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# CORROSION RESISTANCE of the austenitic chromium-nickel stainless steels in CHEMICAL ENVIRONMENTS

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## INTERPRETING CORROSION TEST DATA

*The quantitative data secured in corrosion tests are often of a very low order of magnitude. When the corrosion rate is of the order of less than 0.1 mils penetration per year, the actual numbers carry little significance. If, for example, a test indicates a corrosion rate of .025 mils penetration per year for Steel A, and .05 mils for Steel B, it should not be concluded that Steel A is twice as good as Steel B, but rather that both steels are entirely suitable for service in the environment.*

In many instances, the desirable physical and mechanical properties of austenitic stainless steels may determine their use, but it is generally true that their most important property is their ability to withstand corrosion in a great many of the environments likely to be encountered by modern materials of construction.

The stainless steels possess an especially useful characteristic in resisting corrosion in that they perform best under those oxidizing conditions which are most harmful to ordinary steel and to many of the non-ferrous metals and alloys. It is also highly significant that the stainless steels demonstrate practically complete resistance to the corrosive effects of the most commonly encountered environment—the atmosphere. Not only do they resist structural damage in atmospheric exposure, but in addition, and in line with their descriptive name, they retain their original bright appearance for long periods. Cold forming operations and cold rolling generally do not decrease the corrosion resistance.

The alloys are, of course, not impervious to corrosion in all environments. With respect to certain media, corrosion of different types may occur. The extent can often be minimized by proper composition selection and careful conditioning.

## TYPES OF CORROSION OF STAINLESS STEELS

### INTERGRANULAR CORROSION

When held in the temperature range between 800 and 1650 F, the austenitic stainless steels may undergo a change which renders them susceptible to intergranu-

lar corrosion upon exposure to a number of corrosives, including some which otherwise may have slight effect on them. In this temperature range chromium carbides precipitate in the grain boundaries. The resultant areas of lowered chromium content adjacent to the grain boundaries have less resistance to corrosion. Welding operations, for example, may leave an area near the welds in such a corrosion-susceptible or "sensitized" condition. The intergranular corrosion of a sensitized steel can be insidious, in that after such attack the steel sometimes appears relatively sound, but on more detailed examination may be found to possess very little strength. A steel which has been sensitized (either by heat treatment or by welding) will be seriously subject to intergranular corrosion only in certain specific environments. Table I lists some corrosion environments which have been reported to cause such attack.

The original high corrosion resistance of the chromium-nickel austenitic stainless steels can be restored after sensitizing thermal exposure provided they have not been exposed to an effective corrosive in the meantime. Simple annealing by heating to 1850 to 2050 F followed by rapid cooling through the sensitive range is sufficient for the purpose.

Increasing carbon content tends to increase susceptibility to sensitization. Holding the carbon content to a maximum of .03 per cent, as in Types 304L and 316L, is sufficient to avoid sensitization during welding and stress relief annealing, but a further reduction to .02 per cent maximum is required if there is to be continued operation in the sensitizing temperature range. Additions of titanium or columbium also serve to inhibit the development of sensitization. These elements form carbides more readily than chromium and thus diminish depletion of the latter along grain boundaries. Therefore, if the low carbon grades are not used, Types 321 and 347 are recommended for use in corrosive environments which may cause intergranular attack where welded construction is employed and annealing is not practical. Titanium is reactive with gases at welding temperatures so that it is partially lost during welding. Type 347, containing the less reactive columbium, is usually employed for weld rods in such applications.

An extensive discussion of the effects of steel composition, thermal treatment, and evaluation test procedures has been published by ASTM.

