Los Alamos, -28 Cu , 4 stainless steel.
4. Nellis AFB, Domestic water, -28 Cu, 4 stainless steel.
5 Homestead AFB, Domestic water, -28 Cu, 2 bronze, 2 stainless steel.

In solution 5, the bronze samples were CDA alloy 521 containing nominally 92%Cu, 8%Sn, and 0.05%P. They were prepared in an identical manner to the CDA 122 alloy samples.

The titanium shaft extended through a nylon cover via a stainless steel collar to a right angled gear drive. The whole cell was immersed in a large controlled temperature bath capable of holding 20 cells. The total apparatus is shown schematically in Figure 3. A central drive shaft caused simultaneous rotation of all the titanium shafts at a rate such that the average velocity at the end of each sample was 4 fps. For systems simulating draindown, a hollow titanium tube was incorporated into each cell. Silicone tubing connected to this, passed through a peristaltic pump into an individual storage tank. Operation of the pump permitted draining of the fluid into the storage tank or vice versa, and was intended to simulate the daily fluid stoppage typical of a draindown system. The tank was filled with an inhibited propylene glycol solution. This solution was circulated through an electric heater in order to heat the tank contents to the required temperature. Cooling pipes included in the tank, through which tap water could be passed, permitted forced cooling of the solution.

5. Daily Test Cycle

A Honeywell controller-recorder (Servoline 45) was used to control the temperature of the solution in the tank. The following daily temperature cycle was used.

a. 8:00 a.m. - Bath contents and test fluids at room temperature 60-70°F.

b. 8:10 a.m. - Draindown liquids in reservoirs pumped into the test cells by activation of the peristaltic pump.

c. 8:25 a.m. - Heating loop circuit activated. Drive shaft activated.

d. 9:25 a.m. - Solutions at temperature of 200°F. This temperature was maintained for 6 hrs.

e. 3:25 p.m. - Heaters turned off and solution allowed to cool gradually for 1.5 hours.

f. 4:10p.m.- Peristaltic pump activated and draindown solutions transferred to storage reservoirs.

g. 4:55 p.m. - Cooling water turned on. Solutions cooled to room temperature by 6:25 p.m.

6. Stagnation Test

This test was conducted on the aqueous glycol solutions which would be used in nondraindown systems. It was not conducted on the organic nonaqueous fluids. Preliminary tests in which the organic fluid was exposed to the proposed stagnation temperatures produced large volumes of smoke. In the stagnation test the titanium shaft and its samples were removed from each solution and the wet assembly was placed in an oven at 400°F(±10°F) for 4 hrs. After this time the assembly was removed from the oven, allowed to cool to room temperature, and reinserted into the appropriate test cell. During this period of high temperature sample exposure, the bulk solution was maintained at 200°F. In this sense the simulated stagnation was intended to approximate conditions which would produce boilout of the absorber panel and not pressurized stagnation of the heat transfer fluid.

7. Sample Evaluation

Where possible, two samples of each material were removed from the test cell following intervals of 30, 60, 90, and 180 days. In the case of the special metal mixes described in section 5, two samples of Cu and 1 sample of the second material were withdrawn. The corrosion product films were removed by the following chemical treatments:

a. Copper Samples

The copper samples were immersed in 10 (wt.)% HCl for 1 to 2 minutes. The acid was deaerated and contained an inhibitor of Rhodine 213 at the 0.2% level.

b. Aluminum Samples

These were immersed in a solution of 20 g/l CrO_3 in 5(vol.)% H_3PO_4 at 85°C. The immersion time varied with the sample condition but was generally in the range 3-5 mins.

c. Mild Steel Samples

These were cleaned by immersion in 35% HCl containing 20 g/l antimony trioxide and 50 g/l stannous chloride at room temperature. Immersion times varied considerably with these samples.

d. Stainless Steel

These were cleaned as for mild steel.

In many of the above cases, cleaning of the samples was assisted by brushing with a soft nylon brush. Following cleaning, the samples were thoroughly rinsed in running distilled water, rinsed with acetone, and dried in a stream of cold air. They were then reweighed. The sample weight loss due to corrosion was calculated.

The bimetallic samples were removed from the solutions only after exposure for the full 180 days. Samples in which one of the metals was mild steel, were cleaned by short immersion times in 35% HCl inhibited with antimony oxide and stannous chloride. Stainless steel-Cu samples were cleaned by immersion in 12 wt.%H_2SO_4 at 50°C also with the application of a soft nylon brush. The use of these cleaning procedures on the unexposed bimetallic samples resulted in no observable localized corrosion or weight loss.

8. Localized Corrosion Observations

Each cleaned sample was examined by optical microscopy to determine the type of corrosion attach which had occurred during exposure to the solutions. In general, the procedure was to start at the lowest magnification, 10X, and then examine the surfaces at increasing magnifications up to 1000X. When pits or crevice corrosion was evident, the maximum depth of attack was determined by adjusting the focal plane of an optical microscope in conjunction with a Starrett dial micrometer. Evaluation of the bimetallic samples was limited to this optical examination of the sample surfaces.

Because of the extensive surface roughening, optical micrographs failed to provide sufficient depth of field to accurately document many of the topographical features associated with the corrosive attack. Accordingly, selected samples were examined by means of scanning electron microscopy. Electron micrographs were prepared of areas of interest.

Other selected samples were metallographically prepared in cross section. In particular, this technique was utilized for examination for crevice areas. Optical micrographs were prepared where required.

9. Solution Monitoring

When samples were removed to conduct the stagnation tests or at one of the monthly withdrawals, some properties of the solutions were routinely measured. For all aqueous solutions, the pH was measured using an Orion pH meter (Model 801). The freeze protection (i.e. - % glycol remaining) of the solutions of water and propylene or ethylene glycol were determined using an AO Duo-Chek tester. This instrument uses only a few drops of solution to determine the refractive index. Since there is a known relationship between refractive index and freezing point of such solutions, the instrument is calibrated in terms of this latter quality. The reserve alkalinity of many of the solutions was also determined during the test.

10. Simulated Heated Swimming Pool Water Test

The apparatus used in this test is shown schematically in Figure 4. It consisted of a reservoir containing 100 liters of the appropriate solution. The resevoir contained a glass sheathed heating element and a thermostat in order to maintain test temperature at 104°F.

The samples were fixed into micarta holders as illustrated in Figure 5. Each sample holder contained 20 samples. The assembly was located in the inclined PVC troughs. Water was pumped from the resevoir into the heater tank and allowed to flow over the samples at a linear flow rate of 4 fpm. The volumetric flow rate was sufficient to cause complete immersion of the samples. The apparatus operated in a two part cycle. Flow of water at 104°F was allowed to occur for 8 hrs. The flow was then turned off and the samples left for 16 hrs exposed to the atmosphere.

The total duration of this test was 180 days. Samples were withdrawn after periods of 30, 60, 90, and 180 days and treated in an identical manner to those withdrawn from the higher temperature test.

RESULTS

1. Weight Loss-Time Relationship

Figures 6-29 show weight loss-time plots for materials exposed in the high temperature simulated solar energy collector test. In all cases, a line corresponding to the weight loss associated with a uniform metal penetration of either 1 or .1 mil per year (labelled as mpy) is included as a reference point. Figures 6-8, 10-11, and 12-13 show the results for Cu alloy 122, aluminum alloy 1100, and mild steel, respectively, in uninhibited solutions. Figure 9 shows the results for Cu alloy 122 in the domestic waters from Los Alamos. Figures 14-17, 19-22, and 24-28 show the results for Cu alloy 122, Al alloy 1100, and mild steel, respectively, in the various inhibited aqueous based systems. In each figure plots for several solutions are included. Division of the results among the various plots was done only from the basis of clarity of presentation. Figures 18, 23, and 29 show the results for Cu alloy 122, Al alloy 110, and mild steel, respectively, in the non-aqueous fluids.

The weight losses for the ferritic stainless steel samples obtained during this test were scattered and not amenable to graphical presentation. Accordingly, these results are shown tabulated in Table 2.

2. Localized Corrosion Observations

The localized corrosion observations are presented in tabulated form in Tables 3 to 33 for the materials in the various solutions. These observations are essentially pictorial descriptions of the surfaces of the corroded alloys. Three main types of corrosion were observed. The first of these was general corrosion where the metal surface shows uniform attack without the appearance of pits. The two other forms of attack were pitting and crevice corrosion. As appropriate, the maximum depth of the localized attack is given in mils. Table 34 shows the localized corrosion observations for the bimetallic samples following exposure for 180 days in the test.

3. Micrographs

Figures 31 to 40 show representative scanning electron micrographs of the metal surfaces after testing in various solutions. The micrographs for Cu alloy 122, Figures 31 to 36, illustrate various degrees of surface roughening due to general corrosion. Figures 37, 39, and 40 illustrate pitting of Al alloy 1100, mild steel, and stainless during immersion in selected solutions. Figure 39 illustrates severe intergranular corrosion of Al alloy 1100 following exposure for 180 ddays in Sunsol 60.

Figures 41-44 show optical micrographs of cross sections of samples taken at the crevice region illustrating the nature of this form of localized attack.

4. Fluid Properties

Table 37 shows the variation in pH of several of the fluids tested together with their freezing points. Table 38 shows the initial and final pH values of the remaining aqueous based fluids.

The initial and final reserve alkalinities of some of the aqueous based fluids is shown in Table 39. This table does not include the results of degraded propylene glycol which was to be maintained at a reserve alkalinity of 10. It was found for this solution that the reserve alkalinity could be maintained at this value by the addition of Na_2HPO_4 for only 42 days. After this the solubility limit of the phosphate was exceeded. At the end of the test the reserve alkalinity was 4.8.

5. Simulated Swimmming-Pool Water Test

Weight loss-time plots for Cu alloy 122 immersed in the trough test are shown in Figure 30 with chloride ion content as a parameter. The weight losses of the stainless steel samples were again scattered. These are shown in Table 35. The localized corrosion observations for these samples are shown in Table 36.

DISCUSSION

General Background

This project was undertaken to provide baseline data for the solar community. Specifically, the test program was designed to identify corrosive interactions between metals usedfor solar absorbers and a variety of heat transfer liquids promoted for use in flat plate collectors. In designing the actual experimental work, it was recognized that the type and severity of the corrosive attack would depend on three major variables.

1) Alloy Composition

Based on a review of the general literature and conversations with a variety of manufacturers, it was generally agreed that the wetted areas of most flat plate collectors were copper. However, at the time this program was initiated, a number of manufacturers were exploring alternative materials including low carbon steels, aluminum, and stainless steels. This program was designed to include a representative alloy from each group. The specific alloys selected were 122 Cu, 1100 Al, 1010 steel, and 444 stainless steel. These alloys were selected not only as generic representatives, but were thought to be the most likely candidate material for actual fabrication into an absorber panel.

2) Environmental Conditions

In developing a test procedure to assess corrosion compatability for solar applications, a number of factors must be considered. First, in aqueous solutions, many metals are known to demonstrate parabolic corrosion kinetics. This is especially true under conditions where the initial corrosion reaction produces a stable, protective oxide layer. During the oxide formation stage, the instantaneous corrosion rate can often be quite high. However, after the oxide is completed, the long term, steady state rates are extremely low, and in many cases approach zero. Therefore, it is important that the test duration be sufficient to establish the corrosion rate that would be representative of the anticipated service period. For solar applications, economic payback considerations suggest that period be measured in terms of years.

Additionally, the test duration must be long enough to allow some reasonable measure of fluid stability. For many heat transfer liquids, corrosion protection is provided through a series of proprietary additives (i.e . - buffers, inhibitors, anti-oxidents, etc). Improper selection of these additives can produce a condition where frequent replenishment is required to maintain the desired level of corrosion protection. Complete depletion of the additive package can result in catastrophic short term failures. Therefore, the test period should be adequate to demonstrate reasonable long term fluid stability. For the comparative nature of this program, a test period of six months was felt to provide an adequate balance between problems arising from either short term transients or long term stability.

Second, metal-fluid combinations which rely upon a protective oxide to control corrosive attack are often suspectible to erosion-corrosion. This form of localized attack is a function of both the relative metal to fluid velocity as well as the corrosive/erosive nature of the fluid. As a general rule, the combination of fluid channel diameter and desired mass flow rate (for optical heat transfer in a collector) will keep the relative velocity below the threshold levels required for this form of attack. However, since fluid circulation is required for most conventional flat plate designs, it is important to incorporate relative fluid/metal motion into the test program. This test program utilized a maximum specimen tip velocity of 4 fps.

Third, under specific conditions, each of the metals tested can be susceptible to localized corrosion in the form of pitting or crevice corrosion. Pitting can be associated with chlorides, localized galvanic cells, or localized differential aeration cells associated with a surface film. In this program, chlorides were intentionally introduced into all the aqueous systems through the use of New Haven tap water as a stock material (typical chlorides 15-20 ppm). In addition, a sample attachment procedure was developed which provided an intentional crevice. The presence of the crevice was used to document the overall susceptibility to crevice related attack. In an actual solar system, it is virtually impossible to prevent crevice formation during fabrication/installation. The most common sites for crevices are at joints. Both mechanical and soldered/welded joints are susceptible to crevice formation.

3) Heat Transfer Fluid - It was noted earlier that the relative corrosion susceptibility of these metals was strongly dependent on the specific chemical formation of the heat transfer fluid. Since one of the primary objectives of the test program was to provide comparative corrosion data for commercially available fluids, efforts were made to incorporate a wide variety of commercial fluids. (For initial test sequence, only commercially available fluids were tested. For the second round, available test cells permitted testing of various experimentation formulations still under development by the manufacturer.)

In general, the heat transfer fluids used in solar collectors can be grouped into three categories: 1) Aqueous based - no inherent freeze protection, 2) Glycol based - usually mixed to 50v/o with water, and 3) Non-aqueous - hydrocarbon or silicone based fluids used without water dilution. In each case, the fluid chemistry is generally proprietary to the manufacturer. In no cases were efforts made to analyze either the initial formulations nor the degradation products formed during testing. Reserve alkalinity and pH were followed for both the aqueous based and glycol based systems.

In addition to testing the commercially available systems, a number of "special" fluids were tested to provide background information. First, in cooperation with the D.O.E. technical monitor, Mr. John Avery of Los Alamos National Laboratory, fluid samples were taken from three operating solar heating systems being monitored by Los Alamos. These fluids (labeled Nellis Air Force Base, Homestead Air Force Base, and Dowfrost (Los Alamos)) were tested with metal samples representative of the actual on-site materials. Data comparison was intended to provide correlation data between actual field service and the laboratory test data.

The second set of non-commercial "special" fluids were based on the known corrosive nature of a thermally degraded propylene glycol solution. These solutions had been initially "heat treated" at 355°F for 120 hrs. prior to incorporation into the test program. This treatment was intended to document the nature of the chemical changes produced by prolonged stagnation of a glycol based heat transfer fluid. Additionally, in an effort to document the effects of a customer useable additive, two tests were performed using Na_2HPO_4 additions to the thermally degraded glycol.

The test program utilized in this program was, therefore, specifically designed to incorporate factors which favored corrosive attack. All metal samples were tested in a multi-metal environment under thermal conditions representative of a flat plate collector. The specific cycle was selected to slightly more aggressive than most current service applications. It should be noted, therefore, that the test procedure was not developed to predict service lifetime of a specific metal-fluid combination. It was intended primarily as a screening tool to identify incompatibility problems, and suggest fluid-metal combinations whose initial (six month) corrosion performance warrants further, more in depth testing. The experimental data will now be reviewed on a metal by metal basis, with further distinctions being made within the three fluid categories noted earlier.

General Guidelines

In reviewing the corrosion data, it is useful to establish some benchmark guidelines of the various metal-fluid combinations. For those cases where uniform dissolution is the predominant form of attack, a level of 1 mpy provides a convenient comparison standard. For this reason, a 1 mpy reference line is drawn on the majority of the plots of weight loss vs. time. On a weight loss (or uniform corrosion) basis, meaningful comparisons can only be made when the experimental weight loss curves show a constant or decreasing slope. An increasing slope indicates an accelerated rate of attack, and in that sense, makes it impossible to extrapolate the data beyond the test period (i.e. - six months).

This accelerated rate of attack is often a sign of chemical instability/degradation within the fluid. Laboratory evidence of an increasing weight loss vs. time curve suggests very careful field monitoring of the heat transfer fluid is warranted. Since most of the commercial fluids contain proprietary additives, it is the responsibility of the fluid manufacturer to provide guidelines and techniques for monitoring.

In addition to considering the rate of uniform metal removal (weight loss), it is also essential to consider the susceptibility to localized attack. As with the uniform attack, a sustained penetration rate in excess of 1 mpy would again be of concern. Since the test period is limited to six months, this would correspond to a localized penetration of only .0005". Unfortunately, at that level it is difficult to differentiate true localized attack from general surface roughening. Additionally, it is often difficult to extrapolate a sustained rate of attack beyond the test period. This is especially true where an incubation period is involved and the onset of localized attack is delayed until well into the test. There are also cases where after an initial period, the localized attack stops after penetrating only a few mils into the surface. A pit that penetrates just two mils into a surface and stops is not of great concern. However, a sustained pitting rate of 4 mpy is of great concern.

Therefore, because of these problems, two reference levels have been selected for this report. Penetration beyond 2 mils after six months is generally regarded as unacceptable. Penetration below 1.0 mils/six months is generally regarded as acceptable. Penetration levels between 1-2 mils will be regarded as cautionary and in need of longer test periods to accurately determine the sustained, long term penetration rate.

It should also be noted that since no recognized standards exist, these guidelines are best viewed as arbitrary reference points. Based on Olin's past participation in the solar collector market, these guidelines are intended to be realistic, but not binding.

Low Carbon (1010) Steel

Of the four metals tested, the most extensive attack was observed on the low carbon steel samples. This was especially true in the uninhibited, water containing solutions. For example, in two of the three pure aqueous (draindown type) solutions, NHTW and ASTM water, uniform attack was at a rate of nearly 10 mils per year, and crevice attack was sufficient to perforate the samples after 180 days' exposure. Only one inhibitor package, Nutek 876, was examined for use in potable waters. As shown in Figure 27, this produced a low, stable weight loss, but also showed crevice attack to 3 mils after both 3 and 6 months exposure. This level of sustained localized attack would be unacceptable, however, since no further penetration was observed between 3 and 6 months, additional testing would be required to determine the actual long term response.

In considering the response for non-draindown systems, the results for the reagent grade glycols clearly demonstrate the need for an effective inhibitor package. For both the ethylene and propylene glycols, the rate of uniform corrosion was estimated at 20 mpy at 90 days, and shortly thereafter, the samples fragmented. Corrosion in the thermally degraded glycol was even more severe, and again, complete sample fragmentation occurred shortly after 90 days.

Adjusting the initial reserve alkalinity of the degraded solution to 10 significantly reduced the uniform dissolution rate, (Figure 13). However, localized corrosion in the form of pitting and severe crevice corrosion occurred. Figure 44 shows a cross section of a sample immersed in such a solution for 180 days. This shows a deep pit which has formed in the crevice region. Adjustment of the reserve alkalinity to 10 for the first 42 days of the test results in a slightly lower weight loss. However, localized corrosion becomes even more severe. Pits up to 7 mils deep were formed and perforation of a sample at the crevice occurred in one sample.

As shown in Table 42, a wide range of responses can be found for the various commercially inhibited glycols. Nutek 835 was ineffective with relatively high uniform weight loss (an increasing slope and penetration at 1 mpy, see Figure 27) coupled with deep crevice and pitting attack. In all other cases, the rate of uniform attack was significantly reduced, and in all cases was well below the 1 mpy reference line.

Additionally, for all but the Nutek 835, the slope of the weight loss-time curve appears to be constant or decreasing. In only two cases, Climax B and NPC-218, did the maximum localized attack exceed 1 mpy. Crevice attack on the Climax B is viewed as unacceptable and NPC-218 was in the regime where additional testing is requested.

All of the non-aqueous fluids were very effective in reducing to uniform weight loss to nearly insignificant levels. In all four cases, however, pitting was observed in the range of .5 to 1.0 mil at six months. Based on the very low weight loss levels, these values are significant and extended tests would be needed to determine whether the pit/crevice attack would extend beyond these nominal levels.

Aluminum (Alloy 1100)

As with the low carbon steel, extensive corrosion was observed on aluminum samples exposed to the uninhibited aqueous based solutions. In New Haven Tap Water (NHTW), both deep pitting (up to 4 mils at 1 month) and aggressive uniform attack (an extrapolated rate of ~2.5 mpy @180 days) were observed. In ASTM water the overall corrosion rate is lower than in New Haven tap water. General corrosion of the metal occurred together with the formation of many pits. Although the number of pits was greater than in New Haven tap water, they were much shallower. After 180 days they were still less than 1 mil deep. The weight loss time-curves for the samples in both these uninhibited waters were essentially linear, Fig. 10. This indicates that no retardation of the overall corrosion process occurred due to the presence of corrosion products.

In uninhibited ethylene glycol solutions the rate of corrosion increased with time. This may partly be due to this solution becoming more acidic with time, and therefore more corrosive, during the test (see Table 37). The final overall corrosion rate was 2.6 mpy, similar to that observed in New Haven tap water. The depth and number of pits formed was also similar but in this uninhibited glycol solution much more pronounced crevice corrosion occurred. In one sample this had attained a depth of 8 mils in only 3 months. Similar increase in corrosion rate with time was observed in uninhibited propylene glycol solution with the rates at a given time being greater than that in uninhibited ethylene glycol solution. In both reagent grade glycol solutions severe pitting and crevice corrosion occurred on all Al specimens.

Prior degradation of the propylene glycol renders it much more corrosive to Al alloy 1100, Fig. 11. The rate of corrosion increased significantly with time resulting in a final overall corrosion rate of 13.5 mpy. Severe general corrosion, deep pitting and crevice corrosion occurred. This is evident from the micrograph of a cross section of a sample exposed for 180 days to this solution, Fig. 42. By adjusting the reserve alkalinity to 10 the overall rate of corrosion was significantly decreased. Many pits were formed, although not as deep as those formed in the degraded glycol without adjustment of the reserve alkalinity. However, the phosphate additions had no effect on the extent of crevice corrosion (i.e. - 6 mils penetration at 180 dyas). Only slightly lower overall corrosion rates resulted when the reserve alkalinity was maintained at a value of 10 for the first 42 days of the test. A similar amount of pitting and deep crevice corrosion was observed in this solution (i.e. - crevice attack to 5 mils @ 180 days).

The effect of the various aqueous inhibited solutions on the corrosion rate of Al alloy 1100 is summarized in Table 41. This shows the final weight losses, the depth of pitting, and crevice attack and a brief description of the alloy surface after testing for 180 days. The terminal corrosion rates are not given since the presence of pitting or crevice attack negate the generally low levels of uniform dissolution.

With Nutek 876 the initial rate of attack is significantly lower than in New Haven tap water. However, the rate of attack increased significantly with time so that after 180 days the weight loss was double that of samples exposed in the potable water. It is not known whether this transition results from inhibitor depletion or inhibitor degradation. Heavy general corrosion occurred in this solution without the formation of discrete pits. However, the solution promoted severe crevice corrosion, not typical of the material in uninhibited potable water. Clearly, this inhibitor package is not effective in providing long term protection for Al in multimetal systems.

Least effective of the inhibited propylene glycol solutions in preventing corrosion of Al alloy 1100 were Nutek 835, Climax B and Sunsol 60. Although these solutions significantly decrease the overall weight loss they are not effective in preventing localized corrosion. Climax B had minimal effect in decreasing the depth of pitting and crevice attack. Climax A was more effective and prevented crevice corrosion. Pits up to 1 mil deep were observed. The electron micrograph in Fig. 37(a) shows the typical pitted surface of the aluminum alloy after exposure to this solution for 180 days.

Sunsol 60 decreases the extent of pitting and crevice corrosion without preventing their occurrence. However, this solution had a unique effect in promoting intergranular corrosion of the alloy. This form of attack is shown in the electron micrographs presented in Fig. 38. It should be noted, however, that Sunsol 60 was specifically formulated for use with copper.

The remaining inhibited propylene glycol solutions were extremely effective in decreasing the overall weight loss of the Al alloy. However, although they also significantly decreased the depth of pitting or crevice corrosion, none of them were effective in completely preventing it. From the results in Table 41, the most effective fluids were HTF-273 and Olin experimental fluid X-M. In both cases, however, shallow pits were observed in the samples exposed for 180 days.

The three inhibited ethylene glycol solutions also resulted in very low weight losses. Again, however, localized corrosion was not prevented. The results illustrated that NPC-218 and Prestone II were the most effective of these solutions. Both were effective in preventing crevice corrosion but some shallow pits were observed. Fig. 37(b) is an electron micrograph of the sample exposed for 180 days in Prestone II illustrating the appearance of the shallow pits in the alloy surface.

All the non-aqueous fluids resulted in low weight losses after 180 days. However, only Dow Corning 200 completely prevented the appearance of any localized attack. Shallow pitting was observed for each of the other non-aqueous fluids. The Therminol 44 was also found to have shallow crevice attack. Fig. 37(c) shows an electron micrograph of a sample exposed to Union Carbide Silicone fluid for 180 days. Pitting of the alloy is evident.

Copper (Alloy 122)

In contrast to both the aluminum and steel samples, copper is compatible with potable water systems. The weight loss data indicates an average metal penetration at rates below .25 mpy, with the rate actually decreasing with increasing exposure time. The general corrosion produced a slight roughening of the surface, and except for a few isolated, shallow pits in the crevice region, there was no evidence of localized attack. The ASTM water produced a slightly higher rate of uniform penetration, and a slightly higher frequency of shallow pits in the crevice. As shown in Figure 6, the weight loss data decreased with increased exposure time. This is produced by a thin surface layer of oxide which acts as a diffusion barrier between the solution and the bulk metal. This mechanism is well documented for copper tubing used in most residential plumbing applications.

As shown in Figure 7, similar weight loss responses were observed for a Cu-SS cell as well as the standard four metal test vessel. However, the presence of excess solder flux produced a marked increase in both the rate of general dissolution and crevice attack. Since the standard plumbing fluxes are known to contain $ZnCl_2$ and NH_4Cl, this response is somewhat predictable. Figure 32(b) shows intergranular attack in the exposed portion of the sample, and Figure 41 documents the increased crevice attack.

In general, the uninhibited glycol solutions produced a response very similar to that observed for NHTW. Low metal dissolution rates were observed for both the reagent grade propylene and reagent grade ethylene glycol solutions. Shallow crevice attack was observed in the propylene glycol with no surface pitting evident in either solution. In both cases, the solution pH drifted generally downward with exposure time. However, within the limits of this test the resultant pH levels (4.3 for the P.G. and 4.8 for the E.G.) did not significantly accelerate the corrosive attack on copper. Since the samples were covered with a uniform corrosion film, it is likely that the film formed during early in the test program was sufficiently stable to maintain protection throughout the entire exposure period. Prolonged exposure to the uninhibited glycol solutions could produce further degradation of the glycols. The effect of this continued degradation has not been fully examined. (Data from a previous study suggests copper is reasonably resistant to accelerated corrosion in the degraded glycols[1] - see appendix.)

The relative stability of the oxide film is somewhat supported by the experiments with the thermally degraded propylene glycol. This solution was intended to demonstrate the effect of collector stagnation on the glycol. The prior thermal treatment of the glycol produced a significant increase in the rate of uniform attack between three and six months (the instantaneous rate exceeded of 10 mpy @ 180 days). No significant increase in the localized attack was observed. Adjusting the R.A. to 10 reduced the rate of metal dissolution that observed for the reagent grade glycols. Attempting to maintain the R.A. at 10 offers no additional advantage.

In assessing the performance of the various inhibitor packages, it is necessary to reference the performance to a similar uninhibited fluid. For example, the Nutek 826 offers no apparent advantages over the two pure water systems (NHTW & ASTM water), and as a matter of fact, actually produced a slightly higher rate of corrosion than the pure water. However, there are some locations in the U.S. where the local well water is known to be corrosive to copper water tubing, and in those cases, use of an inhibitor would be required. Unfortunately, since the water chemistry changes from site to site, the applicability of a specific inhibitor system would have to be tested with the local water.

In terms of the glycol systems, the performance should be measured against the reagent grade product. Since copper was found to be compatible with the reageant glycols, the inhibitor package should be viewed as a back-up system to prevent corrosion under conditions which degrade the glycol to the point of making it a corrosive fluid (i.e. - prolonged collector stagnation). Additionally, the inhibitor package should accomplish two other functions: 1) since multi-metal systems are common in flat plate collector system, the inhibitor should be selected to protect the more corrosion susceptible materials, and 2) the inhibitor package should not be corrosive to copper (i.e. - the additives should not degrade the performance of the glycol-water system).

In terms of conditions favorable to glycol degradation, it has been demonstrated that at least one inhibitor package can overcome the aggressive nature of a thermally degraded glycol. In the case of this study, the replenishment package was Na_2HPO_4. Additional tests would be required to verify the effects for other inhibitor packages. Additionally, degradation tests should also be performed in the presence of the inhibitor.

In terms of the corrosive nature of the inhibitor packages, the data in Table 40 indicates that only the experimental Olin X-6 formulation produced localized corrosion in excess of .5 mils (at 180 days). Additionally, other than the X-6 formulation, the remainder of the glycol formulations produced uniform penetration at a rate equal to or less than that found for the reagent grade propylene glycol.

Somewhat lower overall weight losses were, however, observed in the non-aqueous fluids. By six months, the weight loss values appear to be approaching nearly stable values thereby resulting in extremely low instantaneous corrosion rates. The Union Carbide Silicone and Dow Corning 200 fluids were found to have instantaneous values (180 days) of only 0.005 mpy. A few shallow pits were observed on samples exposed in Therminol 44 and the Union Carbide Silicone fluid. In general, the appearance of the samples tested for 180 days was little different from that of untested samples. These samples were not, however, subjected to a simulated stagnation test. Accordingly, direct comparison of the results with those obtained in aqueous-base systems is not warranted.

Ferritic Stainless Steel (Alloy 444)

The ferritic stainless steel was the most corrosion resistant material tested. The weight losses of the samples, presented in Table 2, are extremely scattered and irreproducible. The values generally correspond to corrosion rates much less than 1 mpy and more often to rates less than 0.1 mpy. Occasionally, significantly higher weight losses were obtained, for example in ASTM water, uninhibited propylene glycol solution, the Olin phosphate inhibited PG and DowFrost. However, visual examination of the samples revealed little, if any, corrosion.

Generally, the samples of the ferritic stainless steel appeared visually similar after testing to samples prior to testing. The shining metallic luster of the metal was still evident although in some cases this was hidden by a light rust-colored film presumably consisting of corrosion products from the mild steel samples. In some instances surface discoloration of the metal occurred typical of intereference colors associated with thin oxide layers. These proved to be extremely difficult to remove by chemical treatment. They were removed by gently rubbing with a soft rubber eraser. No attack of the surface could be visibly seen following this treatment.

In some cases extremely shallow pits were formed, with these being occasionally deeper within the crevice region. When pitting did occur, the pits were extremely small and usually clustered in groups. Figure 40 shows electron micrographs of the crevice region of the samples following 180 days exposure in Nellis domestic water and the NPC inhibited propylene glycol solution. These typify the small size of the pits.

In Table 43 the depth of the pits formed inside and outside the crevice region is listed. It is clear from this that pitting is prevalent in the uninhibited aqueous and glycol solutions. However, except for the degraded propylene glycol solution, the pit depth was always less than 0.1 mils. Attack sustained at this rate is felt to be insignificant.

In the presence of Cu alloy samples, only, pitting did not occur inside or outside the crevice. Additionally, no sample discoloration associated with a deposited rust film was evident. The pitting observed in the presence of the low carbon steel may, therefore, have been promoted by the rust film and be a form of deposit attack.

The presence of Cu alloy together with solder flux resulted in the appearance of pits and pitting within the crevice was promoted to a depth of 0.4 mils. This is likely due to the aggressive nature of the flux, especially the high chloride content typical of most plumber's fluxes. In the other uninhibited aqueous solutions pitting within the crevice was only observed after exposure in the Nellis domestic water. In this case the pits were only 0.1 mil deep.

Shallow pitting also occurred with the reagent grade glycol solutions. Pitting was observed in the crevice region on samples exposed to the ethylene glycol solution. Similar pitting in the crevice was promoted by prior thermal degradation of the propylene glycol. Adjustment of the initial reserve alkalinity to 10 had little effect whereas maintenance of the reserve alkalinity at 10 for 42 days resulted in increased pit depth in the crevice (0.7 mils @ 180 days exposure).

