NBSIR 74-429

Corrosion of the Stainless Steel Piping in the Kuwait Water Supply System

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U. S. DEPARTMENT OF COMMERCE, Frederick B. Dent, Secretary
NATIONAL BUREAU OF STANDARDS, Richard W. Roberts, Director

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SUMMARY

The Ministry of Electricity and Water (MEW), Kuwait, contacted the U.S. Department of State, which requested the assistance of the National Bureau of Standards (NBS), U.S.A., in the problem of the corrosion of the stainless steel pipes in their water supply system. This request was honored, and accordingly, Gilbert M. Ugiansky of the Corrosion and Electrodeposition Section, NBS, visited Kuwait from April 8 to April 22, 1973, to carry out an examination and collect samples of material for analysis and investigation.

This investigation shows that the stainless steel pipes in the Kuwait water supply system are susceptible to localized attack under the conditions that were reported to have been used during the disinfecting procedure. Thus, it is reasonable to conclude that the severe pitting found in the pipes occurred during this operation.

The NBS data and observations show that both alloys type 304L and 316 cannot be used with confidence in their ability to resist localized corrosion attack in the Kuwait water supply system unless new protective measures are undertaken.

Recommendations to make the water system operative as soon as possible are as follows:

(1) Repair penetrated pipes by welding;

(2) Install cathodic protection system using sacrificial zinc ribbon or cable anode. Reference electrode ports should be included in

this system. Special care should be taken to see that the anodes used do not contain any toxic materials. All internal surfaces of the pipes should be polarized (or protected) to a potential at least as negative as -0.65 V vs SCE (Saturated Calomel Reference Electrode).

Measures to minimize the chances of future failures are:

(1) Test coupons of unprotected pipe steels should be installed in the water system;

(2) Disinfection should take place after cathodic protection system has been installed and should occur immediately before the system is put into operation;

(3) If available, a non-Cl containing non-oxidizing disinfectant should be used in low chloride water. The solution should be drained and pipes rinsed and put into use without delay;

(4) Inspection should be made when the system is ready to be put into operation;

(5) Periodic inspections of the pipes, cathodic protection system, and coupons should be made at three-month intervals for the first year of operation. Future inspection intervals should be decided on at the end of the first year of operation;

(6) During the time the short-term solution is in use, possible long-term solutions should be investigated. The possibilities to be considered are: Replacement of the pipes with another material; cathodic protection using sacrificial anodes; cathodic protection using an impressed current system; protection by coating or lining the pipes; and the possibility that the pipes can be used as designed at some of the sites.

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I. INTRODUCTION

The Ministry of Electricity and Water (MEW), Kuwait, contacted the U.S. Department of State, which requested the assistance of the National Bureau of Standards (NBS), U.S.A., in the problem of the corrosion of the stainless steel pipes in their water supply system. This request was honored, and accordingly, Gilbert M. Ugiansky of the Corrosion and Electrodeposition Section, NBS, visited Kuwait from April 8 to April 22, 1973, to carry out an examination and collect samples of material for analysis and investigation. The historical and background material in this introduction was provided to Ugiansky by MEW.

Kuwait, with a population of approximately 900,000 and a limited natural water supply consisting of virtually all brackish water, produces its drinking water at several desalination plants. These plants, with a daily capacity of approximately 50 million gallons, distill seawater from the Arabian Gulf and blend this distilled water with brackish water from ground wells or seawater to make it palatable. The distribution of this potable water has in the past been accomplished primarily by tank truck with reservoirs on location at residences and commercial facilities.

With the growth and modernization of the city of Kuwait, the design and construction of a water distribution system was initiated. A schematic diagram of the Kuwait water supply system is shown in Figure 1. It can

be seen from this diagram that along with the potable water system there is a parallel distribution system for brackish water primarily for agricultural and industrial uses. Because potable and brackish waters are to be distributed throughout Kuwait, the entire system is designed to be compatible with both. The piping in the main part of the system is cement-lined cast iron. Type 316 stainless steel (0.05%C) was specified for piping at the water storage tower sites, blending plants, and pumping stations. The specification for piping at most of the tower sites was later changed to type 304L.

The Kuwait water distribution system includes six sites of water storage towers. Five of these sites consist of clusters of mushroom-shaped reinforced concrete towers which will store both potable and brackish waters. A description of the number of towers, heights, etc., at each of these sites is given in Table 1. The piping at the above sites is constructed of type 304L stainless steel. The sixth site (designated D-6) is the Kuwait Tower, a combination of water storage towers and visitors' center (Figure 2). It is at this site that the pressure required for the water distribution system is produced. Type 316 (0.05%C) stainless steel was used for the pipes at the Kuwait Tower.

Type 316 (0.05%C) stainless steel is also used at the two blending stations in the water distribution system. These sites are designated P and P-5.

During the summer of 1972 several of the sites reportedly underwent leak tests using brackish water with sodium hypochlorite (NaOCl) added for disinfection. This water was never analyzed. However, the specifications for disinfecting the reservoirs stated the following: "Water shall be fed into the reservoirs with chlorine applied in amounts to produce at least

10 ppm after 24 hours' standing. The dosage must not exceed 50 ppm without the approval of the Engineer. The disinfecting solution shall remain in the reservoirs for such periods as the Engineer instructs, but in no case for less than 24 hours." Although NBS has had some difficulty in reconstructing the exact details of what took place during the disinfection operation, it appears that the disinfecting solution remained in at least some of the pipes for from four to six weeks; in some of these pipes the water was apparently drained, but some 10 cm of water remained in the bottom. Whatever the case, after this exposure, the stainless steel pipes at these sites were found to be perforated by pitting corrosion attack. Table 2 lists the tower and blender sites and information on the state of the stainless steel as of April 1973. As can be seen in Table 2 the pipes at tower sites D-1 (Figure 3) and D-2 (Figure 4) were perforated as was also the pipe at blender P. These were the sites that underwent leak tests.

A number of organizations studied the corrosion problem for the Government of Kuwait, Ministry of Electricity and Water (MEW), and for the contractors and consultants. Because a number of questions still remained unanswered, MEW asked the U.S. Department of State to request the assistance of NBS in accomplishing the following objectives:

(1) Resolve discrepancies in the analyses of the stainless steels; (2) determine the cause of failure; (3) recommend a short-term solution (to get the water supply system operational as quickly as possible); and (4) recommend a long-term solution that would meet the design criteria of reliability for 50 years at 50°C and 9 kg/cm^2. This report deals with the first three objectives. The long-term solution should be studied after the implementation of the short-term solution.

II. CHEMICAL ANALYSES

A. Stainless Steel Specimens Collected in Kuwait

Stainless steel pieces for analysis at NBS were cut from the pipes in Kuwait as directed by Ugiansky. A list of the pertinent information on the specimens removed is given in Table 3. At NBS a 3.5 cm square was cut from each of the specimens, turned down to a 3.18 cm diameter disk, and polished to a 6 µm diamond finish. The specimens were analyzed by NBS, along with appropriate standard reference materials, by X-ray fluorescence analysis. Carbon was determined by a combustion chromatographic method. Qualitative X-ray fluorescence analysis was made for each specimen; the range of elements considered included all those above scandium (atomic number 21). The qualitative tests indicated no element which would prevent the specimens from being classified as type 304L or 316 stainless steels was present above 0.1%. The results of the quantitative analyses are given in Table 4. (See appendix A for NBS certificate of Analysis).

All specimens were found to conform to ASTM specifications A312 for 304L stainless steel and A409 for 316 stainless steel. There is an apparent slightly high silicon content in two samples of the 316 stainless. However, when the analysts' estimate of accuracy is taken into account, these values are also within specifications.

As a check, duplicate analyses were performed by a commercial laboratory. Within the levels of accuracy of the methods used, the results of both analyses were identical. NBS analyzed quantitatively for only the more important elements while the commercial laboratory's analysis also included phosphorus and sulfur. These two elements were also found to be within specifications.

Cross sections were made along the weld bead centerline of specimens of both type 304L and 316 stainless steels. The composition of the weld bead was then determined by the same techniques discussed above. The results of this analysis are also given in Table 4. (See Appendices B and C for NBS certifates of analysis.) All the specimens were within specifications with respect to Mn, Ni, Cr, and C. A possible, but not likely, exception is specimen SW whose C was not determined. Specimen 9 and SW (316) met specifications for Mo, but specimen 2 (304L) also contained 1.92% Mo, indicating that a Mo containing welding rod was used for this weld. Such a rod is not ordinarily specified for welding 304L stainless steel. Differences in the composition of the weld and base metal could lead to galvanic corrosion, although this is not likely in this case. This is discussed later in this report.

B. Water Samples Collected in Kuwait

In Kuwait, Ugiansky collected water samples at both the Shaiba Desalination Plant and at the (Old) Shuwaikh Pumping Station. For chemical analyses, the samples were collected in polyethylene bottles. For biological studies, they were collected in sterile glass bottles. The chemical analysis of the waters was performed at the U.S. Environmental Protection Agency. The results are listed in Table 5 along with the analyses of several "synthetic" waters; i.e., waters made up for performance of laboratory tests to be discussed later in this report. The Kuwait sample of brackish water was found to be similar in composition to the typical brackish waters as stated in the water towers contract specifications.(1) Two one-ml samples from each of the Shaiba seawater and Shuwaikh brackish, potable, and distilled water samples (Table 5) were tested at NBS in accordance with American Petroleum Institute Recommended Practice 38, Second Edition, 1965, "API Recommended Practice for Biological Analysis

of Subsurface Injection Waters." One-ml samples were added to vials containing Bacto-Sulfate, API Broth, and incubated at 28±1°C for four and a half months. At the end of that time no blackening was observed in any of the bottles. The test, therefore, indicated an absence of sulfate reducing organisms in the water samples.

A second method was also used to test duplicate samples of the Shaiba seawater and Shuwaikh potable and distilled water samples for sulfate reducing bacteria. This method was devised and performed by Iverson(2) of NBS. After incubation for four and a half months, no evidence of blackening in the medium was present, again indicating the absence of sulfate-reducing bacteria in the water samples.

If the brackish water that caused the failure were similar in bacterial content to the water analyzed at NBS, it is likely that the cause of failure was not due to the presence of sulfate reducing bacteria, nor would there be future problems from this source if the water's bacteria content is the same as that determined above.

C. Corrosion Products

Several pitted specimens were examined to determine if any unexpected corrosion products were present. A few particles from a pit on stainless steel specimen 8 were examined using the X-ray Debye-Scherrer technique. Lines were found that could be ascribed to the spinel structure, the FeO structure, and the alpha iron structure.

Elemental analysis was also carried out on pit corrosion products on specimens 2 and 5 by nondispersive X-ray analysis in conjunction with the scanning electron microscope (SEM). Elements found in the corrosion

products were Ni, Fe, Cl, Ca, and possibly S. Considering the composition of the alloys and of the brackish water, all the above corrosion product structures and elements are not at all unusual.

III. FAILURE ANALYSIS

A. Examination of Damaged Pipes

Substantial portions of the inside of the 800 mm diameter pipe at site D-1 and 1000 mm diameter pipe at site D-2 were examined by Ugiansky. Pits, which in some cases penetrated the 6 mm wall thickness, were found to be mostly at the bottom of the pipes where the water had reportedly remained the longest; however, pits were also found at other positions on the inside circumference of the pipes. There was some evidence that pitting was associated with scratches, welds, weld splatter, and other irregularities in the surface, but there were also numerous other examples of pitting of otherwise regular surfaces. The overall surface condition of the pipe interiors was good in terms of corrosion except for the scattered pitting. There was very little if any general surface attack - merely severe pitting of otherwise uncorroded surfaces.

Specimens removed from pipes in Kuwait were examined for a determination of pit locations with respect to any gross irregularities in the surface of the steel. Figures 6 through 14 show the nine stainless steel pipe samples removed from Kuwait as described in Table 3. Before the photographic record was made, pieces were taken from these samples for chemical analysis as seen by the areas missing from the originally rectangular pieces.

Atmospheric pitting was evident on specimen 1 (Figure 15). The pipe from which this specimen was removed was exposed to the seacoast atmosphere of site D-6 on the Arabian Gulf. This pipe was not installed in the system. It was being stored.at the site.

Examples of pitting caused by the exposure to brackish water with sodium hypochlorite are seen in Figures 16 through 19. Figure 16 shows pits adjacent to a weld and Figure 17 a pit associated with a scratch on type 304L stainless steel. Pits on type 316 stainless are seen in Figures 18 and 19. These two latter pits were not associated with any observable flaw in the surface.

On the basis of the above observations and laboratory(studies to be described later)of the samples brought back to NBS, and on the inspection of the pipes by NBS in Kuwait, it is concluded that the presence of gross surface flaws is not a necessary condition for the initiation of pitting corrosion under these conditions.

Pits were examined using both the optical microscope and the scanning electron microscope (SEM) to characterize the exact nature of the pitting attack. Figure 20 shows a pit at the end of a scratch on specimen 5. Observation at higher magnification shows the crystallographic nature (i.e., faceting and etch pitting) of the attack (Figures 21 and 22) and combined crystallographic etching within grains and grain boundary delineation (Figure 23). All these characteristics of attack were found to be common to most of the pits examined.

Figures 24 and 25 show the cross section of one of the large pits which penetrated the wall of the 1000 mm pipe at site D-2. These two micrographs show another feature that was typical of many of the pits examined, namely, the stepwise process of the pitting. Figure 25 also shows the immunity of the molybdenum containing weld metal as compared to the base 304L. Because the attack occurred near the Mo rich weld, it is possible that in this particular case galvanic action was instrumental in producing the attack. However, in numerous other cases, pits were found

where galvanic action was not to be expected, and hence it is concluded that in the system as a whole galvanic action is not necessary to explain the attack.

Another example of pitting near a weld is shown in Figures 26-28. In this case the type 316 base metal is nearly the same composition as the weld metal and the probability for galvanic corrosion effects is very low. Figure 27 shows two types of corrosion attack within the pit, both a honeycomb surface in what is probably the heat affected zone of the weld and the faceted surface farther away from the weld. This faceted surface is seen (Figure 28) also to have the same grain boundary delineation as described earlier for the type 304L stainless (Figure 23).

In general the pits on both the type 304L and 316 stainless steels showed the same characteristics in surface structure. Both steels appeared to have pitted in a manner described by Frankenthal and Pickering.(3) In the work of these authors a typical pit initiated at an inclusion and grew radially under the metal surface away from the inclusion; further surface penetration came from underneath, giving rise to the lace-like structure covering the pit (Figures 29-31). As the pit grew the cover eventually was completely dissolved, leaving a large open pit, the bottom of which was normally rough with occasional evidence of faceting (Figure 32). Similar observations were also made by Streicher(4) and by Rosenfeld and Danilow(5), but they did not associate the initiation of these pits with inclusions. The type of pitting described above was the most common type observed on stainless steels by Frankenthal and Pickering (3) in solutions containing chloride and sulfate ions (both of which are present in the brackish water). The observation of this type of pitting is indicative of corrosion occurring at highly anodic potentials (positive) and is discussed further in the

section entitled Environmental Investigations.

Numerous examples of faceting at the bottom of pits as described above were found. Examples for both the type 304L and 316 alloys are shown in Figures 21 through 23 and 28.

Microscopic examination of the localized atmospheric attack of specimen 1 (Figures 6 and 15) was also made. As seen in Figure 33 this attack typically resulted in a corrosion product (rust colored) on the surface of the pipe.