**TABLE I**  
**Corrosive Environments Causing Intergranular Attack of Sensitized Austenitic Stainless Steels**

| Media   | Concentration, wt % | Temperature, F C | Length of Exposure | AISI Type of Stainless Steel | Type of Exposure   | Method of Sensitization                       |
|---|---------------------|------------------|--------------------|------------------------------|--------------------|---|
| Acetic Acid                                   | 99.6                | 245 118          | 2 yr               | 316                          | Field              | as-cast                                       |
| Acetic Acid with Salicylic Acid               | 55-75<br>.02-0.3    | 220 104          | —                  | 316                          | Field              | as-welded                                     |
| Acetic Acid                                   | 20                  | Boiling          | 503 hr             | 316                          | Lab                | 2 hr at 1250 F 677 C                          |
| Chromic Acid                                  | 10                  | Boiling          | 110 hr             | 304, 316                     | Lab                | *   |
| Citric Acid                                   | 20                  | Boiling          | 1082 hr            | 316                          | Lab                | 2 hr at 1250 F 677 C                          |
| Ferric Chloride                               | 5                   | Boiling          | —                  | 316                          | Lab                | *   |
| Ferric Chloride                               | 25                  | Cold             | 17 hr              | 302                          | Lab                | *   |
| Formic Acid (inhibited with ferric ions)      | 10                  | Boiling          | 2400 hr            | 304                          | Lab                | *   |
| Hydrofluoric Acid & Ferric Sulfate            | 1.8-2<br>6-8        | 170 77           | 15 min             | 302                          | Field              | flame annealed                                |
| Lactic Acid                                   | 50                  | Boiling          | 240 hr             | 304                          | Lab                | *   |
| Lactic Acid                                   | 85                  | Boiling          | 96 hr              | 304                          | Lab                | 2 hr at 1250 F 677 C                          |
| Nitric Acid                                   | 65                  | Boiling          | 240 hr             | 316                          | Lab                | 2 hr at 1250 F 677 C                          |
| Nitric Acid                                   | 12.5                | Boiling          | 96 hr              | 302                          | Lab                | *   |
| Nitric Acid                                   | 55                  | Boiling          | 144 hr             | 304                          | Lab                | *   |
| Nitric Acid                                   | 70                  | 210 99           | 2400 hr            | 302, 304                     | Lab                | *   |
| Nitric Acid & Hydrofluoric Acid               | 10-12<br>1.5        | 140 60           | 5-16 mo            | 304, 316                     | Field              | as-welded                                     |
| Oxalic Acid                                   | 10                  | Boiling          | 120 hr             | 316                          | Lab                | 2 hr at 1250 F 677 C                          |
| Phosphoric Acid                               | 60, 70 & 85         | Boiling          | 96 hr              | 304, 316                     | Lab                | *   |
| Phosphoric Acid                               | 50                  | Boiling          | 264 hr             | 316                          | Lab                | 2 hr at 1250 F 677 C                          |
| Sodium Bisulfate (inhibited with ferric ions) | 10                  | Boiling          | 2400 hr            | 304                          | Lab                | *   |
| Sultamic Acid (inhibited with ferric ions)    | 10                  | Boiling          | 2400 hr            | 304                          | Lab                | *   |
| Sulfuric Acid                                 | 0.5                 | Boiling          | 24-48 hr           | 302, 316                     | Lab                | *   |
| Sulfuric Acid                                 | 3                   | Boiling          | 15 hr              | 316                          | Lab                | *   |
| Sulfuric Acid (air free)                      | 10                  | 158 70           | 96 hr              | 316, 317                     | Lab                | *   |
| Sulfuric Acid                                 | 30                  | 96 36            | 72 hr              | 316                          | Lab                | 2 hr at 1250 F 677 C                          |
| Mixed Sulfuric Acid and Nitric Acid           | 0.6<br>0.4          | 212 100          | —                  | 309                          | Field              | Too slowly cooled by spray quenching          |
| Sulfuric Acid and Ferrous Sulfate             | 9<br>7              | 65 18            | 21 days            | 304                          | Specimens in Field | Welded & stress relieved 2 hr at 1250 F 677 C |

\* Specific heat treatment not given but varied from 1 to 1000 hours at temperatures from 1000 F to 1400 F.  
540 C to 760 C

Warren<sup>1</sup>

## STRESS CORROSION CRACKING

In certain solutions, particularly chloride solutions, stainless steels that contain residual stresses may develop stress corrosion cracking if the exposed surface is in tension. Some typical examples of solutions which have been observed to cause stress corrosion cracking are given in Table II.

A thorough compilation of case histories of stress corrosion cracking has been published by the ASTM<sup>4</sup>.

870 C Additions of other elements have little value in reducing stress corrosion cracking. To avoid all danger of cracking in those specific environments known to be capable of causing this difficulty, as, for example, those listed in Table II, practically complete elimination of internal stresses, such as those introduced by welding, is necessary. This requires annealing at quite high temperatures. For media such as those listed, the annealing temperatures may need to be in excess of 1600 F. Even so, stresses introduced on cooling can be a problem.

## PITTING CORROSION

When passive metals such as the stainless steels corrode, the corrosion develops where passivity has been destroyed. This may occur at very small areas and result in a pitted surface. Once the passivity has been lost at a local spot, this area will be anodic to the remaining passive surface. The subsequent develop-

ment of these active anodic areas into pits will depend upon electrolytic current flowing between the small anodic area and the large unattacked cathodic area outside of the pits.

Some oxidizing agents serve to depolarize this large cathode area and thus accelerate the rate of pitting. Oxygen in stagnant solutions, ferric chloride, hypochlorous acid, and mercuric chloride are typical oxidizing agents which will promote pitting. On the other hand some oxidizing agents will prevent the activation of local areas on stainless steel and thus prevent corrosion. The nitrates and chromates are good examples of this group.

The role of dissolved oxygen in pitting may assume different aspects. In the complete absence of oxygen, or other oxidizing agent, the cathodic areas will not be depolarized and the development of pits will be arrested. If oxygen is present in small amounts, and the corroding solution is stagnant, the passivity may not be preserved over the entire surface and pits may develop. Liberal aeration may in some instances supply a concentration of oxygen which is sufficient to maintain a protective passive film over the entire surface and pits will not develop. Thus good aeration and moderate velocities or turbulence are useful in maintaining adequate oxygen supply; for example, in sulfuric acid, and in sea water and other salt solutions.

If debris of any kind is allowed to accumulate on the surfaces of stainless steel equipment, it will reduce the

TABLE II

Some Chloride Solutions Which May Cause Stress Corrosion Cracking of Stainless Steels

| Salt               | Concentration, wt % | Temperature, |     | Source (see below) |
|--------------------|---------------------|--------------|-----|--------------------|
|                    |                     | F            | C   |                    |
| Ammonium Chloride  | 30                  | Boiling      |     | a                  |
| Calcium Chloride   | 37                  | Boiling      |     | b                  |
| Cobalt Chloride    | Saturated           | 212          | 100 | b                  |
| Lithium Chloride   | 30                  | Boiling      |     | a                  |
| Magnesium Chloride | 40 (pH 4)           | 220          | 104 | b                  |
| Magnesium Chloride | 60 (pH 4.4)         | 240          | 116 | b                  |
| Magnesium Chloride | 42                  | 310          | 154 | c                  |
| Mercuric Chloride  | 10                  | Boiling      |     | a                  |
| Sodium Chloride    | Saturated           | 212          | 100 | b                  |
| Zinc Chloride      | 54                  | Boiling      |     | b                  |