Much less pitting occurred in the inhibited glycol solutions. Exceptions to this were pits seen in the crevice region of samples exposed to HTF-273, Olin experimental fluids X-6 and X-M and Prestone II. In the latter solution pits as deep as 1 mil were observed in the crevice. Outside the crevice region pitting was only observed in samples exposed to Olin X-E fluid and Prestone II. In the remaining inhibited glycol solutions, and in Nutek 876, the inhibited aqueous solution, pitting did not occur inside or outside the crevice region.

In the non-aqueous fluids exposure to Brayco or Therminol 44 resulted in no localized corrosion. In Union Carbide Silicone fluid a few shallow pits were observed in the crevice region while in DC 200 pits were observed outside and within the crevice.

Corrosion of Bimetallic Samples

In uninhibited aqueous or glycol solutions mild steel was most affected by galvanic contact with either copper alloy 122 or ferritic steel 444. In all these solutions the mild steel component of the bimetallic was essentially totally dissolved during the test. This was equally true in degraded propylene glycol solution with or without prior adjustment of the reserve alkalinity to 10. Maintenance of the reserve alkalinity at 10 for the first 42 days of the test caused a minor decrease in corrosion rate. However, coupled with Cu, the low carbon steel was completely dissolved within the crevice, whereas in contact with the stainless steel, perforation of the alloy occurred in several regions outside the crevice.

For the various inhibited solutions, the results in Table 34 demonstrate that the extent of corrosion of mild steel (when coupled to the stainless steel or copperalloy 122) was generally similar to its behavior in the uncoupled condition (of Table 40). In fact, in several instances the degree of localized attack was less. In particular, examples of this are the samples exposed to Nutek 835, Olin PIPG, Climax A and B, and Prestone II, where only general corrosion of the mild steel was observed. In contrast to this, more severe localized corrosion of the alloy occurred in NPC-218 when coupled with the more electrochemically noble partners.

In non-aqueous fluids less localized corrosion was also observed when mild steel was coupled with stainless steel or copper alloy 122.

As with the mild steel, the results for Cu alloy 122 in Table 34 show little difference from those presented for single Cu alloy samples in Table 40. An exception to this is ASTM water where quite pronounced crevice corrosion occurred. When coupled with the stainless steel, slightly more corrosion of Cu alloy 122 was generally observed. Thus, in New Haven tap water, crevice corrosion occurred to a depth of 5 mils when the bimetallic sample was exposed with all other materials. In contrast to this, exposure with the copper, stainless steel and solder flux resulted in crevice attack only 1 mil deep. This compares to the 6 mil deep attack for

Cu alloy samples exposed without galvanic coupling.

In inhibited glycol solutions pitting was generally seen within the crevice region of the copper alloy when coupled to stainless steel. This was often evident with uncoupled samples. However, pitting was also promoted in Dowfrost, Climax B and Olin fluids X-6 and X-E. Prestone II was the only inhibited glycol solution which prevented localized corrosion of Cu alloy 122 coupled to either the stainless steel or the low carbon steel. In non-aqueous fluids localized corrosion (crevice pitting) was absent only in Dow Corning 200 fluid.

There was little or no noticeable effect on the corrosion of the ferritic stainless steel by coupling with mild steel 1010 or Cu alloy 122.

Comparison with Previous Results

In a previous test,(see ref. 2 and 3 in appendix) the same apparatus was used to determine the behavior of copper alloys 122 and 194, aluminum alloys 1100 and 3003 in various fluids. The rate of uniform weight loss of copper alloy 122 in that study (in New Haven tap water) was only some half of that observed in this study, although the behavior of aluminum alloy 1100 was similar. The higher weight loss of copper in the present case is likely due to the presence of mild steel which corroded rapidly. This is supported by the lower weight loss levels reported in this study for the cell containing only the Cu and SS samples. In addition, significant amounts of iron corrosion product, likely the hydroxide, were found on the copper samples following testing. This nonprotective layer may have promoted corrosion of the copper by a phenomenon of differential aeration (deposit attack).

In the previous test, the fluids studies, which were included in the present test were Nutek 835 and 876, Dowtherm SR1, Prestone II, Therminol 44, and Dow Corning 200. For Cu alloy 122, similar results were obtained for Prestone II and Dowtherm SR1 but the weight losses were slightly higher in the previous test for the other solutions.

For aluminum alloy 1100, similar results were obtained for Nutek 876, Nutek 835, and Prestone II, but the weight losses observed in the previous test for the other solutions were slightly higher. The reason for this discrepancy is again likely related to the presence of the relatively rapidly corroding mild steel samples in the present work. For aluminum, which fails predominately by localized corrosion phenomenon, it is important to note that the localized attack was very similar in both test sequences.

The behavior of aluminum alloy 1100 in Nutek 876 in both studies is of particular interest. In both cases, the rate of attack is greater than observed in NHTW.

Fluid Degradation

The pH of the various antifreeze solutions all varied during the test, as evidenced from Tables 37 and 38. Similarly, the freezing point of the solutions, where measured, all increased, Table 37. It should be noted that the data contained in Table 37 is based on changes in the refractive index for the various water glycol solutions. In calculating the freeze point, it has been assumed that changes in the fluid chemistry did not significantly alter the published relationship between refractive index and freeze point. No empirical verification of freeze points was undertaken during this study.

For uninhibited propylene glycol solution this value rose from -40 to 5°F while the solution pH fell from 4.9 to 4.3. For ethylene glycol solution the freezing point rose from -30°F to -19°F while the pH fell from 7.3 to 4.8. These results likely reflect partial oxidation of the glycols to their corresponding acids during the test. This can render the solutions more corrosive to the various metals.

Prior degradation of propylene glycol resulted in an initial pH of 4.2 which fell during the test to 3.8. Adjustment of the reserve alkalinity to 10 resulted in a starting solution pH of 6.9 although this gradually fell to 4.7. By maintaining the reserve alkalinity at 10 for the first 42 days of testing the final solution pH after testing was 6.1.

With the exception of Nutek 835 the pH values of the solutions all decreased during the test. Where measured the freezing points (Table 37) increased and the reserve alkalinities (Table 39) decreased. This is evidence that the proprietary fluids are also being degraded, presumably by oxidation of the glycols. Clearly, additives within the fluids designed to buffer the solution are being depleted.

In a practical system the above results imply that the solution be changed on a regular basis. However, the low corrosion rates observed for the commercially formulated glycols suggest this replenishment/replacement period is greater than six months.

The pH of uninhibited New Haven tap water rose from 7.06 to 8.6 during the test. The presence of solder flux appeared to decrease the pH. Similar increases in pH were observed with ASTM water and the Los Alamos/Homestead water. In contrast, the pH of the Nellis domestic water decreased. Increase in pH of Nutek 876 during the test also occurred from an initial value of 7.49 to a final high value of 9.42. This result may explain the increasing rate of corrosion of Al alloy 1100 and the decreasing rate of corrosion of mild steel with time in this solution.

Corrosion in Simulated Swimming Pool Waters

In the trough testing using New Haven potable water, the rate of weight loss of Cu alloy 122 a function of the chloride ion contents is shown in Fig. 30. The highest final rate of corrosion of 0.2 mpy was obtained with an intermediate chloride content of 1000 ppm. At 1500 and 500 ppm chloride the rates were 0.09 and 0.1 mpy, respectively. These results were in accordance with the visual appearance of the alloy after testing for various times. After 180 days in the water with 1000 ppm chloride the alloy surface showed the most roughened surface. Together with this was crevice corrosion to a depth of 1 mil. At the other chloride levels the degree of surface roughening (general corrosion) was significantly less. Crevice corrosion occurred in both solutions. With 500 ppm chloride the final depth of attack was 1 mil but with 1500 ppm chloride this fell to 0.4 mils.

The weight losses of stainless steel samples, Table 35, were extremely low. There is some indication that the higher weight losses were obtained in the solution containing only 500 ppm chloride ion. Examination of the samples by optical microscopy revealed little difference in their behavior as a function of chloride content. In all cases, after 180 days a few small patches of general corrosion were observed together with some extremely shallow pits (.1 mils).

In both cases, the overall rate of corrosive attack (both general dissolution and localized attack) was quite low. Unfortunately, it is not known how performance in this test correlates with a swimming pool collector environment. These results are quite promising and thereby, suggest further testing is warranted. The data also correlates well with field experience in that both copper and stainless steel absorbers have been successfully used for pool heaters. Unfortunately, any correlation attempts will be somewhat limited by a need to document/understand the local water chemistry.

Los Alamos Test Solutions

As noted earlier, three test solutions were provided by Mr. John Avery of Los Alamos National Laboratory. Each solution was taken from solar water heating system owned by the U.S. government. As part of system reliability program, Los Alamos was installing corrosion test coupons in the fluid loops of these specific systems. By comparing the type and severity of the corrosive attack on the laboratory (Olin) versus field (Los Alamos monitored) samples, it will be possible to assess the applicability of the laboratory data. At the conclusion of the laboratory study, the field samples/data were not available. The comparisons will, therefore, become part of the overall Los Alamos monitoring program.

In terms of the laboratory data, the metal samples were selected in an effort to best match the overall materials of construction used in the field systems (i.e. - Copper and stainless steel in the Dow frost and Nellis Air Force Base (potable water) solutions; copper and bronze in the Homestead Air Force Base (potable water) solution).

In terms of localized attack, the Homestead AFB water appeared to duplicate the performance found in NHTW with the Nellis AFB water being slightly more aggessive. Additionally, the overall weight loss values for the Homestead and New Haven waters are reasonably similar (Figure 9). However, the Nellis water produces a dramatic rise in the overall copper weight loss between three and six months. The reason for this marked change in performance is not understood.

A comparison of the two Dowfrost solutions (Dowfrost; NHTW - Table 18 and Dowfrost; Los Alamos - Table 7) suggest similar modes of attack for both the copper and stainless steel samples. The copper samples are characterized by surface roughening and some localized attack in the Los Alamos sample. The stainless steel samples show some isolated deep (4 mil) pits in both solutions. In both cases, these pits were limited to selected samples and not present on the three or six month samples. Therefore, although the change in potable water supply did produce some variations in the recorded depth of attack, these variations are felt to be within accepted variations for corrosion testing.

In addition to providing field correlation data under the relatively benign conditions for the three Los Alamos solutions, field correlation will also be attempted using a known corrosive media. After reviewing the test data, the thermally degraded propylene glycol was chosen as test vehicle. To this end, twenty gallons of a 50 v/o propylene glycol were thermally treated (355°F, 120 hr.) at Olin and shipped to Los Alamos for field testing.

CONCLUSIONS

1. Ferritic steel 444 was shown to have the highest resistance to corrosion in the simulated solar energy collector test. In uninhibited solutions some extremely small shallow pits were formed. In inhibited solutions, pitting generally was not observed. The presence of solder flux in potable water promoted pitting within crevice regions to a depth of 0.4 mils.

2. In uninhibited waters or glycol solutions Cu alloy 122 demonstrated a corrosion rate significantly less than 1 mpy with the appearance of only a slight amount of localized corrosion. The presence of excess solder flux, however, promoted crevice corrosion. Moreover, prior thermal degradation of propylene glycol solutions also resulted in significantly higher corrosion rates. In all cases corrosion resulted in roughening of the alloy surface.

3. In inhibited glycol solutions the uniform corrosion rate of Cu generally remained quite low. Shallow pitting within the crevice region was sometimes observed. The most effective solutions from the point of view of causing low weight losses with no localized corrosion were the propylene glycol based solutions HTF-273 (Union Carbide) and Olin fluid with additions of sodium molybdate and Cobratec. Ethylene glycol solutions NPC-218 (Northern Petrochemical) and Prestone II (Union Carbide) were equally effective. Extremely low corrosion rates with little evidence of localized corrosion resulted from exposure to the non-aqueous solutions.

4. Aluminum alloy 1100 corroded at high rates in uninhibited water or glycol solutions. Severe pitting and in the glycol solutions crevice corrosion occurred. This material would be completely inadequate as a component in a mixed metal system and an uninhibited water containing heat transfer fluid.

5. Many of the inhibited glycol solutions resulted in extremely low corrosion rates of Al alloy 1100 as calculated from the slopes of the weight gain-time curves but none of them fully prevented localized corrosion from occurring. The more successful fluids were Olin X-M, HTF-273, NPC-218, and Prestone II. However, shallow pits were formed in the alloy after 180 days testing in all these solutions.

6. Pitting was observed in Al alloy 1100 after exposure to three of the four non-aqueous solutions. Samples exposed in Dow Corning 200 demonstrated very low corrosion rates with no observable localized corrosion.

7. The Al data contained in this report deals entirely with multi-metal systems, and therefore, does not predict the performance of these fluids in an all aluminum system.

8. Potentially catastrophic corrosive attack was found in both the thermally degraded and uninhibited glycol solutions. Therefore, use of Aluminum with inhibited glycol solutions mandates frequent monitoring of solution chemistry. Specific manufacturers should be consulted for recommendations regarding technique and frequency.

9. In uninhibited water and glycol solutions mild steel showed extremely high corrosion rates. In the glycol solutions samples fragmented sometime after 90 days of testing. The use of this alloy in such solutions is completely unacceptable.

10. In inhibited glycol solutions the corrosion rate was drastically reduced. However, none of these solutions prevented pitting of the alloy which would make their usage within a multimetal system questionable. Most effective of the solutions tested were Climax A, Sunsol 60, and Olin experimental fluid X-M.

11. Potentially catastrophic corrosive attack was found in both the thermally degraded and uninhibited glycol solutions. Therefore, use of mild steel with inhibited glycol solutions mandates frequent monitoring of solution chemistry. Specific manufacturers should be consulted for recommendations regarding technique and frequency.

12. Very low corrosion rates of mild steel resulted when they were exposed in the non-aqueous solutions. However, in all cases pitting of the alloy was evident.

13. Galvanic contact of stainless steel with Cu or mild steel had little effect on the corrosion resistance of the stainless. Similar contact of copper alloy 122 with stainless steel or mild steel had only marginal effect in increasing the corrosive attack of the copper.

14. Coupling mild steel with Cu or stainless steel increased its rate of corrosion in uninhibited waters or glycol solutions. The accelerated corrosion resulted in complete dissolution of the mild steel portion of the galvanic couple. No significant difference in the type or severity of

localized attack was, however, observed in the inhibited glycol solutions. No estimates of uniform attack were obtained.

15. During testing, the pH of the glycol solutions decreased. This was generally accompanied by a decrease in reserve alkalinity and an increase in the freezing point of the solutions. Although these changes are evident of fluid degradation during the test, the value of these parameters will not universally predict the corrosion performance of a commercially formulated glycol solution on any of the metals tested.

16. In simulated swimming pool water Cu alloy 122 demonstrated corrosive attack at a rate below 1 mpy. The highest rates were obtained with the intermediate chloride content of 1000 ppm. With the six month test period, localized corrosion occurred in the form of crevice corrosion to a maximum depth of 1 mil. For all three chloride solutions, the ferritic steel 444 showed low uniform corrosion rates with some shallow pitting.

TABLE 1

SOLAR HEAT TRANSFER SOLUTIONS AND TEST CONCENTRATIONS

A. Aqueous Draindown System

Product Name	Formulation	Concentration
New Haven Potable water.	Potable water from various lakes and surface resevoirs. Liquid contained in titanium vessels.	100%
ASTM water.	Distilled water with 100ppm each of Cl^-, $SO_4^=$, and HCO_3^-. Liquid contained in titanium vessels.	100%
Nutek 876 (Nuclear Technology Inc)	Polycarboxylic organic inhibited orange liquid.	1.47%
Homestead $A_OF_OB_O$	Domestic water, titanium vessel.	100%
Nellis $A_OF_OB_O$	Domestic water, titanium vessel.	100%

TABLE 1(cont'd 2)

SOLAR HEAT TRANSFER SOLUTIONS AND TEST CONCENTRATIONS

B. Aqueous Nondraindown System

Product Name	Formulation	Concentration
Ethylene Glycol (Baker reagent)	Uninhibited ethylene glycol solution in titanium vessel.	50%
Propylene Glycol (Baker reagent)	Uninhibited propylene glycol solution in titanium vessel.	50%
Thermally degraded propylene glycol	Propylene glycol solution degraded by autoclaving 50% solution for 120 hrs at 355°F. Titanium vessel.	50%
Thermally degraded propylene glycol Initial RA = 10	Degraded propylene glycol solution with initial reserve alkalinity adjusted to 10 by addition of Na_2HPO_4. Ti vessel.	50%
Thermally degraded propylene glycol RA = 10	Degraded propylene glycol solution with reserve alkalinity maintained at 10 by monthly additions of Na_2HPO_4. Ti vessel.	50%
SunSol 60 (Sunworks)	Inhibited propylene glycol glycol red solution in Pyrex vessel.	50%
HTF-273 (Union Carbide Corp.)	Inhibited propylene glycol yellow-green solution in Pyrex vessel.	50%
Olin (Olin Corporation)	Inhibited propylene glycol solution in Pyrex vessel.	50%
Olin (Olin Corporation)	Inhibited propylene glycol solution in Pyrex vessel. 2000ppm Na_2MO_4 and 625ppm Cobratec TT-100 added to diluted solution.	50%
Olin X6 (Olin Corporation)	Inhibited propylene glycol solution in Pyrex vessel.	50%

TABLE 1(cont'd 3)

SOLAR HEAT TRANSFER SOLUTIONS AND TEST CONCENTRATIONS

B. Aqueous Nondraindown System

Product Name	Formulation	Concentration
Olin X-E (Olin Corporation)	Inhibited propylene glycol solution in Pyrex vessel.	50%
Olin X-M (Olin Corporation)	Inhibited propylene glycol solution in Pyrex vessel.	50%
Dowfrost (Union Carbide Corporation)	Inhibited propylene glycol solution in Pyrex vessel.	50%
Climax A (Climax Molybdenum Co.)	Experimental inhibited propylene glycol solution containing sodium molybdate. Supplied premixed with water. Pyrex vessel.	-
Nutek 835	Organic inhibited propylene glycol solution. Pyrex vessel.	50%
Dowfrost Los Alamos	Inhibited solution supplied from D.O.E. site. Pyrex vessel.	-
Dowtherm SRI (Dow Chemical Company)	Inhibited ethylene glycol. Red solution contained in Pyrex vessel.	50%
Prestone II(1981) (Union Carbide Co.)	Inhibited and buffered ethylene glycol. Yellow solution in Pyrex vessel.	50%
NPC-218	Inhibited ethylene glycol. Blue-green solution in Pyrex vessel.	50%

TABLE 1(cont'd 4)

SOLAR HEAT TRANSFER SOLUTIONS AND TEST CONCENTRATIONS

C. Nonaqueous Nondraindown System

Product Name	Formulation	Concentration
Therminol 444 (Monsanto)	Aromatic based liquid. Clear yellow solution in Pyrex solution.	100%
Brayco 888 (Bray Oil Co.)	Reddish brown organic liquid in Pyrex vessel.	100%
Dow Corning 200 (Dow Corning Corp.)	Silicone liquid, 20 centistoke viscosity at 25°C. Colorless liquid in Pyrex vessel.	100%
Union Carbide Silicone Fluid L-45 (Union Carbide Co.)	Low viscosity silicone fluid in Pyrex vessel.	100%

TABLE 2

WEIGHT LOSS OF STAINLESS STEEL SAMPLES ($\mu g/cm^2$)

Solution	Time (Days)			
	30	60	90	180
NHTW (with Al, Cu, mild steel)	0 0	557 225	707 230	195 245
NHTW (with Cu only)	14.1	18.2	11.3	8.0
NHTW (with Cu and solder flux)	21.6	20.8	23.6	11.7
ASTM water	159 890	91 70	478 44	1290
Uninhibited Ethylene glycol	85 85	90 64	130 92	259 246
Uninhibited Propylene glycol	9.6 117	40 23	3120 1676	761 306
Degraded Propylene glycol	4.2	9.8	21.1	16.8
Degraded Propylene glycol (Initial RA=10)	2.9	11.7	14.3	11.7
Degraded Propylene glycol (Maintained at RA=10)	16.4	11.2	9.4	29.3
Los Alamos Water	14.1	18.8	18.2	17.4
Nellis Domestic	2.1	13.6	12.9	6.5
Homestead	-	-	13.6	18.1
Nutek 876	376 299	112 181	92 112	108 382

TABLE 2(cont'd 1)

WEIGHT LOSS OF STAINLESS STEEL SAMPLES
($\mu g/cm^2$)

Solution	Time (Days)			
	30	60	90	180
SunSol 60	377	59	187	61
		70	212	86
NPC 218	64	135	814	832
	104	-	14	191
Nutek 835	44	12	213	40.4
	43	2.7	129	106
HTF 273	68	107	12	61
	42	58	15.5	86
Climax A	162	226	526	192
	168	144	35	247
Climax B	2.9	7.6	8.4	11.7
	17.2	13	8.4	23
Dowfrost	445	5198	902	288
	346	3458	279	36
Olin (PIPG)	182	37	1.6	1218
	94	155	211	68.6
Olin (with BTA)	17.4	28.1	2	6.4
	118	15	204	9.6
Olin X-6	11.7	8.3	4.7	7.0
Olin X-E	7.4	18.8	15.3	7.0
Olin X-M	9.3	8.2	22.8	10.6
Prestone II	238	161	11.5	859
	506	13	-	
Dowtherm	38	61	42	19.7
	56	102	106	628
Brayco 888	150	178	64	207
		343	105	221

TABLE 2(cont'd 2)

WEIGHT LOSS OF STAINLESS STEEL SAMPLES
($\mu g/cm^2$)

Solution	Time (Days)			
	30	60	90	180
Therminol 44	211	612	561	220
	243	277	886	303
DC 200	224	359	448	136
	275	488	288	332
Union Carbide	14.7	12.9	12.9	10.0
Silicone	18.2	23.6	28.6	9.6
1 mil/year	1700	3400	5100	10,200

TABLE 3

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLE IMMERSED IN NEW HAVEN TAP WATER

Alloy	Time (months)	Localized Corrosion	Max Pit Depth (mils)
Al	1	Roughened surface with high frequency of pits several larger pits at crevice 3 mils deep.	4
	2	Very rough surface. Increased no. of large pits on sample and crevice.	4
	3	Very rough surface. Large pits visible	5
	6	Surface very rough Some large pits More pronounced attack at crevice	4
Cu	1	General corrosion, discolored surface areas	-
	2	General corrosion, discolored surface areas but no pits	-
	3	As above.	-
	6	As above but pits to 1 mil deep in crevice	-
Mild Steel	1	Very rough surface with several large pits. Pits of crevice 9 mils deep.	3
	2	Very rough surface with deep pits. Crevice corrosion.	3
	3	Very large pits, Deep crevice corrosion.	3
	6	Very rough pitted surface. Perforation at interface.	3

TABLE 3(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLE IMMERSED IN NEW HAVEN TAP WATER

Alloy	Time (months)	Localized Corrosion	Max Pit Depth (mils)
Stainless Steel	1	Some discolored areas with scattered shallow pits.	<1
	2	High frequency of Shallow pits.	<1
	3	High frequency of Shallow pits.	<1
	6	High frequench of Shallow pits.	<1

TABLE 4

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN NEW HAVEN TAP WATER (COPPER AND STAINLESS STEEL ONLY)

Alloy	Time (months)	Localized Corrosion	Max Pit Depth (mils)
Cu	1	Small amount of general corrosin	-
	2	General corrosion, some lightly etched areas	-
	3	General corrosion, no pitting observed. A few very shallow pits within crevice.	-
	6	General corrosion with a patchy appearance. A few very shallow pits. No noticeable crevice corrosion but a few pits with crevice(.2mil)	.1
Stainless	1	No noticeable corrosion	-
	2	No noticeable corrosion	-
	3	Some surface discoloration	-
	6	No evidence of corrosion, sample has retained its initial surface appearance.	-

TABLE 5

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN NEW HAVEN POTABLE WATER (SOLDER FLUX PRESENT)

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth (mils)
Cu	1	General corrosion with evidence of accelerated attack within crevice	-
	2	Heavy general corrosion with appearance of a few shallow pits. Crevice corrosion to 1 mil.	0.3
	3	Roughened surface, no discrete pits, quite severe crevice corrosion to 2 mils.	-
	6	Very roughened surface with an etched appearance. Some wide shallow pits. Very severe crevice corrosion to 6 mils.	1
Stainless	1	No evidence of corrosion	-
	2	Surface discoloration but no evidence of corrosion	-
	3	Very occasional extremely shallow pits; so pitting within crevice to .1mil.	<0.1
	6	Some shallow pits. Deeper small pits in crevice to 0.4 mils.	<0.1

TABLE 6

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN ASTM WATER

Alloy	Time (months)	Localized Corrosion Observations	Pit Depths (mils)
Al	1	Roughened surface but no discrete pits.	-
	2	Fairly uniform surface with many shallow pits.	<1
	3	Some surface roughening with a few shallow pits.	<1
	6	Rough surface with many small pits.	<1
Cu	1	Barely detectable general corrosion	-
	2	General corrosion	-
	3	General corrosion	-
	6	General corrosion, no discrete pits. Surface discolored. 1 mil pits in crevice.	-
Mild Steel	1	Roughened surface with several pits. Crevice corrosion to 4 mils.	3
	2	Very roughened surface with valleys and crests. 4 mil deep crevice corrosion.	4
	3	Extremely roughened surface. Heavy crevice to 4 mils deep.	4
	6	Extremely rough surface. Perforation of crevice.	3
Stainless	1	Little observable corrosion.	<1
	2	Little observable corrosion. A few scattered areas with shallow pits.	<1

TABLE 6(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN ASTM WATER

Alloy	Time (months)	Localized Corrosion	Pit Depths (mils)
	3	Very little corrosion. Some areas with very shallow pits.	<1
	6	Little corrosion. A few discolored areas with very shallow pits.	<1

TABLE 7

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN DOWFROST, LOS ALAMOS

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth (mils)
Cu	1	General corrosion with slight surface roughening	-
	2	Considerable roughening of surface, some occasional small pits. Slight crevice corrosion to 0.3mils with more pits in crevice.	0.2
	3	Roughened surface with occasional pits. Crevice corrosion to 0.6mils. Many pits in crevice to 1 mil.	0.3
	6	Heavily roughened surface with occasional pits. Crevice corrosion to 1 mil More pits within crevice to 1 mil.	1
Stainless	1	Considerable surface roughening with several pits.	2
	2	Heavily roughened surface with many pits. Slightly more attack at crevice.	4
	3	No observable attack.	-
	6	Some surface discoloration Little, if any, attack,	-

TABLE 8

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN HOMESTEAD $A_OF_OB_O$ DOMESTIC WATER

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Cu	1	Some surface roughening	-
	2	Quite severe surface roughening with a few very shallow pits	.1
	3	Surface roughening with several shallow pits Frequency of pits greater inside crevice region.	.1
	6	Heavily roughened surface with several shallow pits. More frequent pits in crevice to 0.3 mils	.2
Bronze (Alloy 521)	6	Slight uniform general corrosion. No apparent attack at crevice.	-

TABLE 9

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN NELLIS AFB, DOMESTIC WATER

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Cu	1	Slight general corrosion. No increase in corrosion at crevice.	-
	2	Surface roughening with grain boundary etching. Occasional shallow pits	0.2
	3	Surface roughening with several pits. Slightly more attack at the crevice.	0.8
	6	Heavy surface roughening with many pits. Attack at crevice to 0.3 mils.	1
Stainless	3	Some surface discoloration A few very shallow pits in crevice (<0.1 mil)	<0.1
	6	Some very shallow small scattered pits. Much heavier pitting in crevice.	1

TABLE 10

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN UNINHIBITED ETHYLENE GLYCOL

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mil)
Al	1	General corrosion with many small pits, ring of large pits at crevice 1.5 mil deep. Few scattered deep pits.	3
	2	General corrosion with many small pits. Increased no. of large pits. Crevice attack to 4 mils.	3
	3	High frequency of small pits 1 mil. Many deep large pits with heavy crevice attack to 8 mils.	3
	6	Many small pits, several large pits up to 4 mils. Crevice attack to 2 mils.	4
Cu	1	General corrosion with surface discoloration.	-
	2	General corrosion.	-
	3	General corrosion.	-
	6	General corrosion with surface discoloration. No discrete pits or crevice attack.	-

TABLE 10(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN UNINHIBITED ETHYLENE GLYCOL

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mil)
Mild Steel	1	Roughened surface with several shallow pits	0.5
	2	Very rough surface but no discrete pits	-
	3	Very rough surface, some small pits.	1
	6	Sample totally dissolved Only portion left in crevice area.	-
Stainless	1	Little observable corrosion	1
	2	Light general corrosion with only occasional shallow pits	<1
	3	A few areas with some very shallow pits	<1
	6	Very little corrosion, few areas of shallow pits. Crevice attack but less than 1 mil.	<1

TABLE 11

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN UNINHIBITED PROPYLENE GLYCOL

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Al	1	Roughened surface with high frequency of pits, large pits at crevice 3 mils deep	4
	2	Very rough surface, increased no. of large pits.	4
	3	Deep pits at crevice region 4 mils deep. High frequency of large pits on surface.	4
	6	Many small pits with a few large deep pits. Crevice attack to 2 mils.	4
Cu	1	General corrosion	-
	2	General corrocion	-
	3	General corrosion	-
	6	General corrosion Sample discolored. No pits evident. Shallow pits evident in crevice 1 mil	-

TABLE 11(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN UNINHIBITED PROPYLENE GLYCOL

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Mild Steel	1	Roughened surface with many pits. Pits at crevice to 1 mil	0.5
	2	Very rough surface with many pits. More pits at crevice.	1
	3	Very rough surface with high frequency of large pits.	2
	6	Sample disappeared. Only area left is crevice.	-
Stainless	1	Very little corrosion observed.	-
	2	Little corrosion, a few discolored areas.	-
	3	As above.	-
	6	Very little corrosion. A few shallow pits.	<1

TABLE 12

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN THERMALLY DEGRADED PROPYLENE GLYCOL

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Al	1	Roughened surface with many pits; pitting in crevice to 3 mils	4
	2	Roughened surface with many deep pits. Pitting in crevice to 6 mils.	5
	3	Roughened surface with many deep pits. Deeper pits in crevice to 6 mils.	5
	6	Severely roughened surface. Deep pits in crevice region to 6 mils.	5
Cu	1	Lightly etched surface occasional shallow pits.	.2
	2	Lightly etched surface Some crevice corrosion to .3 mils.	-
	3	General corrosion with some surface roughening Crevice corrosion to .4 mils	-
	6	Severely roughened surface with occasional pits. No observable crevice corrosion.	0.5

TABLE 12(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN THERMALLY DEGRADED PROPYLENE GLYCOL

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Mild Steel	1	Very roughened surface with many pits.	0.5
	2	Very roughened surface with many pits. Deeper pits at crevice to 3 mils.	2
	3	Heavily roughened surface with deep pits. More attack at crevice region to 5 mils.	5
	6	One corner of specimen completely dissolved. Extremely heavy corrosion over remaining sample.	4
Stainless	1	No observable corrosion.	-
	2	Some surface discoloration but no observable attack.	-
	3	A few very shallow pits in crevice region (<0.1 mils)	-
	6	Some very shallow occasional pits. Occasional deeper pits in crevice to 0.1 mils.	<0.1

TABLE 13

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN THERMALLY DEGRADED PROPYLENE GLYCOL WITH INITIAL RESERVE ALKALINITY ADJUSTED TO 10

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Al	1	No observable attack	-
	2	Many small pits with some crevice corrosion to 1 mil.	0.5
	3	Many deep pits with severe crevice corrosion to 3 mils.	2
	6	Severely corroded surface with many deep pits. Severe crevice corrosion to 6 mils.	2
Cu	1	Only light general corrosion.	-
	2	Some surface roughening. Occasional shallow pit in crevice to 0.2 mils.	-
	3	Roughened surface. Some pits in crevice to 0.4 mils.	-
	6	Extremely roughened surface with scalloped appearance. Pits in crevice to 0.5 mils.	-

TABLE 13(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN THERMALLY DEGRADED PROPYLENE GLYCOL WITH INITIAL RESERVE ALKALINITY ADJUSTED TO 10

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Mild Steel	1	Slightly roughened surface	-
	2	Roughened surface with many small pits. Corrosion outside crevice region to 0.3 mils.	0.4
	3	Very roughened surface with high frequency of pits. Corrosion outside crevice to 0.5 mils.	1
	6	Severe general corrosion with many large pits. Corrosion outside crevice to 6 mils.	2
Stainless	1	No visible corrosion.	-
	2	Occasional extremely shallow pits.	<0.1
	3	Some occasional very shallow pits. Higher frequency of pits in crevice.	<0.1
	6	Similar to 3 month sample.	<0.1