When this corrosion product was cleaned from the surface, some evidence of attack of the metal surface was seen (Figure 34). Apparently in the seacoast atmosphere at site D-6, both chloride and moisture could easily contact the surface of the pipe. Through alternate dissolution and drying, the chloride could have then become concentrated on the surface of the pipe and caused the initiation of pitting attack. This attack is obviously in its early stages here and is manifested mostly by corrosion products. An example of a more advanced case of atmospheric pitting is shown in Figure 35. In this case, the corrosion product has been removed and an attacked area where the surface grains are completely missing is seen. This attacked area (Figure 36) has all the topographical characteristics of the pits caused by the brackish water exposure and appears to have occurred by a similar mechanism.

The final examination made of the specimens removed from Kuwait was of the surface condition of the stainless steels. Observations of the surfaces of the pipe steels in the SEM showed all surfaces to have been attacked in an intergranular mode. Figures 37 through 42 show both inner and outer surfaces of pipes from sites D-2, D-6, and P. Steels from each site were examined because of the different origin of steels at each as

listed in Table 2. Also examined was a piece of hot rolled, annealed, and pickled 304 stock from the NBS Storeroom (Figures 43 and 44). The surface structure of the Storeroom stock 304 is seen to have a very rough, etched surface but no intergranular attack as seen in the steels from the Kuwait water system. Because of the intergranular attack exhibited by the Kuwait pipe steels, the specimens were subjected to tests for sensitization according to the American Society for Testing and Materials Recommended Practices for Detecting Susceptibility to Intergranular Attack on Stainless Steels, ASTM Designation A262-70. Specimens from each of the three sites mentioned above passed these tests; i.e., they were not sensitized. Further studies were carried out to determine the possible causes of the intergranular attack seen. Since both inner and outer surfaces of the pipes exhibited this same type of attack, it was felt that the attack could have originated from the pickling operation during manufacture. Attempts were made with polished specimens of the steels from Kuwait and from the NBS Storeroom to reproduce the intergranular attack by pickling in several of the standard pickling solutions. In the limited number of attempts made, the intergranular attack could not be exactly duplicated. However, a close approximation to the surfaces of the Kuwait samples was reached on the NBS Storeroom stock 304 with a pickling treatment in 25% H_2SO_4 for 30 minutes at 90°C (Figure 45).(6)

It is concluded from the above that the rough, intergranularly attacked surfaces of the pipe steels could have resulted from the pickling treatment of these steels. For a material that is subject to pitting and/or crevice corrosion attack, a smooth surface is to be preferred over a rough one. As will be seen later, both these steels are susceptible to these forms of attack in normal Kuwait waters.

B. Environmental Investigations*

1. Electrochemical Measurements.

Various electrochemical methods are now commonly used to determine the susceptibility of a metal to pitting corrosion. The most common consists of comparing the open circuit or corrosion potential E_R of the metal under investigation with the so-called critical (or breakdown) potential for pitting E_c, both measurements being made in the same environment. The critical potential is defined as the potential above which pits will nucleate. There is, however, some controversy over whether it is possible to observe pitting when a metal is at a potential below E_c. Such a question may arise as a result of the technique used to determine E_c. This may be so because the value of E_c determined depends on the time allowed at a given potential to observe the initiation of pitting. The time for pit nucleation can be rather short when the potential of the metal surface is significantly above E_c. However, as the potential of the surface decreases and approaches E_c, the time for pit nucleation becomes increasingly longer. A technique described by Pessall and Liu(7) makes it possible to determine a value of E_c which is not dependent on time. This technique consists of polarizing the specimen to the desired potential and then lightly scratching the surface. While the potential is held constant, the polarizing current is recorded as a function of time after scratching until the electrode

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*All laboratory tests were conducted at the most severe operating conditions of 50°C and stagnant solutions unless otherwise stated.

either repassivates (the current decreases to the value before scratching) or stable pit growth sets in (the current increases to some high level). Figure 46 shows actual results both above and below the pitting potential (E_c). This process is repeated until the minimum potential is found at which the electrode does not repassivate after scratching. This value was reported(7) to be reproducible and independent of the surface preparation and prior history of the electrode. Scratching provides the initiation step in pitting, so that most of the factors that have caused the lack of agreement among pitting potential measurements are minimized. In the present investigation, this technique was one of the methods used to determine the susceptibility to pitting of the pipe stainless steels. The breakdown or critical potential is referred to as $E_{c,s}$. The "s" is added for "with scratching."

Tests were made on both the 304L and the 316 steels in various environments. The environments used were made up to duplicate as nearly as possible the waters to be used in the Kuwait water distribution system.

The analyses of these "synthetic" waters are given in Table 5 along with the analyses of the water samples collected in Kuwait. Although the composition of the synthetic potable water does not correspond well with the Kuwait Shuwaikh potable water analyzed by NBS, it is close to the composition of some of the potable Kuwait water as given in Table 5. The chlorination of the Kuwait waters was simulated by adding NaOCl to produce the OCl^- equivalent to 2 ppm Cl_2.* The solutions used were also air saturated before the NaOCl addition and kept sealed afterward to minimize

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*Although values are given in this report as ppm Cl_2, additions of NaOCl were made to the solutions to give the equivalent free Cl_2 as that indicated in this report.

loss of the hypochlorite.

The critical potential for pitting, $E_{c,s}$, and the open circuit or corrosion potential, E_R, were determined for the 304L and 316 in both potable and brackish waters with 2 ppm Cl_2. These results, as well as the difference $E_{c,s}-E_R$, are given in Table 6. It should be pointed out that these results were obtained on polished surfaces, since, as will be shown later, the susceptibility to pitting changes greatly when a crevice is introduced (simulating a much more realistic engineering condition). As can be seen in Table 6, the 304L is the most susceptible alloy to use and the 316 is the least susceptible, especially in the potable water.

Another electrochemical measurement was made in the analysis of the failure itself. This measurement consisted of recording E_R as a function of time for both alloys in the brackish water of composition that could have been present during the failure. In this case the brackish water contained 50 ppm Cl_2 (the specified maximum value) and 100 ppm Cl_2 (a possible overdose of Cl_2). As can be seen from the results, also given in Table 6, E_R for both alloys in brackish water with either 50 or 100 ppm Cl_2 reached values above the $E_{c,s}$ determined previously with the 2 ppm Cl_2. This shows two important facts: That Cl_2 is a strong oxidizing agent that raises the potential, E_R, significantly; and, that since the final E_R reached was greater than $E_{c,s}$, pitting would be expected and was, in fact, observed on polished surfaces of both alloys when exposed to the brackish waters with 50 and 100 ppm Cl_2. An example of the early stages of pitting on 316 in brackish water + 50 ppm Cl_2 is shown in Figure 47. (Further examples of pitting on a specimen with a crevice are shown later.) The potential-time curve for the above specimen is shown in Figure 48. As can be seen graphically the potential rose above $E_{c,s}$ and breakdown did take place.

2. Accelerated Short-Term Exposure Tests. A test recently developed for determining the susceptibility of an alloy to localized corrosion by Smith and Peterson(8) of the U.S. Naval Research Laboratory involves the use of an artificial crevice to accelerate the rate of attack. This test is a particularly useful one in evaluating the susceptibility to localized attack (which would include pitting attack) of materials when they are ultimately to be used in a real plant or equipment. In this test an artificial crevice was produced on the surface of a polished coupon of the alloy under consideration by tying a piece of 3.4 mm diameter latex tubing around the coupon. This approximates closely the conditions that could easily exist in the stainless steel pipes in Kuwait where there are almost certainly small crevices associated with the usually observed defects in the steel itself. However, crevices need not be due only to defects in the steel. The production of crevices by stones or debris resting on the steel surface is also highly possible. Likewise, crevices can exist at welds and at flange joints.

This "rubber band" test was first used to evaluate the alloys under the reported conditions of the failure; i.e., both alloys were tested in brackish water + 50 ppm Cl_2. The results of all "rubber band" tests are listed in Table 6. Both the 304L and 316 pitted very rapidly. (These tests were terminated after corrosion product was evident near the rubber band, usually in a time of from a few hours to a few days). Scanning electron micrographs of the attack on the 304L and 316 specimens are shown in Figures 49-52. The same characteristic of surface topography is seen within the pits in these examples as was seen earlier in the actual pipe failures (compare to Figures 21-23, 28, and 32).

To determine the feasibility of disinfecting the pipes with Kuwait distilled water with NaOCl added, the crevice test was carried out on both stainless steel alloy types in the synthetic distilled water + 50 ppm Cl_2. Attack was again observed as can be seen in Table 6 and in Figures 53 and 54. A potentially dangerous situation would exist if the pipes were disinfected even in distilled water if 50 ppm Cl_2 were present.

The next evaluation made with the "rubber band" test was to determine the susceptibility of the alloys to attack in the waters to be carried by the Kuwait distribution system. That is, tests were made in both the brackish water and the potable water with 2 ppm Cl_2 added to simulate the chlorination of the Kuwait waters. In this test, it was seen that the 304L is likely to be attacked in either water (Table 6 and Figures 55-56). The test of the 304L in the potable water was not run long enough to see visible attack; only corrosion product was evident. In these tests, the 316 did not show that it was positively susceptible to attack. However, this does not mean that this alloy is immune to attack in these waters. It should be remembered that these are short-term tests and that the reported design criteria calls for actual specifications of reliability for 50 years at 50°C, and it is very likely, as previously mentioned, that the system would contain crevices.

Since the amount of hypochlorite (or chlorination) of the waters seemed to be an important factor in the susceptibility of the steels to attack, and since the concentration of chlorine in the Kuwait waters is likely to vary at least locally, another series of "rubber band" tests were carried out in the waters with an addition of 4 ppm Cl_2 (to provide for the possibility of too high an oxidizer concentration). Both 304L and 316 were severely attacked in both the brackish and potable waters

with 4 ppm Cl_2 (Table 6 and Figures 57-60). As in previous cases shown, the features of the attack are also very similar to those seen in the pits of the failed pipes, indicating the same type of attack.

Because of the known effect of acceleration of pitting attack (or lowering of E_c) with increasing temperature, all previous tests were carried out at the maximum design temperature of 50°C. As a check on the performance of 304L and 316 in the Kuwait waters at lower temperatures, both of the above alloys were subjected to the crevice test in both potable and brackish waters with 4 ppm Cl_2 added. After several days, there was evidence of corrosion product on all but the 316 in potable water. In fact, the attack of the 316 in the brackish + 4 ppm Cl_2 occurred away from the rubber band crevice. Both samples of 304L were severely pitted. These results are also listed in Table 6.

The type of attack seen in both the actual failures and in the laboratory attack is characteristic of attack on stainless steels occurring at highly anodic (positive) potentials. The surface of the steel can be raised to a highly anodic potential in either of the following ways: By introducing an oxidizing agent (such as hypochlorite or chlorine) into the solution in which the steel is exposed; or by applying a polarizing current between the steel and an auxiliary electrode. In the actual failures and in the laboratory tests explained above, the hypochlorite was the oxidizing agent responsible for raising the potential of the stainless steels. A final test was carried out to produce the highly anodic potential with a polarizing current. In this case, a polished specimen of 316 was polarized potentiostatically to +600 mV vs SCE (saturated calomel reference electrode) in brackish water without hypochlorite. After a 30-minute exposure, the specimen was severely attacked.

This attack produced all the characteristics of attack seen previously. In Figure 61 and 62, the same type of undercutting of the surface as seen in the actual failures (Figure 29-31) can be seen. Also, the same etch pitting, grain boundary delineation, and faceting as seen in actual failure pieces is seen in Figure 63 (compare to Figures 21-23 and 28, and 32 from failed pieces).

IV. DISCUSSION

A. Causes of Failure

The data presented in this report clearly show that both the stainless steel types 304L and 316 used in the Kuwait water supply system are susceptible to pitting attack when exposed to brackish water containing 50 ppm Cl_2 at 50°C. The results in synthetic distilled water containing 50 ppm Cl_2 also indicate that even if this were the disinfecting solution, attack would be likely to occur rapidly at 50°C. Thus, the rapid pitting of the stainless steel pipes appears to have been due to the long exposure (reported to be four to six weeks for the leak test) to water containing approximately 50 ppm Cl_2. Whether such rapid pitting would occur at normal operating conditions is a question that cannot be answered with confidence. However, the NBS data also show both alloys to be positively susceptible to attack at crevices in both brackish and potable waters under stagnant conditions containing as little as 4 ppm Cl_2 (simulating possible local fluctuations in Cl_2 concentration or over-chlorination) at 50°C,in brackish water + 2 ppm Cl_2 at 50°C and in brackish water + 4 ppm Cl_2 at 23°C. Positive susceptibility to attack in crevices was also found for the 304L in potable water containing 4 ppm Cl_2 at 23°C.

The only tests not showing positive susceptibility to attack were for 304L and 316 in potable water + 2 ppm Cl_2 and for 316 in potable water + 4 ppm Cl_2 at 23°C. Perhaps these too would be attacked if sufficient exposure time were allowed. Reliability under even these latter conditions in which the alloys did not show positive susceptibility to attack is thus by no means assured for the design period of 50 years at 50°C.

Based on the above data and observations made by NBS, both the materials used (types 304L and 316 stainless steels) appear to have a great deal of uncertainty associated with their use in the Kuwait water supply system.

Admittedly, the literature shows that these two alloys can be used safely in waters with even higher concentrations of chloride than the Kuwait waters; e.g., seawater;(9) but only when there is a substantially higher flow rate. In fact, 316L is used to carry seawater for desalination in Kuwait. But the literature also points out that under low flow rate or stagnant conditions (flow rate < 1 m/s), these materials are very susceptible to pitting corrosion.(9) The stainless steels used in the Kuwait water supply system will be exposed to essentially stagnant conditions.

Because our tests under stagnant conditions do show tendencies to pitting attack, it is worthwhile to note the statement by Fontana and Green(10) in their book Corrosion Engineering with regard to prevention of pitting corrosion: "Materials that show pitting, or tendencies to pit, during corrosion tests should not be used to build plant or equipment under consideration."

B. Measures to Make System Operative As Soon As Possible

Because of the possible instability of the present pipes even under operating conditions, it cannot be recommended that the present pipes be used without some kind of protection. Since we are concerned here mainly with a short-term solution that will allow the system to be made operative as quickly as possible, replacement of the pipes also would not be recommended. This leaves protection of the present pipes as the only reasonable solution.

Various methods of protection were considered. Coating or lining of the pipe interiors was considered too costly and time consuming. Impressed current cathodic protection was also ruled out due to the difficulty of reliably operating such a system and to its high installation costs for a short-term solution. The method recommended for short-term protection of the Kuwait water system is that of cathodic protection using sacrificial zinc ribbon anodes. This type of cathodic protection has the advantages of being easy and inexpensive to install and maintain.

Before a cathodic protection system can be installed at sites D-1, D-2, and P, the holes in the pipes must be repaired. In any pipes large enough to be welded from the inside, all pits and holes should be patched with the same alloy and/or welded using the proper filler metal for that alloy. The welds should be ground smooth and passivated as per the original contract specifications. With the smaller diameter pipes, all penetrating holes should be welded from the outside with care taken to avoid unnecessary crevices. Any additional holes which are discovered after the system is operative (where shutdown would be difficult) could be drilled and riveted.