<sup>a</sup> Franks, Binder and Brown<sup>4</sup>

<sup>b</sup> Scheil, Zmeskal, Waber and Stockhausen<sup>6</sup>

<sup>c</sup> Scheil<sup>7</sup>

accessibility of oxygen to the covered areas and pits may develop in such locations because of the reduced oxygen concentration. Marine growths such as barnacles, sludge settling to the bottom of tanks, and carbon deposits from heated organic compounds are typical examples of this source of corrosion of stainless steels.

Pitting corrosion is rendered less severe by the addition of 2 to 3 per cent of molybdenum to stainless steel. Molybdenum additions also have the specific effect of reducing corrosion of the austenitic stainless steels in certain media such as sulfurous acid, sulfuric acid, phosphoric acid, formic acid, and some other hot organic acids. To maintain the austenitic structure in these molybdenum-containing stainless steels, the nickel content must be increased. Thus Type 316 contains 10 to 14 per cent nickel as compared with 8 to 10 per cent in Type 302.

### CREVICE CORROSION

In the design of stainless steel equipment, all shapes and joints which form crevices or deep recesses should be avoided. Oxygen does not have ready access to the areas within the crevice and these may become anodic to the remaining exposed, aerated areas of the equipment. The extent of attack within the crevice has been shown to be proportional to the area of the freely exposed metal outside<sup>5</sup>. This form of corrosion of stainless steel may be eliminated or reduced to a minimum by completely sealing such crevices, or by altering design to eliminate them. If gaskets are used, they should be non-porous and pulled up tightly over their entire area.

### GALVANIC CORROSION

When designing equipment to be constructed with several materials, thought must be given to possible galvanic couples. The stainless steels are usually quite cathodic relative to other alloys but their potentials may vary over a wide range depending upon whether they are in an active or passive state. Type 304 stainless steel in sea water has exhibited electrode potentials from +0.5 to -0.28 volt referred to the saturated calomel electrode<sup>6</sup>. The austenitic stainless steels accordingly may be expected to be cathodic to most of the common structural alloys such as ordinary steel and aluminum. This usually will mean a reduction in the normal corrosion rate of stainless steel since it profits from mild cathodic protection. On the other hand the less noble alloy in the equipment will not be excessively attacked if its area is large compared with the area of the stainless steel.

## CORROSION OF STAINLESS STEELS IN VARIOUS ENVIRONMENTS

As it is obviously not practical to discuss individually the behavior of stainless steels in contact with the thousands of corrosive media and under the variety of conditions which may be encountered, corrosive environments will here be divided into several general classes and the behavior of the austenitic chromium-nickel stainless steels in each of these types of environment summarized with appropriate data to illustrate particular points.

### CORROSION BY WATERS

#### Distilled Water

Ordinary 18-8 stainless steel remains practically unattacked by distilled water. For example, specimens of Type 304 exposed for over 1400 hours to distilled water from a condenser were corroded at a rate of only 0.13 mdd,\* equivalent to a penetration of only .02 mpy.\*\* Short time tests usually show no weight loss of 18-8 specimens in hot or cold distilled water. 5μ/year

#### Tap Water

Exposure of specimens for long periods in hot (about 140 F) tap water at several localities has shown that 18-8 stainless steel is highly resistant to corrosion by this medium. This is illustrated by some typical data assembled in Table III referring to waters that are notoriously corrosive to many materials. While the common 18-8 types should suffice in most instances, it would be expected that the Type 316 composition would demonstrate an advantage in waters of unusually high chloride content. In constructing stainless steel apparatus to be used in contact with corrosive waters, unsealed crevices should be avoided since local attack within crevices might occur. 60 C

#### River Waters

As might be expected, the stainless steels offer almost complete resistance to corrosion by river waters, including even those acid waters like the Monongahela which are quite corrosive to many other alloys. This is demonstrated by the data in Table IV. No pitting was encountered in these tests.

Resistance to attack by river waters extends to the extremely severe erosive conditions associated with cavitation effects that are sometimes encountered by

\* mdd—weight loss in milligrams per square decimeter of surface exposed per day.

\*\* mpy—corrosion rate in mils penetration per year.



316 C

conventional boiler waters. They usually are maintained at a pH about 10 with lithium hydroxide or ammonia, and may contain some added hydrogen. Austenitic stainless steels have been extensively evaluated in such waters at temperatures up to 600 F and found to be highly resistant<sup>11</sup>. Many of the reactor structures in contact with these waters have been made of austenitic stainless steels.

### CORROSION BY SALT SOLUTIONS

#### Neutral and Alkaline Salts— Other than Halogen Compounds

The austenitic stainless steels are practically free from corrosion by neutral and alkaline salts, including those of a strongly oxidizing nature. The data in Table VII are indicative.

#### Acid Salts—Other than Halogen Compounds

The behavior of austenitic stainless steels in acid salt solutions follows naturally their performance in the acids released by hydrolysis, except that because of the lesser acidity of the salt solutions their corrosive characteristics are less severe and the stainless steels will resist attack over a broad range of concentration and temperature. The alloys that contain molybdenum frequently demonstrate an advantage under the more severe conditions of acidity and temperature. The results of a number of tests in acid salt solutions are given in Table VIII.