TABLE 14

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN THERMALLY DEGRADED PROPYLENE GLYCOL MAINTAINED AT RESERVE ALKALINITY OF 10

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	No observable corrosion	-
	2	Some occasional small pits.	0.3
	3	Many quite deep pits. Crevice corrosion to 3 mils.	1.5
	6	High frequency of deep pits. Severe crevice corrosion to 5 mils.	3
Cu	1	Slight general dissolution with some surface roughening.	-
	2	Surface roughening.	-
	3	Roughened surface with occasional shallow pits particularly within crevice.	0.2
	6	Similar to 3 month sample.	0.2

TABLE 14 (cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN THERMALLY DEGRADED PROPYLENE GLYCOL MAINTAINED AT RESERVE ALKALINITY OF 10

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Mild Steel	1	Some surface roughening with several shallow pits	0.5
	2	Roughened surface with several quite deep pits Crevice corrosion to 2 mils	2
	3	Roughened surface with many large deep pits. Severe crevice corrosion to 6 mils.	4
	6	Roughened surface with many large deep pits. Very severe crevice corrosion with sample perforation.	7
Stainless	1	No visible attack	-
	2	Some surface discoloration with a few very shallow pits	0.1
	3	Similar to 2 month sample with occasional deeper pit in crevice to 0.2 mils.	
	6	No general corrosion. Some pits in crevice to 0.7 mils.	-

TABLE 15

LOCALIZED CORROSION OBSERVATION FOR SAMPLES IN NUTEK 876

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	General corrosion with some surface roughening	-
	2	General corrosion with more surface roughening	-
	3	General corrosion but with many shallow pits. Large pits of crevice to 3 mils.	<1
	6	Severe general corrosion	-
Cu	1	Very little general corrosion	-
	2	General corrosion with some surface discoloration	-
	3	General corrosion but some surface roughening.	-
	6	Surface roughened. Attack more severe in crevices with a few discrete pits 0.5 mils	-
Mild Steel	1	General corrosion with several small pits. High frequency of crevice to 1 mil.	<1
	2	General corrosion with a high frequency of pits.	1
	3	Very rough surface. Pits to 3 mils deep in crevice.	1
	6	Very roughened surface. A few deep pits. Crevice attack with 3 mil pits.	2

TABLE 15(cont'd)

LOCALIZED CORROSION OBSERVATION FOR SAMPLES IN NUTEK 876

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Stainless	1	Very light general corrosion.	-
	2	Areas with very shallow pits.	-
	3	Very light general corrosion.	-
	6	Little corrosion.	-

TABLE 16

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN NUTEK 835

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Al	1	Many small pits.	-
	2	Many small pits, slightly larger than at 1 month.	-
	3	Many small pits.	-
	6	General corrosion, a few large pits. Severe corrosion of crevice at 4 mils.	0.5
Cu	1	Little corrosion, some discoloration.	-
	2	General corrosion, more in crevice.	-
	3	Some surface roughening.	-
	6	Considerable surface roughening. Several pits within crevice 0.5 mils deep.	-
Mild Steel	1	General corrosion and scattered small pits.	<1
	2	As above.	<1
	3	General corrosion with some small pits. Severe pitting in crevice to 4 mils.	0.5
	6	High frequency of pits with a few deep pits. Many deep pits in crevice.	5

TABLE 16(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN NUTEK 835

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Stainless	1	No corrosion observed.	-
	2	As above.	-
	3	A few areas with very shallow pits.	-
	6	Very little corrosion.	-

TABLE 17

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN HTF-273

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	High frequency of very shallow pits.	<1
	2	High frequency of very shallow pits.	<1
	3	Little corrosion but many shallow pits.	<1
	6	Little corrosion, several shallow pits. No attack of crevice.	<1
Cu	1	Little corrosion, somewhat	-
	2	As above.	-
	3	General corrosion.	-
	6	General corrosion only a few shallow pits in crevice.	-
Mild Steel	1	Roughened surface, some shallow pits.	<1
	2	Roughened surface, no difference of crevice. A few pits.	1
	3	Slightly rough surface. Many pits.	1
	6	Many small ptis. Heavier attack of crevice.	1

TABLE 17(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN HTF-273

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Stainless	1	No observable corrosion.	-
	2	As above.	-
	3	As above.	-
	6	No observable corrosion, a few shallow pits with crevice.	-

TABLE 18

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN DOW FROST

Alloy	Time	Localized Corrosion	Max. Pit Depth
Al	1	A few very shallow pits	1
	2	High frequency of shallow pits	1
	3	High frequency of shallow pits	1
	6	General corrosion, a few shallow pits, deeper pits at crevice.	1
Cu	1	General corrosion.	-
	2	General corrosion.	-
	3	General corrosion.	-
	6	General corrosion, slight surface roughening, more attack in crevice.	-
Mild Steel	1	General corrosion with a few small pits, deeper pits at crevice.	1
	2	General corrosion with many small pits.	1
	3	Several small pits, general corrosion.	1
	6	General corrosion with several small pits. Somewhat deeper pits in crevice.	0.5

TABLE 18(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN DOW FROST

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Stainless	1	Very light general corrosion.	-
	2	Very high frequency of pits. Very shallow	4
	3	Light general corrosion.	-
	6	Very little corrosion.	-

TABLE 19

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN CLIMAX A FLUID

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth(mils)
Al	1	No apparent attack.	-
	2	A few very shallow pits.	<0.1
	3	Slight general corrosion with a few shallow pits.	0.3
	6	Slight general corrosion with a few small shallow pits.	1
Cu	1	Slightly roughened surface.	-
	2	As above.	-
	3	As above. A few shallow pits in crevice to 0.2 mils.	-
	6	General corrosion with some surface roughening. A few shallow pits in crevice to 0.5 mils.	-
Mild Steel	1	Little observable attack.	-
	2	Very slight general corrosion with a few shallow pits.	0.1
	3	Slight general corrosion with some shallow pits.	0.4
	6	Only slightly roughened surface. An increased number of small shallow pits.	0.5
Stainless steel	1	No corrosion.	-
	2	No corrosion.	-
	3	Some surface discoloration but no visible corrosion.	-
	6	No visible corrosion.	-

TABLE 20

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN CLIMAX B FLUID

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (mils)
Al	1	No apparent attack.	-
	2	Some surface roughening with many small pits.	0.5
	3	General corrosion with surface roughening and many pits. More severe pitting in crevice to 2 mils.	1
	6	Very roughened surface with large deep pits More pits in crevice to 4 mils.	3
Cu	1	Very slightly roughened surface.	-
	2	Some surface roughening.	-
	3	As above.	-
	6	Roughened surface but no discrete pits. Small amount of crevice corrosion (0.2 mils).	-
Mild Steel	1	Roughened surface with some small shallow pits. More attack in crevice.	0.2
	2	Roughened surface with several pits. Crevice corrosion to 0.4 mils.	1
	3	Very roughened surface with many large pits. Crevice corrosion to 0.4 mils.	1.8

TABLE 20(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR CLIMAX B

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
	6	Severely roughened surface with many large pits. Severe crevice corrosion to 4 mils.	1.8
Stainless	1	No corrosion.	-
	2	No corrosion.	-
	3	No corrosion.	-
	6	No evidence of localized corrosion. Some surface discoloration.	-

TABLE 21

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN FLUID

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	Many small pits.	<1
	2	Many small pits, particularly of crevice region.	<1
	3	Many small pits.	<1
	6	Several small shallow pits. Slightly more attack at crevice interface.	<1
Cu	1	Very light general corrosion.	-
	2	Very light general corrosion.	-
	3	Very light general corrosion.	-
	6	Very light general corrosion. Some evidence of increased corrosion within crevice.	-
Mild Steel	1	General corrosion with no evidence of pits.	-
	2	Slightly roughened surface with some shallow pits. Pits slightly deeper in crevice region.	-
	3	General corrosion with some some small scattered pits.	1
	6	Several small pits. Heavier concentration of pits in crevice.	1

TABLE 21(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN FLUID

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Stainless	1	Very little corrosion.	-
	2	Very little corrosion.	-
	3	A few discolored areas.	-
	6	Some surface discoloration general corrosion in a few areas.	-

TABLE 22

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN FLUID WITH ADDITIONS

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	High frequency of very shallow pits.	<1
	2	As above.	<1
	3	Many very shallow pits.	<1
	6	General corrosion with a few shallow pits. No attack at crevice.	<1
Cu	1	Little corrosion, a few discolored areas.	-
	2	Little corrosion.	-
	3	Little corrosion. A few discolored areas.	-
	6	Small amount of general corrosion alloy.	-
Mild Steel	1	General corrosion with a few high very shallow pits.	<1
	2	General corrosion with a few very shallow pits.	<1
	3	General corrosion with only a few shallow pits.	<1
	6	Only a few discrete small pits. No evidence of extra attack at crevice.	<1

TABLE 22(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN FLUID WITH ADDITIONS

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Stainless	1	Little corrosion visible.	-
	2	Very little corrosion.	-
	3	Very little corrosion, a few discolored areas.	-
	6	Very little corrosion, a few discolored areas.	-

TABLE 23

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN PROPYLENE GLYCOL X-6

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	Little general attack. A few shallow pits.	0.2
	2	Surface similar to 1 month sample. Some deeper pitting in crevice region to 0.5 mils.	0.2
	3	Slightly roughened surface with some deeper pits. Some crevice corrosion to 0.2 mils with higher frequency of pits in crevice (0.4 mils)	0.4
	6	Similar surface to 3 month sample with deeper pits. Crevice corrosion to 0.3 mils. Pitting in crevice to 1 mil.	0.6
Cu	1	Very slight amount of general corrosion.	-
	2	Slightly roughened surface, occasional small pits in crevice region to 0.3 mils.	-
	3	General corrosion with some surface roughening. A few shallow pits. Deeper pits in crevice to 0.3 mils.	0.2
	6	Roughened, etched surface with several small pits. Many pits in crevice region to 1 mil.	0.7

TABLE 23 (cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN PROPYLENE GLYCOL X-6

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Mild Steel	1	General corrosion with a few shallow pits.	0.2
	2	General corrosion with occasional shallow pits.	0.3
	3	Very similar to 2 month sample.	0.3
	6	General corrosion with a few pits. No evidence of crevice corrosion.	1
Stainless	1	No observable corrosion.	-
	2	No observable corrosion.	-
	3	Some surface discoloration. No evidence of corrosion.	-
	6	No visible corrosion. Very occasional shallow pit in crevice to 0.1 mils.	

TABLE 24

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN PROPYLENE GLYCOL X-E

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	No discernible corrosion.	-
	2	Very slight general corrosion. No evidence of pits.	-
	3	Slight general corrosion with a few very shallow pits. Some pitting in crevice region to 0.3 mils.	0.2
	6	Only slight general corrosion with no evidence of pits. A few pits in crevice region to 0.2 mils.	-
Cu	1	Very slight surface roughening.	-
	2	Little corrosion, occasional shallow pit in crevice to 0.2 mils.	-
	3	Some roughening with occasional small pit in crevice to 0.2 mils.	-
	6	Similar to 3 month sample.	-
Mild Steel	1	A few small pits.	0.2
	2	No observable general corrosion. Occasional small pits with higher pit frequency in crevice to 0.3 mils.	0.2
	3	Only slight general corrosion with a few pits. Higher freqeuncy of similar pits in crevice.	0.3

TABLE 24(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN PROPYLENE GLYCOL X-E

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
	6	Similar to 3 month sample with slightly deeper pits.	0.5
Stainless	1	No observable corrosion.	-
	2	No observable corrosion.	-
	3	Some surface discoloration. A few regions with high frequency of extremely shallow pits.	<0.1
	6	No general corrosion. An occasional very shallow small pit.	0.1

TABLE 25

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN OLIN PROPYLENE GLYCOL X-M

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	No apparent corrosion.	-
	2	As above.	-
	3	As above.	-
	6	High frequency of very shallow pits.	<0.1
Cu	1	No corrosion observed.	-
	2	Very slight surface roughening.	-
	3	As above. Some pits in crevice to 0.5 mils.	-
	6	Slight general corrosion only. No attack in crevice.	-
Mild Steel	1	No general corrosion with only occasional very shallow pits.	0.1
	2	Similar to 1 month sample.	0.1
	3	Some grain boundary etching. Several pits.	0.8
	6	Slightly roughened surface. Occasional pits. No crevice corrosion.	0.5
Stainless	1	No observable attack.	-
	2	As above.	-
	3	As above.	-
	6	No observable corrosion. A few very small pits in crevice (<0.1 mils)	-

TABLE 26

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN SUNSOL 60

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	High frequency of very shallow pits.	<1
	2	High frequency of very shallow pits, particularly at boundaries.	<1
	3	Considerable surface roughening. Grain boundaries attacked a few pits to 0.5 mils. Crevice corrosion to 1 mil.	0.5
	6	Severe roughening, grain boundaries attacked, crevice corrosion to 1 mil.	1
Cu	1	Only slight general corrosion.	-
	2	As above.	-
	3	Surface quite roughened. A few pits in crevice <0.5mils.	-
	6	Surface roughened, many pits in crevice to 0.5 mils.	-
Mild Steel	1	Little corrosion. A few very small pits.	1
	2	As above.	1
	3	Only slight surface roughening. Infrequent pits 0.5 mils crevice corrosion to 1 mil.	0.5
	6	Surface roughening. A few shallow pits.	-

TABLE 26(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN SUNSOL 60

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Stainless	1	Very little corrosion evident.	-
	2	Very little corrosion, a few discolored areas.	-
	3	Little apparent corrosion.	-
	6	Little corrosion, a few discolored areas.	-

TABLE 27

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN NPC-218

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	A few small pitted areas.	<1
	2	High frequency of shallow pits. Slightly deeper at crevice.	<1
	3	Only slight surface roughening. A few shallow pits.	<1
	6	As above.	<1
Cu	1	Very little corrosion.	-
	2	As above.	-
	3	Little general corrosion.	-
	6	General corrosion, a few pits in crevice 0.5 mils deep.	-
Mild Steel	1	General corrosion with several small pits. Slightly deeper in crevice.	<1
	2	Several small pits. Pits 2 mil deep at crevice.	0.5
	3	Slight surface roughening with a few discrete pits, crevice corrosion to 1 mil.	0.5
	6	Slightly roughened surface with a few discrete pits, crevice corrosion to 1.5 mils.	0.5
Stainless	1	Little, if any, corrosion.	-
	2	Little corrosion.	-
	3	Little corrosion.	-
	6	Little corrosion, a few discolored areas.	-

TABLE 28

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN PRESTONE II

Alloy	Time (hours)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	Only a few very shallow pits.	<<1
	2	A few areas with some very shallow pits.	<<1
	3	A few shallow pits.	<1
	6	Little observable attack. Only a few very shallow pits.	<1
Cu	1	Very little corrosion, some discolored areas.	-
	2	As above.	-
	3	Little general corrosion.	-
	6	General corrosion with slight roughening.	-
Mild Steel	1	Roughened surface with a few very shallow pits.	<1
	2	General corrosion with a few very shallow pits.	0.5
	3	General corrosion with some shallow pits.	0.5
	6	Many pits. Higher concentration of pits at crevice.	1
Stainless	1	Scattered areas with extremely shallow pits.	<< 1
	2	Little corrosion observed.	-
	3	A few areas with very shallow pits.	< 1
	6	several small pits, a few larger pits 0.5 mil deep. Crevice attack to 1 mil.	0.5

TABLE 29

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN DOWTHERM SR1

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	A few very shallow pits.	<1
	2	High freqeuncy of shallow pits.	<1
	3	General corrosion with several shallow pits.	0.5
	6	Several shallow pits, slightly more in crevice region.	0.5
Cu	1	Little apparent corrosion.	-
	2	Little corrosion, a few discolored areas.	-
	3	Little corrosion, sample discolored.	-
	6	Very little attack. Occasional pit <0.5 mils deep.	<0.5
Mild Steel	1	General corrosion only.	-
	2	A few scattered shallow pits. Higher concentration at crevice.	<0.1
	3	A few scattered pits. Slightly more in crevice.	0.5
	6	A few pits with a higher pit frequency in crevice.	0.5

TABLE 29(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN DOWTHERM SR1

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Stainless	1	A few discolored areas. Little attack.	-
	2	Shiny surface with very little corrosion.	-
	3	Very little corrosion.	-
	6	Very little attack, a few discolored areas.	-

TABLE 30

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES IN BRAYCO 888

Alloy	Time (months)	Localized Corrosion Observations	Max. Pit Depth (Mils)
Al	1	Little corrosion, a few very shallow pits.	<<1
	2	Some areas containing a few shallow pits.	<<1
	3	Little corrosion, a few very shallow pits.	<<1
	6	Very little corrosion. Only a few extremely shallow pits.	<<1
Cu	1	Very little corrosion.	-
	2	As above.	-
	3	As above, a few discolored areas.	-
	6	Very little corrosion.	-
Mild Steel	1	General corrosion with a few discrete pits.	<<1
	2	As above.	<<1
	3	A few small pits.	0.5
	6	Some surface roughening, a few small pits, higher pit frequency at crevice.	0.5
Stainless	1	A few very shallow pits.	<<1
	2	A few very shallow pits.	<<1
	3	As above.	<<1
	6	Very little attack. A few extremely small pits.	<<1

Table 31

Localized Corrosion Observations for Samples in Therminol 44

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth (mils)
Al	1	Very light corrosion with a few shallow pits.	<<1
	2	Several shallow pits.	<1
	3	As above.	<1
	6	A few pits. Deeper pits in crevice region to 1 mil.	0.5
Cu	1	Very light general corrosion.	-
	2	Slight surface roughening.	-
	3	As above.	-
	6	Roughened surface.	-
Mild Steel	1	Slightly roughened surface with infrequent shallow pits.	<1
	2	Roughened surface with many small pits.	<1
	3	Surface slightly roughened with a few scattered pits.	0.5
	6	Surface slightly roughened. Many pits up to 1 mil deep. More pits at crevice up to 1 mil.	1

(Continued)

Table 31

Localized Corrosion Observations for Samples in Therminol 44

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth (mils)
Stainless	1	Very little corrosion. A few areas with very shallow pits.	<<1
	2	As above.	<<1
	3	A few discolored areas. Little corrosion evident.	-
	6	Very little attack. A few discolored areas.	-

Table 32

Localized Corrosion Observations for Samples in Dow Corning 200

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth (mils)
Al	1	Very little corrosion. No pits visible.	-
	2	As above.	-
	3	As above.	-
	6	Very little corrosion. No pits visible.	-
Cu	1	Very little corrosion. Some discolored areas.	-
	2	As above.	-
	3	As above.	-
	6	Slight surface roughening.	-
Mild Steel	1	No apparent corrosion.	-
	2	A few very shallow pits.	<1
	3	Slight surface roughening. A few shallow pits.	1
	6	Slight surface roughening. Many shallow pits. Pits up to 2 mils in crevice.	1

Table 32(cont'd)

Localized Corrosion Observations for Samples Immersed in Dow Corning 200

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth (mils)
Stainless	1	A few areas of general corrosion.	-
	2	Very low frequency shallow pits.	<<1
	3	A few very shallow pits.	<<1
	6	Surface covered with many small etch pits. Shallow pits <0.5 mils in crevice.	<<1

Table 33

Localized Corrosion Observations for Samples in Union Carbide Silicone Fluid

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth (mils)
Al	1	No observeable corrosion.	-
	2	As above.	-
	3	No general attack, on occasional shallow pits.	0.1
	6	No noticeable general corrosion. Occasional shallow pits.	0.3
Cu	1	No corrosion.	-
	2	No corrosion.	-
	3	Occasional shallow pit in crevice (0.2 mils)	-
	6	Very slight general corrosion. A few pits in crevice to 0.4 mils.	-
Mild Steel	1	No corrosion.	-
	2	Occasional very shallow pit.	0.1
	3	Little general corrosion with occasional shallow pit. More and deeper pits in crevice to 0.3 mils.	0.2
	6	Very light general corrosion with an occasional pit. Deepen pits in crevice region to 1 mil.	0.5

Table 33 (cont'd)

Localized Corrosion Observations for Samples in Union Carbide Silicone Fluid

Alloy	Time (months)	Localized Corrosion Observations	Max Pit Depth (mils)
Stainless	1	No corrosion.	-
	2	No corrosion.	-
	3	No corrosion.	-
	6	No general corrosion. An occasional very shallow small pit in crevice (<0.1 mils)	-

TABLE 34

LOCALIZED CORROSION OBSERVATIONS ON BIMETALLIC COUPLES IMMERSED IN SOLAR FLUIDS FOR 6 MONTHS

Solution	Sample	Corrosion Observations
NHTW	SS-MS	Mild steel, almost completely dissolved. Stainless, little attacked.
	Cu-MS	Mild steel all dissolved. Cu roughened, grain boundaries slightly attacked.
	Cu-SS	Little attack on stainless steel. Crevice attack on Cu to 5 mils.
NHTW Cu-SS only	Cu-SS	Some small patches of general corrosion on stainless steel. General corrosion of Cu with crevice corrosion to 1 mil.
NHTW Cu-SS Solder flux	Cu-SS	Occasional very shallow small pit on SS (<0.1 mil). Surface of Cu very roughened with a few small pits to .2 mils. Crevice corrosion to 1 mil.
ASTM Water	SS-MS	Mild steel completely dissolved. Little attack on stainless.
	Cu-MS	Mild steel almost all dissolved. Cu has crevice attack to 3 mils.
	Cu-SS	Stainless has considerable general corrosion, Cu slightly roughened with discrete pits in crevice to 0.5 mils.
Ethylene Glycol H_2O	SS-MS	Mild steel totally dissolved. Little attack on stainless.
	Cu-MS	Mild steel totally dissolved. Little attack on copper.
	Cu-SS	(Sample broke)
Propylene Glycol/H_2O	SS-MS	Mild steel almost totally dissolved. Little attack on stainless.

TABLE 34(cont'd 2)

LOCALIZED CORROSION OBSERVATIONS ON BIMETALLIC COUPLES IMMERSED IN SOLAR FLUIDS FOR 6 MONTHS

Solution	Sample	Corrosion Observations
	Cu-MS	Mild steel totally dissolved. Slight surface roughening of Cu.
	Cu-SS	Surface roughening of Cu with pits in crevice to 1 mil. Little attack of stainless.
Thermally Degraded Propylene Glycol	SS-MS	Mild steel totally dissolved. Patches of general corrosion on SS.
	Cu-MS	Mild steel totally dissolved. Cu surface roughened with pits in crevice to 0.3 mils.
	Cu-SS	Small patches of general corrosion on SS. Cu surface severely roughened. Crevice corrosion to 0.4 mils.
Thermally Degraded Prop. Glycol. Initial RA or 10.	SS-MS	Mild steel totally dissolved. Stainless sample shows little evidence of corrosion.
	Cu-MS	Mild steel totally dissolved. Cu surface severely roughened with a few pits to 0.5 mils. Higher frequency of pits in crevice.
	Cu-SS	Some small shallow pits on stainless in crevice region. Cu surface severely roughened with etched appearance. A few shallow pits (0.1 mils). Higher frequency of deeper pits in crevice (0.2 mils).
Thermally Degraded Prop. Glycol RA = 10	SS-MS	No visible corrosion on stainless. Mild steel totally dissolved in crevice region and on one edge of the sample.

TABLE 34(cont'd 3)

LOCALIZED CORROSION OBSERVATIONS ON BIMETALLIC COUPLES IMMERSED IN SOLAR FLUIDS FOR 6 MONTHS

Solution	Sample	Corrosion Observations
	Cu-MS	Complete perforation of mild steel in several regions including the crevice. Copper surface roughened with a finely etched appearance and a few shallow pits (0.1 mils). More pits in crevice to 0.2 mils.
	Cu-SS	A few small patches of general corrosion on stainless with occasional very shallow pit. Cu surface irregularly roughened. Pits in crevice to 0.5 mils.
Nutek 876	SS-MS	No corrosion of stainless. Mild steel severely roughened with many pits 2 mils deep. Crevice attack to 4 mils.
	Cu-MS	Cu surface roughened. Mild steel very roughened with many pits 2 mils deep. Crevice attack to 2 mils.
	Cu-SS	No corrosion of stainless. Cu surface generally roughened with occasional pits in crevice to 0.5 mils.
Nutek 835	SS-MS	Surface of mild steel roughened. Little attack on stainless.
	Cu-MS	Severe surface roughening of mild steel. Slight surface roughening of Cu with a few pits in crevice to 0.5 mils.
	Cu-SS	Cu severely roughened with a few discrete pits. Little attack of stainless.
HTF-273	SS-MS	Some surface roughening of MS. A few discrete pits <0.5 mils deep. Severe roughening in crevice with pits to 0.5 mils.

TABLE 34(cont'd 4)

LOCALIZED CORROSION OBSERVATIONS ON BIMETALLIC COUPLES IMMERSED IN SOLAR FLUIDS FOR 6 MONTHS

Solution	Sample	Corrosion Observations
	Cu-MS	Surface roughening of mild steel with pits 0.5 mils deep. In crevice pits 1 mil deep. Little attack of Cu.
	Cu-SS	Slight corrosion of Cu with a few pits in crevice to 0.5 mils.
Dow Frost	SS-MS	General corrosion of mild steel with a few shallow pits. No attack of stainless.
	Cu-MS	Mild steel slightly roughened with a few 0.5 mil pits. Cu surface slightly roughened.
	Cu-SS	Little attack of stainless, Cu surface slightly roughened.
Climax B	SS-MS	Stainless slightly discolored but no evidence of corrosion. A few patches of general corrosion on mild steel with some associated shallow pits (0.2 mils).
	Cu-MS	Very light general corrosion of Cu with some small pits in crevice (0.1 mils). Patches of general corrosion of mild steel with some shallow pits (0.1 mil).
	Cu-SS	Light general corrosion of Cu with some crevice corrosion (0.1 mils) and pitting (0.2 mil). A few very shallow pits on steinless.
Olin (P126)	SS-MS	Slight general corrosion of mild steel. Little attack of stainless.
	Cu-MS	Little attack of mild steel. Some roughening of Cu surface. Discrete pits in Cu in crevice to 0.5 mils.

TABLE 34(cont'd 5)

LOCALIZED CORROSION OBSERVATIONS ON BIMETALLIC COUPLES IMMERSED IN SOLAR FLUIDS FOR 6 MONTHS

Solution	Sample	Corrosion Observations
	Cu-SS	Slight general corrosion of stainless. A few pits in Cu in crevice to 0.5 mils.
Olin(with molybdate)	SS-MS	General corrosion of mild steel, a few shallow pits. No attack of stainless.
	Cu-MS	General corrosion of mild steel with a few 0.5 mil pits. Some general corrosion of Cu.
	Cu-SS	No attack of stainless. Cu surface slightly roughened with 1 mil pits in crevice.
Olin X-6	SS-MS	General corrosion of mild steel with several small pits to 0.3 mils. No attack on stainless.
	Cu-MS	Little general corrosion of mild steel with only a few small pits to 0.3 mils. Cu surface uniformly corroded with fine etch appearance. Occasional small pits in crevice (0.2 mils).
	Cu-SS	No general corrosion of stainless. A few very shallow small pits. Cu surface roughened with finely etched appearance. Several shallow pits (0.4 mils).
Olin X-E	SS-MS	Occasional small pits (0.3 mils) in a slightly roughened mild steel surface. No corrosion of stainless.
	Cu-MS	Patches of general corrosion on mild steel with some small pits to 0.2 mils. Copper surface moderately roughened with occasional small pits (0.1 mils).

TABLE 34(cont'd 6)

LOCALIZED CORROSION OBSERVATIONS ON BIMETALLIC COUPLES
IMMERSED IN SOLAR FLUIDS FOR 6 MONTHS

Solution	Sample	Corrosion Observations
	Cu-SS	No corrosion of stainless. Cu surface roughened wtih fine etched appearance and some small pits (0.1 mils).
Olin X-M	SS-MS	No corrosion of stainless. Mild steel surface showed patches of general corrosion with a few shallow pits (0.1 mil)
	Cu-MS	Uniform finely etched Cu surface with a few pits in crevice to 0.1 mils. Mild steel showed a few small patches of general corrosion with occasional small pits to 0.3 mils.
	Cu-SS	Light uniform fine etching of Cu with some pits in crevice to 0.2 mils. No corrosion of stainless.
NPC-218	SS-MS	No observable corrosion of stainless. General corrosion of mild steel with several pits to 2 mils. Crevice corrosion to 2 mils.
	Cu-MS	Fairly uniform general corrosion of Cu with a few shallow pits in crevice (0.2 mils). Mild steel general corroded with some pits to 2 mils. Crevice corrosion to 1 mil.
	Cu-SS	No corrosion of stainless. Uniform general corrosion of Cu with surface roughening.
SunSol 60	SS-MS	Discoloration of stainless but no observable attack. Mild steel shows discrete regions of general corrosion with some pits to 0.3 mils. Crevice corrosion to 0.5 mils.
	Cu-MS	General corrosion and surface roughening of Cu with several pits in crevice to 0.5 mils.

TABLE 34(cont'd 7)

LOCALIZED CORROSION OBSERVATIONS ON BIMETALLIC COUPLES IMMERSED IN SOLAR FLUIDS FOR 6 MONTHS

Solution	Sample	Corrosion Observations
		Mild steel generally corroded with several small ptis (0.4 mils) Crevice corrosion to 0.5 mils.
	Cu-SS	Discoloration of stainless. A few very shallow pits in crevice. Cu surface roughened with a few pits in crevice to 0.2 mils.
Prestone II	SS-MS	Slight general corrosion of mild steel. No attack of stainless.
	Cu-MS	Slight general corrosion of mild steel. Little attack on Cu.
	Cu-SS	No attack of stainless. Slight general corrosion of Cu.
Dowtherm SR1	SS-MS	Some general corrosion of mild steel with a few shallow pits <0.5 mils. No attack of stainless.
	Cu-MS	Surface roughening of mild steel with a few pits 0.5 mils. Some general corrosion of Cu.
	Cu-SS	No attack on stainless. Some general corrosion of Cu with a few shallow pits in crevice.
Brayco 888	SS-MS	Only slight general corrosion of mild steel, slightly more in crevice. No attack of stainless.
	Cu-SS	A little general corrosion of Cu with a few pits in crevice <0.5 mils. No attack of stainless.
	Cu-MS	Surface roughening of mild steel with a few pits in crevice to 0.5 mils. No attack of Cu.

TABLE 34(cont'd 8)

LOCALIZED CORROSION OBSERVATIONS ON BIMETALLIC COUPLES IMMERSED IN SOLAR FLUIDS FOR 6 MONTHS

Solution	Sample	Corrosion Observations
Therminal 44	SS-MS	A few scattered pits in mild steel <1 mil. No attack on stainless.
	Cu-MS	Considerable surface roughening of mild steel. No attack of Cu.
	Cu-SS	Little general corrosion. Pits in Cu in crevice to 0.5 mils.
Dow Corning 200	SS-MS	A few corroded areas on mild steel. No attack of stainless.
	Cu-MS	Slight general corrosion of mild steel, no attack of Cu.
	Cu-SS	Very little attack.
Union Carbide Silicone	SS-MS	No corrosion of stainless. Very light general corrosion of mild steel with occasional shallow pit (0.1 mils). More pits in crevice region.
	Cu-MS	Very light general corrosion of Cu with a few pits in crevice to 0.2 mils. Light general corrosion of mild steel with occasional very shallow pit (<0.1 mils).
	Cu-SS	No corrosion of stainless. Very light general corrosion of Cu with a few pits in crevice to 0.3 mils.

TABLE 35

WEIGHT LOSS OF STAINLESS STEEL SAMPLES IN SIMULATED SOLAR ENERGY HEATED SWIMMING - POOL WATER TEST

Days	Weight Loss ($\mu g/cm^2$)		
	500 ppm Cl^-	1000 ppm Cl^-	1500 ppm Cl^-
30	35	3	13
	43	5	13
60	30	10	9
	28	14	14
90	35	24	13
	28	27	17
180	36	15	28
	39	24	31

TABLE 36

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES EXPOSED TO CHLORIDE CONTAINING WATER IN TROUGH TEST

Alloy	ppm Cl^-	Time (months)	Localized Corrosion Observations
Cu	500	1	Lightly etched surface.
		2	Roughened surface with a finely etched appearance. Some crevice corrosion to 0.3 mils.
		3	Similar to above with occasional very shallow pit (0.1 mil). Crevice corrosion to 0.8 mils.
		6	Roughened surface with a finely etched appearance. No discrete pits. Crevice corrosion to 1 mil.
Stainless Steel	500	1	No corrosion.
		2	No corrosion.
		3	Occasional small patches of general corrosion.
		6	Small patches of general corrosion with some associated very shallow pits (<0.1 mils)
Cu	1000	1	Slightly roughened surface with more attack at crevice.
		2	Roughened etched surface with crevice corrosion to 0.4 mils.
		3	Heavily roughened surface. Some areas with grain boundaries etched. Crevice corrosion to 0.5 mils.
		6	Very rough surface with some grain boundary etching. Occasional pits in crevice to 1 mil Crevice corrosion to 0.5 mils.