After completion of the sealing of holes in the pipes, the sacrificial anode cathodic protection system should be installed by a competent cathodic protection company. The type of anode most desirable for the Kuwait system is the zinc ribbon or cable anode. Note: Care should be taken that the zinc is a high purity zinc especially made for potable water systems; i.e., it should not contain cadmium or any other harmful material. This anode is easy and inexpensive to install because it can lie on the bottom of horizontal pipes (or against the side in vertical pipes) and needs only to be connected to the pipe at the ends of the cable, which can be installed in relatively long lengths. The zinc anodes should be installed

in sufficient number and size to maintain the surface of the stainless steels at a potential at least as negative as -0.65V vs SCE at all points.(11) That is, the anodes should be installed along the entire lengths of the stainless steel pipes and no point on the surface of the pipe should be at a potential greater than (not more positive than) -0.65 V vs SCE.

Much service experience exists to show that the stainless steel alloys type 304L and 316 can be satisfactorily protected for long times in chloride containing waters at about 25°C when cathodically protected to -0.65 V vs SCE. However, there is little experience in the cathodic protection of stainless steels in brackish and potable waters identical to those in Kuwait and at the high temperatures experienced in Kuwait (50°C). Thus, it would be highly risky to predict reliable service for 50 years under the above conditions. However, considering the urgency to make the Kuwait water supply system operational as soon as possible, cathodic protection at a potential of -0.65 V vs SCE using high purity zinc ribbon or cable anodes seems to be the best choice for the short-term solution. It is felt that the cathodic protection system described above is the best possible solution for making the water system operative as soon as possible with the minimum expenditure in time and money.

C. Measures to Minimize the Chances of Future Failures. Since the pipe stainless steels appear to be extremely unstable in the disinfecting solution, safeguards must be taken to avoid this type of exposure. The zinc anodes will impart some protection even in the disinfecting solution used previously. Therefore, disinfecting should take place only after the cathodic protection system is completely installed. It is highly recommended that health experts be consulted to find, if possible, a non-Cl

containing non-oxidizing disinfectant (i.e., one not containing hypochlorite or chlorine, etc.). Any disinfectant used should be applied in preferably distilled (low Cl^-) water and should be exposed to the pipes for as little time as possible and then drained and rinsed with potable or preferably distilled water. After disinfection, the pipes should be put into use without delay.

As mentioned previously, there is little data for cathodic protection of a system identical to that in Kuwait. Therefore, although pitting should be minimized by the steps spelled out above, various precautions must be taken and contingency plans considered. The first of these precautions involves the installation by a reliable cathodic protection company of reference electrode ports for the monitoring of the potential of the stainless steel pipes. These ports should preferably be of the porous plug type that would allow potential measurements without keeping reference electrodes installed at each measurement site. These ports should be installed at various points on the circumference of each different diameter pipe for both types of water at each site. The cathodic protection company can advise on the exact locations of these reference electrode ports in order to monitor the potential of the pipes.

In order to determine the feasibility of using cathodic protection as a long-term solution or, in fact, whether or not this protection is actually needed under real operating conditions, several other steps are advisable. The installation of test coupons of actual pipe pieces (with original surfaces intact) would be advisable. These coupons should be installed without cathodic protection at sites to be determined later. Periodic inspections of both the cathodically protected pipes and the unprotected coupons is also necessary in order to determine the best long-term solution. The first of these inspections should be made just before

the system is put into operation. Later inspections would preferably be at three-month intervals for the first year (due to the uncertainties inherent in the system). Before the first year is past, a decision can be made on future inspections.

During the time that the above short-term solution is in use, a replacement material for the pipes or protection by coating or lining the pipes can be investigated in the event that cathodic protection is deemed inadvisable for the long-term solution. Also, during this time if cathodic protection seems to be the likely long-term solution, it can be evaluated whether this protection should be accomplished via the sacrificial anode (which would require a quick, simple replacement periodically) or via an impressed current system. Also, the possibility that cathodic protection will not be necessary at all sites can be investigated through the examination of the test coupons.

V. CONCLUSIONS

The stainless steel pipes in the Kuwait water supply system are susceptible to localized attack under the conditions that were reported to have been used during the disinfecting procedure. Thus, it is reasonable to conclude that the severe pitting found in the pipes occurred during this operation.

The NBS data and observations show that both alloys type 304L and 316 cannot be used with confidence in their ability to resist localized corrosion attack in the Kuwait water supply system unless new protective measures are undertaken.

Recommendations to make the water system operative as soon as possible are as follows:

(1) Repair penetrated pipes by welding;

(2) Install cathodic protection system using sacrificial zinc ribbon or cable anode. Reference electrode ports should be included in this system. Special care should be taken to see that the anodes used do not contain any toxic materials. All internal surfaces of the pipes should be polarized (or protected) to a potential at least as negative as -0.65 V vs SCE.

Measures to minimize the chances of future failures are:

(1) Test coupons of unprotected pipe steels should be installed in the water system;

(2) Disinfection should take place after cathodic protection system has been installed and should occur immediately before the system is put into operation;

(3) If available, a non-Cl containing non-oxidizing disinfectant should be used in low chloride water. The solution should be drained and pipes rinsed and put into use without delay;

(4) Inspection should be made when the system is ready to be put into operation;

(5) Periodic inspections of the pipes, cathodic protection system, and coupons should be made at three-month intervals for the first year of operation. Future inspection intervals should be decided on at the end of the first year of operation;

(6) During the time the short-term solution is in use, possible long-term solutions should be investigated. The possibilities to be considered are: Replacement of the pipes with another material; cathodic protection using sacrificial anodes; cathodic protection using an impressed current system; protection by coating or lining the pipes; and the possibility that the pipes can be used as designed at some of the sites.

ACKNOWLEDGEMENTS

The authors gratefully acknowledge the following persons for their invaluable contributions to this study: E. Passaglia, J. R. Ambrose, C. H. Brady, C. J. Bechtoldt, U. Bertocci, D. E. Harne, K. F. J. Heinrich, W. P. Iverson, M. L. Picklesimer, S. D. Rasberry, T. R. Shives, J. I. Shultz, J. L. Weber, Jr., and S. A. Wicks of the National Bureau of Standards; T. J. Lennox, Jr., and M. H. Peterson of the U.S. Naval Research Laboratory; E. McFarren of the U.S. Environmental Protection Agency; and L. P. Sudrabin of the of the Wallace and Tiernan Division of the Pennwalt Corporation.

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FORM NBS-348
(12-65)

APPENDIX A

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF ANALYSIS

310.02-11/73

on
X-ray Fluorescence Analysis
of
Nine Samples of Stainless Steel Plate
Submitted by 310.04
Attention: G. Ugiansky

Date Received : 5-10-73
Laboratory Nos.: 310.02-38750 thru 38758
References : Book 245, pp. 113-219; Carbometric Book 1, p. 61
Analysts : J. L. Weber and S. D. Rasberry

Problem: Determine if specimens 1, 7, 8, 9, and S. W. are type 316 with 0.05% carbon maximum, and if specimens 2, 3, 5, and 6 are type 304L stainless steels according to ASTM specifications A409 and A312.

Procedure: A 1 3/8-inch square was cut from each of the specimens, turned down to a 1 1/4-inch diameter disk and polished to a 6-micron diamond finish. The specimens were analyzed, along with appropriate standard reference materials, by x-ray fluorescence analysis. Carbon was determined by a combustion chromatographic method.

Results: Qualitative x-ray fluorescence analysis was made for each specimen; the range of elements considered was all those above scandium (atomic number 21). The qualitative tests indicated that no element which would prevent the unknowns from being type 316 or 304 stainless steels were present above 0.1%. The results of the quantitative x-ray fluorescence spectrometric analysis are given in Table 1.

Joseph L. Weber, Jr., Physicist
Coordination Chemistry Section

SD Rasberry

S. D. Rasberry, Physicist
Spectrochemical Analysis Section

James I. Shultz
Service Analysis Coordinator
Analytical Chemistry Division

73-144
May 22, 1973

APPENDIX A (Con't)

Table 1.

Specimen No.	Percent Concentration*						
	C	Mn	Si	Ni	Cr	Mo	Ti
1	0.050	1.97	0.9	13.8	16.9	2.38	<0.02
7	0.042	1.90	0.5	11.4	17.4	2.06	<0.02
8	0.035	1.78	0.6	12.1	17.4	2.23	<0.02
9	0.035	1.80	0.6	12.1	17.4	2.23	<0.02
S.W.	0.050	1.97	0.9	14.1	17.1	2.38	<0.02
ASTM Specification A409, type 316	0.08 max.	2.00 max.	0.75 max.	11.0-14.0	16.0-20.0	2.0-3.0	Not Specified
2	0.019	1.59	0.4	9.2	18.4	0.04	<0.02
3	0.025	1.68	0.5	9.4	18.3	0.05	<0.02
5	0.023	1.70	0.5	9.4	18.3	0.05	<0.02
6	0.026	1.77	0.6	9.2	17.9	0.07	<0.02
ASTM Specification A312, type 304L	0.035 max.	2.00 max.	0.75 max.	8.00-13.0	18.0-20.0	Not Specified	Not Specified

*The analysts' estimate of accuracy for the following elements is: Mn, ±0.05; Si, ±0.2; Ni, ±0.2; Cr, ±0.2; Mo, ±0.04.

FORM NBS-348
(12-65)

APPENDIX B

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF ANALYSIS 310.02-18/73

by
X-ray Fluorescence Analysis
of
Three Weld Specimens
Submitted by 312.04
Attention: G. Ugiansky

Date Received : 9/6/73
Laboratory Nos.: 310.02-38778 thru 38780
References : Book 245, pp 156-166
Analyst : S. D. Rasberry

Problem: We were requested to determine manganese, silicon, nickel, chromium, molybdenum and titanium in each of three small weld surfaces. The surfaces are approximately 2.0 by 0.4 cm and are too small for determination of titanium and silicon (present only in minor amounts) at a level of accuracy useful to Ugiansky. We decided to go ahead with the determination of the other four elements.

Procedure and results: Results of quantitative determination of manganese, nickel, chromium and molybdenum are presented in Table I.

The molybdenum in all three specimens is consistent with type 316 specifications and not like type 304 stainless which is nearly zero in molybdenum concentration. The other three elements are at appropriate concentrations for the three welds to be of type 316 stainless.

Stanley D. Rasberry

Stanley D. Rasberry, Physicist

K. Heinrich

Kurt F. J. Heinrich, Chief
Surface Microanalysis Section
Analytical Chemistry Division

74-29

September 21, 1973

APPENDIX B (Con't)

Table I. Results of X-ray Analysis of Three Weld Samples

Element	304L	316	2	9	Sw
	Concentration (in weight percent)*				
Mn	2.00 max.	2.00 max.	0.65	1.40	0.61
Ni	8.00-13.0	11.0-14.0	11.0	12.1	12.7
Cr	18.0-20.0	16.0-18.0	18.2	17.2	17.6
Mo	---	2.0-3.0	1.92	2.30	2.50

---

*The analyst's estimate of accuracy for the following elements is: Mn, ±0.08; Ni, ±0.3; Cr, ±0.3; Mo, ±0.06.

FORM NBS-348
(12-65)

APPENDIX C

U.S. DEPARTMENT OF COMMERCE
NATIONAL BUREAU OF STANDARDS
WASHINGTON, D.C. 20234

REPORT OF ANALYSIS

Steel Specimen

Weld Metal

Carbon Determination

Project No: 3120575

Requested By: Mr. Ugiansky

Work Order No: 4412

Analyses:

Sample No	%C
2	0.024
9	0.029

Combustion-thermoconductivity Method

S. A. Wicks
S. A. Wicks, Chemist

J Shultz
James I. Shultz
Services Analysis Coordinator
Analytical Chemistry Division

October 11, 1973

74-29

Table 1. Kuwait Water Storage Towers

Site Designation	No. of Towers		Height, m		High Water Level, m	
	Potable	Brackish	Potable	Brackish	Potable	Brackish
D-1	6	3	40	40	+60.0	+60.0
D-2	6	3	37	37	+62.0	+62.0
D-4	3	3	30	25	+83.0	+78.0
D-5	3	3	30	25	+85.0	+80.0
D-7	1	-	42	-	+125.0	--

Table 2. State of Stainless Steel Piping as of April, 1973(1)

Site	Pipe Material (Stainless Steel Type)	Condition of Pipes	Stainless Steel Source Country	Contractor
D-1 Towers	304L	Perforated(2)	France	Stexab
D-2 Towers	304L	Perforated(2)	France	Stexab
D-3 Towers	Non-existent	-	-	-
D-4 Towers	304L	Complete - No tests	France	Stexab
D-5 Towers	304L	Hydrostatic test with potable water, cleaned and dried; small 2-3 mm rust spots observed.(2)	France	Stexab
D-6 Kuwait Tower	316	Complete - No tests(2)	Japan	Union Engineering
D-7 Towers	304L	Not installed - only short pieces at concrete valve housing in place.	France	Stexab
P Blender	316	Perforated(2)	West Germany	Stepri
P-5 Blender	316	Tested with potable water. No leaks.	West Germany	Stepri

---

(1) Information in this table is from discussions between MEW staff and Ugiansky and various contract specifications and reports examined by Ugiansky.

(2) Inspection made at these sites by NBS.

Table 3. Stainless Steel Specimens Collected in Kuwait in April, 1973

Specimen No.(1)	Removal Location	Stainless Steel Alloy Type
1	D-6 (Kuwait Towers) from pipe stored at site.	316
2(2)	D-2 1000 mm diameter pipe	304L
3(2)	" " " " "	"
5	" " " " "	"
6(2)	" 800 " " "	"
7	P (Shuwaikh Blending Plant)	316
8	" " " "	"
9(2)	" " " "	"
S.W.(2)	D-6 "Special weld" section made especially for NBS	"

(1) Specimen 4 was not removed from site D-2 due to difficulties in cutting the pipe specimen from a support member.

(2) These specimens contained welds.

Table 4. Analysis of Stainless Steel Specimens Collected in Kuwait.

	Percent Concentration*						
Specimen No.	C	Mn	Si	Ni	Cr	Mo	Ti
ASTM Specification A409, type 136	0.08[†] max.	2.00 max.	0.75 max.	11.0-14.0	16.0-20.0	2.0-3.0	Not Specified
1	0.050	1.97	0.9	13.8	16.9	2.38	<0.02
7	0.042	1.90	0.5	11.4	17.4	2.06	<0.02
8	0.035	1.78	0.6	12.1	17.4	2.23	<0.02
9	0.035	1.80	0.6	12.1	17.4	2.23	<0.02
9 weld	0.029	1.40	-	12.1	17.2	2.30	-
S.W.	0.050	1.97	0.9	14.1	17.1	2.38	<0.02
S.W. weld	-	0.61	-	12.7	17.6	2.50	-
ASTM Specification A312, Type 304L	0.035 max.	2.00 max.	0.75 max.	8.00-13.0	18.0-20.0	Not Specified	Not Specified
2	0.019	1.59	0.4	9.2	18.4	0.04	<0.02
2 weld	0.024	0.65	-	11.0	18.2	1.92	-
3	0.025	1.68	0.5	9.4	18.3	0.05	<0.02
5	0.023	1.70	0.5	9.4	18.3	0.05	<0.02
6	0.026	1.77	0.6	9.2	17.9	0.07	<0.02

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*The analysts' estimate of accuracy for the following elements is: Mn, ±0.05; Si, ±0.2; Ni, ±0.2; Mo, ±0.04; Cr, ±0.2.

[†] Special specification for 316 in question, C = 0.05 max.