### Halogen Salts

Because of the strong effects of halogen ions in penetrating passive films so as to induce pitting, caution is required in the application of stainless steels in contact with these chemicals. This is especially the case with the acid salts, which are likely to cause pitting if the solutions are at all oxidizing in nature, or considerable general attack if they are reducing. The following discussion relative to behavior in sodium chloride solutions will apply in a general way to behavior in other neutral or slightly alkaline halide solutions.

It has been observed that pitting attack may increase abruptly once some apparently critical temperature has been exceeded. This critical temperature is likely to be appreciably higher in the case of the alloys that contain molybdenum, such as the Type 316 composition. Tests by Brennert<sup>12</sup> in 3-normal sodium chloride solution indicated a critical temperature of about 130 F for Type 304 and over 160 F for Type 316. Similarly Uhlig<sup>13</sup> found that with Type 304 corrosion tended to increase sharply above 140 F and to reach a maximum at about 195 F. At higher temperatures the lower solubility of oxygen tended to reduce the intensity of pitting attack.

Uhlig also disclosed that corrosion increased with sodium chloride concentrations up to about 4 per cent, beyond which there was little further effect of increasing concentration.

TABLE VI

Results of Some Tests in Acid Mine Waters

| Type of Mine | Acidity as H <sub>2</sub> SO <sub>4</sub> , ppm <sup>a</sup> | Ferric Sulfate, ppm | Copper Sulfate, ppm | Duration of Test, days | Corrosion Rate, mpy μ/year |                      |
|--------------|--|---------------------|---------------------|------------------------|----------------------------|----------------------|
|              |  |                     |                     |                        | Type 304                   | Type 316             |
| Copper       | 150  | 603                 | —                   | 61                     | 17 432                     | <0.1 <3              |
| Copper       | 270  | 9424                | —                   | 61                     | <0.1 <3                    | <0.1 <3              |
| Metal        | —  | 6700                | 1020                | 6                      | <0.1 <3                    | <0.1 <sup>a</sup> <3 |
| Coal         | —  | —                   | —                   | 480                    | Nil                        | Nil <sup>b</sup>     |
| Nickel       | 251  | —                   | —                   | 365                    | —                          | 0.2 <sup>c</sup> 5   |

<sup>a</sup> ppm = parts per million.

<sup>b</sup> Corrosion of carbon steel in same test—1000 mpy. 25mm/year

<sup>c</sup> Corrosion of acid resisting bronze in same test—15 mpy. 380μ/year

<sup>d</sup> Data refer to complex alloy containing about 21% Ni, 19% Cr, plus Mo, Cu, and Si.

TABLE VII

## Results of Some Corrosion Tests of Type 304 Stainless Steel in Neutral and Alkaline Salt Solutions

| Corrosive Medium                     | Concentration        | Temperature,<br>F      C | Aeration | Velocity | Duration of Test | Location of Test Specimens | Corrosion Rate, mpy* $\frac{1}{100}$ year |
|--------------------------------------|----------------------|--------------------------|----------|----------|------------------|----------------------------|---|
| Ammonium Nitrate                     | Any                  | Any                      | —        | —        | —                | —                          | Unattacked                                |
| Ammonium Sulfamate                   | 10%                  | Atmospheric              | —        | —        | —                | Laboratory immersion       | Unattacked                                |
| Ammonium Thiocyanate                 | 460 gpl <sup>a</sup> | Atmospheric              | Nil      | Nil      | 27 days          | In tank                    | <0.1 <3                                   |
| Ammonium Thiocyanate                 | 30%                  | 154    68                | Nil      | —        | 17 days          | In vapors in evaporator    | 0.1    3                                  |
| Copper Cyanide                       | Plating solution     | 120    49                | Complete | Agitated | 7 days           | Laboratory immersion       | 0.16    4                                 |
| Magnesium Sulfate                    | Any                  | Any                      | —        | —        | —                | —                          | Unattacked                                |
| Potassium Dichromate                 | 20%                  | 212    100               | —        | —        | 144 hours        | Laboratory immersion       | Nil                                       |
| Potassium Persulfate                 | 5%                   | 95    35                 | Nil      | Nil      | 476 hours        | In tank                    | Nil                                       |
| Sodium Aluminate                     | 10%                  | 60    16                 | Yes      | Nil      | —                | Laboratory immersion       | Nil                                       |
| Sodium Bicarbonate with Free Ammonia | Mother liquor        | 200    93                | —        | —        | 71 days          | In tank                    | <0.1 <3                                   |
| Sodium Carbonate                     | 10%                  | 60    16                 | Yes      | Nil      | —                | Laboratory immersion       | Nil                                       |
| Sodium Phenolate                     | 20% as NaOH          | 250    121               | Nil      | —        | 329 days         | In tower                   | <0.1 <3                                   |
| Sodium Phosphate                     | 5%                   | 60    16                 | Yes      | Nil      | —                | Laboratory immersion       | Nil                                       |
| Sodium Sulfide                       | 0.4%                 | 108    42                | Nil      | Low      | 43 days          | In tank                    | 0.2    5                                  |
| Sodium Sulfide                       | 50%                  | 320    160               | —        | —        | 324 hours        | Immersed                   | 68    1,750                               |

\* No pitting observed in any of these tests.

<sup>a</sup>gpl = grams per liter.