TABLE 36(cont'd)

LOCALIZED CORROSION OBSERVATIONS FOR SAMPLES EXPOSED TO CHLORIDE CONTAINING WATER IN TROUGH TEST

Alloy	ppm Cl^-	Time (months)	Localized Corrosion Observations
Stainless Steel	1000	1	No corrosion.
		2	A few small patches of general corrosion. Occasional very shallow pit in crevice (<0.1 mils)
		3	As above.
		6	Some small patches of general corrosion with occasional very shallow pits (<0.1 mils).
Cu	1500	1	Slightly roughened surface.
		2	Roughened surface with crevice corrosion to 0.4 mils.
		3	Irregular roughened surface. Crevice attack to 0.5 mils.
		6	More uniformly roughened surface with no discrete pits. Crevice attack to 0.4 mils.
Stainless Steel	1500	1	A few small patches evident of general corrosion.
		2	As above.
		3	Some patches of general corrosion with occasional irregular shallow pit in crevice (<0.1 mils).
		6	Some small patches of general corrosion with in some cases very small shallow pit (<0.1 mil).

TABLE 37

PROPERTIES OF FLUIDS DURING SIMULATED SOLAR TESTING

Fluid	Day	pH	Freezing Pt(°F)*
NHTW (all metals)	1	7.06	32
	61	7.96	32
	84	7.86	32
	98	8.4	32
	112	8.2	32
	140	8.43	32
	180	8.6	32
ASTM water	1	7.24	32
	56	9.06	32
	70	8.7	32
	112	7.91	32
	168	8.5	32
	180	8.7	32
Propylene Glycol	1	4.87	<-40
	28	4.82	-40
	112	4.77	- 5
	140	4.68	0
	180	4.28	- 5
Ethylene Glycol	1	7.27	-30
	28	4.81	-35
	56	6.3	-30
	84	5.05	-30
	112	4.94	-25
	180	4.8	-19
Olin	1	9.23	<-40
	42	8.6	<-40
	60	8.41	<-40
	84	8.1	-40
	112	7.8	-35
	140	7.87	-27
	180	7.7	-18
Olin (with BTA)	1	8.69	-27
	32	8.34	-28
	84	8.12	-25
	112	8.04	-15
	168	7.9	-12
	180	7.9	-12
Nutek 876	1	7.49	32
	29	8.61	32
	42	8.5	32
	60	8.67	32
	140	9.33	32
	168	9.42	32

TABLE 37(cont'd)

PROPERTIES OF FLUIDS DURING SIMULATED SOLAR TESTING

Fluid	Day	pH	Freezing Pt(^{o}F)*
Nutek 835	1	7.72	10
	28	7.83	8
	56	7.9	10
	84	7.8	10
	112	7.96	10
	180	7.76	15
Dowtherm SR1	1	9.06	-37
	42	8.93	-40
	61	8.75	-33
	112	8.47	-33
	140	8.43	-21
	180	8.25	-17
Dowfrost	1	9.23	-40
	28	8.6	-35
	61	8.42	-27
	112	8.2	-20
	180	8.1	-20
HTF-273	1	10.5	-35
	28	10.2	-35
	56	9.8	-25
	84	9.3	-20
	141	9.2	-15
	180	9.0	-11
Prestone II	1	10.8	-25
	30	10.42	-27
	42	10.33	-27
	112	9.5	-27
	168	9.2	-6
	181	9.2	-6
NPC 218	1	10.31	-35
	28	9.1	-35
	56	8.95	-35
	168	8.56	-15
	180	8.94	-10

*Calculated from refractive index measurements assuming optical properties of a pure water-glycol mixture.

TABLE 38

INITIAL AND FINAL PH VALUES OF FLUIDS IN SIMULATED SOLAR TEST

Fluid	Initial pH	Final pH
NHTW (Cu and Steel)	5.9	6.4
NHTW (Cu, steel, solder flux)	5.1	5.4
Thermally degraded propylene glycol	4.2	3.8
Thermally degraded propylene glycol Initial RA = 10	6.9	4.7
Thermally degraded propylene glycol, maintained at RA = 10	6.9	6.1
Los Alamos, Dowfrost	8.45	7.8
Nellis Domestic	6.8	6.3
Homestead	7.15	7.8
Climax A	7.4	6.9
Climax B	7.8	6.8
Sunsol 60	8.7	8.1
Olin X-6	8.5	7.6
Olin X-E	8.8	7.6
Olin X-M	8.4	7.7

TABLE 39

RESERVE ALKALINITY OF SOLAR FLUIDS EXPRESSED IN MLS OF 0.1N HCL REQUIRED TO TITRATE 10 MLS OF SOLUTION

Solution	Reserve Alkalinity	
	Initial Value	6 month Value
NHTW	.1	.05
ASTM	.15	.15
Prop. glycol/H_2O	.05	.05
Ethyl glycol/H_2O	.05	.05
Nutek 876	.9	1.2
Nutek 835	.85	.6
Olin	3.05	1.9
Olin(with BTA)	3.0	1.8
HTF	5.5	3.9
Prestone II	6.6	4.83
NPC 218	5.7	4.3
DowFrost	5.8	4.4
Dowtherm	6.5	5.8
Degraded prop. glycol	0	0
Degraded prop. glycol RA adjusted to 10	10	0.3

TABLE 40

WEIGHT LOSS, CORROSION RATE, AND DEPTH OF PITTING AND CREVICE ATTACK FOR CU ALLOY 122 AFTER 180 DAYS.

Fluid	Weight Loss (mg/cm^2)	Instantaneous Corrosion Rate (mpy)	Pit Depth (mils)	Crevice Attack (mils)
New Haven tap	1.5	0.21	-	1
Propylene glycol	1.4	0.25	-	1
Ethylene glycol	2.2	0.11	-	-
Nutek 876	3.8	0.54	-	0.5
Nutek 835	1.4	0.18	-	0.5
HTF 273	0.76	0.1	-	-
Dow Frost	2.8	0.06	-	<.1
Climax A	1.6	0.29	-	0.5
Climax B	1.4	0.29	-	0.2
Olin	1.6	0.18	-	-
Olin(BTA, molybdate)	0.58	0.015	-	-
Olin X-6	1.53	0.42	0.7	1
Olin X-E	1.02	0.26	-	0.2
Olin X-M	0.9	0.26	-	-
Sunsol 60			-	0.5
NPC 218	0.73	0.11	-	0.5
Dowtherm	0.82	0.11	0.5	-
Prestone II	0.42	0.013	-	-

TABLE 41

AMOUNT OF GENERAL CORROSION, WEIGHT LOSS, DEPTH OF PITTING AND CREVICE CORROSION OF AL ALLOY 1100 AFTER 180 DAYS

Fluid 1	General Corrosion	Weight Loss (mg/cm^2)	Pit Depth (mils)	Crevice Attack (mils)
New Haven tap water	Heavy	9.8	4	-
ASTM water	Heavy	6.96	<1	-
Ethylene glycol	Heavy	6.9	3	8
Propylene glycol	Heavy	11.08	4	4
Thermally degraded Propylene glycol	Severe	21.5	5	6
Degraded Glycol Reserve Alkalinity at 10	Heavy	10.9	2	6
As above but maintained at 10	Heavy	7.38	3	5
Nutek 876	Heavy	16.3	-	3
Nutek 835	Moderate	0.76	0.5	4
HTF-273	Little	0.004	1	-
DowFrost	Little	0.13	<1	1
Climax A	Moderate	2.6	1	-
Climax B	Heavy		3	4
Olin	Little	0.031	<1	-
Olin(BTA,molybdate)	Little	0.018	<1	-
Olin X-6	Little	0.027	0.6	0.3
Olin X-E	Little	0.027	-	0.2
Olin X-M	Little	0.020	0.1	-

TABLE 41(Cont'd)

AMOUNT OF GENERAL CORROSION, WEIGHT LOSS, DEPTH OF PITTING AND CREVICE CORROSION OF AL ALLOY 1100 AFTER 180 DAYS

Fluid 1	General Corrosion	Weight Loss (mg/cm^2)	Pit Depth (mils)	Crevice Attack (mils)
Sun Sol 60	Grain Boundary attack	3.1	1	1
NPC-218	Little	0.018	<1	-
Dowtherm SRI	Little	0.032	0.5	0.5
Prestone II	Little	0.016	1	-
Brayco 88	V.Little	0.027	<.1	-
Therminol 44	None	0.034	0.5	1
Dow Corning 200	None	0.011	-	-
Union Carbide Silicone	None	0.010	0.3	-

TABLE 42

AMOUNT OF GENERAL CORROSION, WEIGHT LOSS, DEPTH OF PITTING AND CREVICE CORROSION OF MILD STEEL ALLOY 1010 AFTER 180 DAYS

Fluid	General Corrosion	Weight Loss (mg/cm^2)	Pit Depth (mils)	Crevice Attack (mils)
New Haven tap w.	Heavy	132	3	perf.
ASTM water	Heavy	153	-	perf.
Ethylene glycol	Fragmented	-	-	-
Propylene glycol	Fragmented	-	-	-
Degraded glycol	Fragmented	-	-	-
As above, initial reserve alkalinity=10	Heavy	53	7	perf.
Nutek 876	Moderate	2.2	2	3
Nutek 835	Moderate	8.0	5	5
HTF-273	Slight	1.1	1	-
DowFrost	Moderate	2.4	0.5	1
Climax A	Slight	0.4	0.5	-
Climax B	Moderate	0.75	1.8	4
Olin	Moderate	2.2	1	1
Olin(BTA,molybdate)	Little	0.5	<1	-
Olin X-6	Little	0.26	1	-
Olin X-E	Little	0.12	0.3	0.3
Olin X-M	Little	0.08	0.5	-
SunSol 60	Moderate		0.5	-
NPC-218	Moderate	2.7	0.5	1.5
Dowtherm	Moderate	2.1	0.5	0.5
Prestone II	Moderate	2.3	1	1

TABLE 42(Cont'd)

AMOUNT OF GENERAL CORROSION, WEIGHT LOSS, DEPTH OF PITTING AND CREVICE CORROSION OF MILD STEEL ALLOY 1010 AFTER 180 DAYS

Fluid	General Corrosion	Weight Loss (mg/cm^2)	Pit Depth (mils)	Crevice Attack (mils)
Brayco 88	Little	0.13	0.5	-
Therminol 44	Little	0.075	1	1
Dow Corning 200	Little	0.085	1	2
Union Car. Silicone	Little	0.043	0.5	1

TABLE 43

DEPTH OF PITTING AND CREVICE ATTACK ON FERRITIC STEEL 444 AFTER 180 DAYS

Fluid	Pit Depth (mils)	Crevice Attack (mils)
New Haven tap water	<.1	-
As above with Cu only	-	-
As above with solder-flux	<.1	0.4
Nellis Domestic	<.1	0.1
Homestead Domestic	<.1	-
Los Alamos Dow Frost	-	-
ASTM water	<.1	-
Ethylene glycol	<.1	0.1
Propylene glycol	<.1	-
Degraded glycol	0.1	-
As above, reserve alkalinity=10	<.1	<.1
As above, RA maintained at 10	-	0.7
Nutek 876	-	-
Nutek 835	-	-
HTF-273	-	<.1
DowFrost	-	-
Climax A	-	-
Climax B	-	-
Olin	-	-
Olin(BTA, molybdate)	-	-
Olin X-6	-	0.1
Olin X-E	0.1	-
Olin X-M	-	<.1
Sunsol 60	-	-
NPC-218	-	-
Dowtherm SRI	-	-
Prestone II	0.5	1
Brayco 88	-	-
Therminol 44	-	-
Dow Corning 200	<.1	<0.5
Union Carbide Silicone	-	<.1

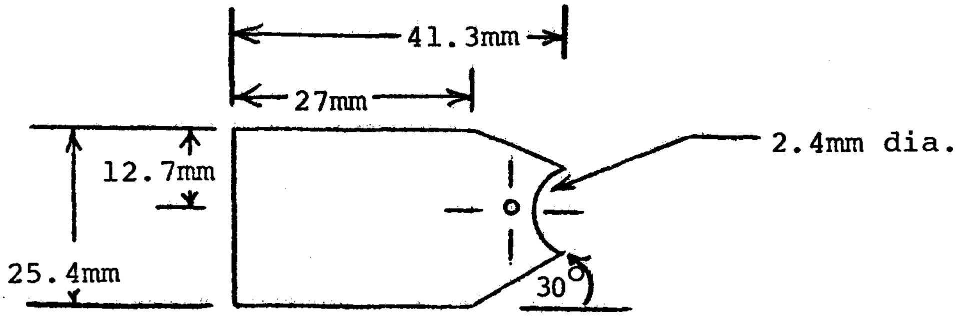


Figure 1. Sample geometry used in solar energy corrosion test program.

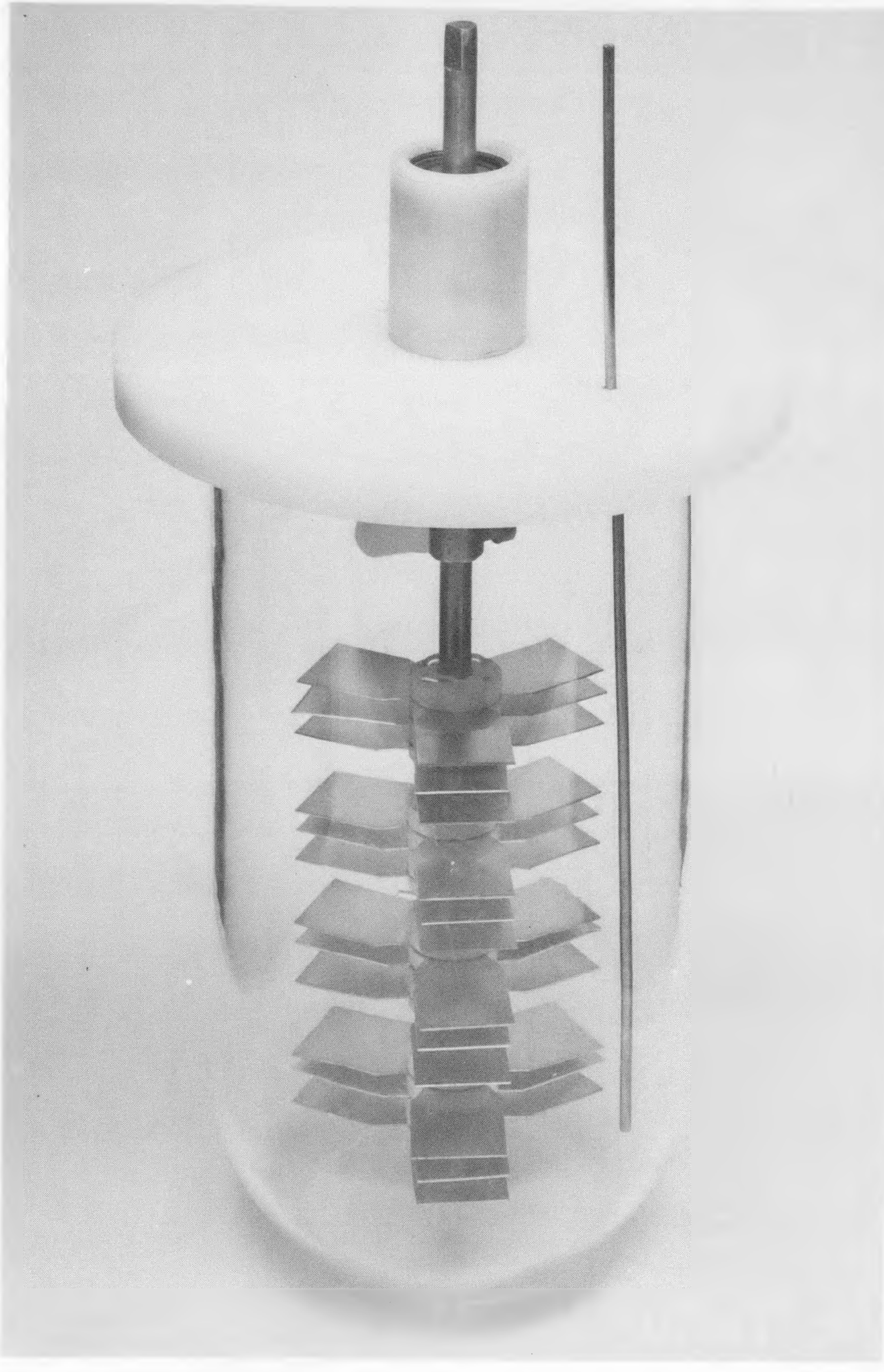


Figure 2. Assembled test cell used in solar corrosion test program.

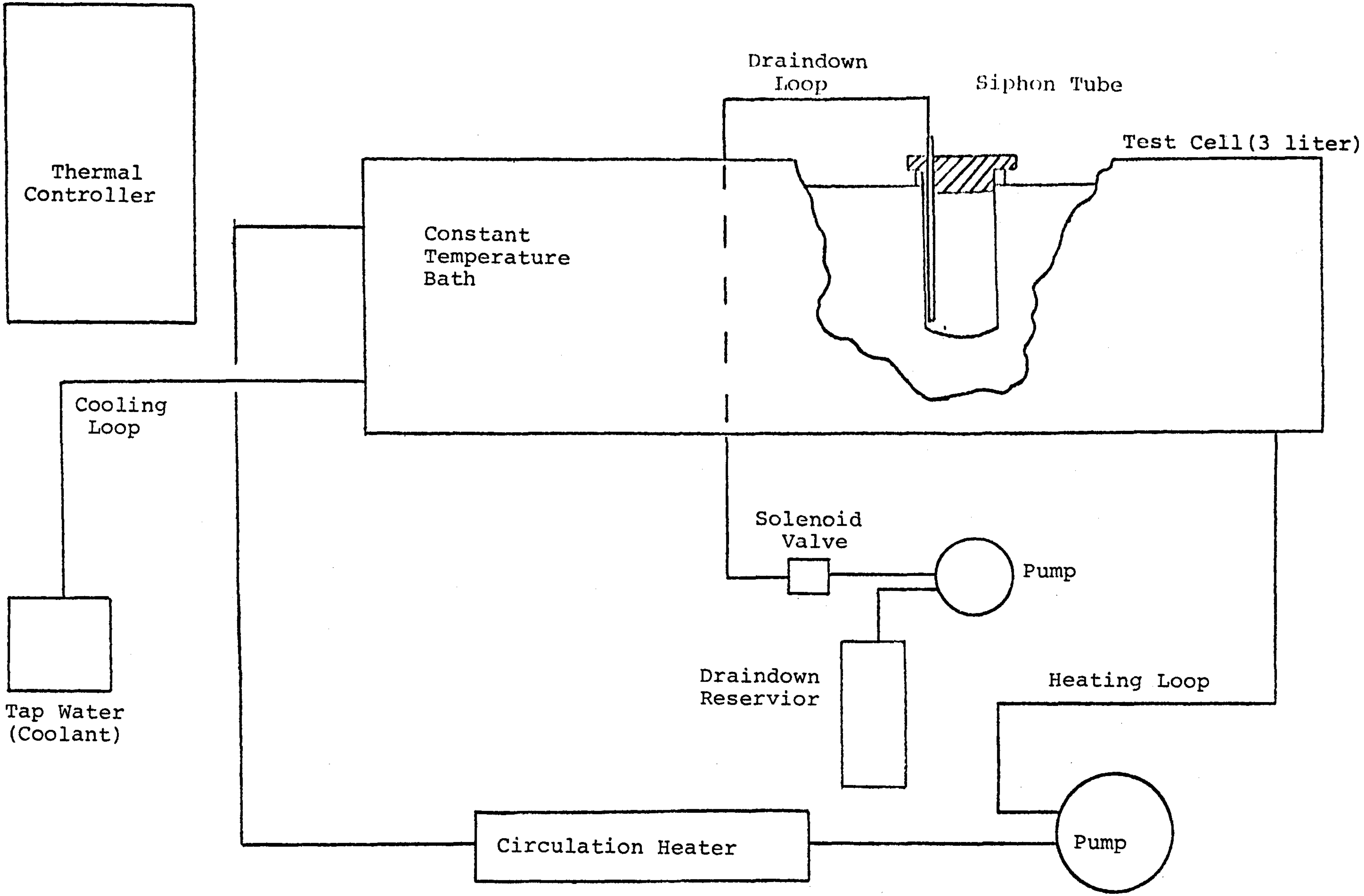


Figure 3. Schematic drawing of temperature control equipment used to establish the desired thermal profile.

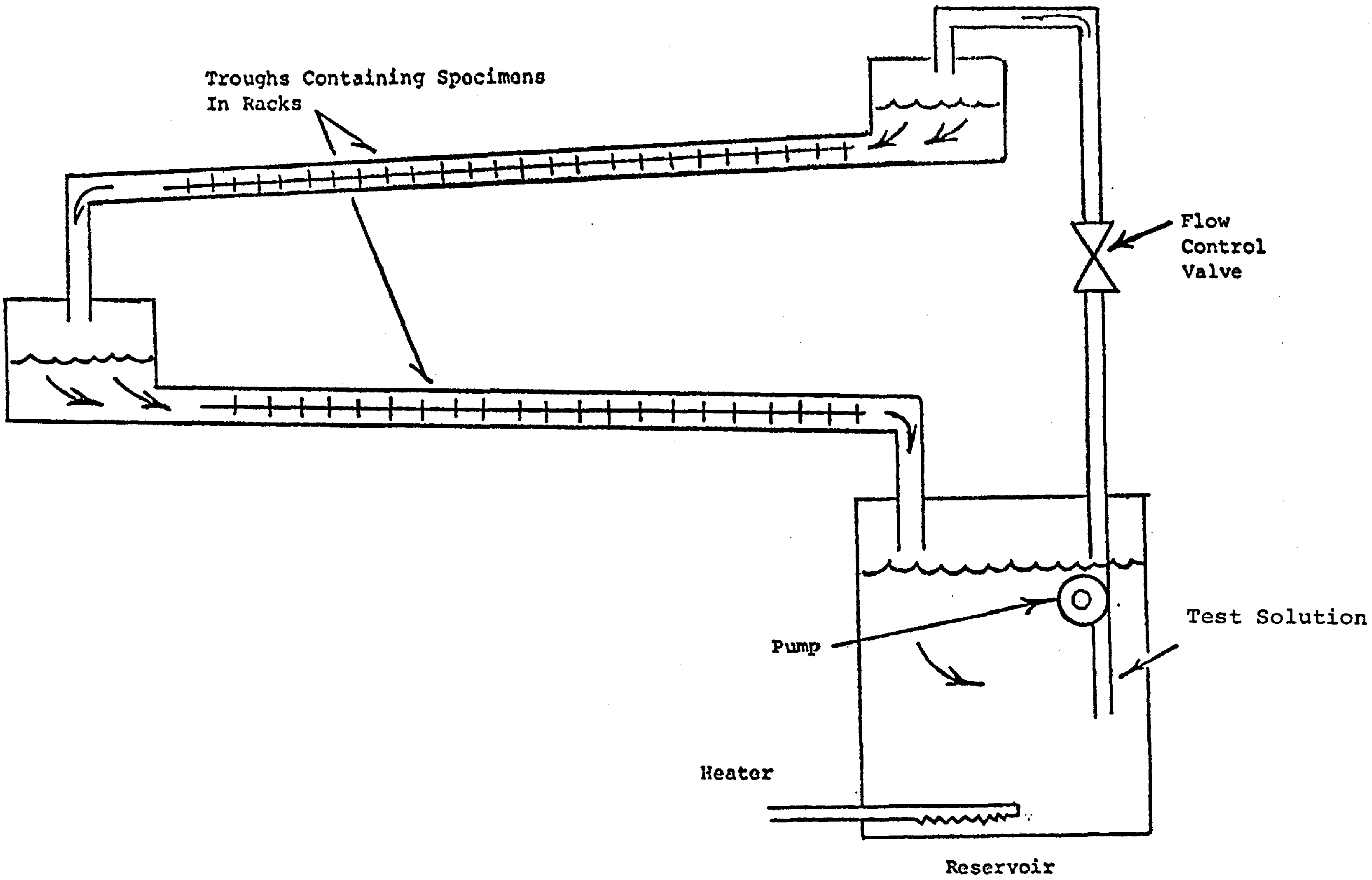


Figure 4. Apparatus used to test effect of chloride ion concentration on corrosion of copper and stainless steel.

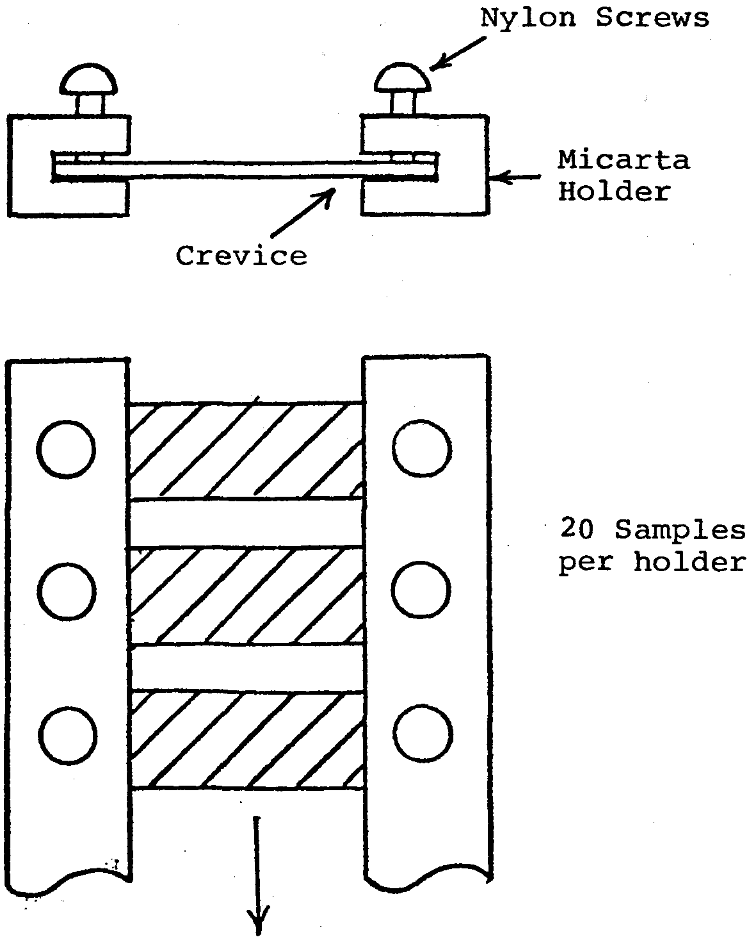


Figure 5. Sample holder used in test loops for evaluating effect of chloride ion on the corrosive attack in copper and stainless steel.

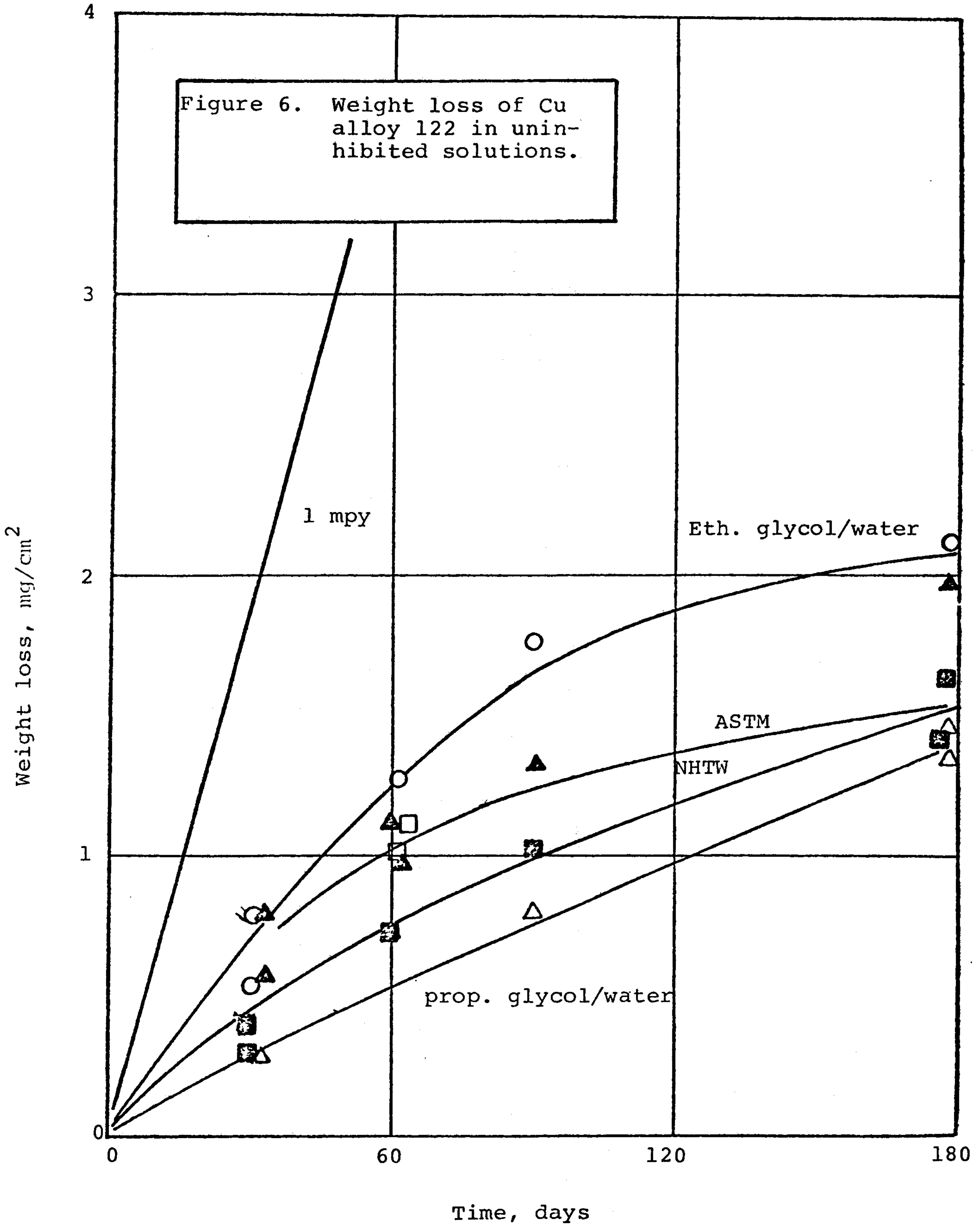


Figure 6. Weight loss of Cu alloy 122 in uninhibited solutions.