Table 5. U.S. Environmental Protection Agency Water Analysis Results.

ppm	Shaiba Seawater	Shaiba Distilled	Shuwaikh Brackish	Shuwaikh Potable (Blended)	Shuwaikh Distilled	Synthetic Brackish	Synthetic Potable	Synthetic Distilled	Shaiba[1] Distilled Variations	Shaiba[1,2] Potable Variations
Total Dissolved Solids	42 100	2.6[3]	3 980	280	12	4 130	671	192	3.0-180	360-580
Chloride	22 130	1.5	848	64	6	1 100	184	13	2.0-50.0	125-200
Sulfate	3 100	<25	1 600	105	<25	1 500	230	39	Trace-20.0	20-40
Sodium	12 400	<0.5	550	51	4	700	170	6	-	-
Alkalinity	120	1.4	128	24	3.2	34	4	70	Trace-20.0	20-40
Hardness	7 500	1.6	1 860	100	3	1 750	210	122	Trace-20.0	60-90
Specific Conductance (Micromohs @25°C)	45 750	4	5 300	465	30	5 720	1 420	310	5.0-300	500-800
pH	7.8	5.5	7.8	7.5	6.6	7.6	6.6	7.4	6.8-10.0	9.0-9.5

(1) MEW Shaiba Power Station report of June 3, 1970.
(2) Greater variations in several components were seen in the Kuwaiti analyses of Shuwaikh potable water in analyses for the period January-August 1972.
(3) Calculated.

Table 6. Results of Tests to Determine Susceptibility of Stainless Steel Types 304L and 316 to Corrosion Attack in Synthetic Kuwaiti Waters.

Alloy	From Pipe Specimen No.	Synthetic Water Type	Temp. °C	Cl_2 Conc., (1) ppm	Max. E_R, mV vs SCE (2)	Min. $E_{c,s}$ mV vs SCE (3)	Separation $E_{c,s}-E_R$, mV (4)	Short-Term Exposure Tests	
								Attack on Polished Surface	Attack on Specimen with Crevice
304L	2	Brackish	50	2	-20	+110	130	-	yes
"	"	"	"	4	-	-	-	-	yes
"	"	"	23	4	-	-	-	-	yes
"	"	"	50	50	+360	-	$E_R>E_{c,s}$	yes	yes
"	"	"	"	100	+520	-	$E_R>E_{c,s}$	yes	-
"	"	Potable	"	2	+120	+200	80	-	no
"	"	"	"	4	-	-	-	-	yes
"	"	"	23	4	-	-	-	-	yes
"	"	Distilled	50	50	-	-	-	-	yes
316	1	Brackish	50	2	+95	+340	245	-	yes
"	"	"	"	4	-	-	-	-	yes
"	"	"	23	4	-	-	-	yes (5)	yes (5)
"	"	"	50	50	+495	-	$E_R>E_{c,s}$	yes	yes
"	"	"	"	100	+600	-	$E_R>E_{c,s}$	yes	-
"	"	Potable	"	2	+125	+680	555	-	no
"	"	"	"	4	-	-	-	-	yes
"	"	"	23	4	-	-	-	-	no
"	"	Distilled	50	50	-	-	-	-	yes
"	"	Brackish	"	0	+600 (6)	-	-	-	yes

(1) Solutions air saturated, then sealed after NaOCl was added.
(2) Saturated calomel reference electrode.
(3) Lower $E_{c,s}$ indicates greater susceptibility to pitting attack under the conditions tested.
(4) The smaller the difference $E_{c,s}-E_R$, the greater the chances of pitting attack; where $E_R>E_{c,s}$ pitting will occur.
(5) Attack occurred on specimen with crevice, but attack did not take place under crevice.
(6) Potentiostatically polarized to +600 mV vs SCE for 30 minutes.

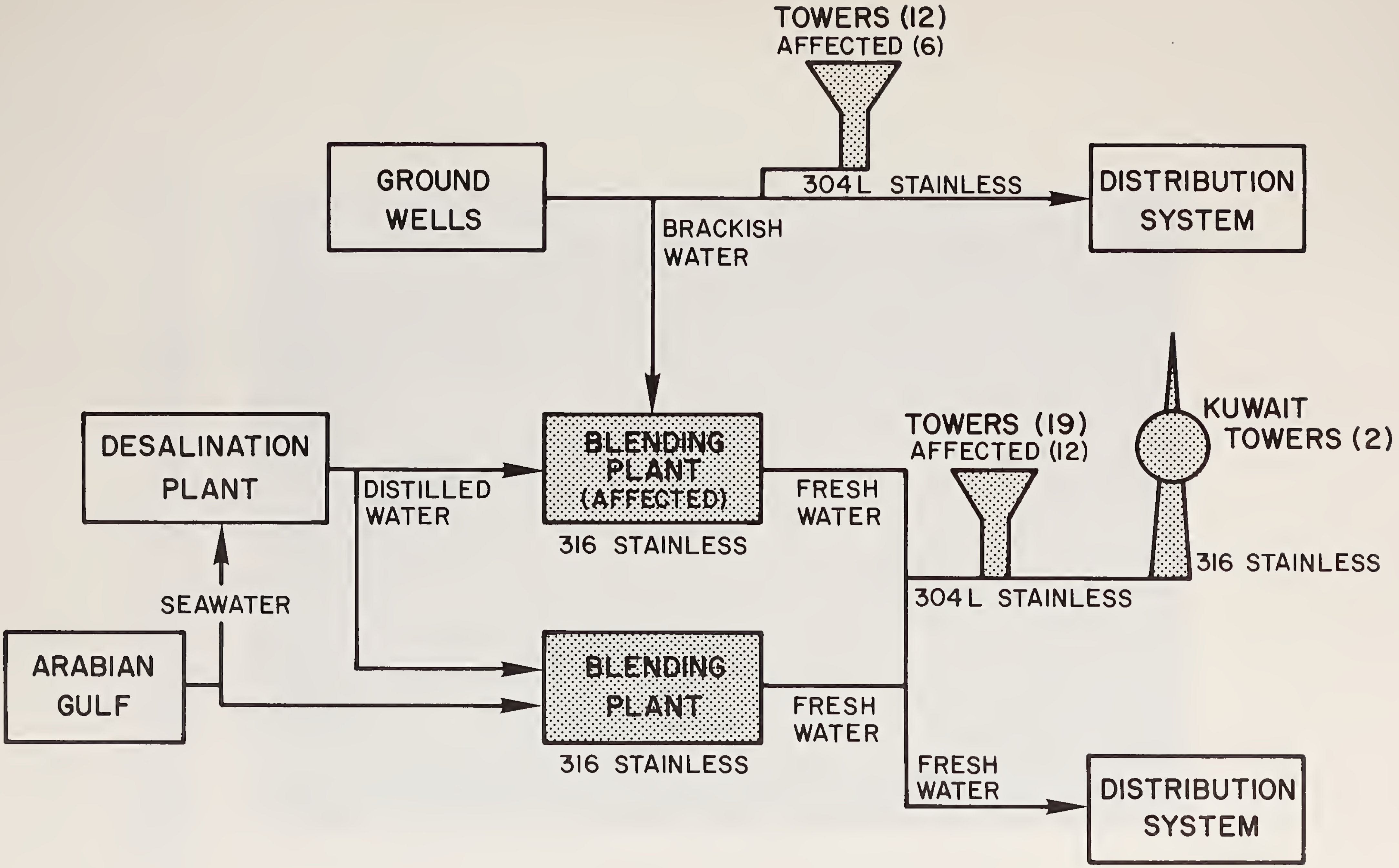

FIGURE 1

KUWAIT WATER SUPPLY SYSTEM

Figure 2. Kuwait Towers, site D-6, water storage towers, and visitors' center as of April 1973. Stainless steel type 316 pipes installed and protected externally with polyethylene.

Figure 3. Towers site D-1. Stainless steel type 304L pipes perforated at time of inspection in April 1973.

Figure 4. Towers site D-2. Stainless steel type 304L pipes perforated at time of inspection in April 1973.

Figure 5. Towers site D-5. Stainless steel type 304L pipes in fairly good condition at time of inspection in April 1973. (Small 2-3 mm rust deposits inside pipe.)

Figure 6. Interior view of stainless steel (type 316) specimen 1 removed from site D-6 (Kuwait Towers). The specimen is shown minus the pieces removed for chemical analysis. The pipe from which this specimen was removed was in storage exposed to the atmosphere at site D-6. Marker at lower left is 1 inch (2.54 cm) long.

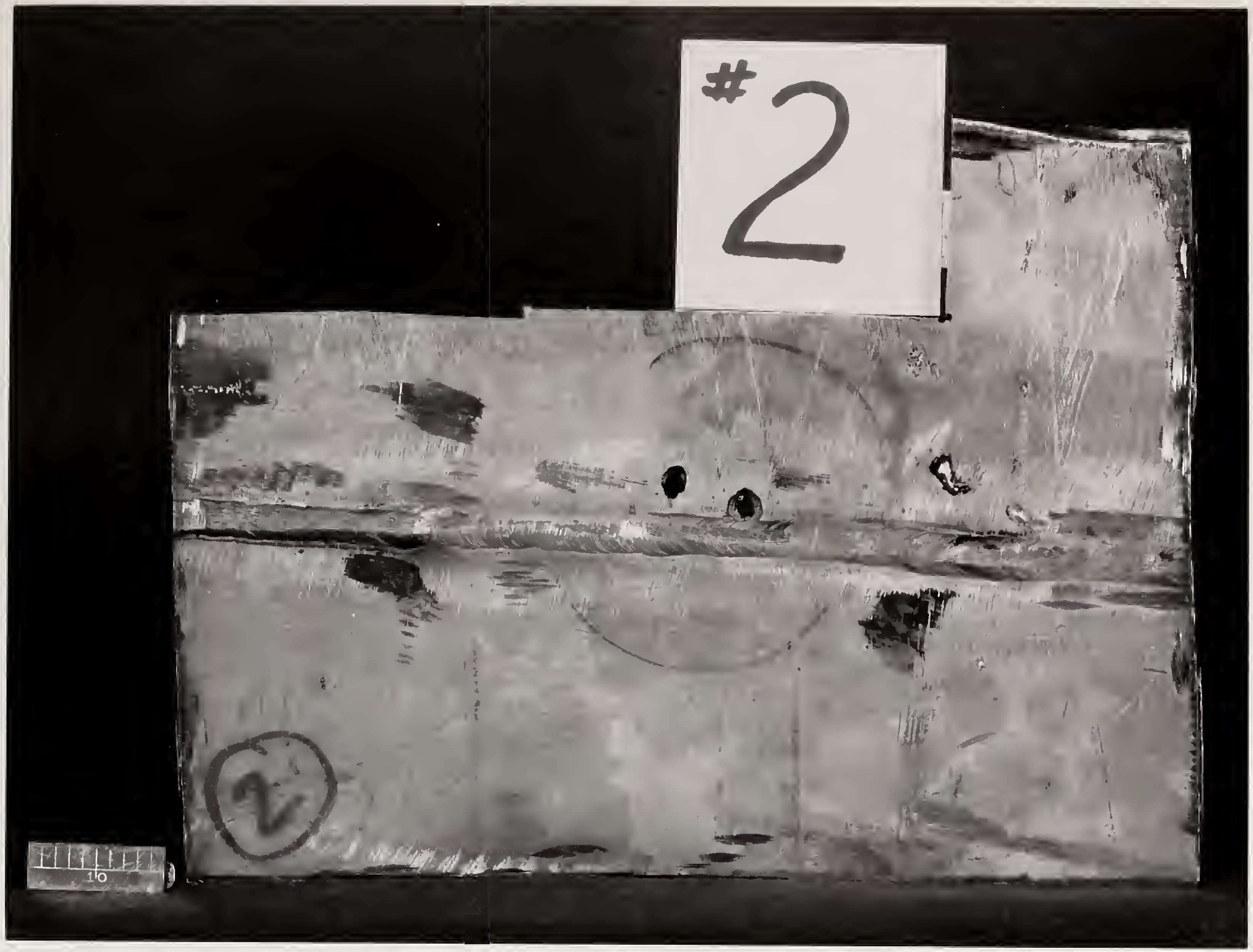

Figure 7. Interior view of stainless steel (type 304L) specimen 2 removed from the 1000 mm pipe at site D-2 (Towers). Note penetrating pits near weld at center of piece. The specimen is shown minus the pieces removed for chemical analysis. Marker at lower left is 1 inch (2.54 cm) long.

Figure 8. Interior view of stainless steel (type 304L) specimen 3 removed from the 1000 mm pipe at site D-2 (Towers). The specimen is shown minus the pieces removed for chemical analysis. Marker at lower left is 1 inch (2.54 cm) long.

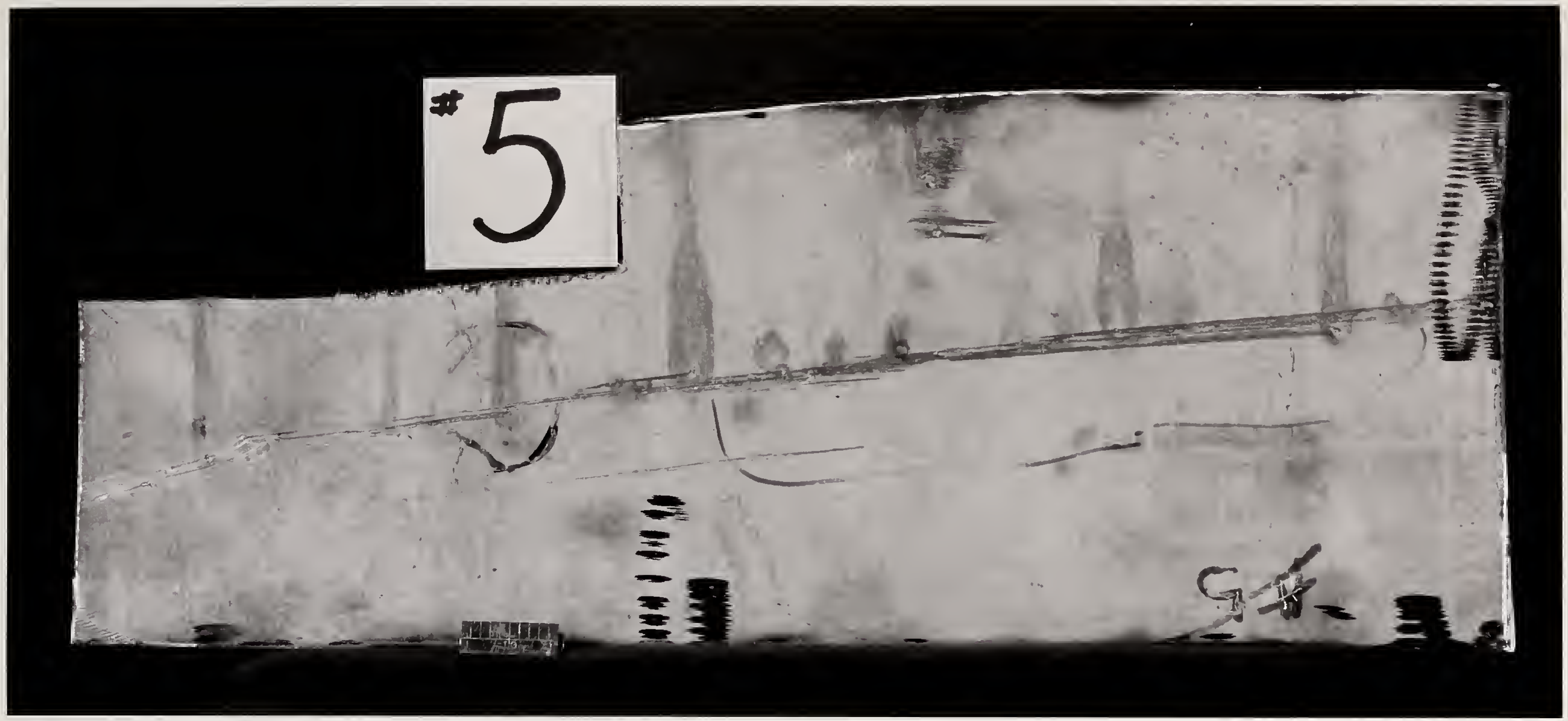

Figure 9. Interior view of stainless steel (type 304L) specimen 5 removed from the 1000 mm pipe at site D-2 (Towers). Note scratch with small pits along center of piece. The specimen is shown minus the pieces removed for chemical analysis. Marker at lower left center is 1 inch (2.54 cm) long.