**TABLE VIII**  
**Results of Some Corrosion Tests of Stainless Steels in Acid Salt Solutions**

| Corrosive Medium               | Concentration            | Temperature, F C | Aeration | Velocity                     | Duration of Test | Location of Test Specimens   | Corrosion Rate, mpy $\mu$ /year |            | Depth of Pitting, mils $\mu$ |           |
|--------------------------------|--------------------------|------------------|----------|------------------------------|------------------|------------------------------|---------------------------------|------------|------------------------------|-----------|
|                                |                          |                  |          |                              |                  |                              | Type 304                        | Type 316   | Type 304                     | Type 316  |
| Aluminum Sulfate               | 7%                       | 86 30            | Complete | 16 ft/min<br>5m/min.         | 20 hours         | Immersed                     | —                               | 1.0<br>25  | —                            | —         |
| Aluminum Sulfate               | 20%                      | 95 35            | Nil      | Nil                          | 10 weeks         | Immersed in storage tank     | <0.1 <3                         | Nil        | Nil                          | Nil       |
| Aluminum Sulfate               | Concentrated             | 240/116          | Nil      | Some                         | 144 hours        | In evaporator                | >820<br>>20,800                 | —          | —                            | —         |
| Ammonium Di-hydrogen Phosphate | 40%                      | 140 60           | Nil      | Nil                          | 22 days          | Immersed                     | <0.1 <3                         | <0.1<br><3 | Nil                          | Nil       |
| Ammonium Sulfate               | 47% + free acid          | 150 66           | Nil      | Some                         | 77 days          | In crystalliser              | 32 840                          | —          | 4<br>100                     | —         |
| Copper Sulfate                 | 14% + 4.7% free acid     | 215/102          | Nil      | Some                         | 68 days          | In evaporator                | 0.2 5                           | 0.1<br>3   | 8<br>200                     | Nil       |
| Copper Sulfate                 | 10%                      | 60 16            | Some     | Nil                          | —                | Immersed                     | Nil                             | —          | —                            | —         |
| Copper Sulfate                 | Plating solution         | 160 71           | Some     | Some                         | 7 days           | Immersed                     | 0.4 10                          | —          | —                            | —         |
| Ferric Sulfate                 | 1.5% + 4% free acid      | 160 71           | Nil      | Some                         | 31 days          | In tank                      | <0.1 <3                         | —          | <0.1<br><3                   | —         |
| Ferrous Sulfate                | With free acid, pH 1     | 100 38           | Some     | Some                         | 67 days          | In sump                      | 0.5 13                          | 13<br>325  | 4<br>100                     | 14<br>350 |
| Manganese Sulfate              | 140 gpl pH 1-2           | 140 60           | Complete | 2-4 ft/sec<br>0.6-1.2 m/sec. | 8 days           | In trough                    | Destroyed                       | 2.9<br>68  | —                            | Nil       |
| Manganese Sulfate              | 1.3 s.g. pH 4*           | 235/113          | Nil      | Some                         | 11 days          | In evaporator                | 0.5 13                          | 0.3<br>8   | 8<br>200                     | 2<br>50   |
| Nickel Sulfate                 | 115 to 238 gpl Nickel    | 190 88           | Nil      | Nil                          | 232 days         | Immersed                     | <0.1 <3                         | <0.1<br><3 | Nil                          | Nil       |
| Potassium Aluminum Sulfate     | 10%                      | 60 16            | Some     | Nil                          | —                | Immersed                     | <0.1 <3                         | —          | Nil                          | —         |
| Potassium Chromium Sulfate     | 45% + 5% free acid       | 50-122<br>10-50  | Nil      | Nil                          | 46 days          | Immersed in tank             | 57 1,450                        | <0.1<br><3 | >31<br>Perf.<br>>790         | Nil       |
| Potassium Persulfate           | 4.8% pH 3                | 90 32            | Nil      | Nil                          | 13 days          | Immersed in tank             | Nil                             | Nil        | Nil                          | Nil       |
| Zinc Sulfate                   | Plating solution pH 3    | 145 63           | Some     | Some                         | 31 days          | Immersed in tank             | <0.1 <3                         | <0.1<br><3 | Nil                          | Nil       |
| Zinc Sulfate                   | Saturated plus free acid | 218<br>103       | Nil      | Vigorous                     | 35 days          | Immersed in evaporator       | Destroyed                       | 26<br>650  | —                            | 3<br>75   |
| Zinc Sulfate                   | Impure electrolyte       | 104 40           | Slight   | Slight                       | 21 days          | Immersed in thickener trough | <0.1 <3                         | <0.1<br><3 | Nil                          | Nil       |

\* s.g. = Specific gravity

With respect to pH, Uhlig observed that pitting was the normal form of attack in 4 per cent sodium chloride at 195 F at pH above 2.8, with fairly rapid general attack at lower pH values. In the pitting region above pH 2.8 the deepest pits occurred in the range pH 6 to 7, with less intense pitting in the more alkaline solutions, and with very little corrosion at pH 12.

Table IX lists test results on corrosion of stainless steels in halogen salt solutions. Although some of these rates appear low and the pitting is slight, caution must be observed to avoid stresses which may give rise to stress corrosion cracking, especially if the solutions are hot and have an opportunity to become concentrated in crevices or under deposits.

### CORROSION BY INORGANIC ACIDS

The behavior of stainless steels in inorganic acids is specific for each acid and, in some cases, for the concentration and temperature. Accordingly no general statement can be made and each acid must be discussed separately.