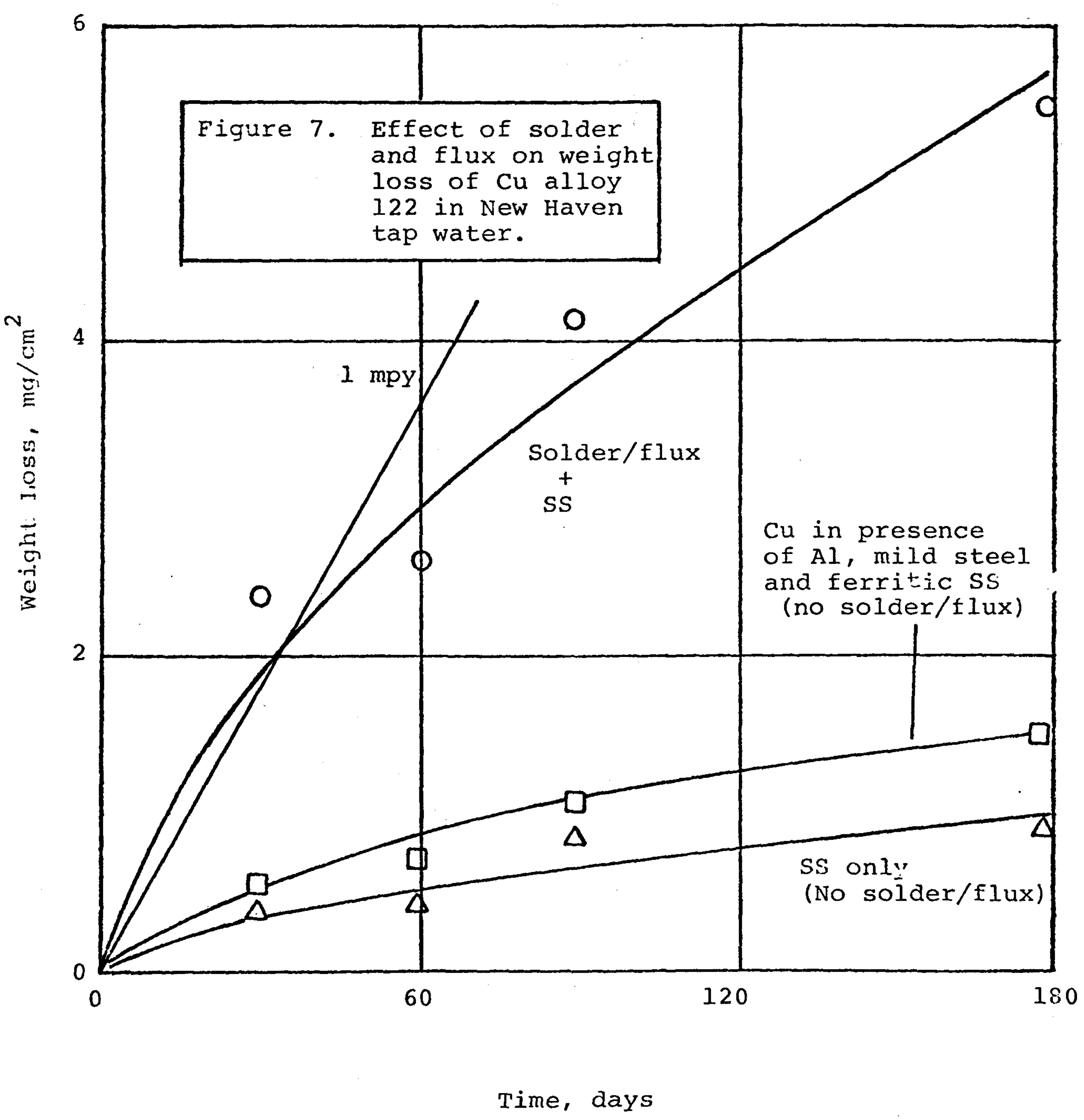


Figure 7. Effect of solder and flux on weight loss of Cu alloy 122 in New Haven tap water.

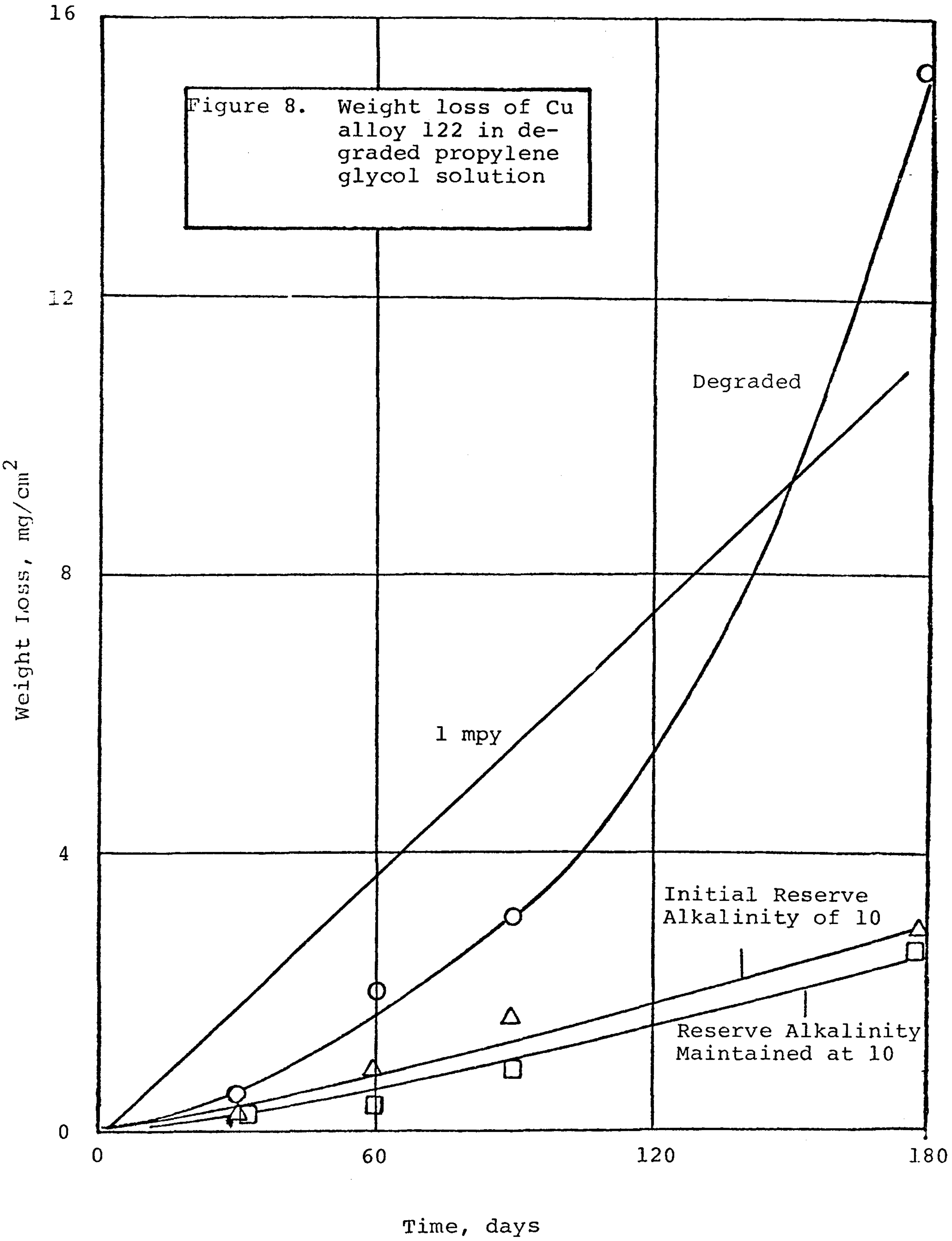


Figure 8. Weight loss of Cu alloy 122 in degraded propylene glycol solution

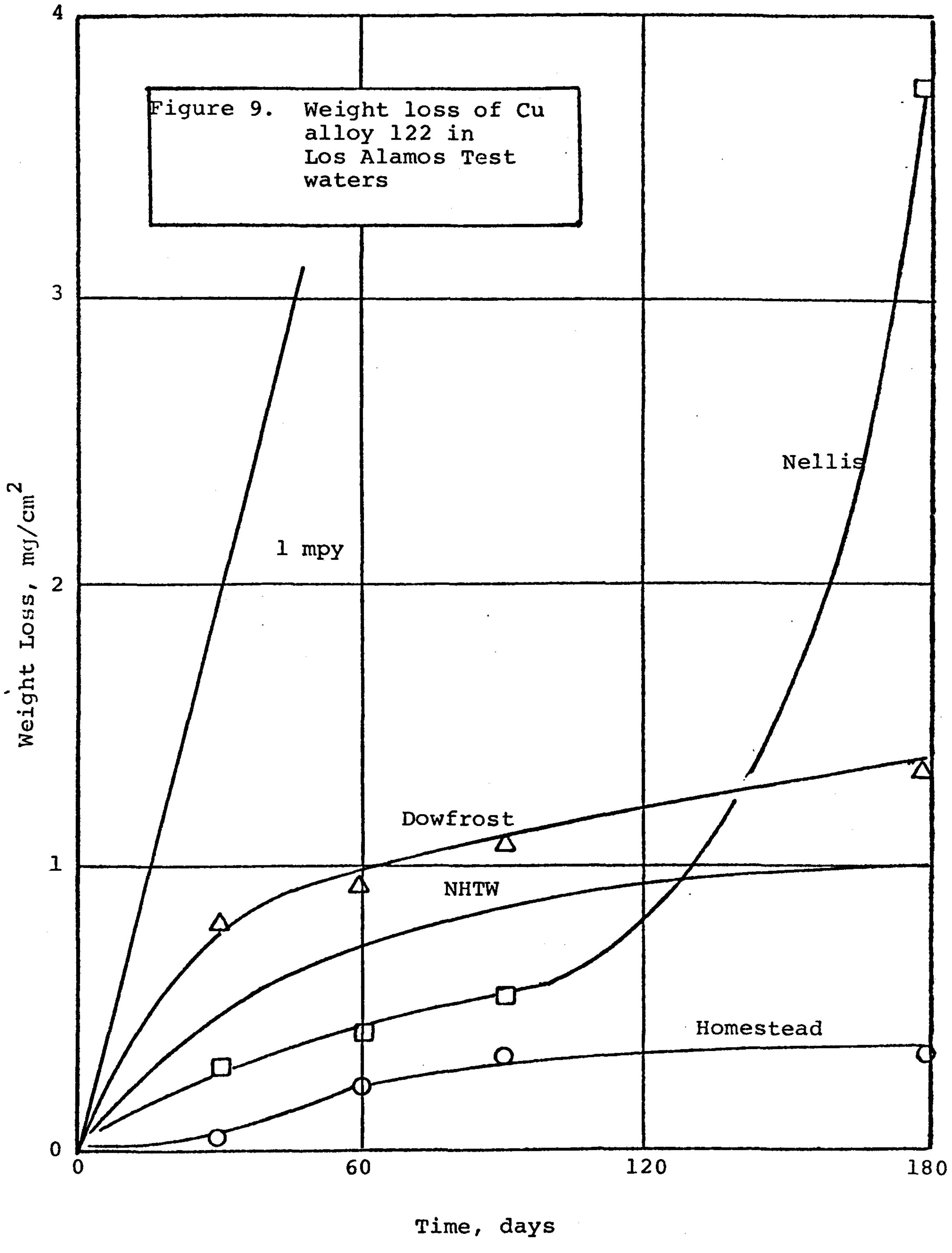
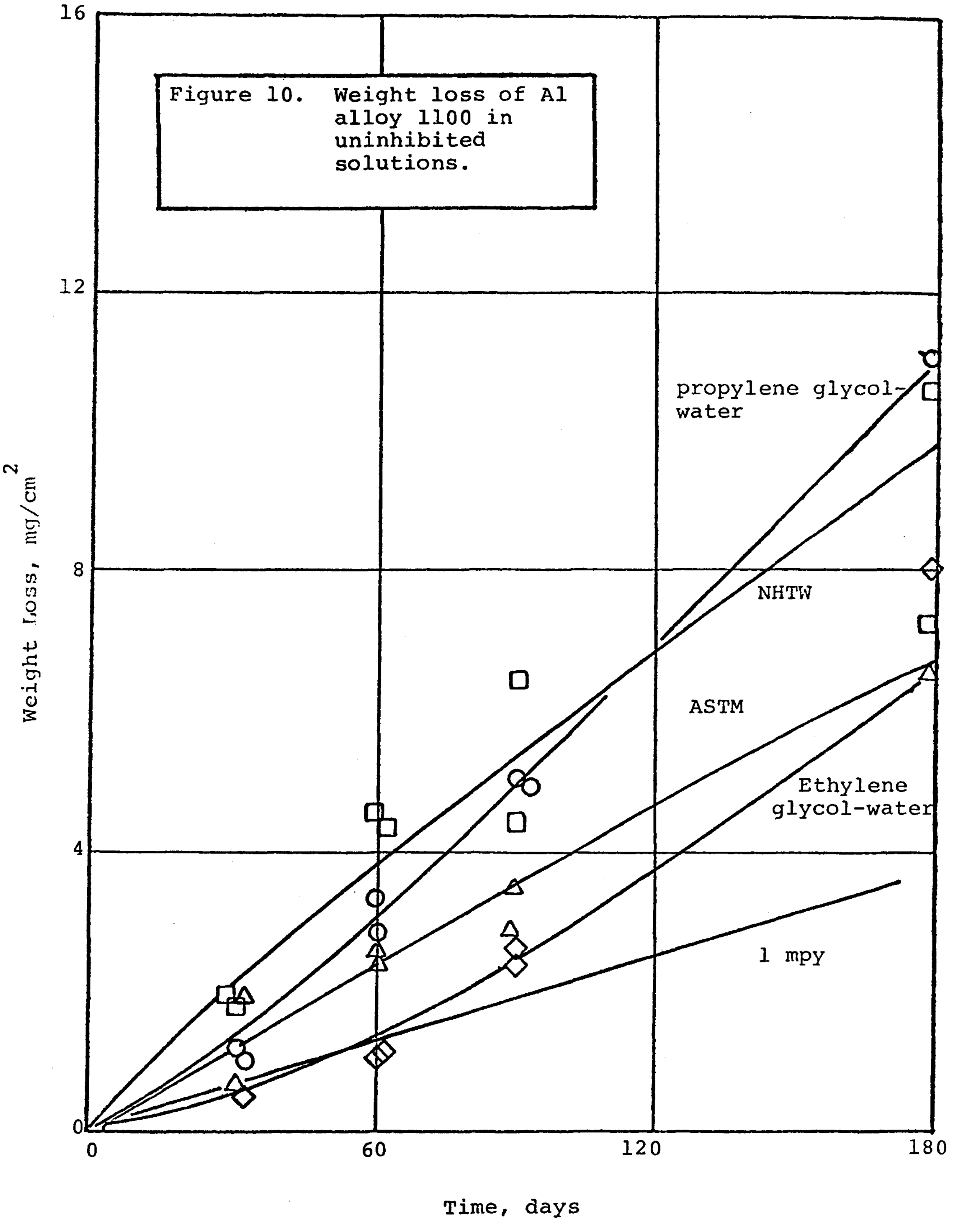


Figure 9. Weight loss of Cu alloy 122 in Los Alamos Test waters

Figure 10. Weight loss of Al alloy 1100 in uninhibited solutions.



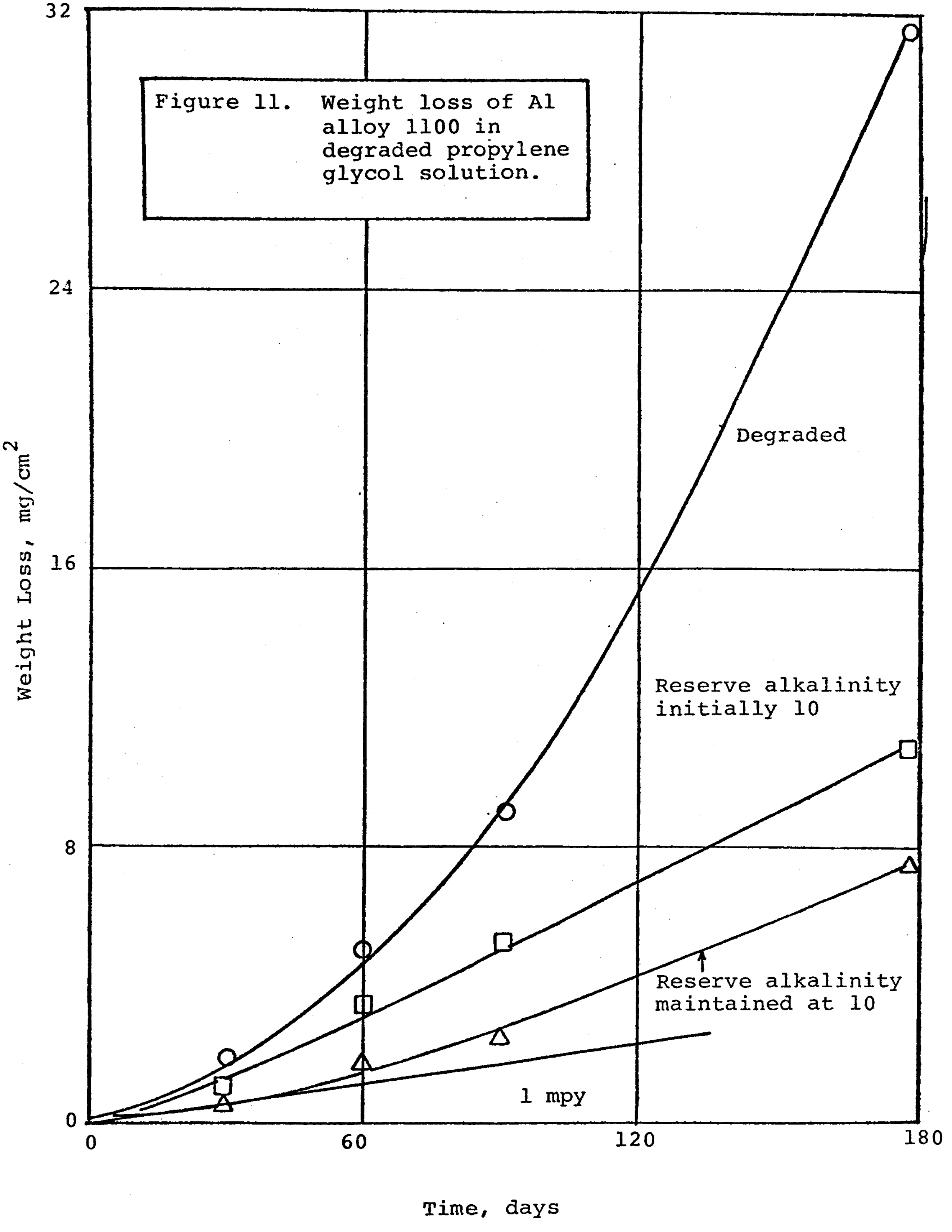


Figure 11. Weight loss of Al alloy 1100 in degraded propylene glycol solution.

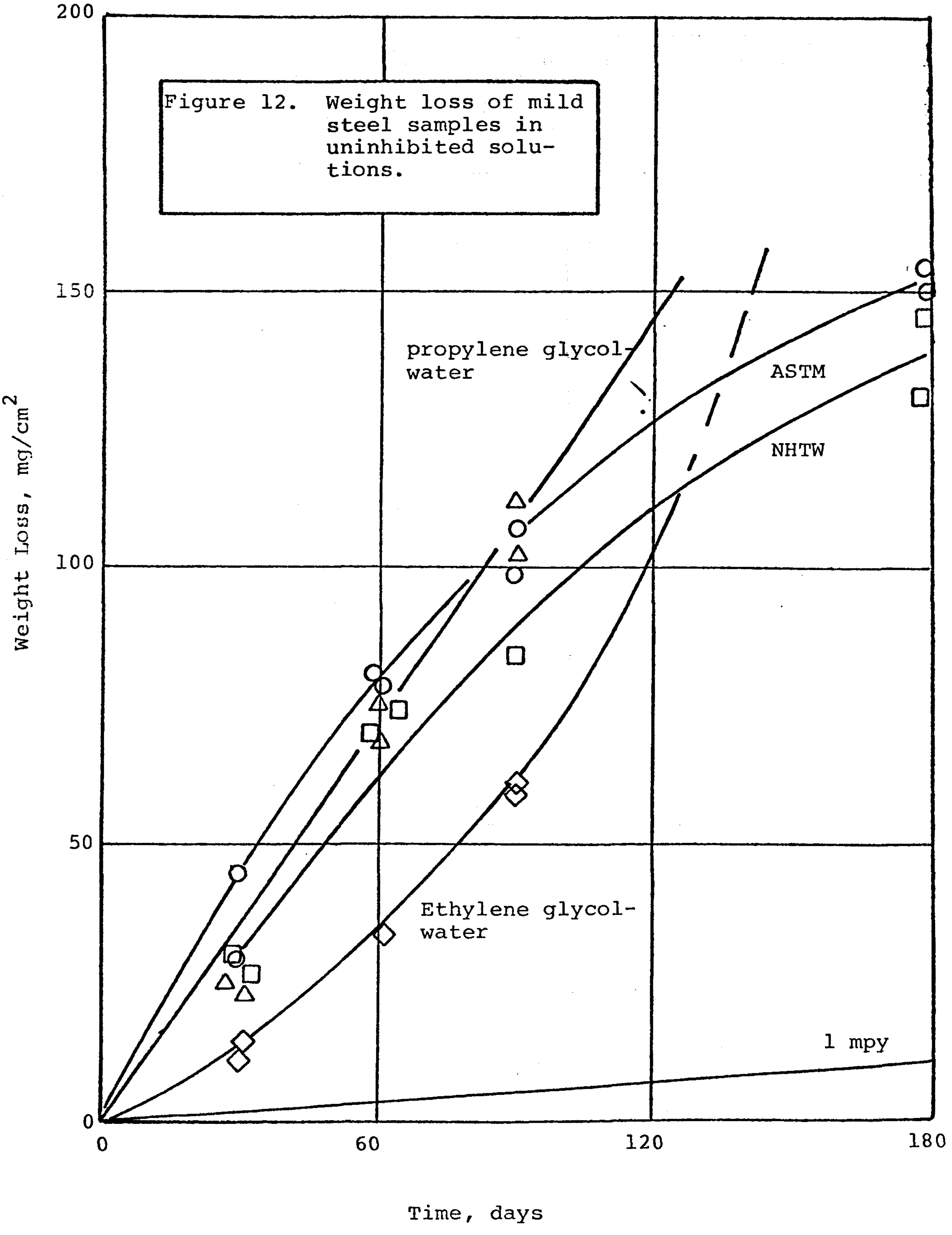


Figure 12. Weight loss of mild steel samples in uninhibited solutions.

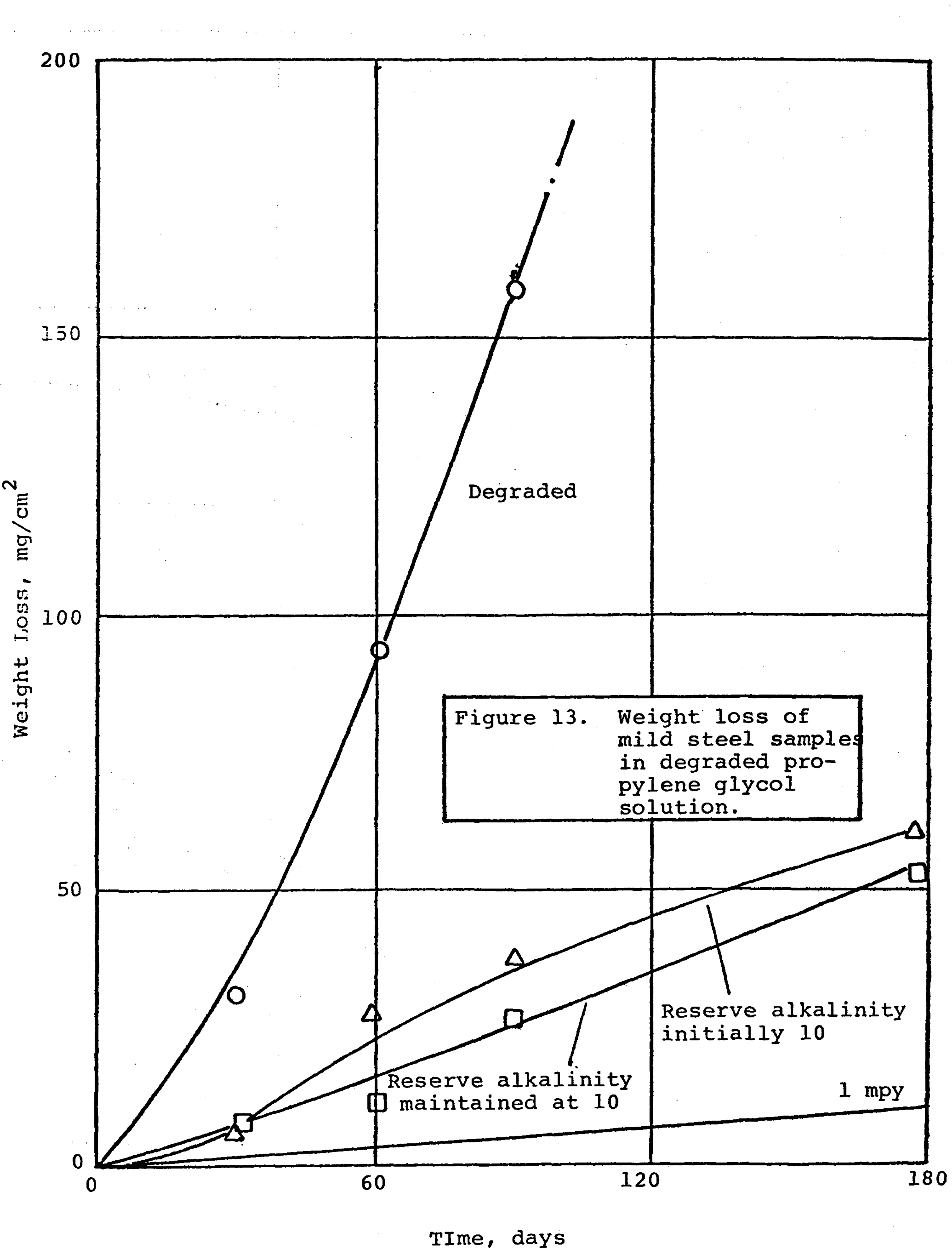


Figure 13. Weight loss of mild steel samples in degraded propylene glycol solution.

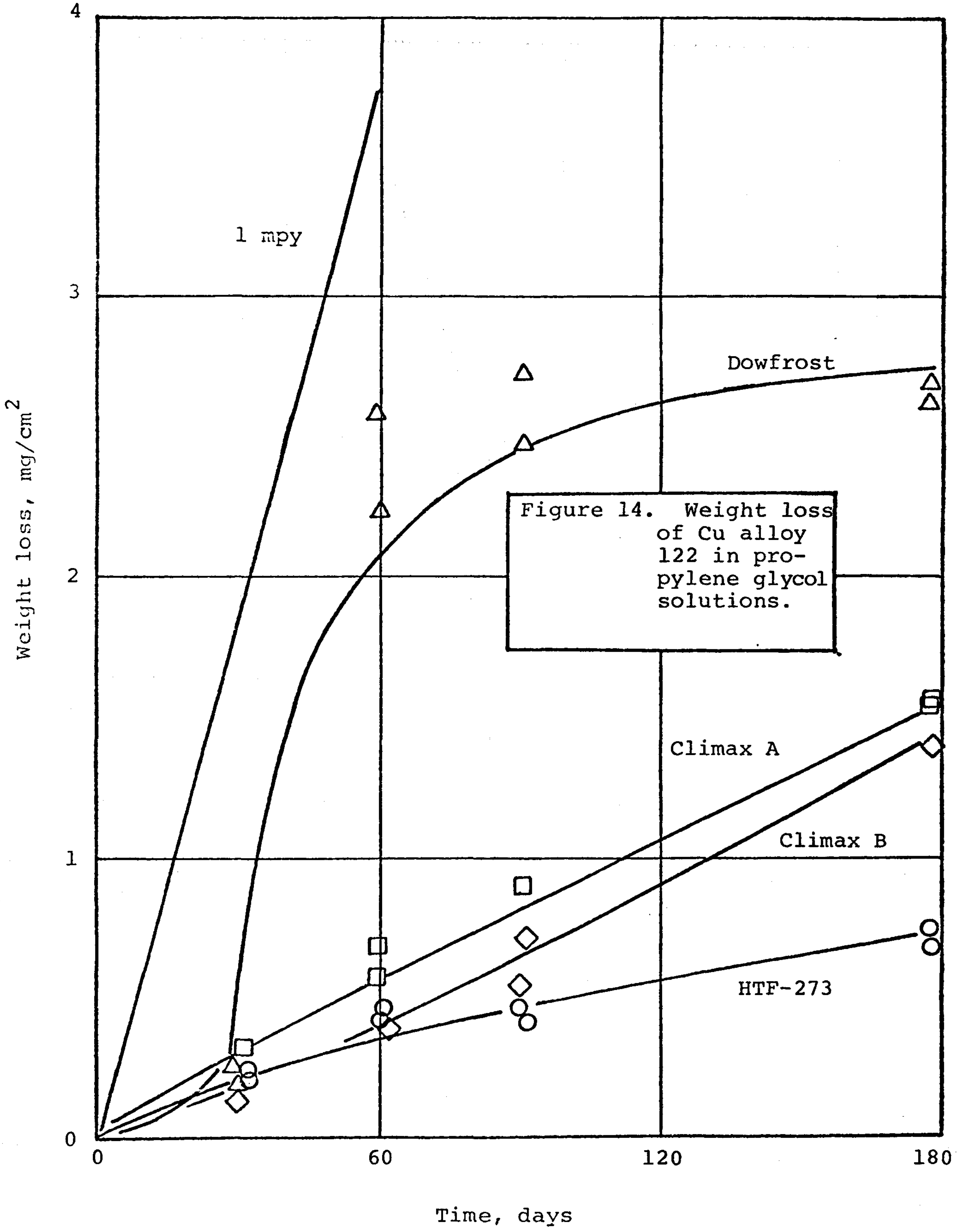


Figure 14. Weight loss of Cu alloy 122 in propylene glycol solutions.

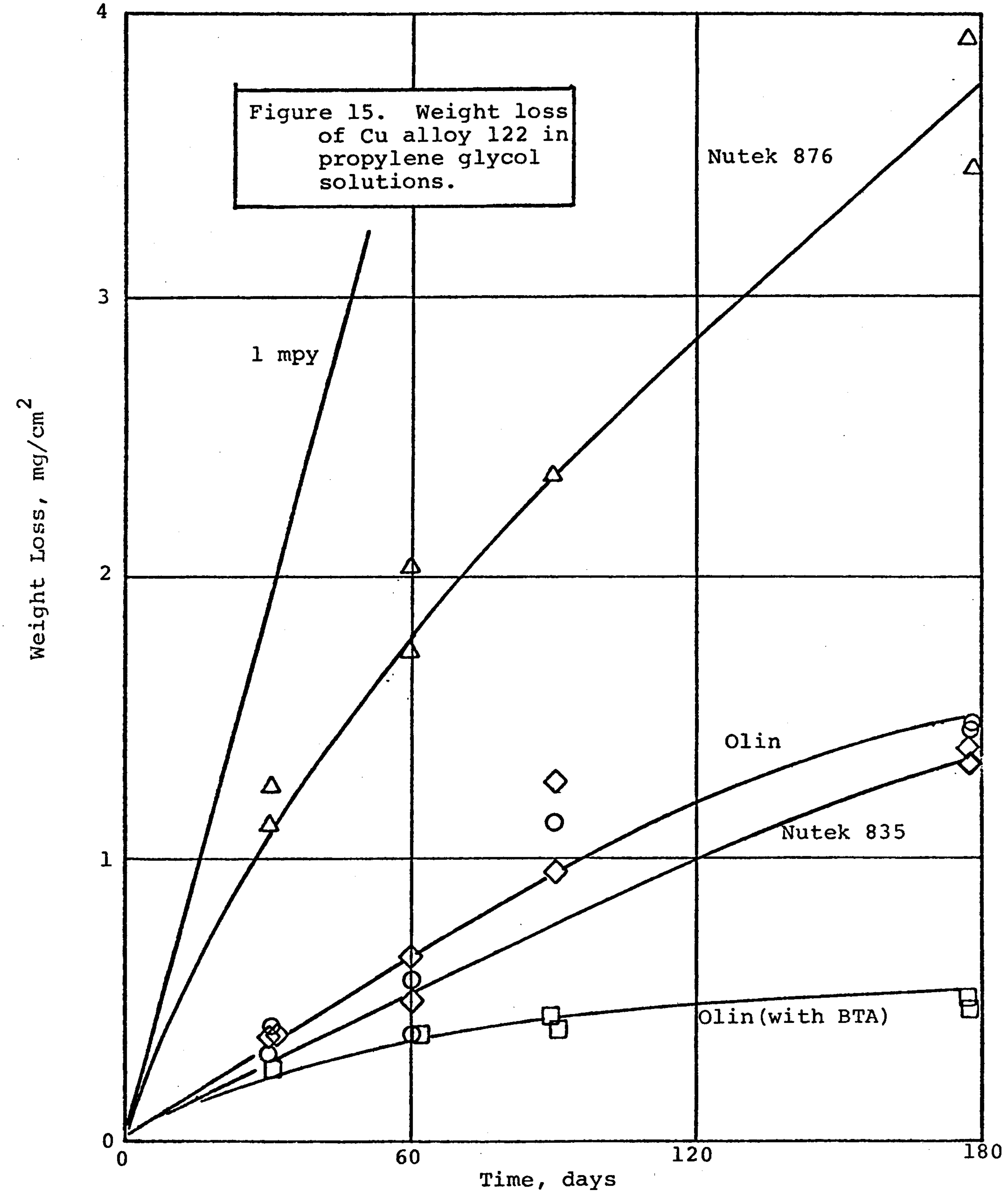


Figure 15. Weight loss of Cu alloy 122 in propylene glycol solutions.