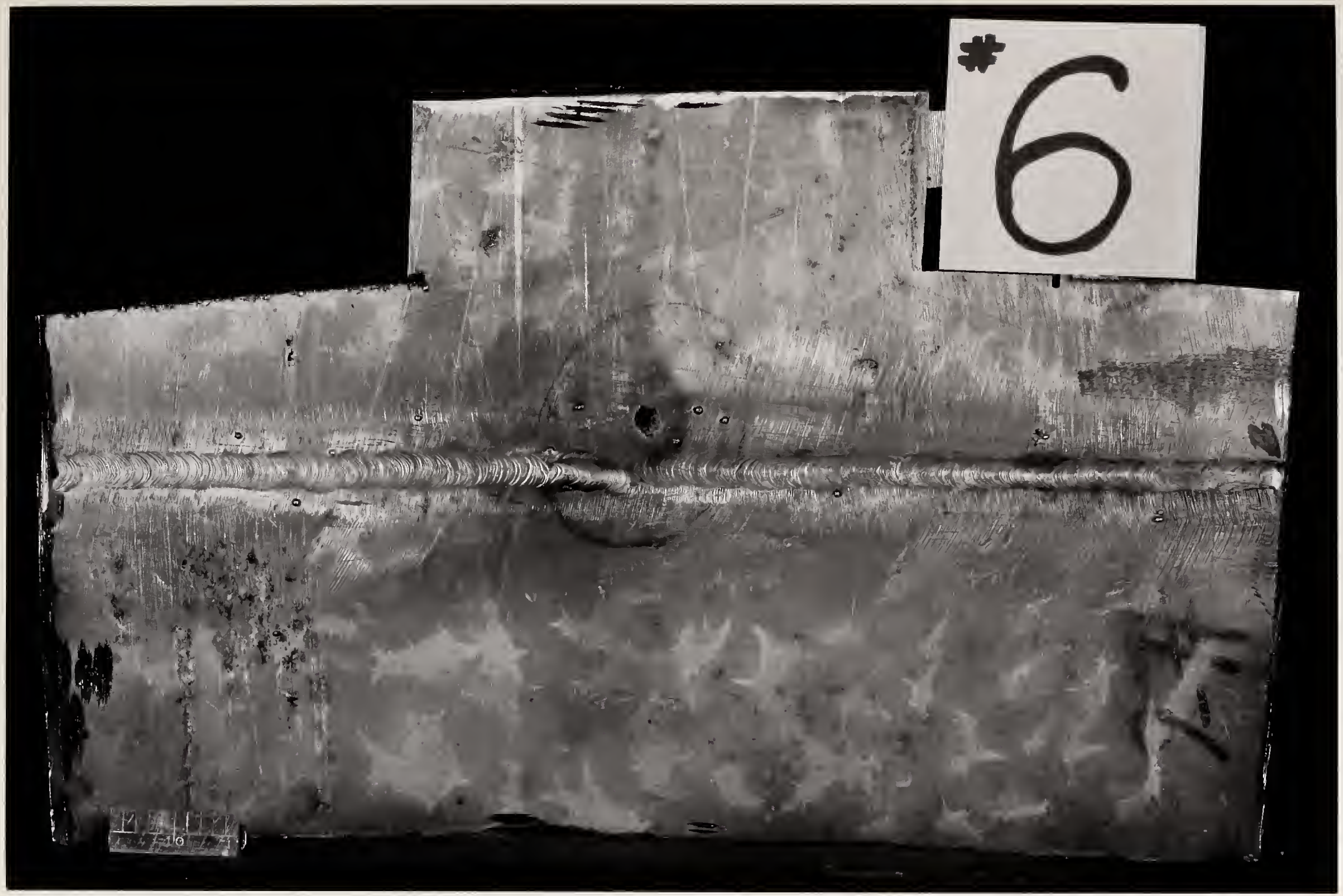

Figure 10. Interior view of stainless steel (type 304L) specimen no. 6 removed from the 1000 mm pipe at site D-2 (Towers). Note penetrating pit near weld at center of piece. The specimen is shown minus the pieces removed for chemical analysis. Marker at lower left is 1 inch (2.54 cm) long.

Figure 11. Interior view of stainless steel (type 316) specimen 7 removed from site P (Blender). This specimen shows an example of pitting initiated on the inside surface of the pipe. The specimen is shown minus the pieces removed for chemical analysis. Marker at bottom left is 1 inch (2.54 cm) long.

Figure 12. Interior view of stainless steel (type 316) specimen 8 removed from site P (Blender). This specimen shows an example of pitting initiated on the inside surface of the pipe. The specimen is shown minus the pieces removed for chemical analysis. Marker at bottom left is 1 inch (2.54 cm) long.

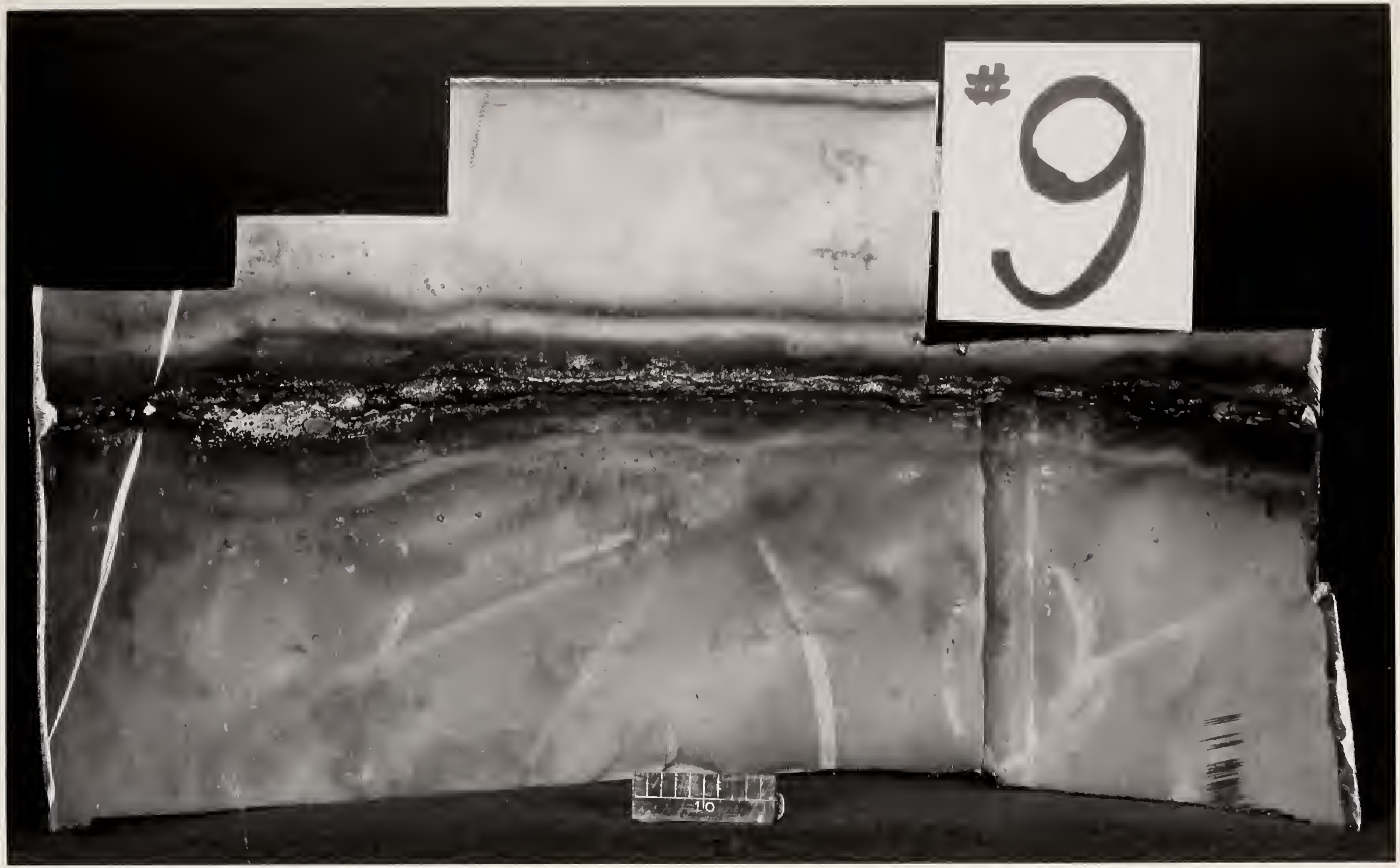

Figure 13. Interior view of stainless steel (type 316) specimen 9 removed from site P (Blender). Several small pits (initiated on the inside surface) were found adjacent to weld on this specimen. The specimen is shown minus the pieces removed for chemical analysis. Marker at bottom center is 1 inch (2.54 cm) long.

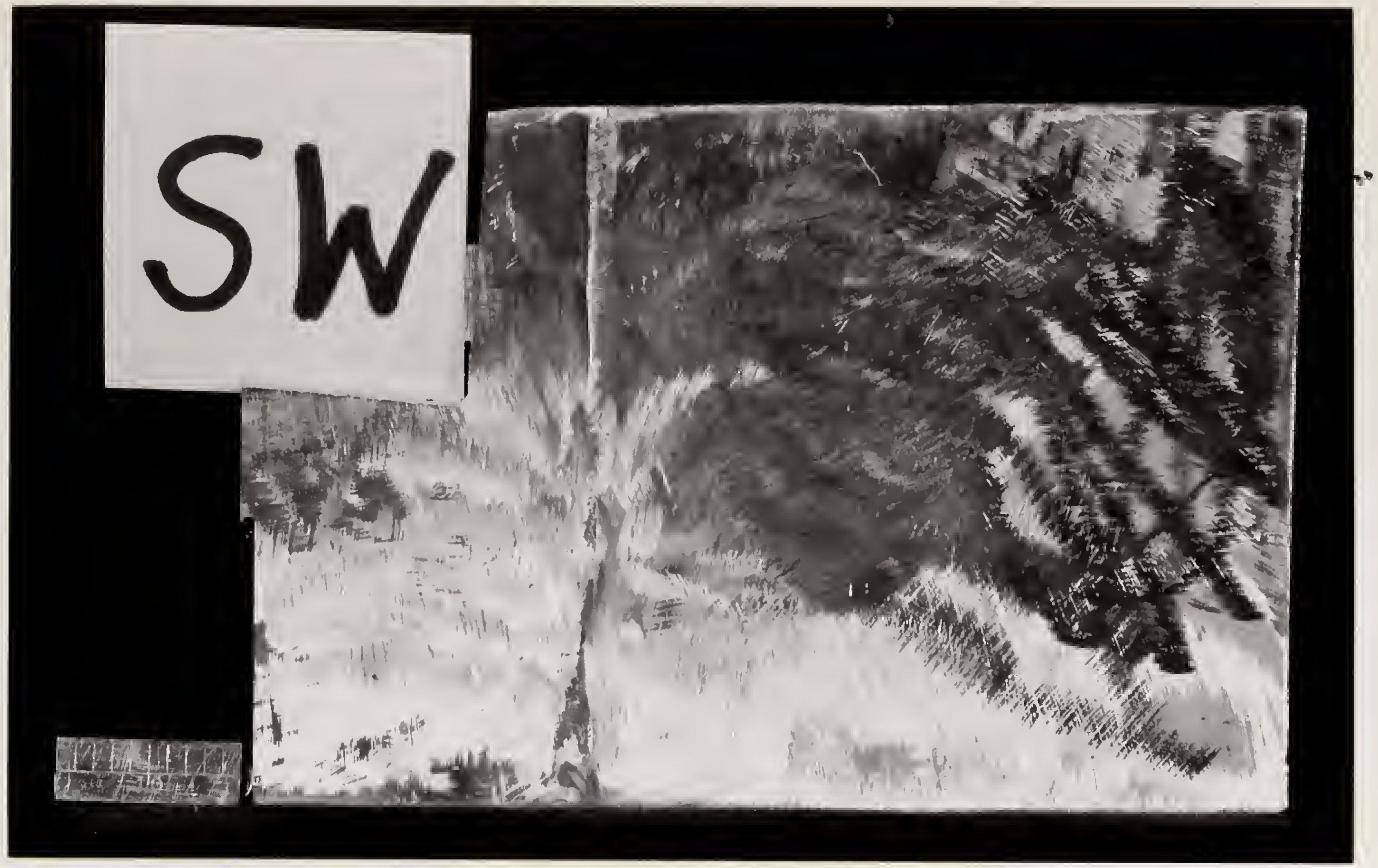

Figure 14. Interior view of stainless steel (type 316) weld specimen S.W. especially prepared by the contractor at site D-6 (Kuwait Towers) for NBS. The specimen is shown minus the pieces removed for chemical analysis. Marker at lower left is 1 inch (2.54 cm) long.