#### Hydrochloric Acid

All concentrations of hydrochloric acid will attack stainless steels since the acid readily destroys their passivity. In hot moderately strong solutions the alloys are rapidly attacked with evolution of hydrogen. In cold solution the attack is also too rapid to permit use of stainless steels. Mixtures containing small amounts of hydrochloric acid may cause pitting. Typical observations are given in Table X.

#### Sulfuric Acid

Type 316 stainless steel gives useful service at room temperature in sulfuric acid of concentrations lower than 20 per cent and higher than 85 per cent. Between 20 and 80 per cent acid concentration it is subject to rapid attack. At elevated temperatures the corrosion rate increases and even Type 316 is not very useful in the acid alone except in very low acid concentrations. However, additions of ferric sulfate, copper sulfate<sup>14</sup>, nitric acid, chromic acid<sup>15</sup>, or oxygen greatly reduce attack by sulfuric acid and permit many economical applications of this stainless steel. Thus, nitration reactions involving mixed acid are accomplished in stainless steel equipment. Mixed acid is also stored and shipped in stainless steel containers. Figure 1 illustrates the general corrosion behavior of Type 316 in sulfuric acid as a function of acid concentration and temperature.

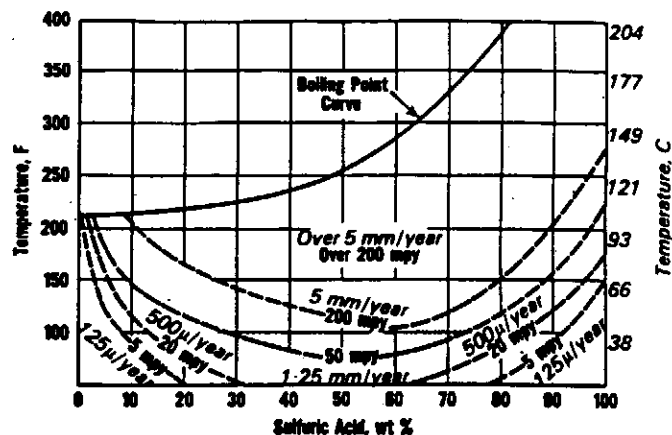


FIG. 1—Corrosion of Type 316 stainless steel by sulfuric acid as a function of temperature. Fontana<sup>16</sup>

In sulfuric acid at concentrations and temperatures where the usual 18-8 types cease to be useful, stainless steel alloys containing molybdenum with copper and/or silicon, along with higher levels of nickel and chromium, provide good resistance to attack. Thus, an alloy containing 29 per cent nickel, 20 per cent chromium, 2 per cent (minimum) molybdenum, 3 per cent (minimum) copper, 1 per cent silicon, and .07 per cent (maximum) carbon is very useful for handling hot, wet sulfur dioxide containing sulfuric acid in amounts which are too corrosive for the ordinary 18-8 alloys. Other alloys containing 29 to 42 per cent nickel, 20 per cent chromium, 2 to 3 per cent molybdenum, 1.7 to 3.6 per cent copper, 1 per cent silicon and .07 per cent (maximum) carbon are considered to have suitable resistance at 175 F to sulfuric acid concentrations up to 65 per cent and above 85 per cent. In concentrations between 65 per cent and 85 per cent, the most highly corrosive range of sulfuric acid concentrations, they are usefully resistant up to about 125 F and may sometimes be used at somewhat higher temperatures. At boiling temperature they can be used with dilute solutions up to about 10 per cent concentration where the corrosion rate is about 30 mils penetration per year. In fact, in some instances where other materials are present, as in certain oil refinery processes, 45 per cent acid has been successfully handled up to 240 F.

Another alloy which is useful for sulfuric acid applications contains 24 per cent nickel, 20 per cent chromium, 3 per cent molybdenum, 3.5 per cent silicon, 1.75 per cent copper, 0.6 per cent manganese, and .05 per cent (maximum) carbon. The test results indicate that it is suitable for use at 175 F with sulfuric acid concentrations up to 50 per cent and higher than 90 per cent. At 140 F it may be useful with acid concentrations up to about 65 per cent. In the concentration range from 65 to 85 per cent, the limiting temperature is in the neighborhood of 125 F.