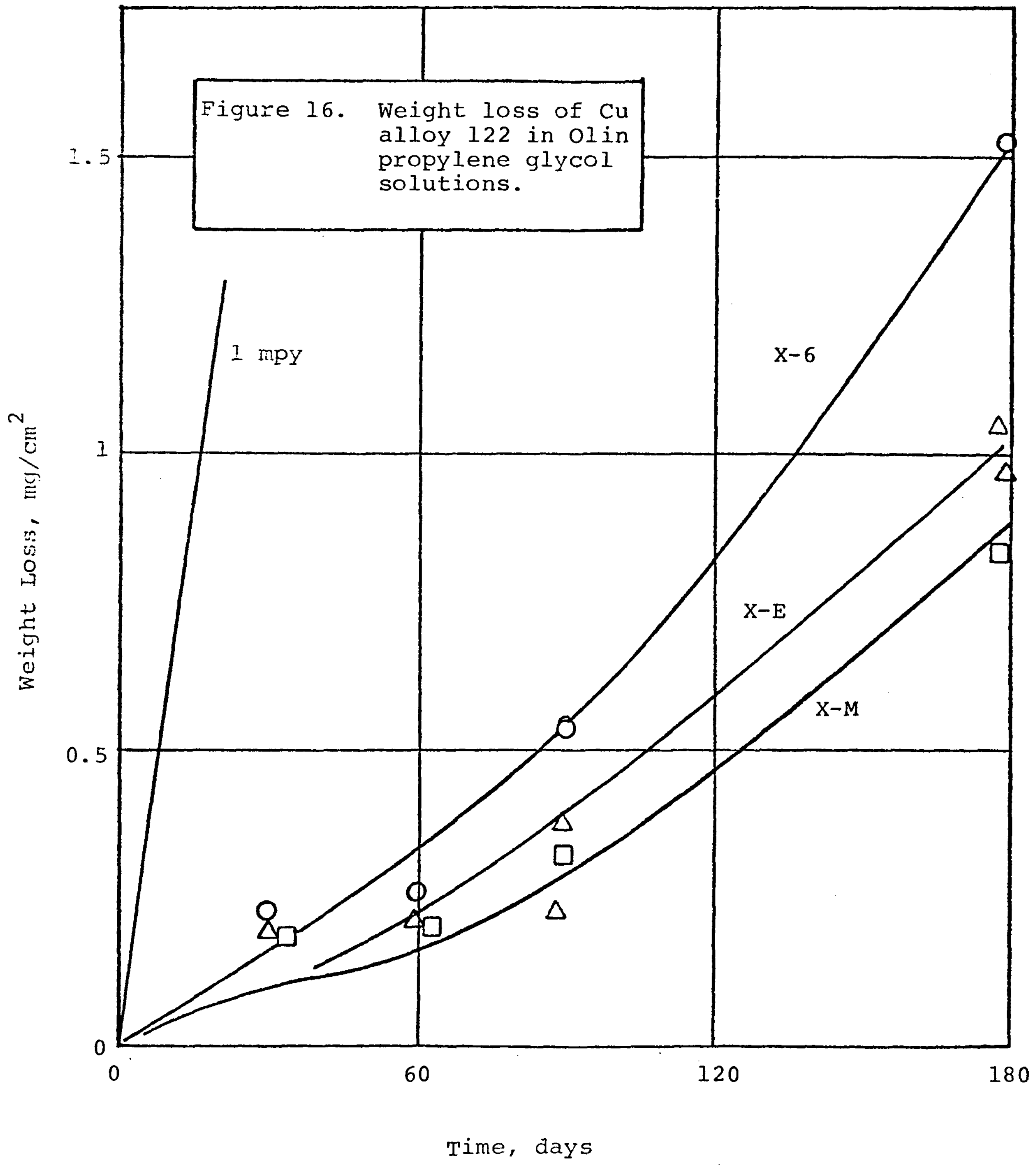


Figure 16. Weight loss of Cu alloy 122 in Olin propylene glycol solutions.

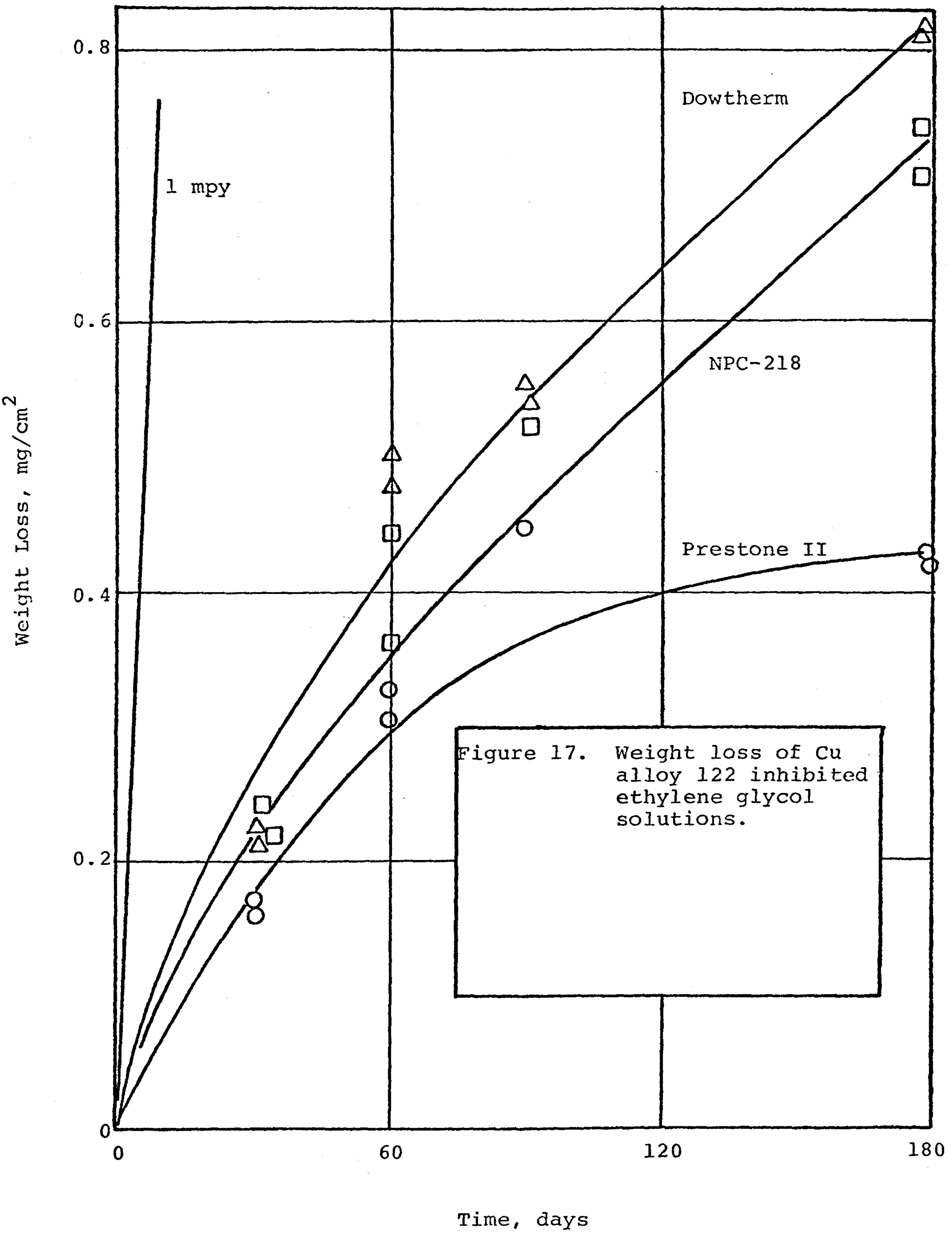


Figure 17. Weight loss of Cu alloy 122 inhibited ethylene glycol solutions.

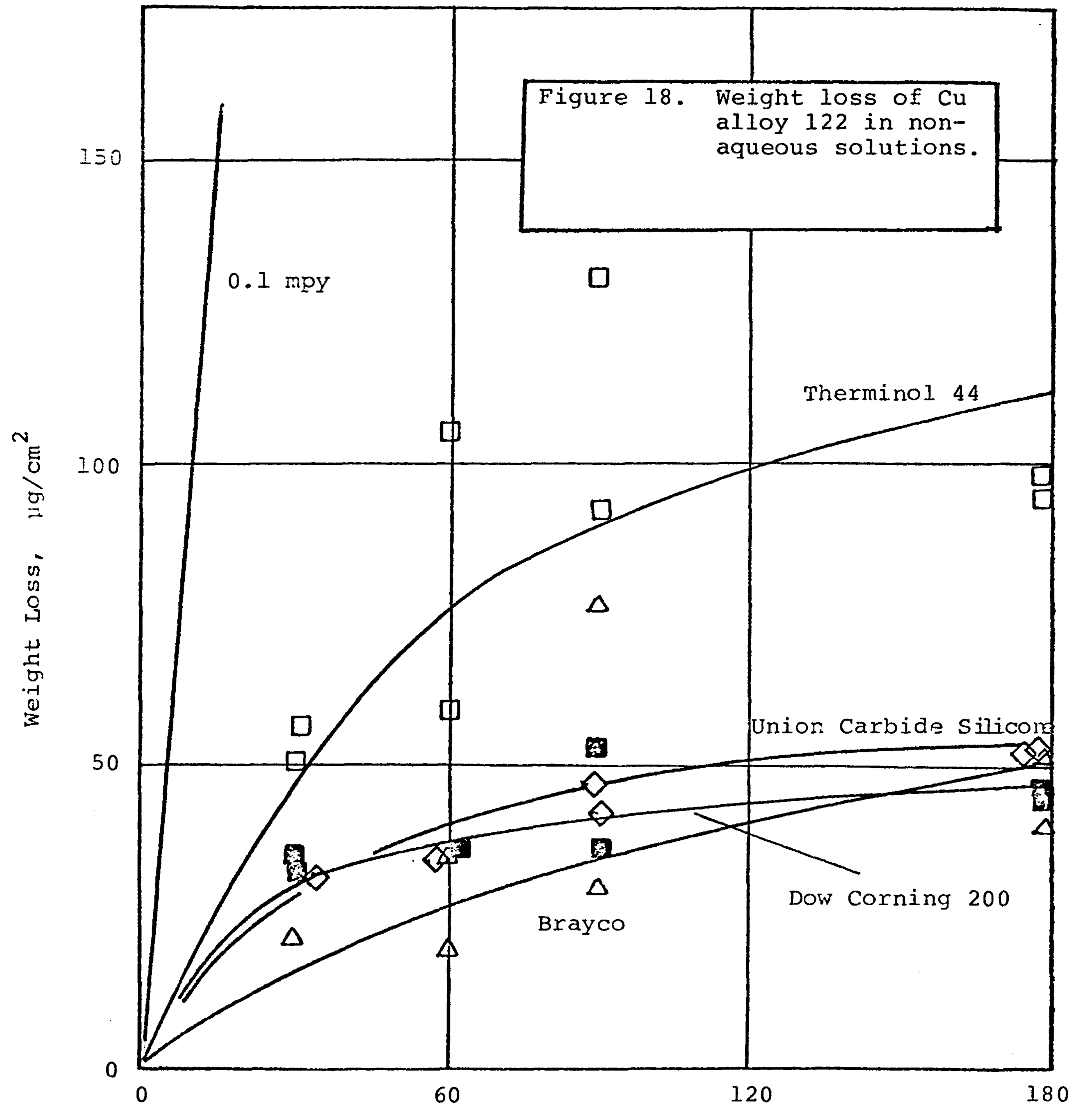


Figure 18. Weight loss of Cu alloy 122 in non-aqueous solutions.

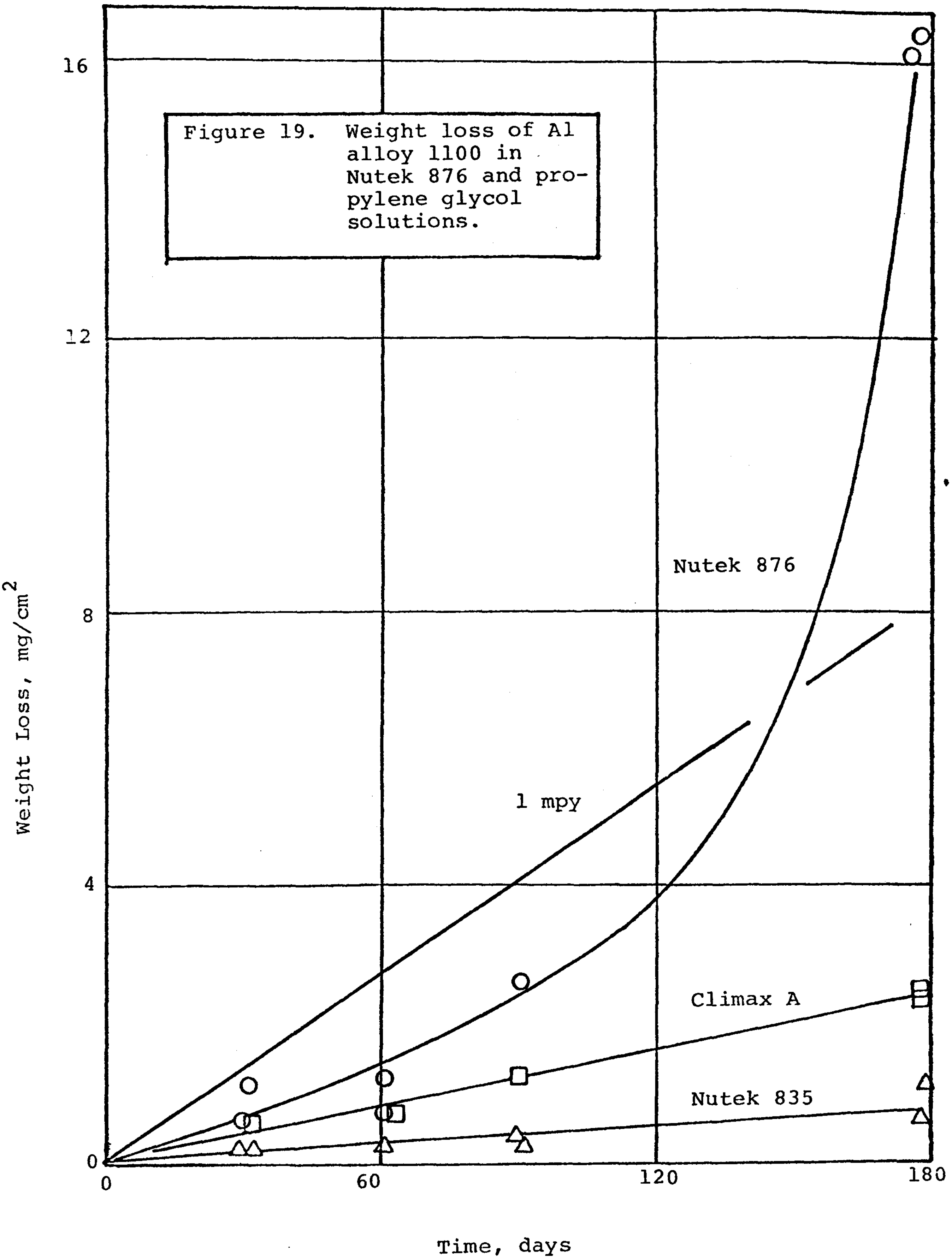


Figure 19. Weight loss of Al alloy 1100 in Nutek 876 and propylene glycol solutions.

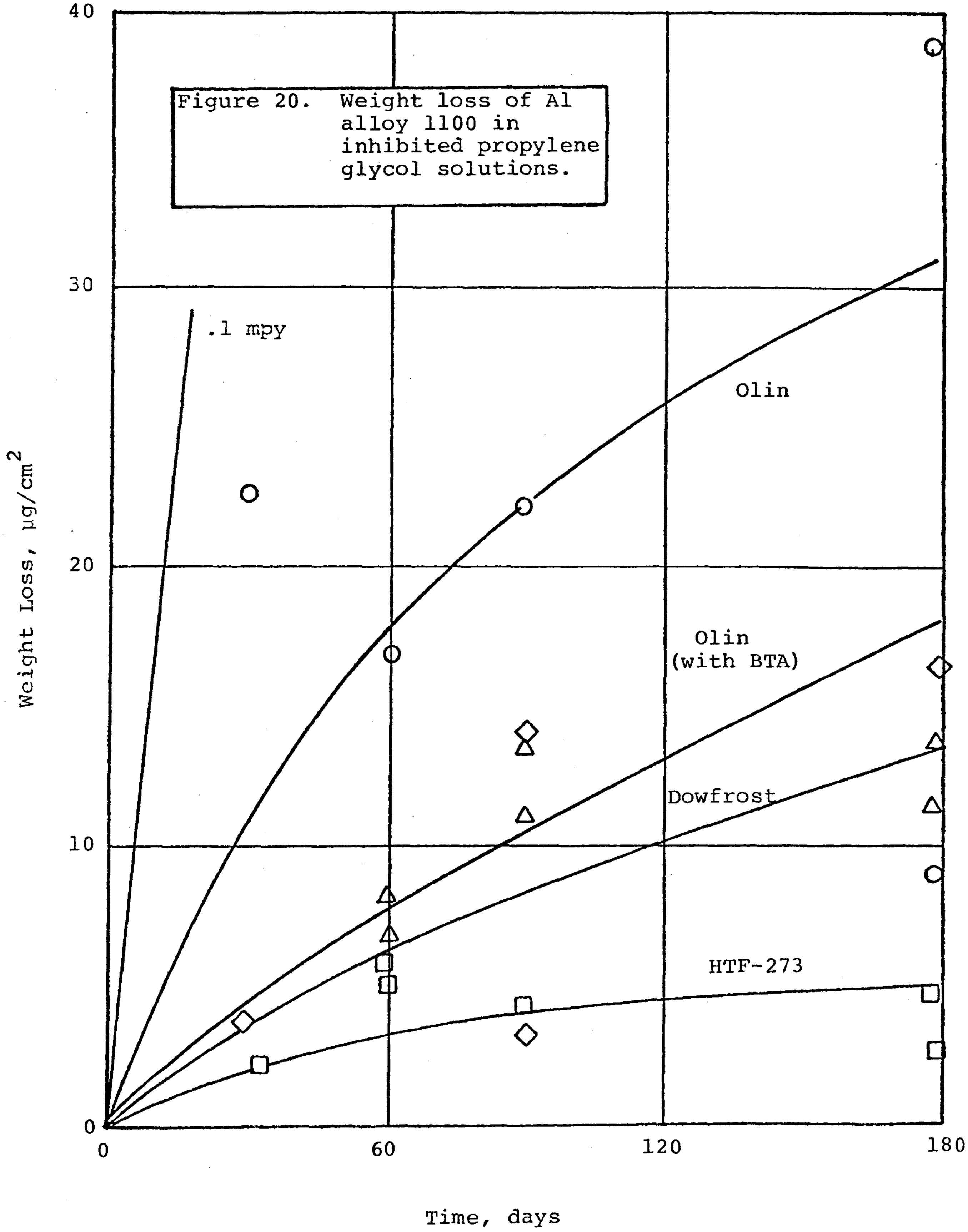


Figure 20. Weight loss of Al alloy 1100 in inhibited propylene glycol solutions.

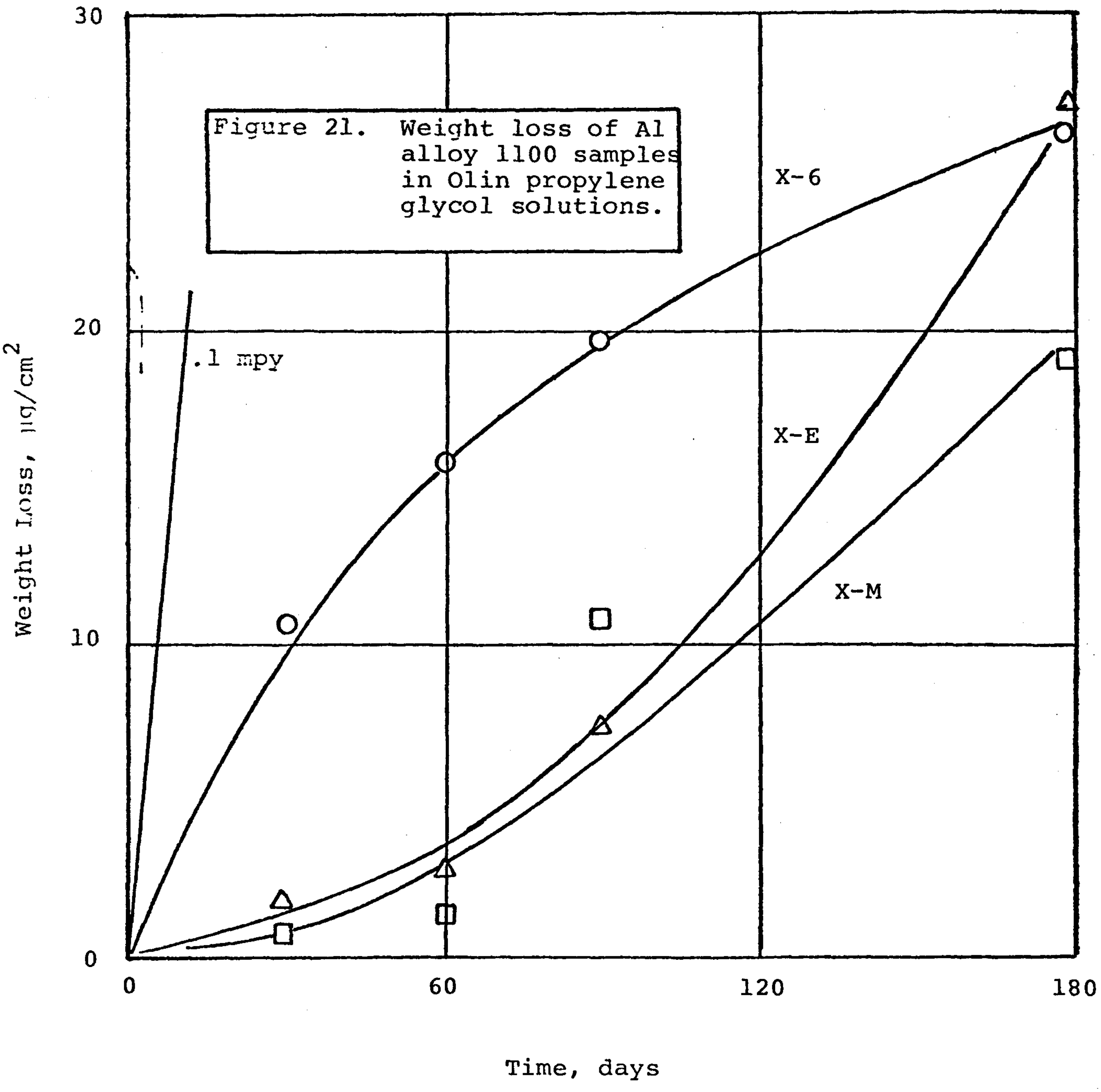


Figure 21. Weight loss of Al alloy 1100 samples in Olin propylene glycol solutions.

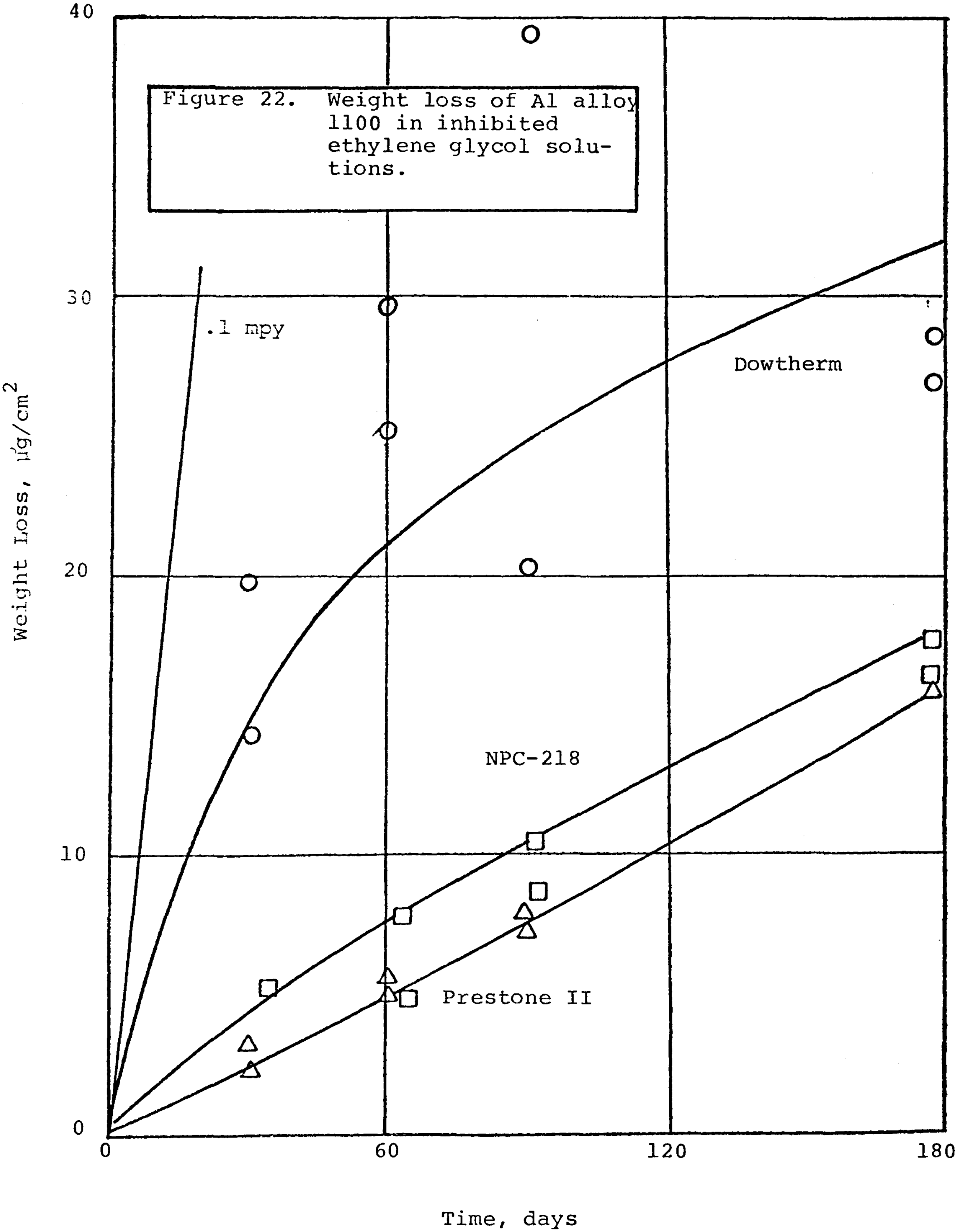


Figure 22. Weight loss of Al alloy 1100 in inhibited ethylene glycol solutions.

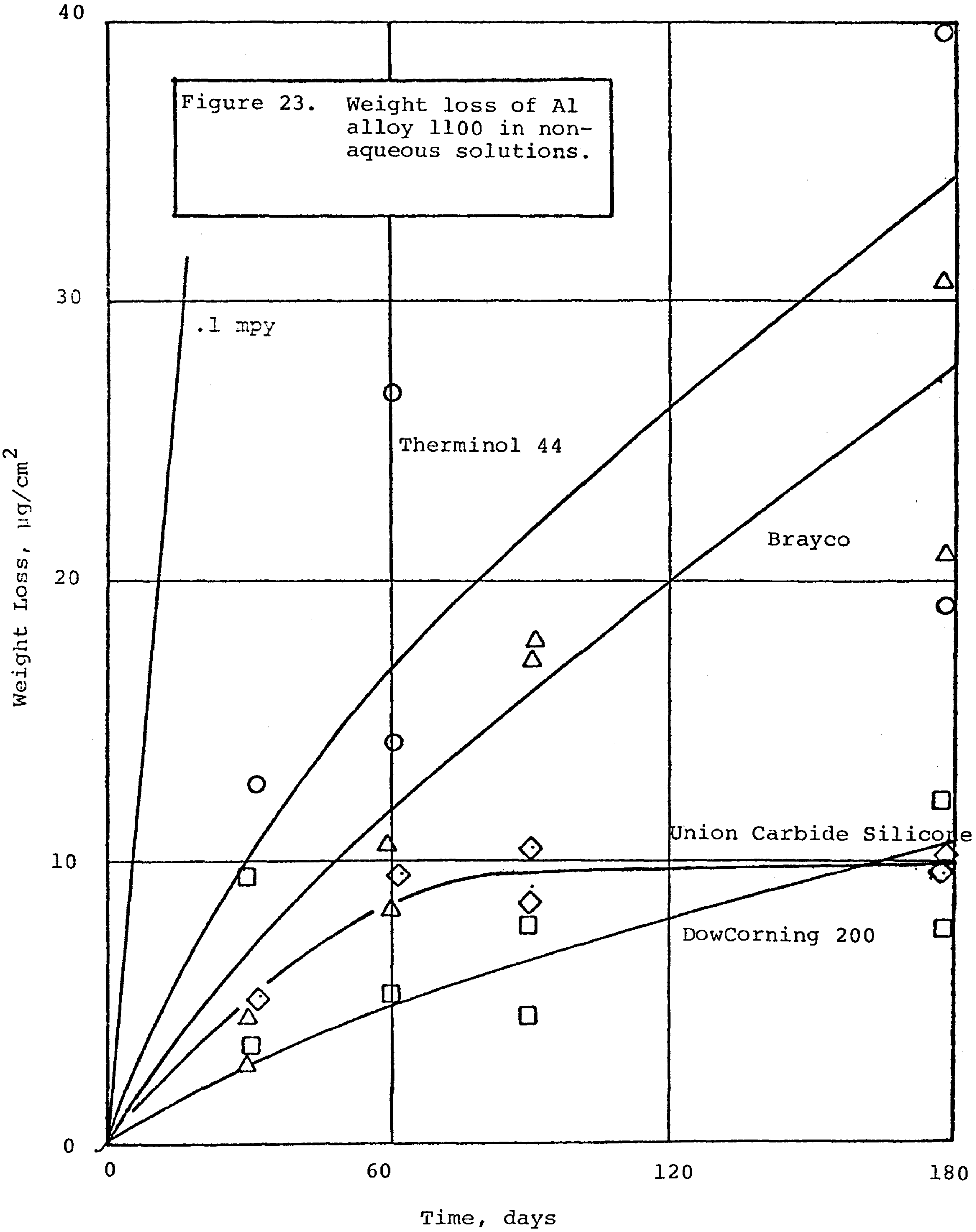


Figure 23. Weight loss of Al alloy 1100 in non-aqueous solutions.