Figure 15. Enlarged view of an area of specimen 1 showing atmospheric pitting (dark spots). (304L) X2

Figure 16. Enlarged view of area of specimen 2 containing penetrating pits adjacent to weld. (304L) X2

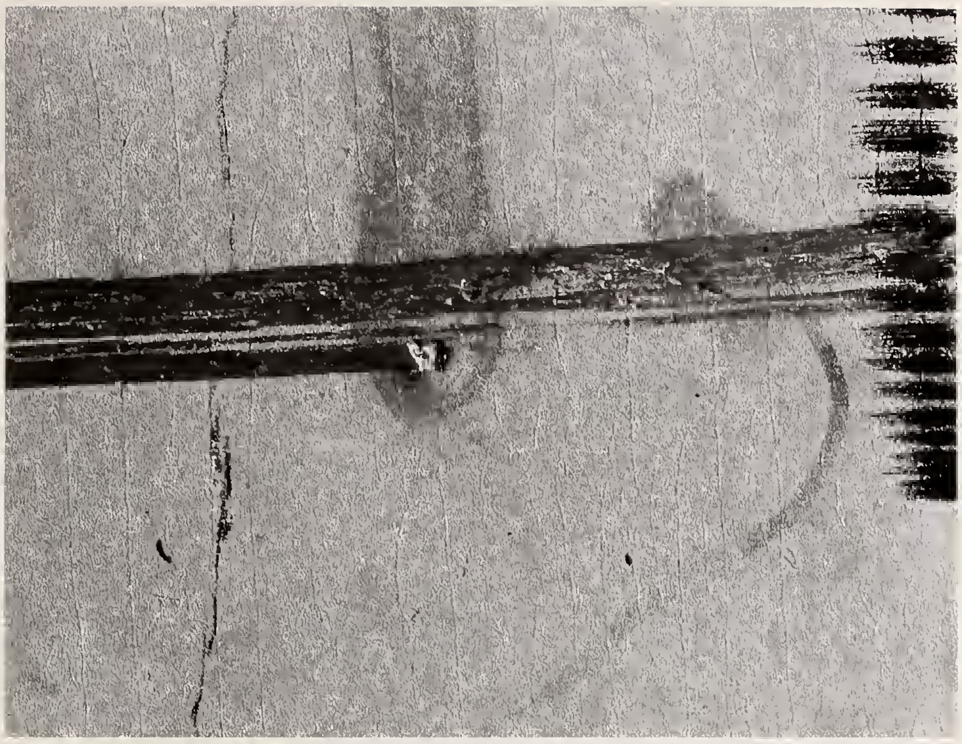

Figure 17. Enlarged view of area of specimen 5 showing pit at end of scratch. (304L) X2

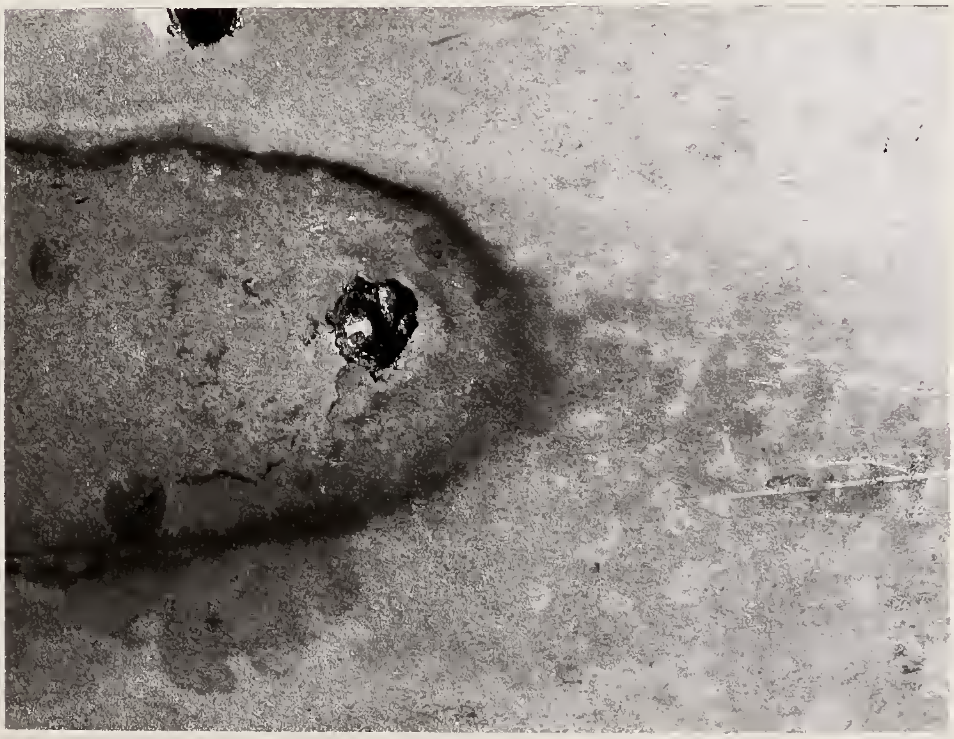

Figure 18. Enlarged view of area of outer surface of specimen 7 showing penetrating pit and oxide stain. (316) X2

Figure 19. Enlarged view of area of inner surface of specimen 8 showing pit and oxide stain. (316) X2

Figure 20. Scanning electron micrograph (SEM) of pit on specimen 5 shown in Fig. 17. (304L) X20

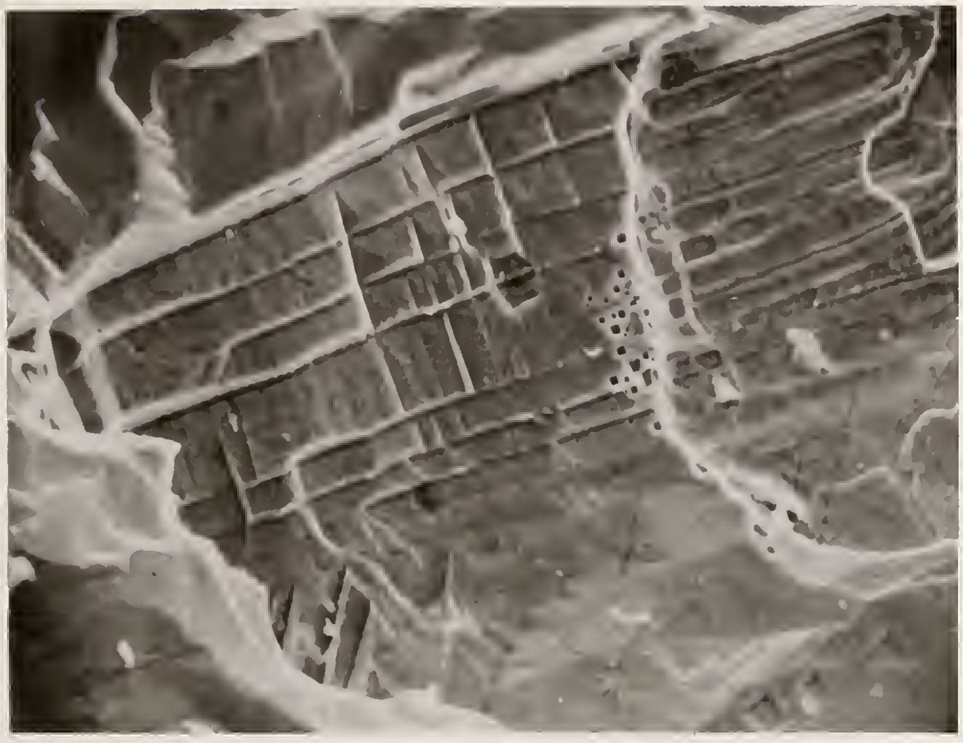

Figure 21. Surface within pit shown on Fig. 20 (specimen 5) showing etch pitting and faceting of surface. (304L) SEM X1000

Figure 22. Surface within pit shown in Fig. 20 (specimen 5 showing faceting. (304L) SEM X1000

Figure 23. Surface within pit shown in Fig. 20 (specimen 5) showing faceting and grain boundary delineation. (304L) SEM X800

Figure 24. Cross section of one of the large pits near the weld in specimen 2 (see Fig. 16). White areas are corrosion product. (304L) SEM X16

Figure 25. Cross section of the other half of pit shown in Fig. 24. Note relative resistance of weld metal to attack. (304L) Etched in 10% oxalic acid. X6

Figure 26. Pit adjacent to weld bead of specimen 9 seen in Fig. 13. (316) SEM X40

Figure 27. Surface within pit of Fig. 26. Note honeycomb structure of what is probably the heat affected zone and faceting further away from weld. (316) SEM X400

Figure 28. Area within pit of Fig. 26 showing both faceting and grain boundary delineation. (316) SEM X1600

Figure 29. Area of specimen 6 showing lace-like structure covering pit. (304L) SEM X16

Figure 30. Area of specimen 6 showing lace-like structure covering pit near weld splatter metal. (304L) SEM X14

Figure 31. Cross section of pit shown in Fig. 29. White area is cut surface. Lace-like metal is seen folded over at right of pit. (304L) SEM X40

Figure 32. Area within pit shown in Fig. 31 showing faceting. (304L) SEM X400

Figure 33. Microscopic view of one of the pits seen on specimen 1 in Figs. 6 and 15. Corrosion product is in form of barnacle-like incrustation. (316) SEM X500

Figure 34. Identical area as shown in Fig. 33 with most of corrosion product removed. Some attack other than intergranular effect is present. (316) SEM X500

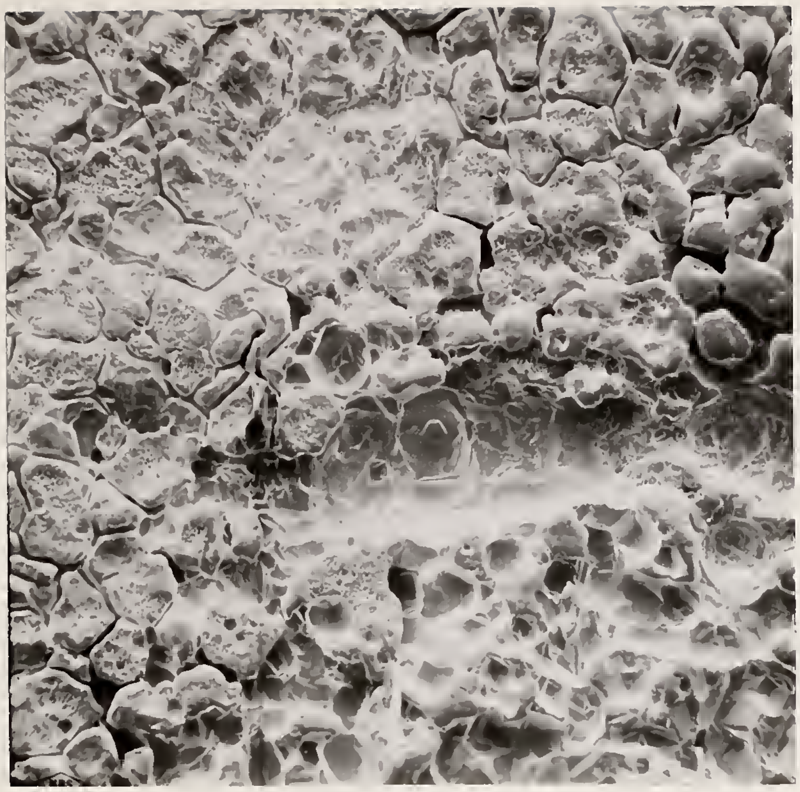

Figure 35. Area of specimen 1 in which grains of metal are missing from surface. (316) SEM X240

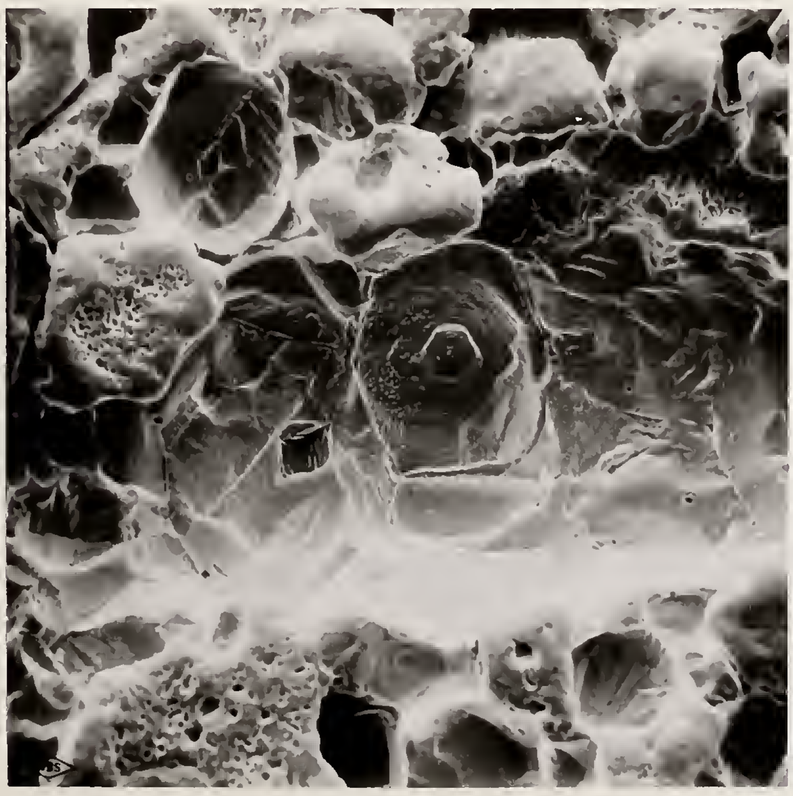

Figure 36. Area within attacked region shown in Fig. 35. Note faceting, etch pitting, and grain boundary delineation. (316) SEM X600

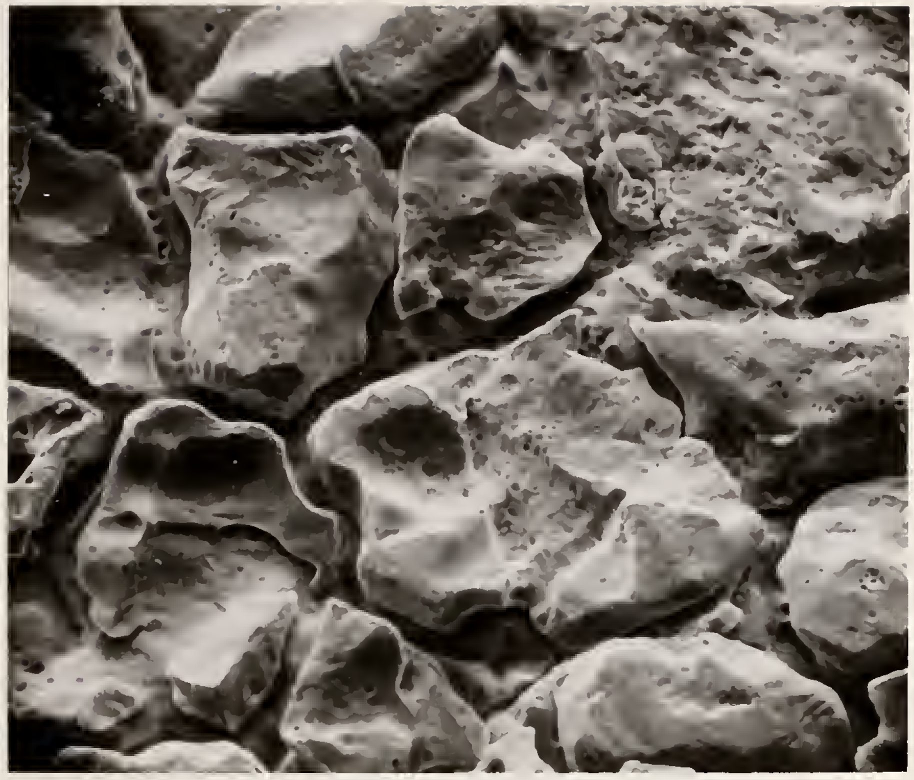

Figure 37. Typical area of inner surface of specimen 5 from site D-2. (304L) SEM X650

Figure 38. Typical area of outer surface of specimen 5 from site D-2. (304L) SEM X600

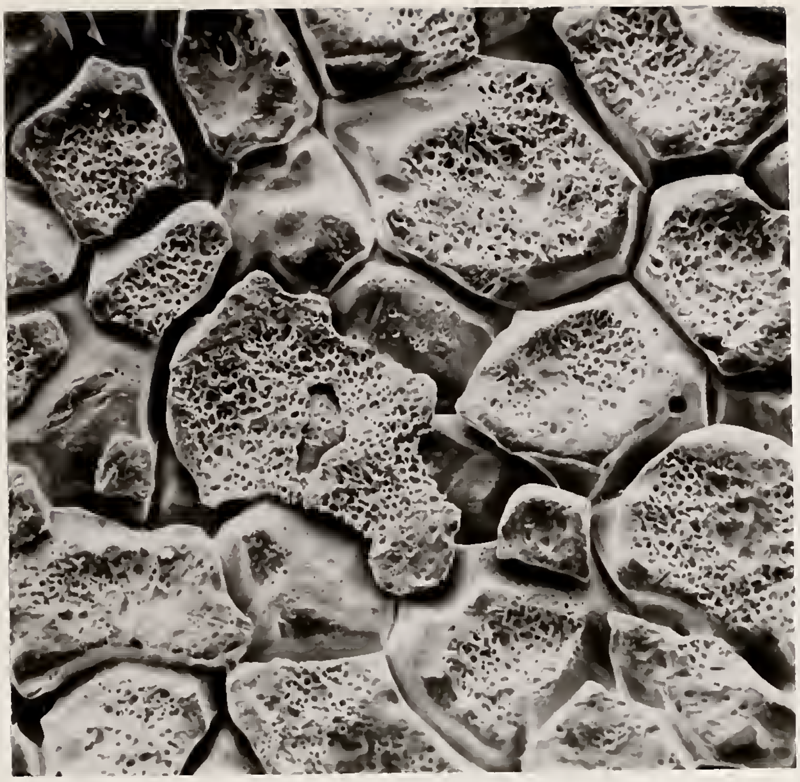

Figure 39. Typical area of inner surface of specimen 1 from site D-6. (316) SEM X600