TABLE IX

## Results of Some Corrosion Tests of Stainless Steels in Halogen Salts

| Corrosive Medium                           | Concentration              | Temperature, |        | Aeration     | Velocity              | Duration of Test |
|--|----------------------------|--------------|--------|--------------|-----------------------|------------------|
|  |                            | F            | C      |              |                       |                  |
| Aluminum Chloride                          | 14%                        | 50           | 10     | Nil          | Nil                   | 500 hours        |
| Ammonium Bifluoride                        | 10%                        | 77           | 25     | Some         | Nil                   | 61 days          |
| Ammonium Chloride                          | 3.4%                       | 75-215       | 24-102 | Nil          | Some                  | 528 hours        |
| Ammonium Chloride                          | 35%                        | 225          | 107    | —            | —                     | 68 days          |
| Ammonium Chloride                          | 28-40%                     | 77-216       | 25-102 | —            | —                     | 32 days          |
| Ammonium Perchlorate                       | 500 gpl                    | 194          | 90     | Nil          | Some                  | 300 hours        |
| Barium Chlorate                            | 350 gpl                    | 212          | 100    | Nil          | Some                  | 400 hours        |
| Boron Trifluoride                          | Anhydrous                  | 77           | 25     | Nil          | Nil                   | 12 days          |
| Boron Trifluoride + 0.08% H <sub>2</sub> O | 1.5% in Hydrocarbon medium | 175          | 79     | Nil          | Some                  | 12 days          |
| Calcium Chloride                           | 58%                        | 330          | 166    | Nil          | Considerable          | 31 days          |
| Calcium Chloride                           | 30%                        | 10           | -12    | Nil          | Low                   | 355 days         |
| Cupric Chloride                            | 10%                        | 70           | 21     | —            | Nil                   | 24 hours         |
| Ferric Chloride                            | 10%                        | 86           | 30     | Saturated    | 16 ft/min<br>5 m/min. | 91 hours         |
| Ferric Chloride                            | 10%                        | 150          | 66     | Saturated    | 16 ft/min<br>5 m/min. | 16.5 hours       |
| Ferric Chloride                            | 45%                        | 86           | 30     | Saturated    | 16 ft/min<br>5 m/min. | 91 hours         |
| Ferrous Chloride                           | Saturated                  | 275          | 135    | Nil          | Considerable          | 24 hours         |
| Ferrous Iodide                             | 62%                        | 75           | 24     | Some         | Some                  | 66 hours         |
| Lithium Chloride                           | 30%                        | 240          | 116    | Nil          | Considerable          | 40 days          |
| Magnesium Chloride                         | 35%                        | 160          | 71     | Nil          | Low                   | 31 days          |
| Magnesium Chloride                         | 48%                        | 330          | 166    | Nil          | Some                  | 55 days          |
| Manganous Chloride                         | 37%                        | 220          | 104    | Low          | Considerable          | 19 days          |
| Nickel Chloride                            | Saturated                  | 200          | 93     | Nil          | Nil                   | 26 days          |
| Potassium Chloride                         | 31.5%                      | 180          | 82     | Some         | Slow                  | 65 days          |
| Sodium Chloride                            | Saturated                  | 90           | 32     | Considerable | Some                  | 90 days          |
| Sodium Chlorite pH 3.5-5                   | 5%                         | 77           | 25     | —            | Nil                   | 8 days           |
| Sodium Bifluoride                          | 8%                         | 160          | 71     | Considerable | Considerable          | 10 days          |
| Sodium Bifluoride                          | 3.7%                       | 50           | 10     | Considerable | Considerable          | 30 days          |
| Sodium Hypochlorite                        | 2.9%                       | 70           | 21     | Nil          | Nil                   | 25 days          |
| Sodium Hypochlorite                        | 0.1%                       | 140          | 60     | Nil          | Nil                   | 1.3 days         |
| Sulfur Chloride                            | 98.3%                      | 280          | 138    | Nil          | Considerable          | 133 days         |
| Uranium Trichloride                        | 14%                        | Boiling      |        | —            | —                     | 6.8 days         |
| Zinc Chloride                              | 50%                        | 160          | 71     | Nil          | Nil                   | 27 days          |