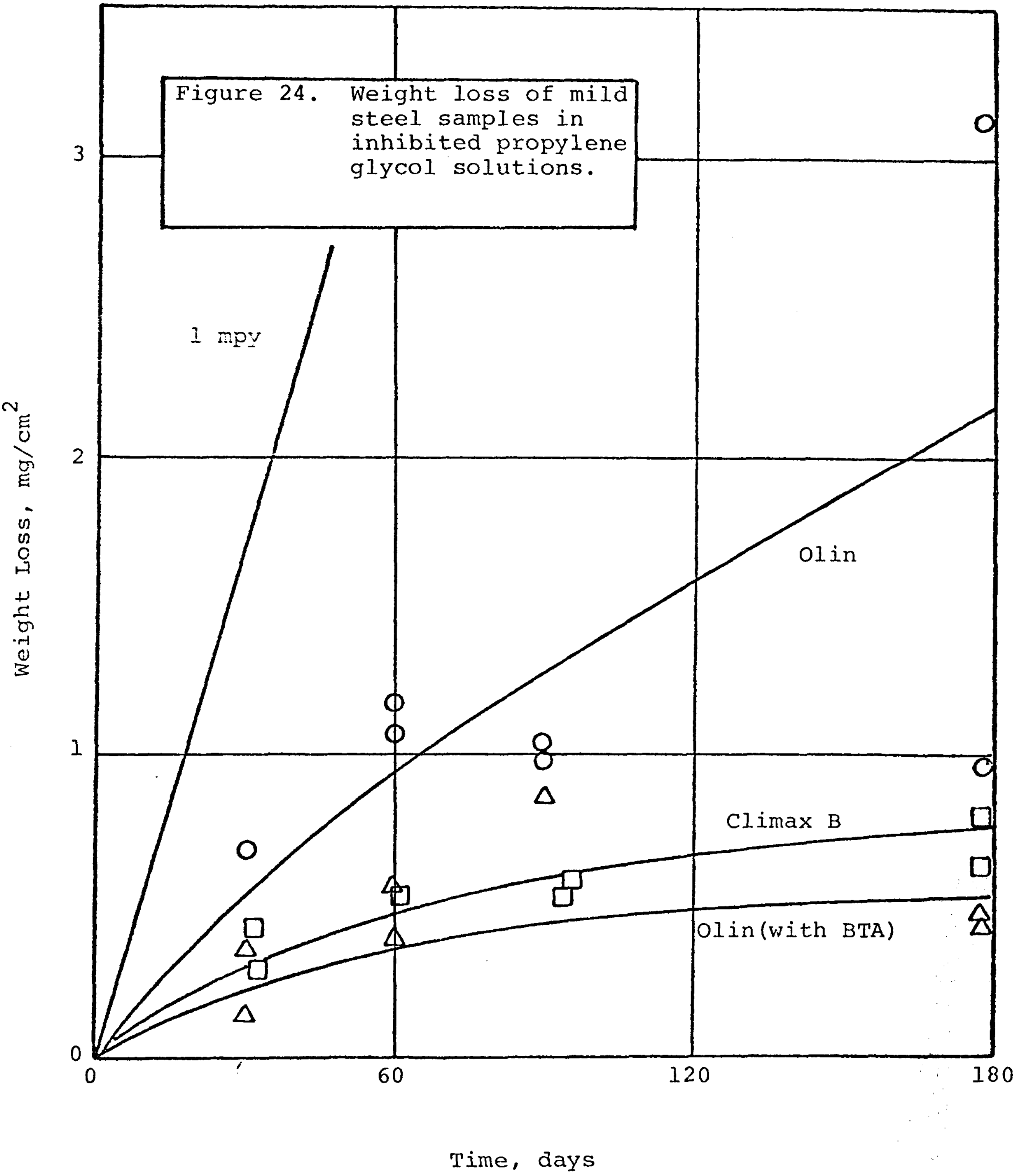


Figure 24. Weight loss of mild steel samples in inhibited propylene glycol solutions.

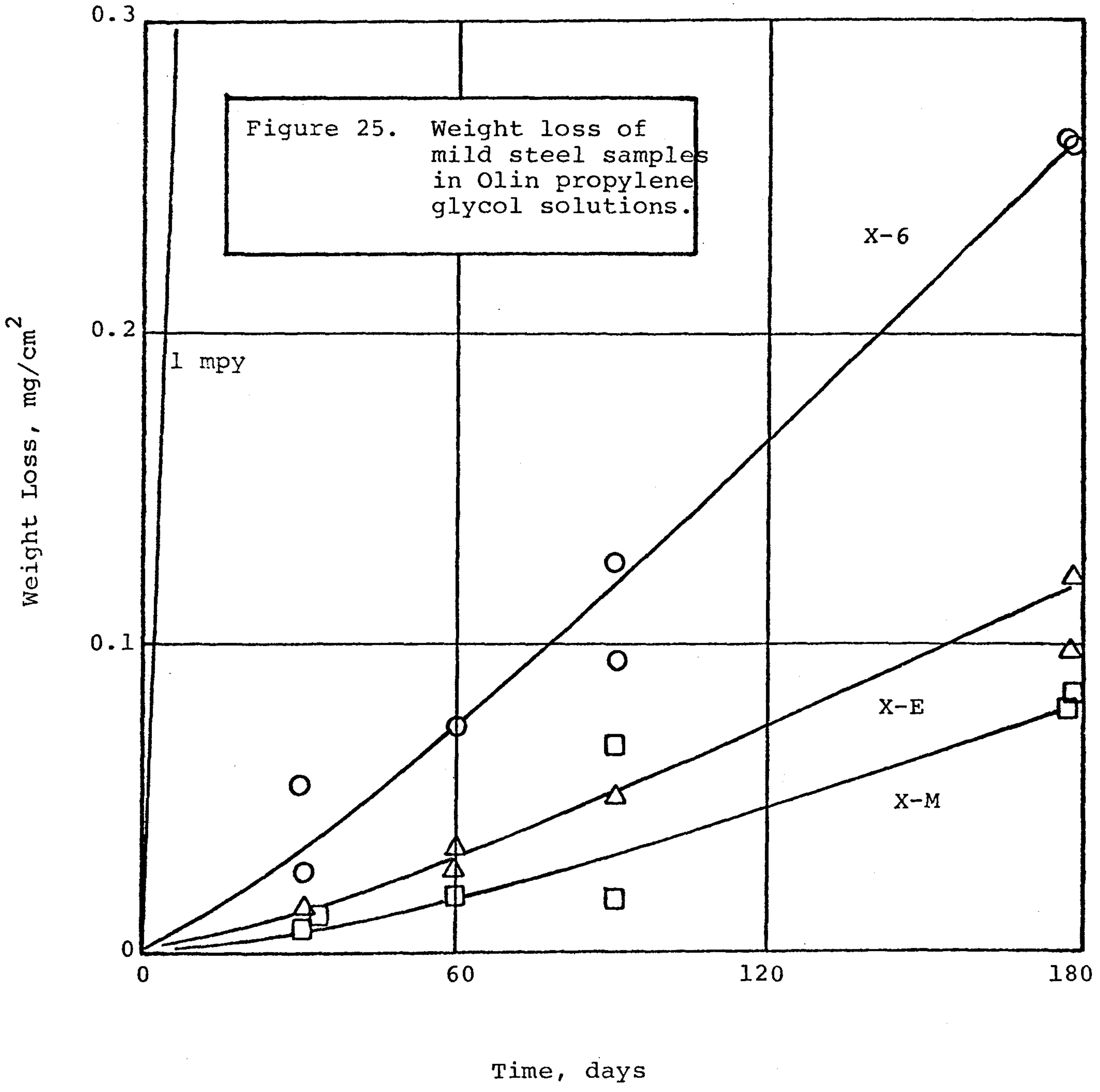


Figure 25. Weight loss of mild steel samples in Olin propylene glycol solutions.

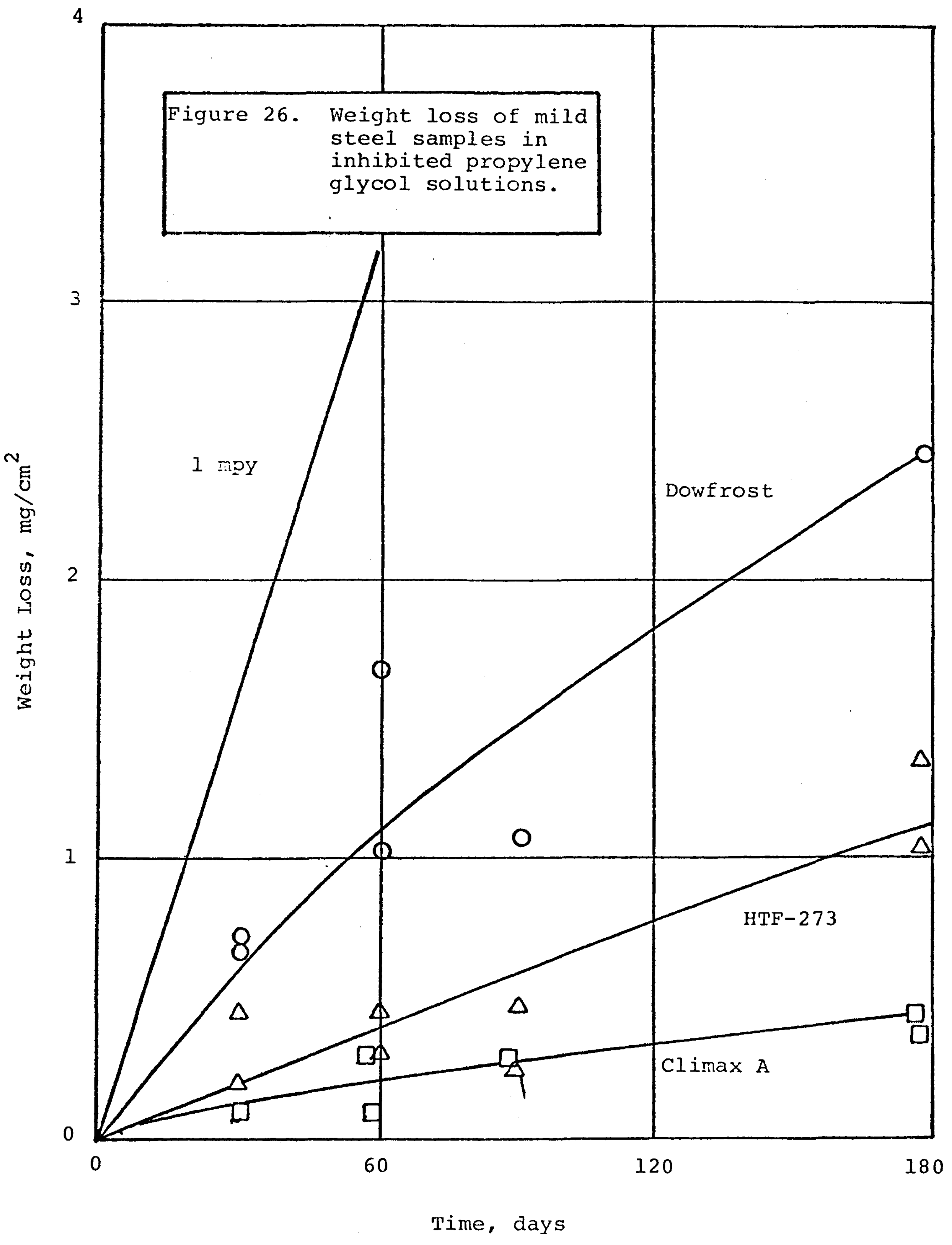


Figure 26. Weight loss of mild steel samples in inhibited propylene glycol solutions.

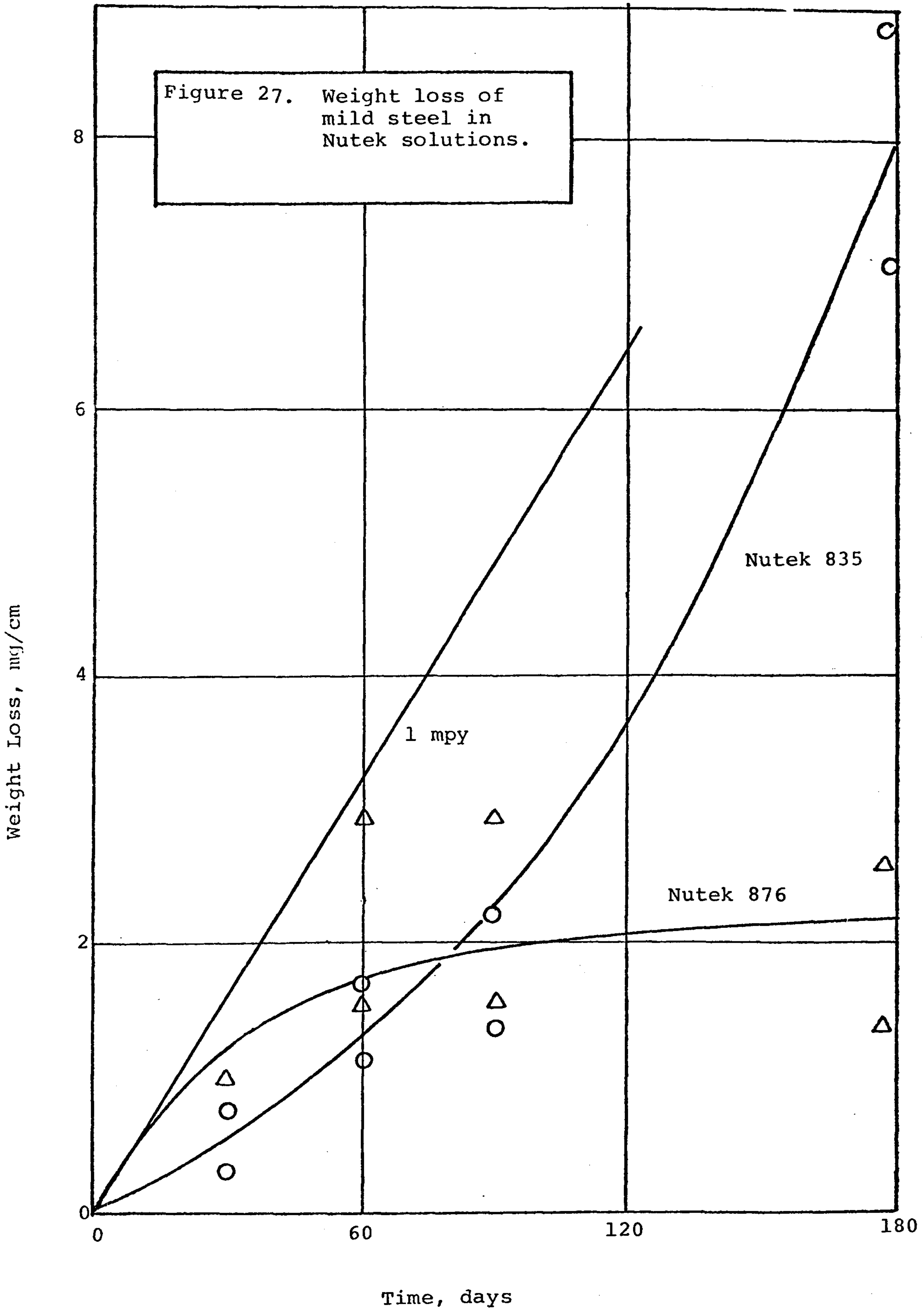


Figure 27. Weight loss of mild steel in Nutek solutions.

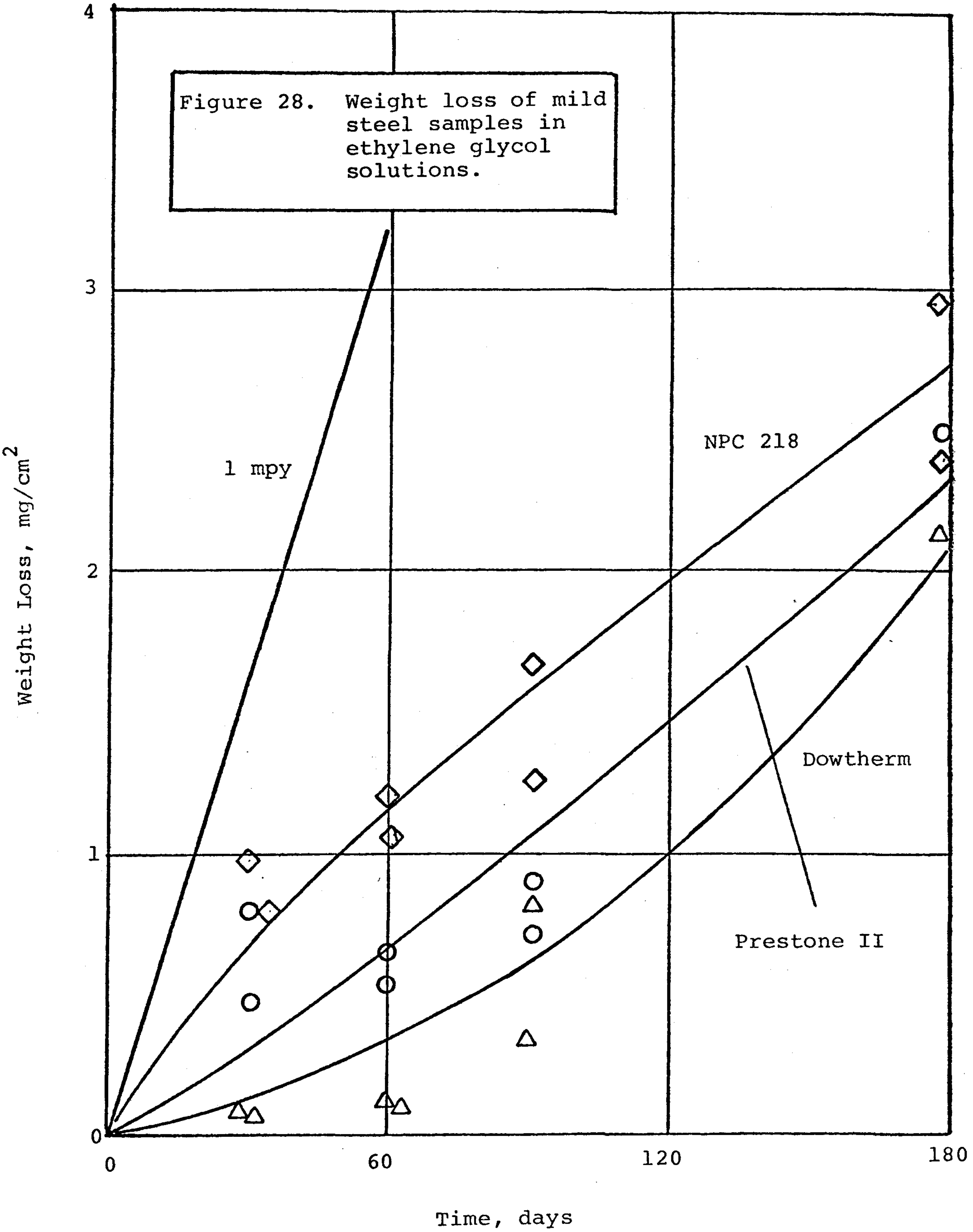


Figure 28. Weight loss of mild steel samples in ethylene glycol solutions.

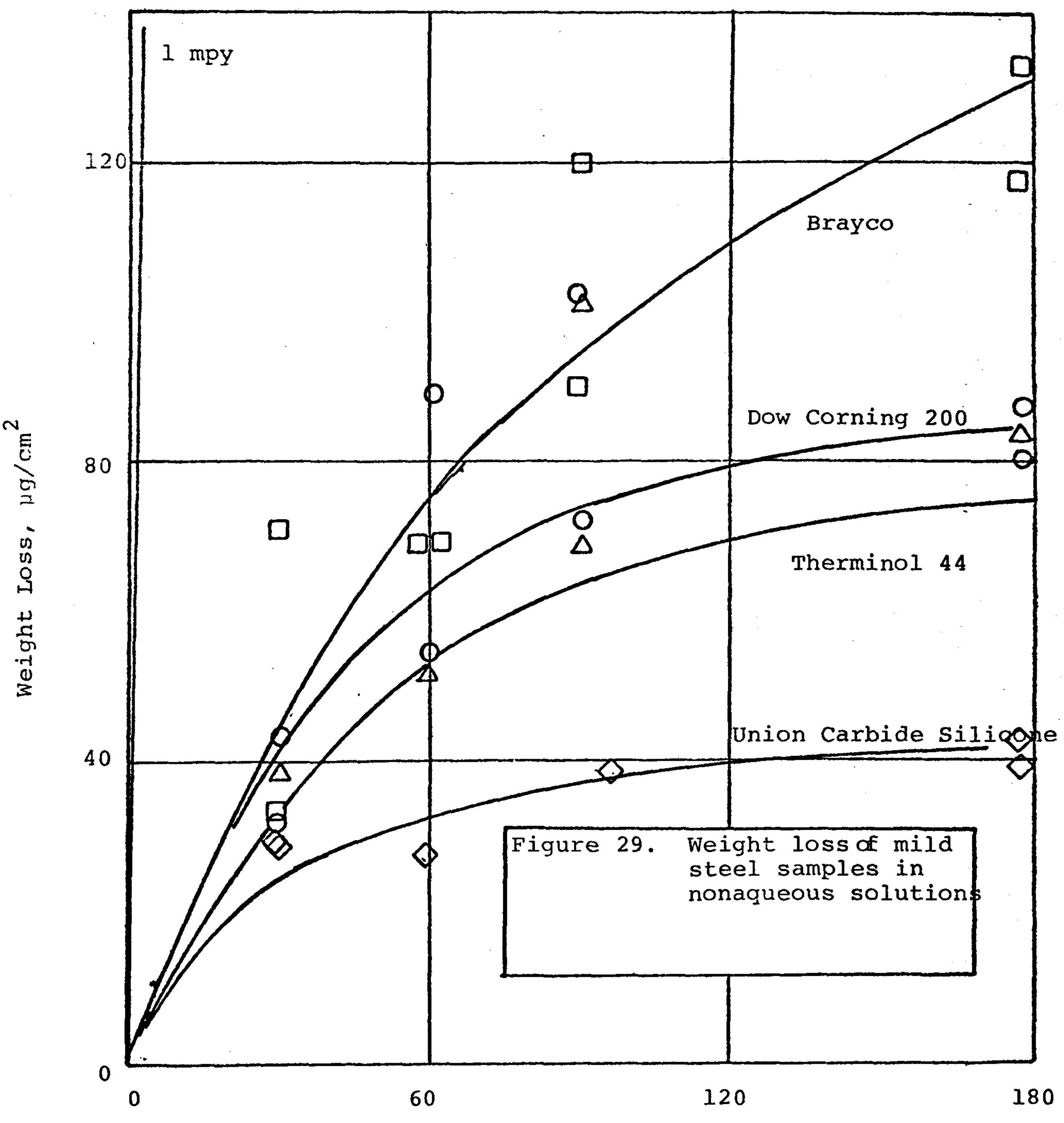


Figure 29. Weight loss of mild steel samples in nonaqueous solutions

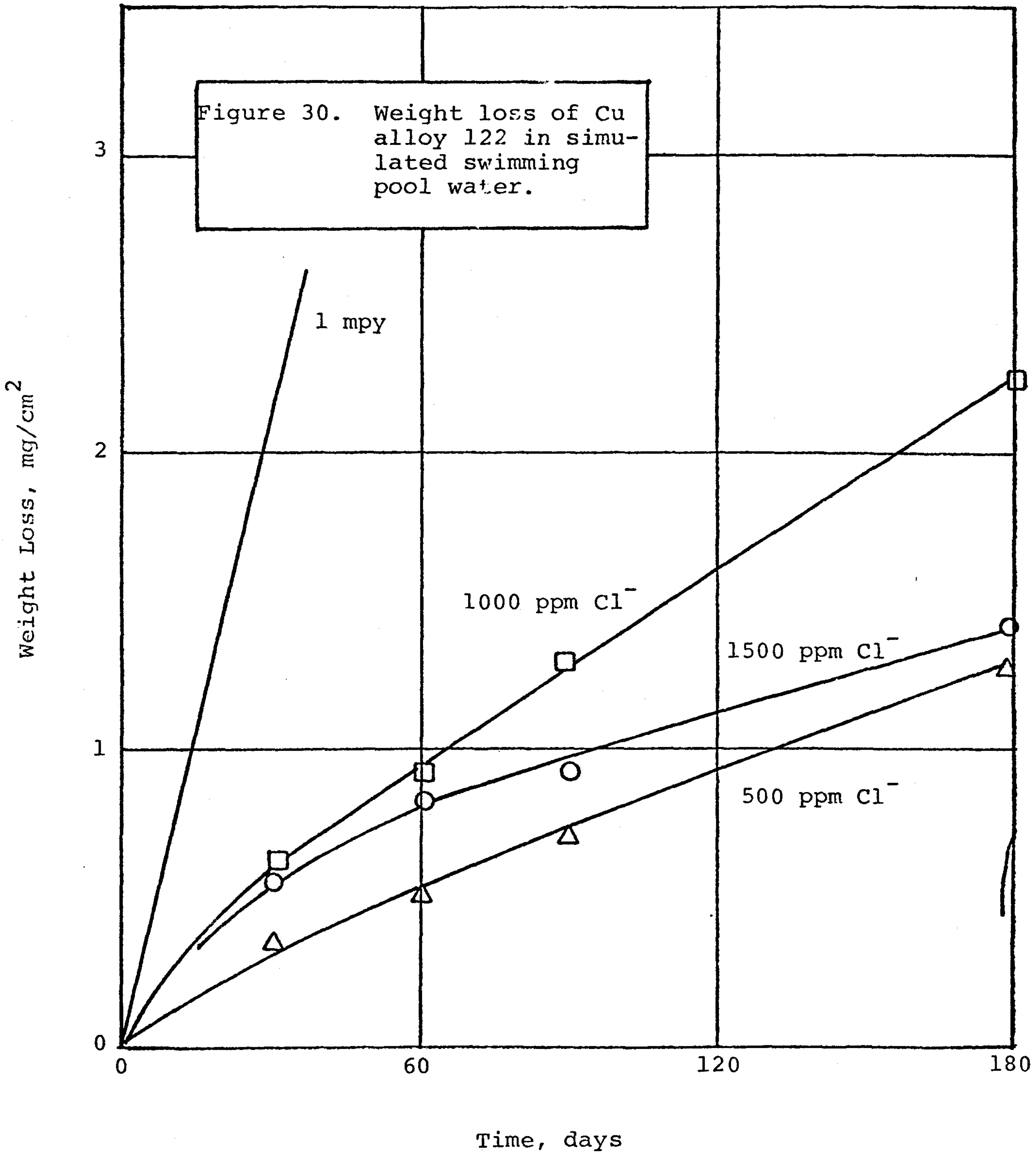


Figure 30. Weight loss of Cu alloy 122 in simulated swimming pool water.

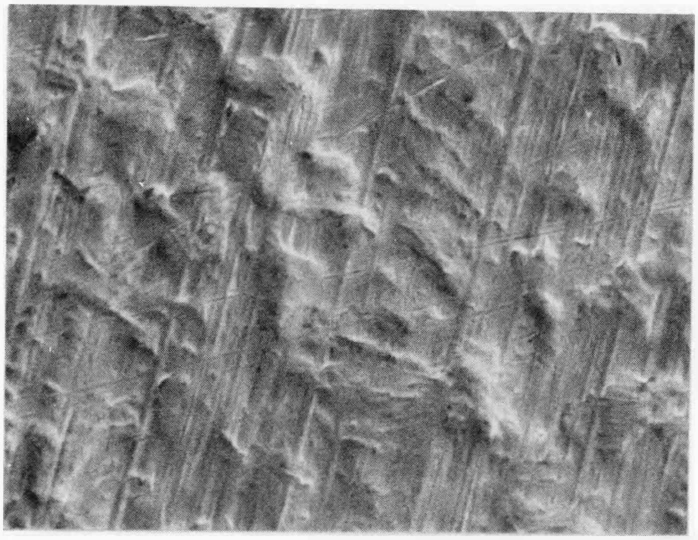


Figure 31. Scanning Electron Micrograph of Cu Alloy 122 Prior to Testing. Magnification 1000X.

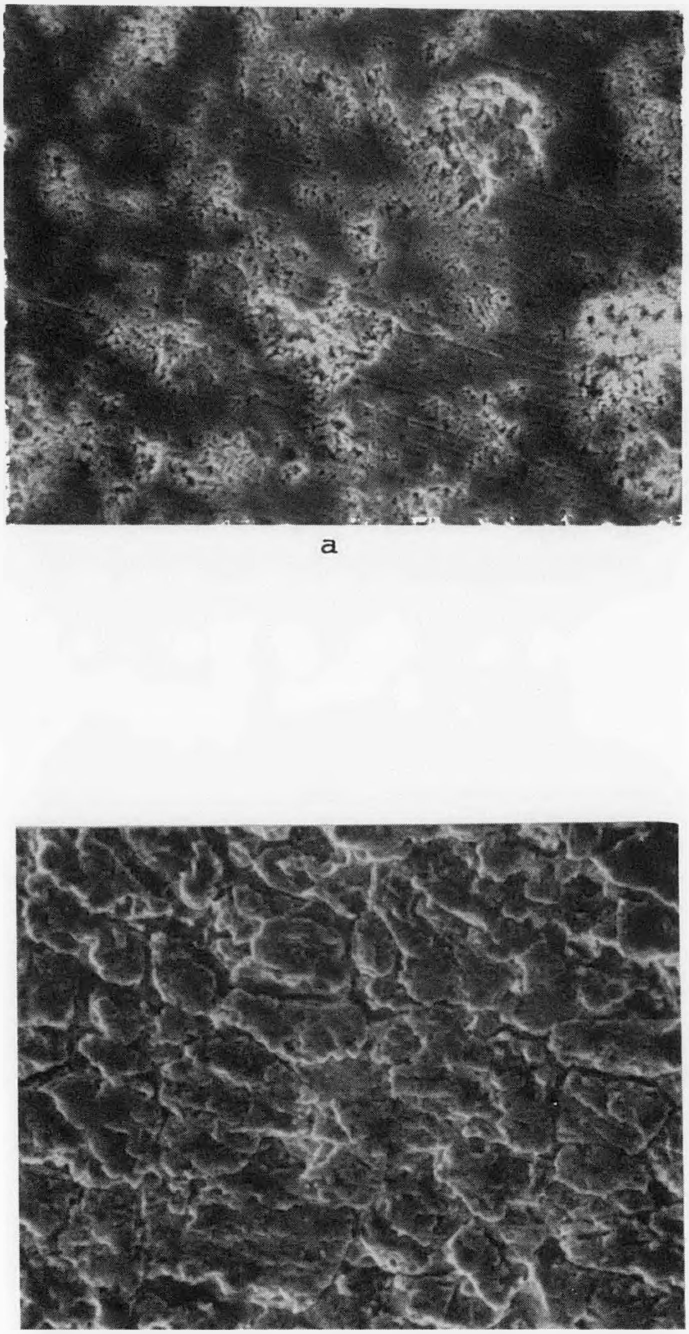


Figure 32. Scanning Electron Micrographs of Cu Alloy 122 after immersion with Stainless Steel Samples only for 6 months in a) New Haven Tap Water and b) in New Haven Tap Water with Solder Flux. Magnification = 1000X.

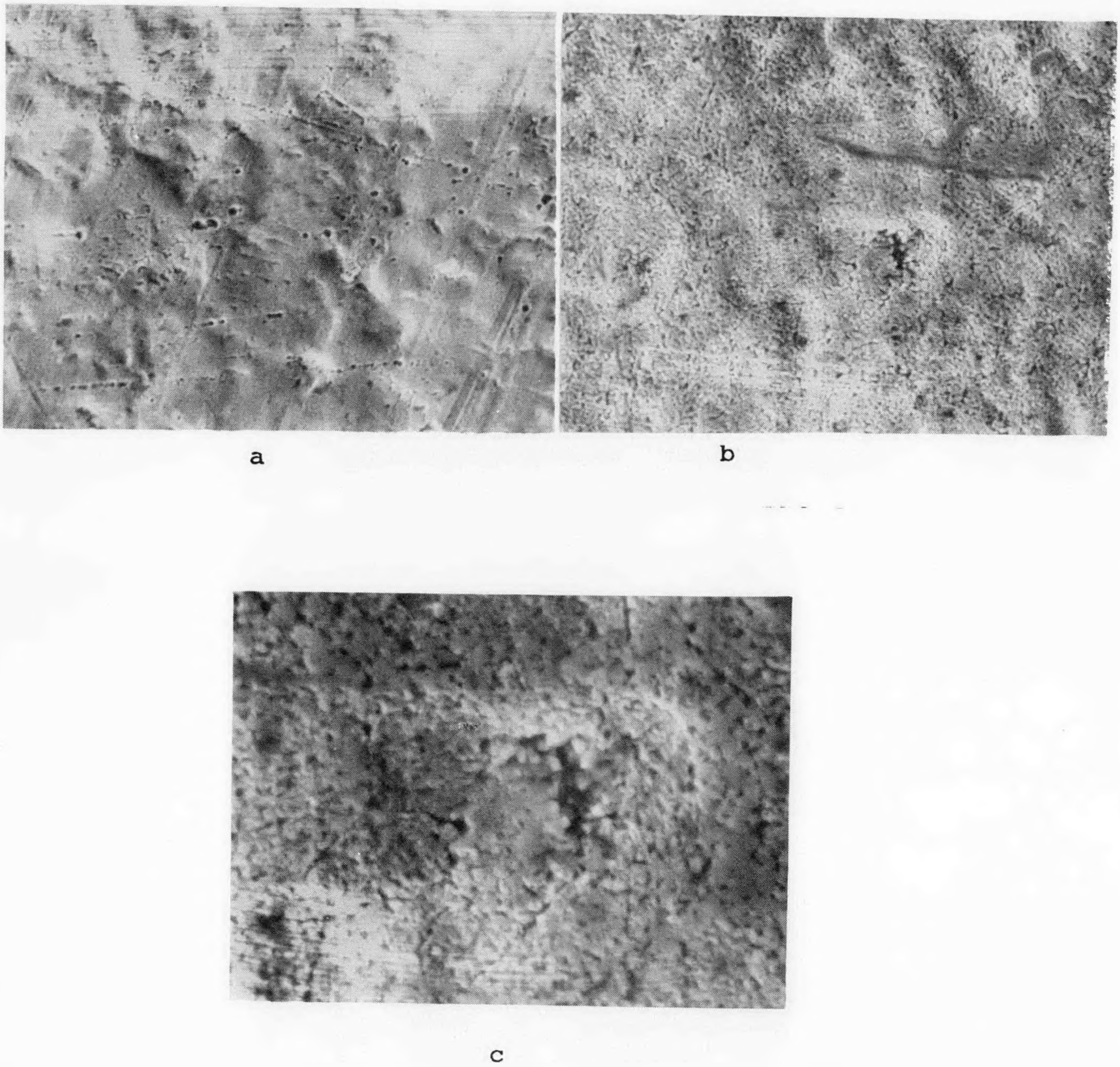


Figure 33. Scanning Electron Micrographs of Cu Alloy 122 after a) 2 months and b) 6 months in Homestead Domestic Water at 1000X. c) shows detail of b) at 2000X.