Figure 40. Typical area of outer surface of specimen 1 from site D-6. (316) SEM X600

Figure 41. Typical area of inner surface of specimen 8 from site P. (316) SEM X600

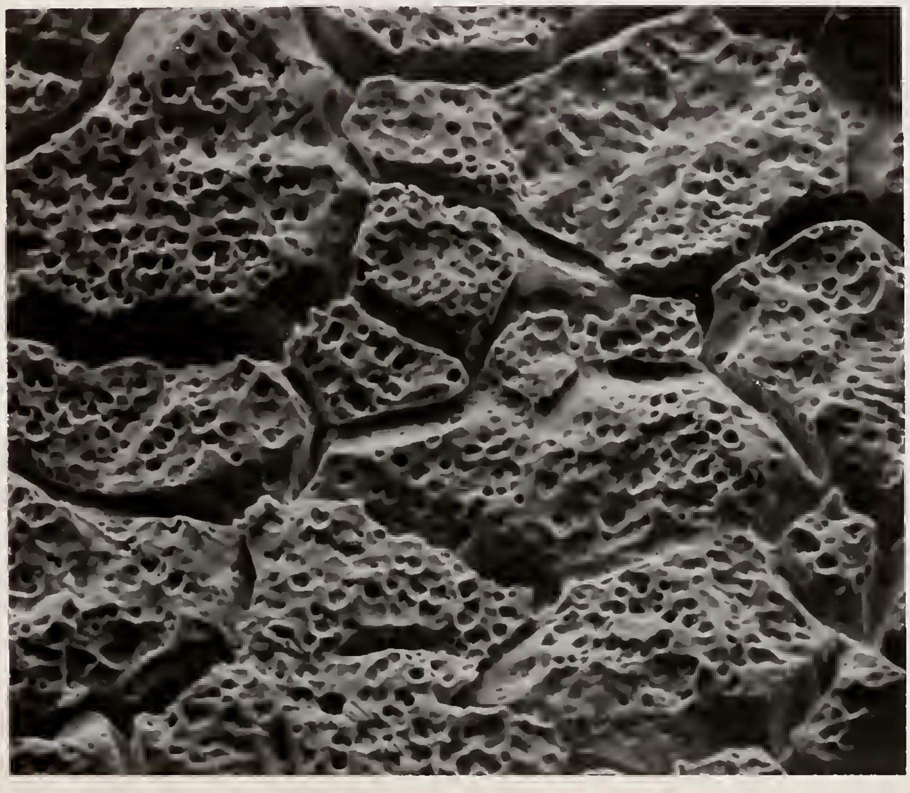

Figure 42. Typical area of outer surface of specimen 8 from site P. (316) SEM X600

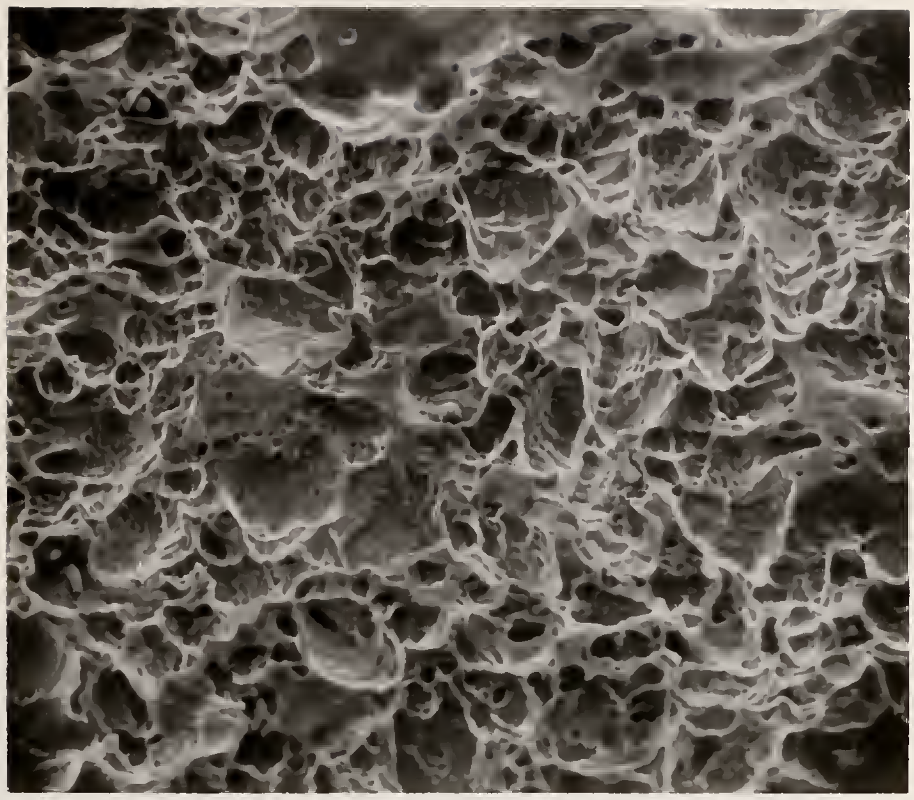

Figure 43. Typical area of surface of NBS storeroom stock type 304 stainless steel. SEM X600

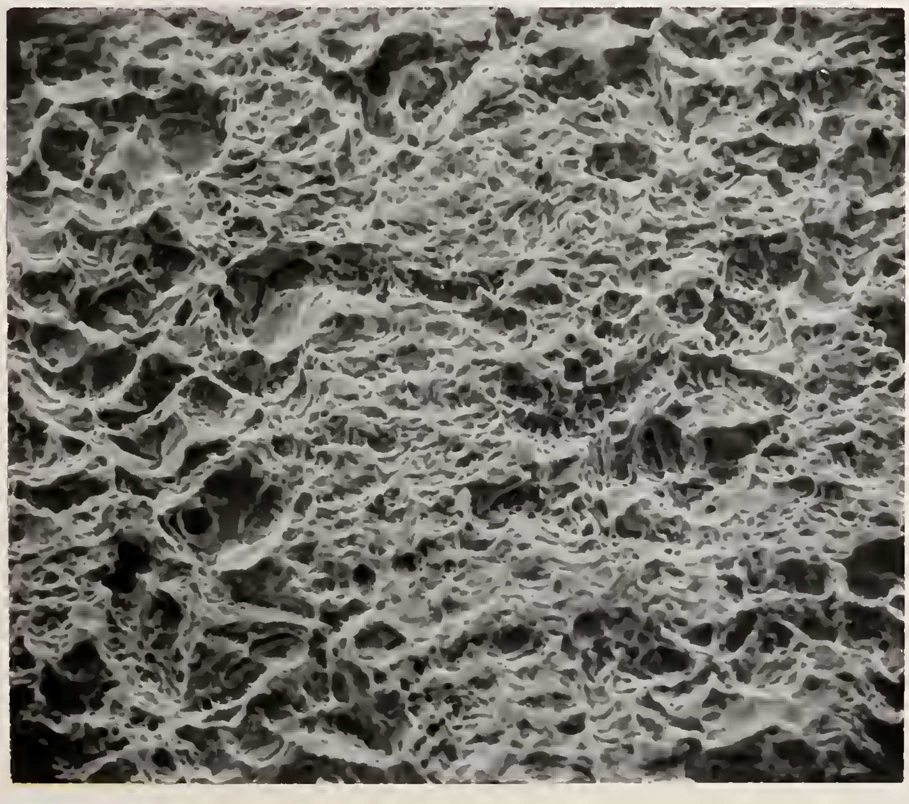

Figure 44. Typical area of surface on other side of 304 piece shown in Fig. 43. SEM X600

Figure 45. Area of NBS storeroom stock 304 after polishing and pickling in 25% H_2SO_4 for 30 minutes at 90°C. SEM 600X

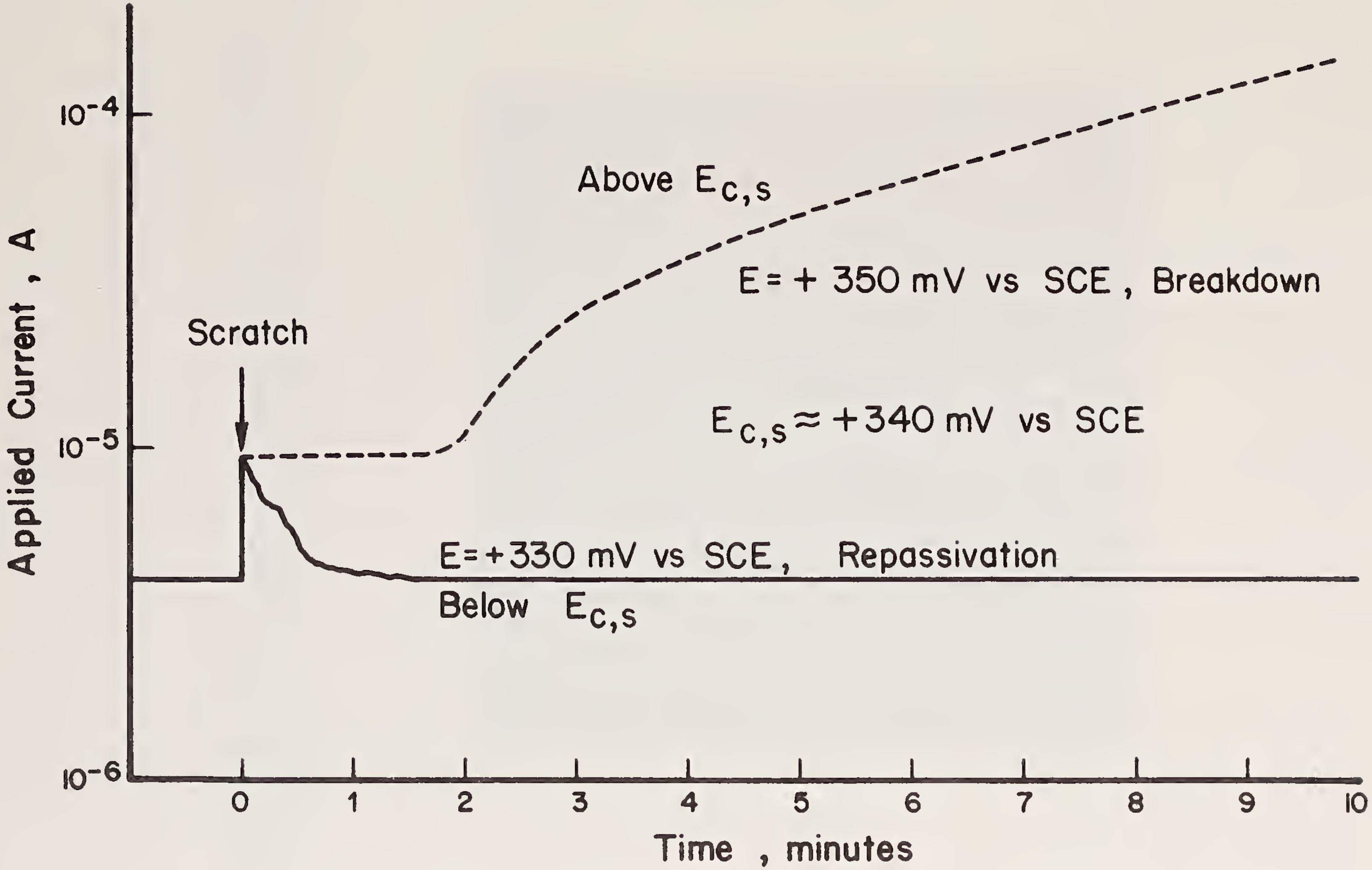

Figure 46. Scratch test current-time curves for specimen 1 in brackish water +2 ppm Cl_2 at 50°C. Curves are shown for specimens at potentials both below and above $E_{c,s}$. (316)

Figure 47. Pit in early stages of propagation on polished surface of specimen 1 exposed to brackish water +2 ppm Cl_2 at 50°C. (316) SEM X2000

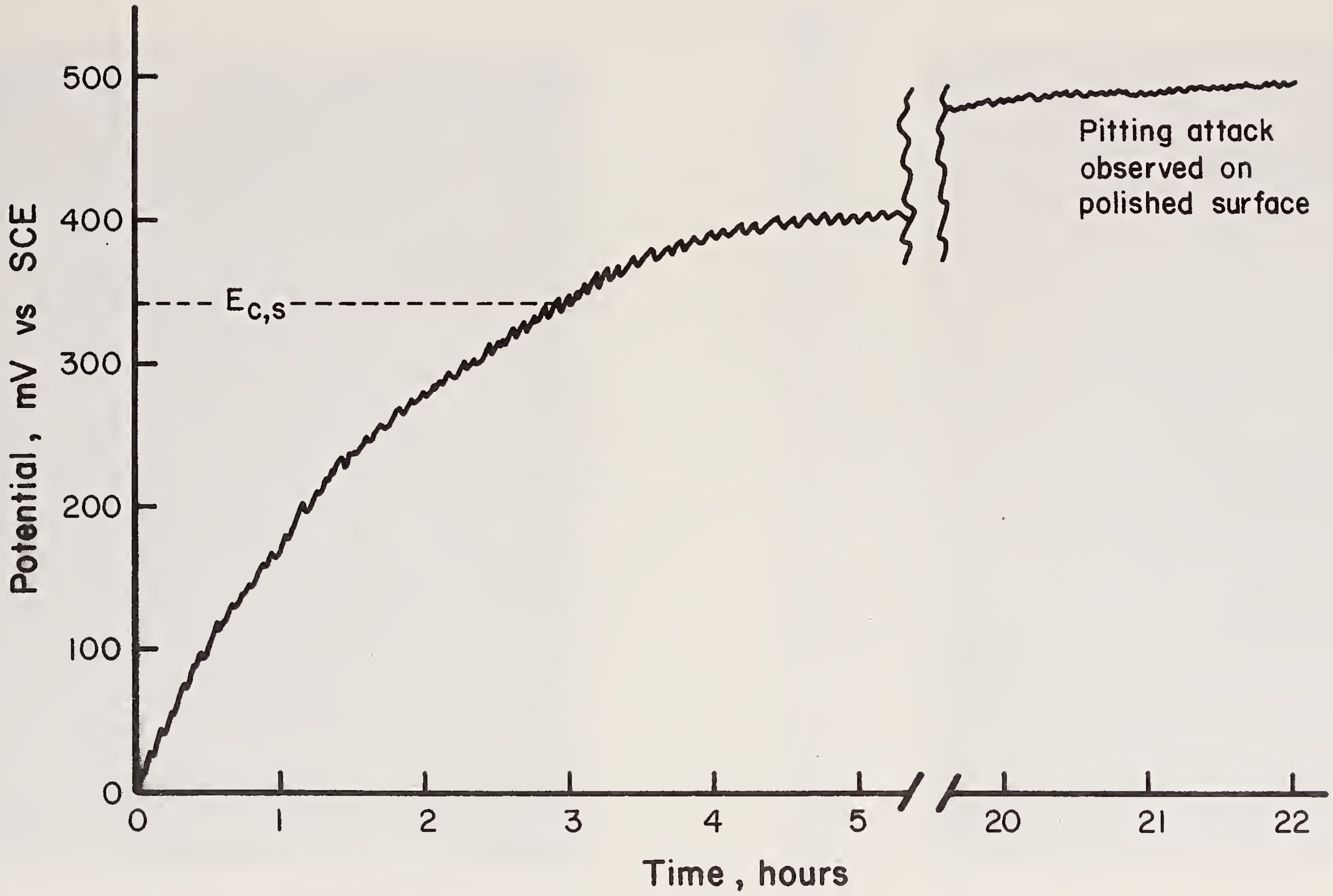

Figure 48. Potential-time curve for specimen 1 in brackish water +50 ppm Cl_2 at 50°C. (316)

Figure 49. Localized attack on surface of specimen 2 after 20-hour "rubber band" test in brackish water +50 ppm Cl_2 at 50°C. (304L) SEM X100

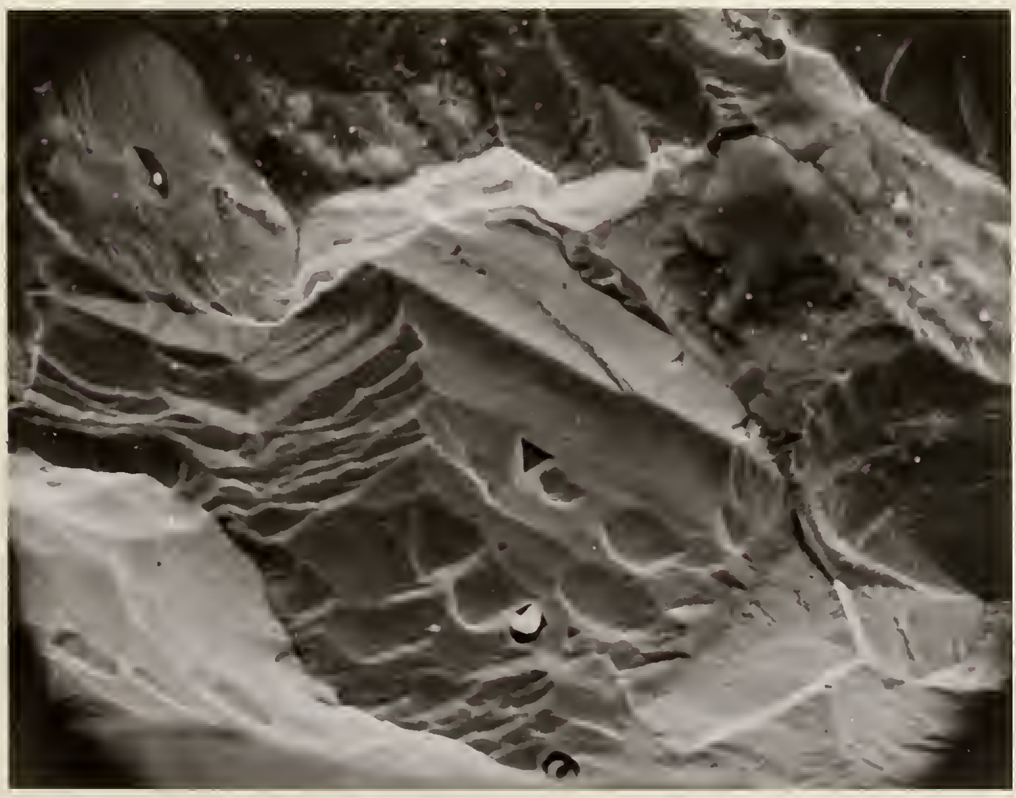

Figure 50. Area of pit shown in Fig. 49 showing etch pitting, faceting, and grain boundary delineation. (304L) SEM X1000

Figure 51. Area on specimen 1 of pit produced by 20-hour "rubber band" test in brackish water +50 ppm Cl_2 at 50°C. Note grain boundary delineation and faceting. (316) SEM X950

Figure 52. Another area of specimen shown in Fig. 51. This area shows examples of etch pitting and faceting. (316) SEM X1000

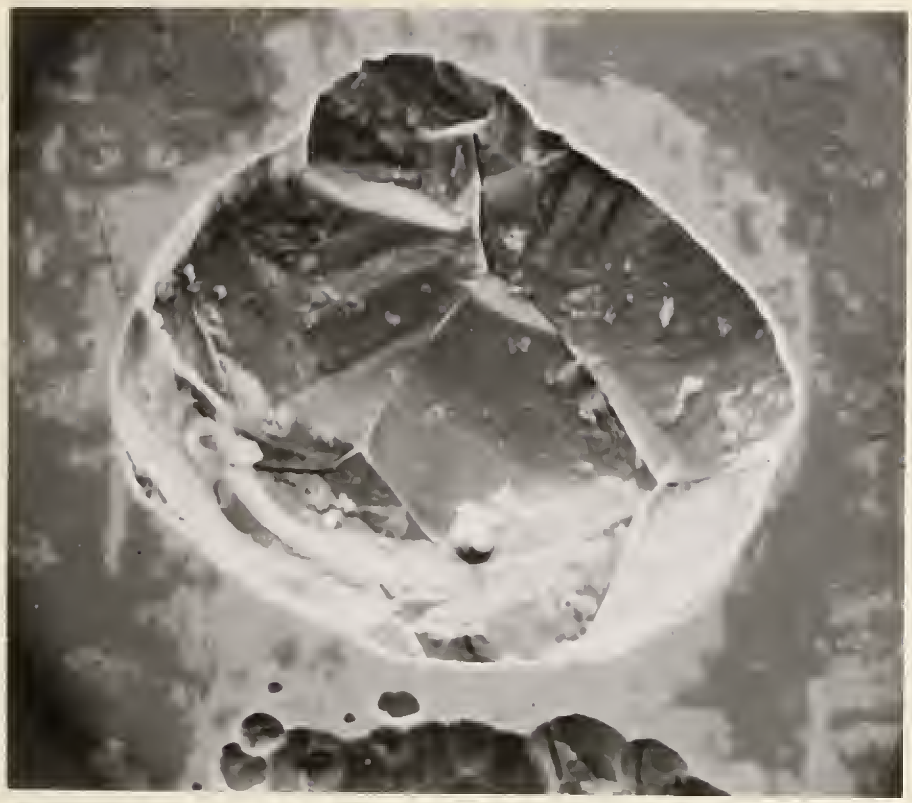

Figure 53. A small pit on specimen 2 after 20-hour "rubber band" test in synthetic distilled water +50 ppm Cl_2 at 50°C. Examples of faceting and grain boundary delineation are evident. (304L) SEM X1000

Figure 54. Attacked area on specimen 1 after 20-hour "rubber band" test in synthetic distilled water +50 ppm Cl_2 at 50°C. Etch pitting, faceting, and grain boundary delineation can be seen. (316) SEM X540

Figure 55. Area on specimen 2 of pit produced by 7-day "rubber band" test in brackish water +2 ppm Cl_2 at 50°C. Note etch pitting. (304L) SEM X900

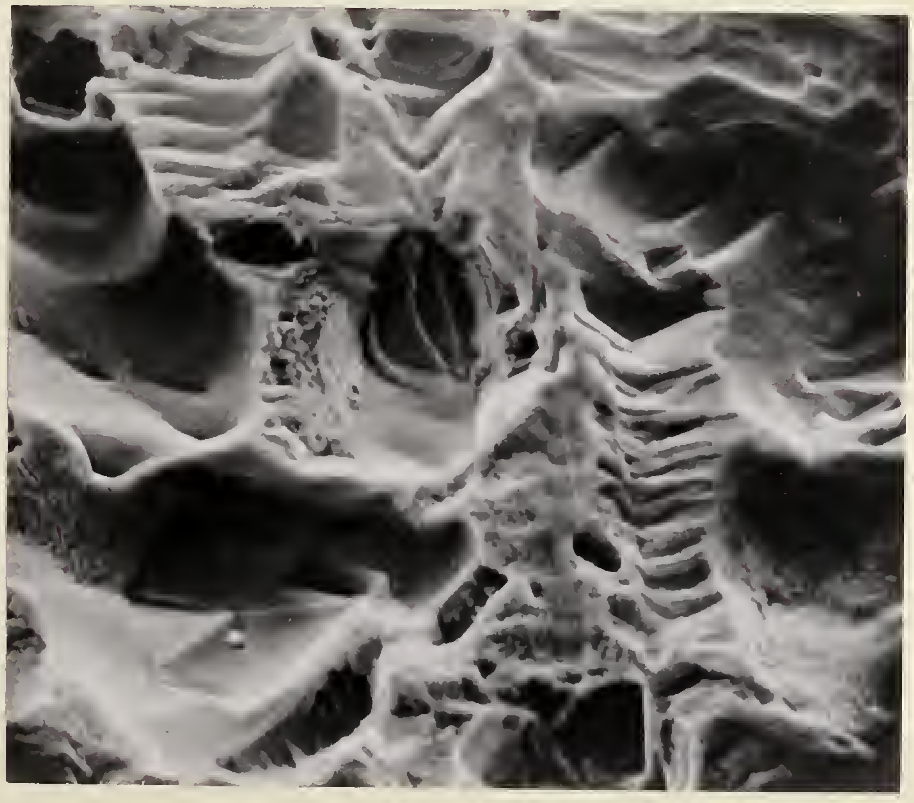

Figure 56. Another area on same specimen shown in Fig. 55. This area shows examples of faceting. (304L) SEM X1800

Figure 57. Area on specimen 2 after 5-day "rubber band" test in brackish water +4 ppm Cl_2 at 50°C. Note grain boundary delineation and some faceting. (304L) SEM X1000

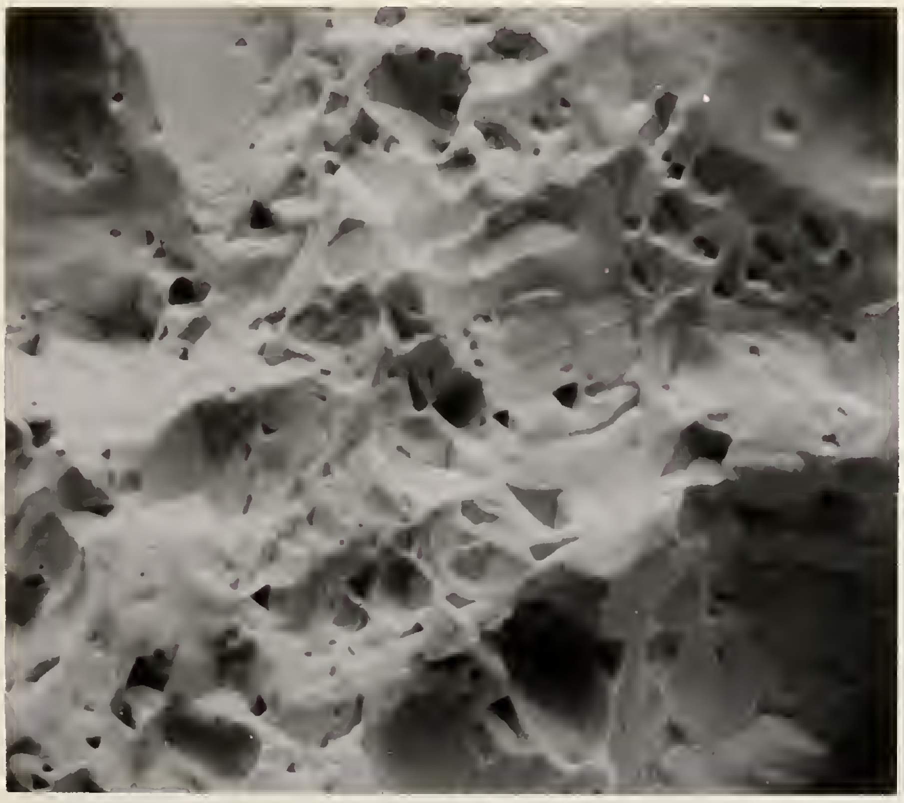

Figure 58. Area on specimen 2 after 5-day "rubber band" test in potable water +4 ppm Cl_2 at 50°C. Note etch pitting and faceting. (304L) SEM X1000

Figure 59. Area on specimen 1 after 5-day "rubber band" test in brackish water +4 ppm Cl_2 at 50°C. Examples of etch pitting, faceting, and grain boundary delineation can be seen. (316) SEM X1000

Figure 60. Area on specimen 1 after 5-day "rubber band" test in potable water +4 ppm Cl_2 at 50°C. Note faceting and grain boundary delineation. (316) SEM X1000

Figure 61. Surface of specimen 1 after 30-minute exposure to brackish water. Specimen was polarized to +600 mV vs SCE. Attack has undercut surface as in actual failure (see Fig. 29 and 30). (316) SEM X210

Figure 62. Cross section of pit shown in Fig. 61. Undercutting nature of pitting is shown. (316) SEM X200

Figure 63. Area of surface within pit shown in Fig. 62. Examples of etch pitting, faceting, and grain boundary delineation are seen. (316) SEM X2800

NBS-114A (REV. 7-73)

U.S. DEPT. OF COMM. **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NO. NBSIR 74-429	2. Gov't Accession No.	3. Recipient's Accession No.

4. TITLE AND SUBTITLE

Corrosion of the Stainless Steel Piping in the
Kuwait Water Supply System

5. Publication Date

1974

6. Performing Organization Code

7. AUTHOR(S)

G. M. Ugiansky and J. Kruger

8. Performing Organ. Report No.

NBSIR 74-429

9. PERFORMING ORGANIZATION NAME AND ADDRESS

NATIONAL BUREAU OF STANDARDS
DEPARTMENT OF COMMERCE
WASHINGTON, D.C. 20234

10. Project/Task/Work Unit No.

3120575

11. Contract/Grant No.

12. Sponsoring Organization Name and Complete Address *(Street, City, State, ZIP)*

Ministry of Electricity and Water
Government of Kuwait
Kuwait, Kuwait

13. Type of Report & Period Covered

14. Sponsoring Agency Code

15. SUPPLEMENTARY NOTES

Through: The Department of State (U.S.)

16. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here.)*

This investigation shows that the stainless steel pipes in the Kuwait water supply system are susceptible to localized attack under the conditions that were reported to have been used during the disinfecting procedure. Thus, it is reasonable to conclude that the severe pitting found in the pipes occurred during this operation.

The NBS data and observations show that both alloys type 304L and 316 cannot be used with confidence in their ability to resist localized corrosion attack in the Kuwait water supply system unless new protective measures are taken.

Recommendations to make the water system operative as soon as possible are made and measures to minimize the chances of future failures are given.

17. KEY WORDS *(six to twelve entries; alphabetical order; capitalize only the first letter of the first key word unless a proper name; separated by semicolons)*

Brackish water; disinfecting solution; pitting corrosion; potable water; sodium hypochlorite; stainless steel; 304L; 316.

18. AVAILABILITY ☐ Unlimited ☒ For Official Distribution. Do Not Release to NTIS	19. SECURITY CLASS (THIS REPORT) UNCLASSIFIED	21. NO. OF PAGES 81
☐ Order From Sup. of Doc., U.S. Government Printing Office Washington, D.C. 20402, SD Cat. No. C13 ☐ Order From National Technical Information Service (NTIS) Springfield, Virginia 22151	20. SECURITY CLASS (THIS PAGE) UNCLASSIFIED	22. Price