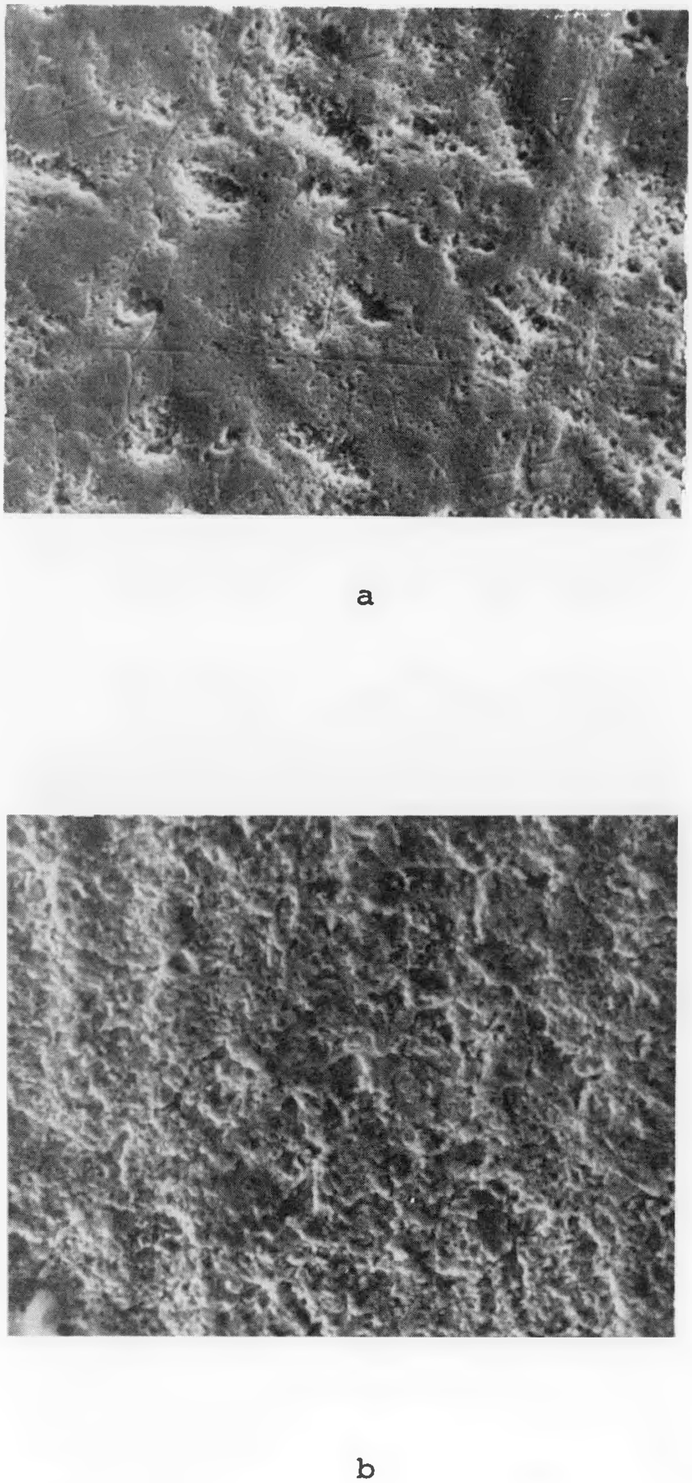


Figure 34. Scanning Electron Micrographs of Cu Alloy 122 after a) 2 months and b) 6 months in Nellis Domestic water at 1000X.

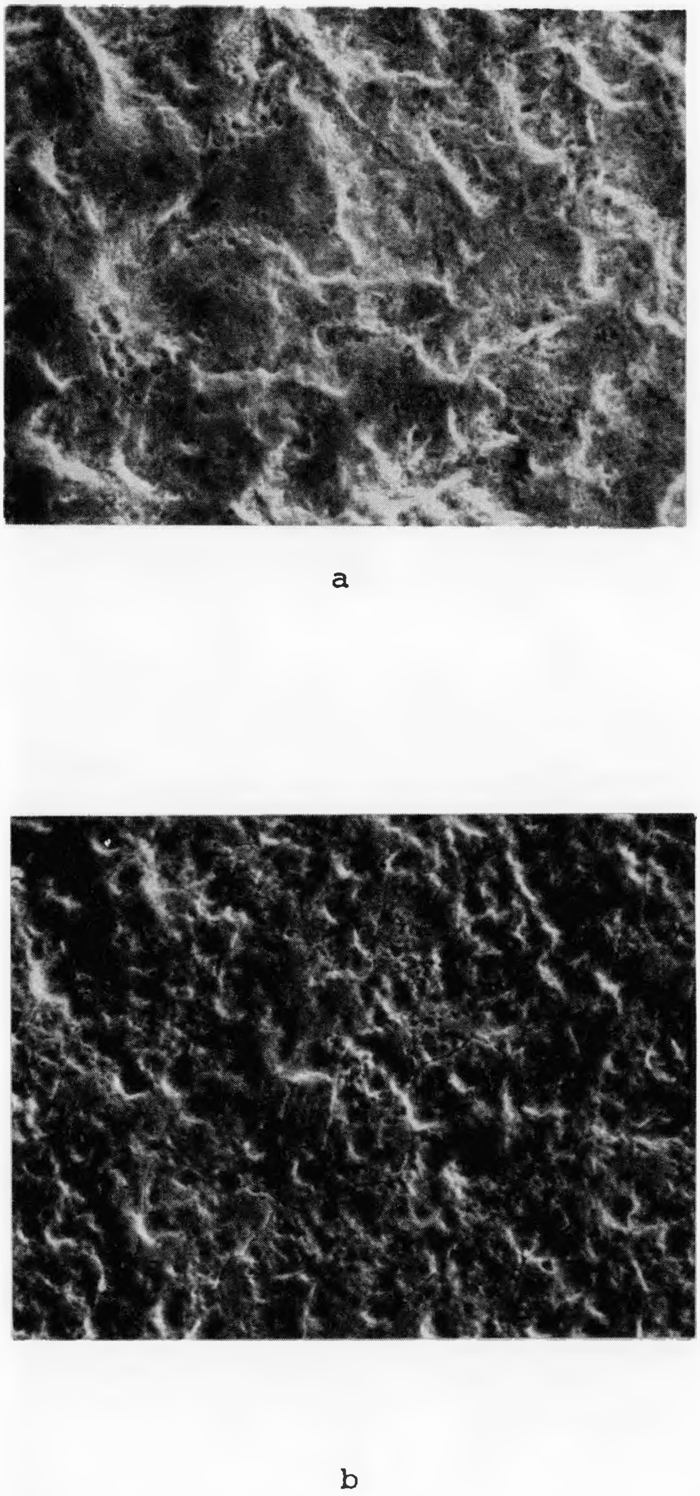
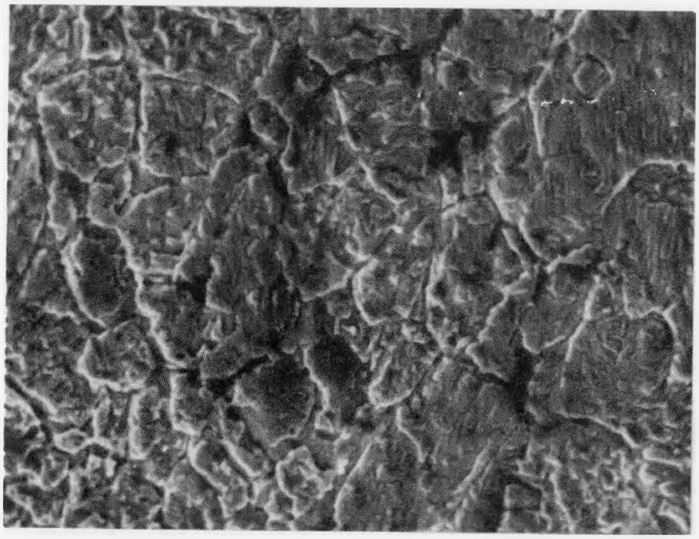
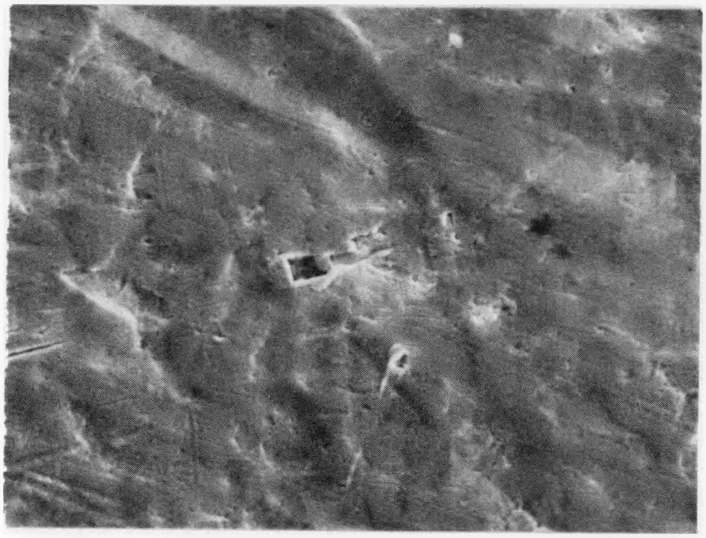


Figure 35. Scanning Electron Micrographs of Cu Alloy 122 after a) 2 months and b) 6 months in Dowfrost at Los Alamos. Magnification = 1000X.

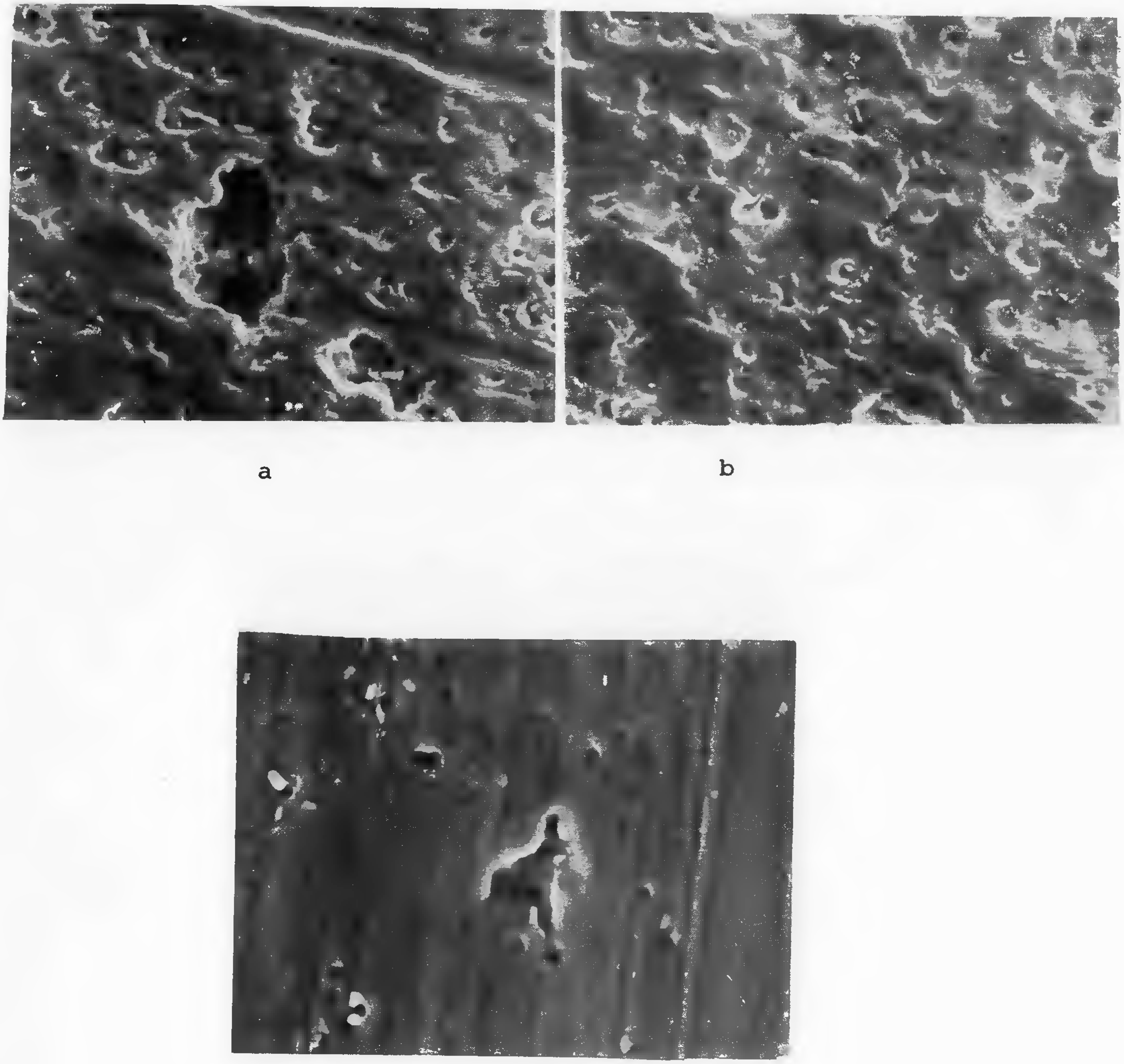


a



b

Figure 36. Scanning Electron Micrograph of Cu Alloy 122 after Immersion for 6 months in a) Degraded Propylene Glycol and b) Prestone II. Magnification = 1000X.



a

b

c

Figure 37. Scanning Electron Micrographs of Al Alloy 1100 after Exposure for 6 months in a) Climax A and b) Prestone II at Magnification of 500X and c) Union Carbide Silicone at 1000X.

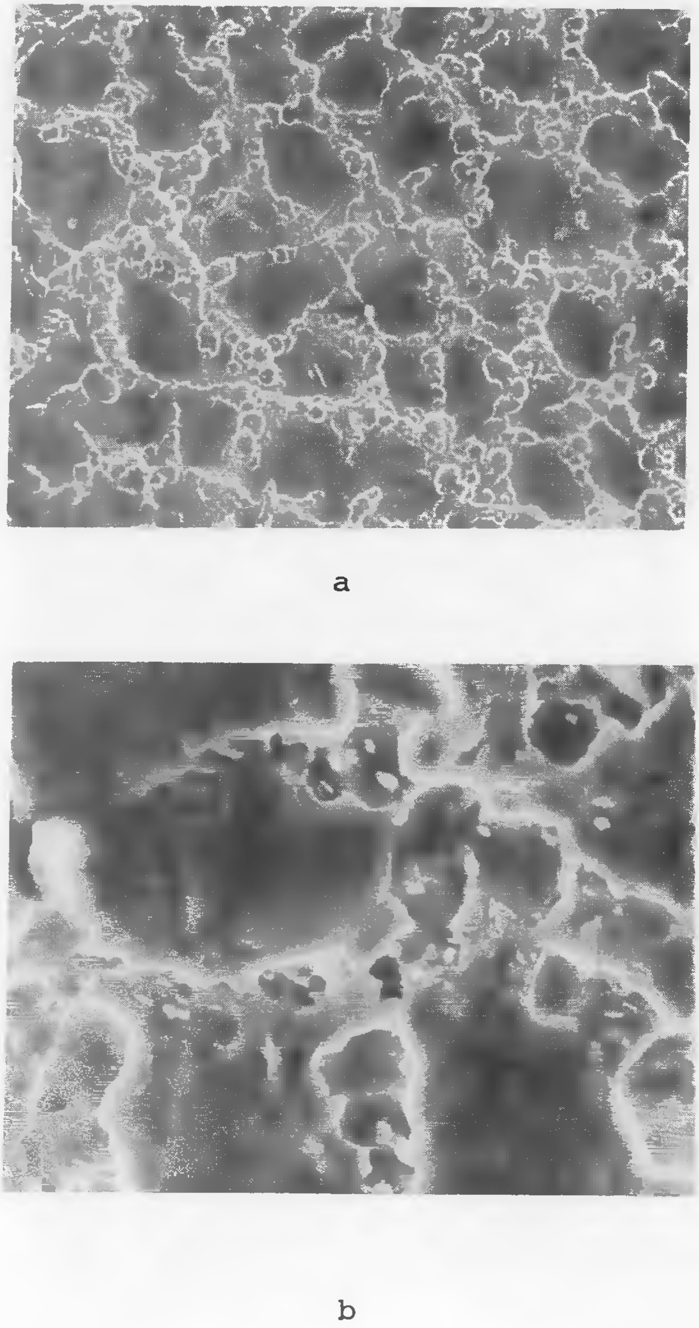
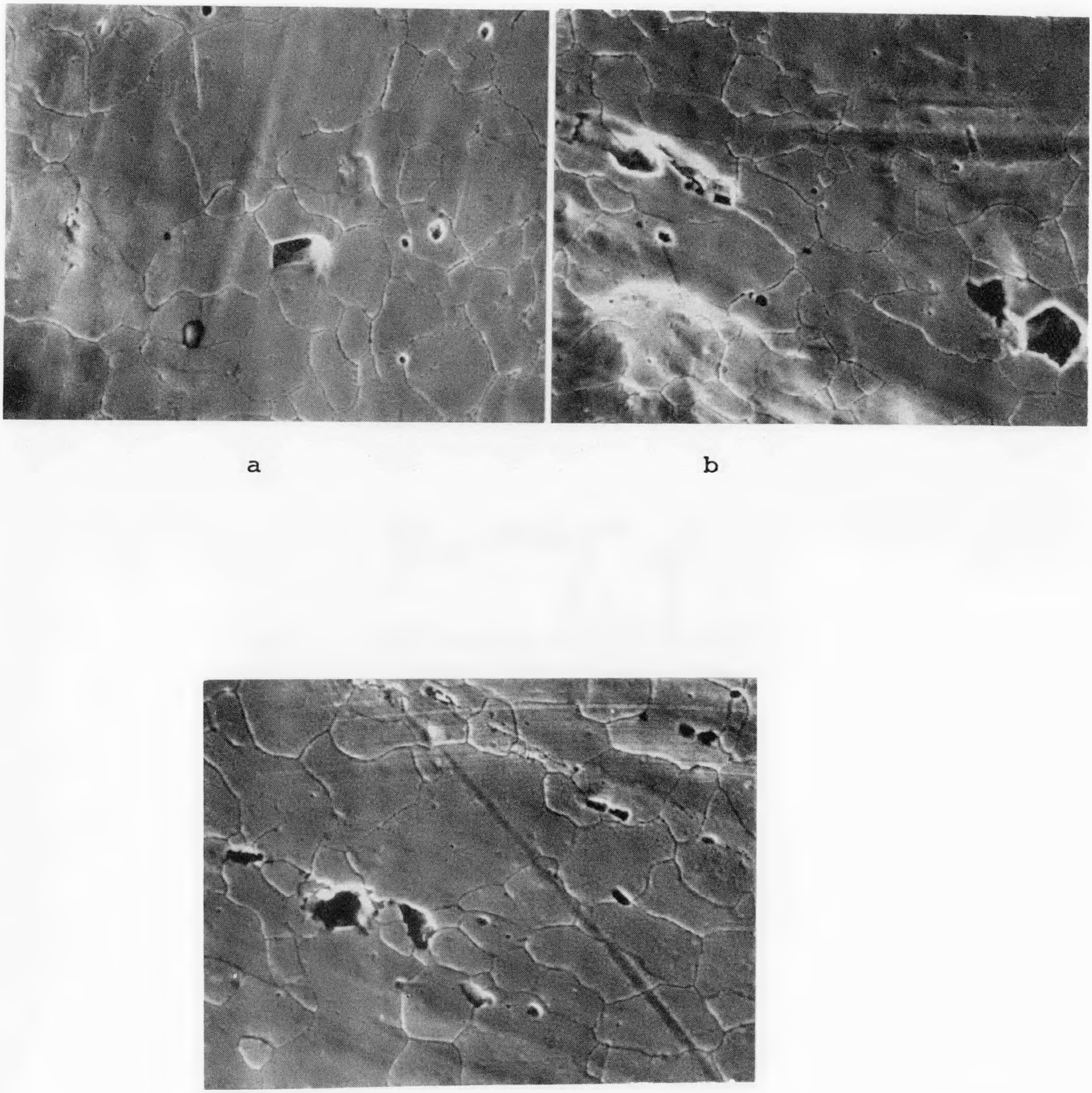


Figure 38. (a) Scanning Electron Micrograph of Al Alloy 1100 after 6 months in Sunsol 60 showing Intergranular Corrosion at 200X. (b) shows details of (a) at 1000X.



a

b

c

Figure 39. Scanning Electron Micrographs of Mild Steel Samples Showing Pits formed after Immersion for 6 months in a) Prestone II, b) Nutek 835 and c) Olin X-M. Magnification = 1000X.

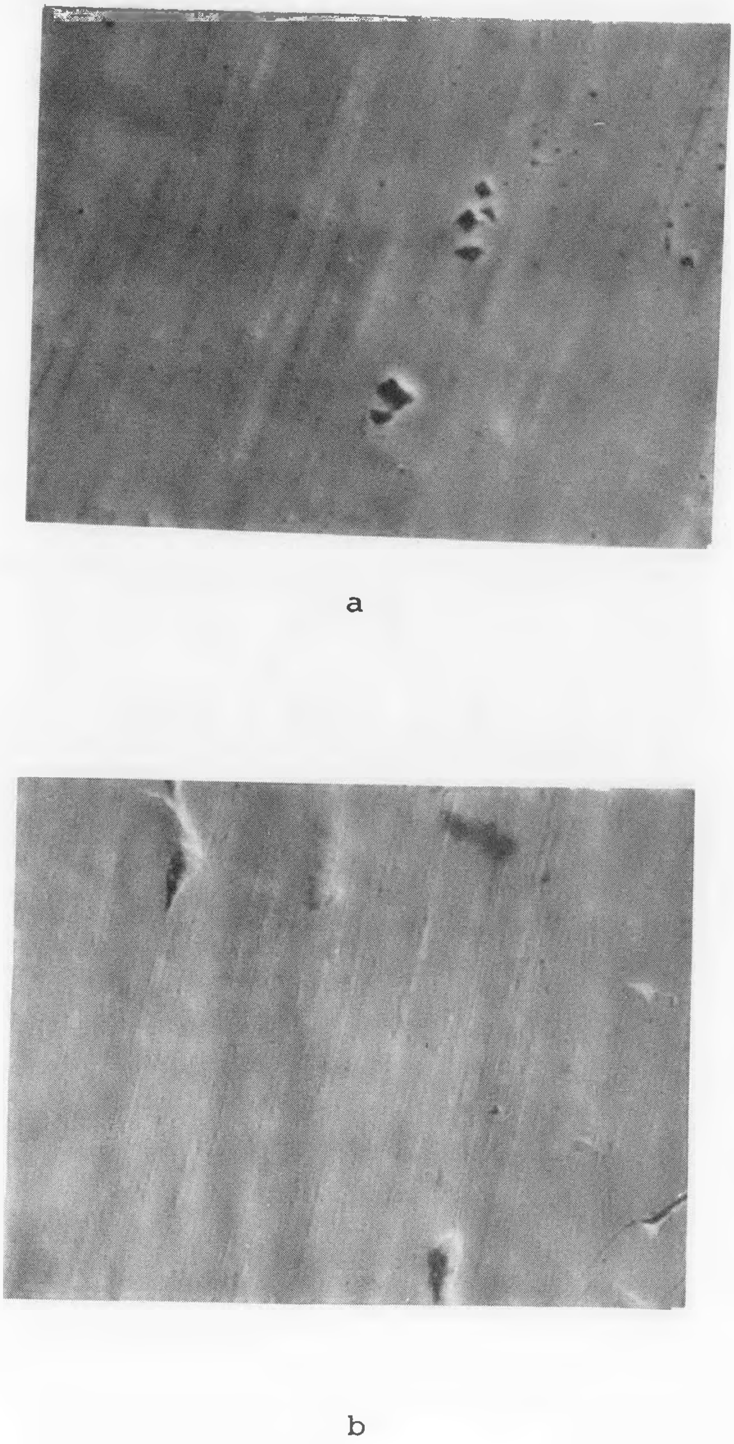


Figure 40. Scanning Electron Micrographs of Stainless Steel after Immersion for 6 months in a) Nellis Domestic Water and b) NPL fluid showing small pits in crevice region. Magnification = 2000X.

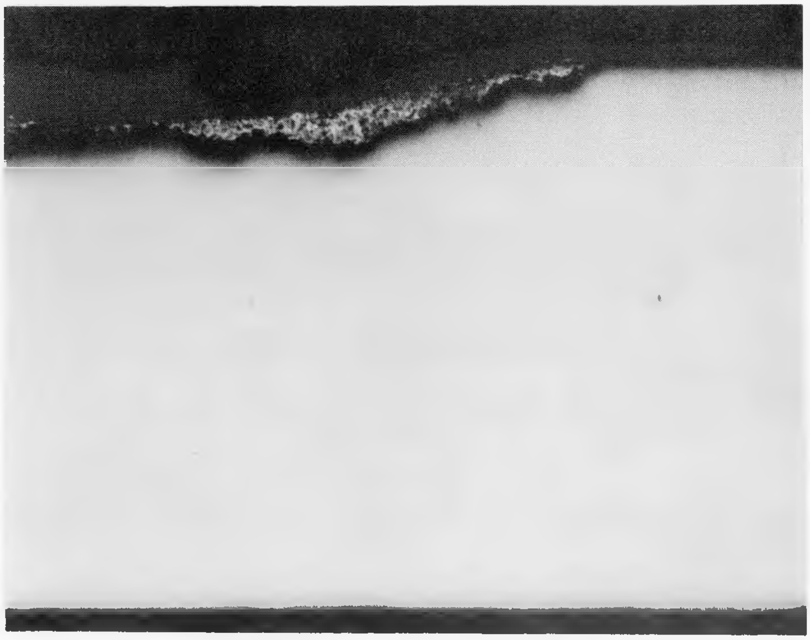


Figure 41. Optical Micrograph of Cu Alloy 122 after Immersion for 180 days in New Haven tap water with Solder Flux present showing corrosion in crevice. Magnification = 200X.

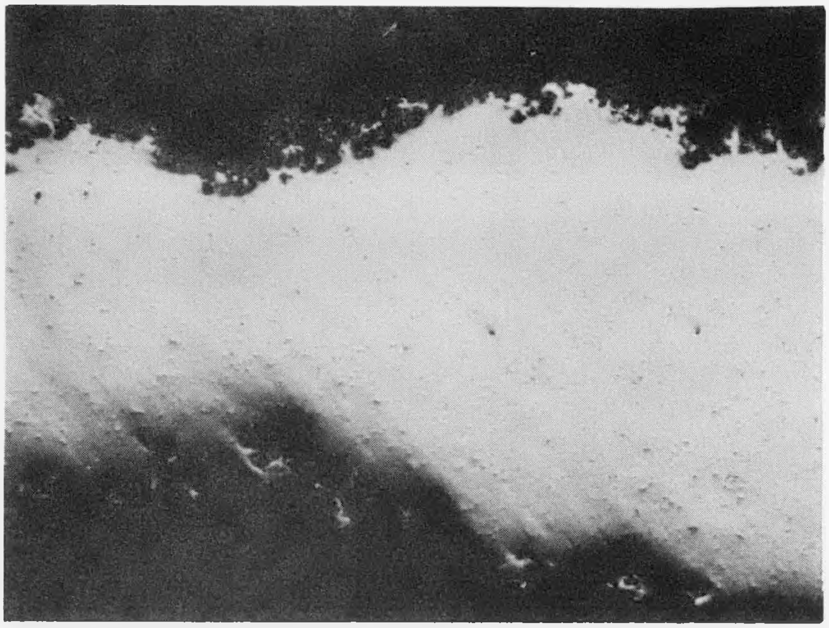


Figure 42. Optical Micrographs of Al Alloy 110 after immersion for 180 days in Degraded Propylene Glycol. Note Severe Pitting and Accelerated Corrosion in Crevice. Magnification = 100X.

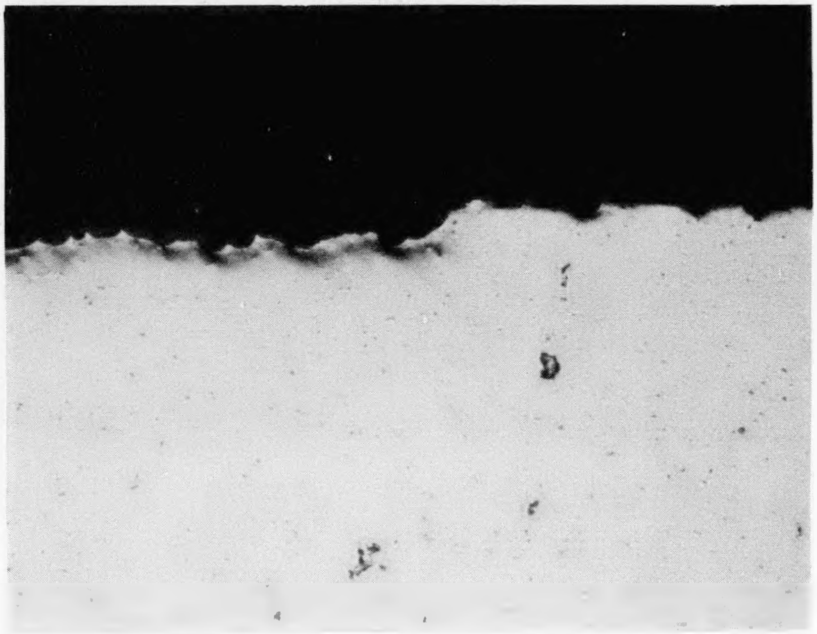


Figure 43. Optical Micrograph of Al Alloy 1100 after 180 days Immersion in Sunsol 60 Illustrating Crevice Corrosion. Magnification = 200X.

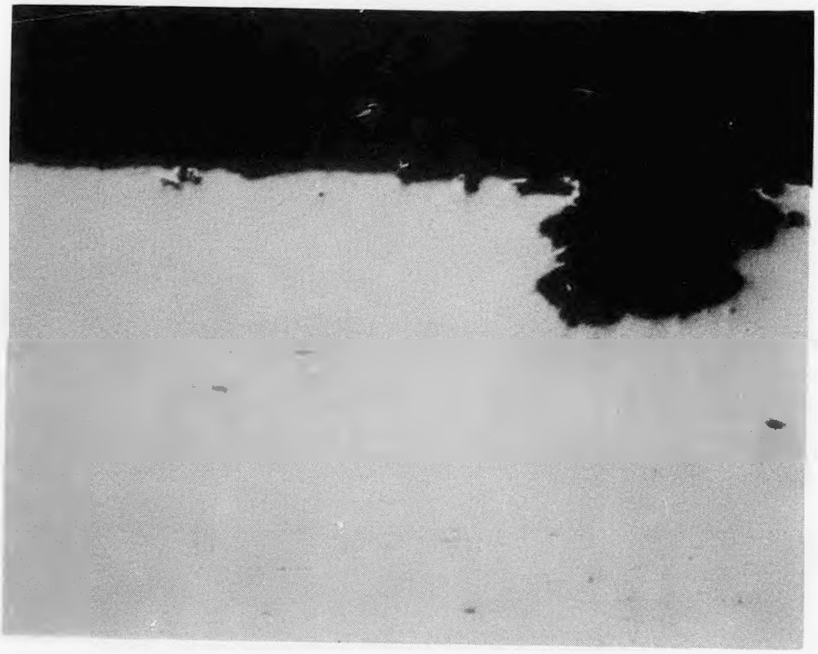


Figure 44. Optical Micrograph of Mild Steel showing large pit in crevice region formed during immersion for 180 days in degraded propylene glycol solution with reserve alkalinity adjusted to 10. Magnification = 200X.

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