TABLE IX

## Results of Some Corrosion Tests of Stainless Steels in Halogen Salts (Continued)

| Location of Test Specimens | Corrosion Rate, mpy $\mu$ /year |        |          |         | Depth of Pitting, mils $\mu$      |                           | Corrosive Medium                           |                   |                          |
|----------------------------|---------------------------------|--------|----------|---------|-----------------------------------|---------------------------|--|-------------------|--------------------------|
|                            | Type 304                        |        | Type 316 |         | Type 304                          | Type 316                  |  |                   |                          |
| Immersed in tank           | 0.9                             | 23     | 0.8      | 20      | 3 (Crevice) <sup>75</sup>         | 3 (Crevice) <sup>75</sup> | Aluminum Chloride                          |                   |                          |
| Immersed                   | 9.5                             | 235    | 11       | 275     | —                                 | —                         | Ammonium Bifluoride                        |                   |                          |
| Immersed in dissolver      | 10                              | 250    | —        | —       | 14                                | 350                       | Ammonium Chloride                          |                   |                          |
| Immersed in tank           | —                               | —      | 1.0      | 25      | —                                 | 20                        | 500  | Ammonium Chloride |                          |
| Immersed in tank           | —                               | —      | 0.5      | 13      | —                                 | 10                        | 250  | Ammonium Chloride |                          |
| Immersed                   | —                               | —      | <0.1     | <3      | —                                 | Nil                       | Ammonium Perchlorate                       |                   |                          |
| Immersed in tank           | —                               | —      | 0.9      | 23      | —                                 | Nil                       | Barium Chlorate                            |                   |                          |
| Immersed in gas            | <0.1                            | <3     | —        | —       | —                                 | —                         | Boron Trifluoride                          |                   |                          |
| Immersed                   | 213                             | 5,325  | 68       | 1,700   | —                                 | —                         | Boron Trifluoride + 0.08% H <sub>2</sub> O |                   |                          |
| In evaporator              | 2.0                             | 50     | 1.7      | 43      | <1.0                              | <25                       | Incipient                                  | Calcium Chloride  |                          |
| In brine tank              | <0.1                            | <3     | <0.1     | <3      | 9                                 | 230                       | 10   | 250               | Calcium Chloride         |
| Immersed                   | 174                             | 4,420  | —        | —       | Pitted                            | —                         | —  | Cupric Chloride   |                          |
| Immersed                   | —                               | —      | 3.8      | 95      | —                                 | —                         | 31 Perf.                                   | 790               | Ferric Chloride          |
| Immersed                   | —                               | —      | 293      | 7,440   | —                                 | —                         | 31 Perf.                                   | 790               | Ferric Chloride          |
| Immersed                   | —                               | —      | 8270     | 206,750 | —                                 | —                         | 31 Perf.                                   | 790               | Ferric Chloride          |
| Immersed in evaporator     | 4.6                             | 115    | 5.4      | 135     | Nil                               | Nil                       | —  | —                 | Ferrous Chloride         |
| Immersed                   | 3.0                             | 75     | 3.0      | 75      | 10                                | 250                       | —  | —                 | Ferrous Iodide           |
| Immersed                   | <0.1*                           | <3     | <0.1*    | <3      | —                                 | —                         | —  | —                 | Lithium Chloride         |
| Immersed in tank           | 0.2                             | 5      | 0.2      | 5       | 1                                 | 25                        | 1  | 25                | Magnesium Chloride       |
| Immersed in evaporator     | 4.3                             | 107    | 3.4      | 85      | —                                 | —                         | —  | —                 | Magnesium Chloride       |
| Partially immersed         | 33                              | 838    | 26       | 660     | Nil                               | Nil                       | —  | —                 | Manganous Chloride       |
| Immersed                   | 1.5                             | 38     | 1.3      | 33      | Incipient                         | Incipient                 | —  | —                 | Nickel Chloride          |
| Immersed                   | 0.2*                            | 5      | 0.2      | 5       | 31 Perf. (Crevice) <sup>790</sup> | 14                        | 350 (Crevice)                              | —                 | Potassium Chloride       |
| Immersed                   | 1.2                             | 30     | 0.1      | 3       | 16                                | 400                       | Slight                                     | —                 | Sodium Chloride          |
| Immersed                   | 6                               | 150    | <0.1     | <3      | 31 Perf.                          | 790                       | Nil  | —                 | Sodium Chlorite pH 3.5-5 |
| Immersed                   | 135                             | 3,430  | 56       | 1,420   | —                                 | —                         | 8  | 200               | Sodium Bifluoride        |
| Immersed                   | 2.3                             | 58     | 1.3      | 33      | —                                 | —                         | —  | —                 | Sodium Bifluoride        |
| Immersed                   | 29                              | 740    | 0.6      | 15      | 31 Perf.                          | 790                       | 12 (Crevice) <sup>300</sup>                | —                 | Sodium Hypochlorite      |
| Immersed                   | 0.8                             | 20     | 0.2      | 5       | 4 (Crevice) <sup>100</sup>        | —                         | 4 (Crevice) <sup>100</sup>                 | —                 | Sodium Hypochlorite      |
| Immersed                   | 0.8                             | 20     | 0.4      | 10      | Nil                               | Nil                       | —  | —                 | Sulfur Chloride          |
| Immersed                   | 920                             | 23,400 | 440      | 11,200  | —                                 | —                         | —  | —                 | Uranium Trichloride      |
| Immersed                   | 32                              | 810    | 32       | 810     | 31 Perf.                          | 790                       | 31 Perf.                                   | 790               | Zinc Chloride            |

\* Stress-corrosion cracking occurred.

## Nitric Acid

The austenitic stainless steels have very good resistance to corrosion by nitric acid in all concentrations and practically all temperatures. This corrosion resistance, which is due to the passivating action of nitric acid, permits extensive use of these steels in handling the acid and other chemicals containing it. The process for producing nitric acid by ammonia oxidation owes much of its success to the good performance of stainless steels in the production equipment. Heat exchangers, valves, pumps, and pipe lines for nitric acid are commonly made with these stainless steels. Similar stainless steel equipment is almost indispensable in the production of dyestuffs, high explosives, and in other industries requiring the satisfactory handling of nitric acid. Stainless steel chambers for fuming nitric acid in rockets are a natural result of the good resistance to the fuming acid liquor and vapor, although the rate of attack can be quite high at elevated temperatures (Table XI).

TABLE X

Corrosion of Stainless Steels in Hydrochloric Acid

| AISI Type | Acid Concentration, % | Temperature, C |     | Exposure Phase | Corrosion Rate, mpy $\mu$ /year |             |
|-----------|-----------------------|----------------|-----|----------------|---------------------------------|-------------|
|           |                       | F              | C   |                | mpy                             | $\mu$ /year |
| 302       | 3.6                   | 76             | 24  | Liquid         | 65                              | 1,650       |
| 302       | 10.3                  | Room           |     | Liquid         | 84                              | 2,130       |
| 302       | 25                    | 76             | 24  | Liquid         | 1,220                           | 31,000      |
| 302       | 37                    | Room           |     | Liquid         | 6,660                           | 169,000     |
| 316       | Dilute                | 77             | 25  | Vapor          | 1.2*                            | 30          |
| 316       | 10                    | 216            | 102 | Liquid         | 2,400                           | 61,000      |
| 316       | 50                    | 230            | 110 | Liquid         | 42,000                          | 1,070,000   |

\* Pitting was 5 mils during test.  
125 $\mu$

Type 304 and Type 347 are commonly used for nitric acid up to the boiling point, while Types 309 and 310, stabilized with columbium, are better suited for use under pressure at temperatures above the boiling point. Unmodified chromium-nickel stainless steels, when they contain precipitated carbides resulting from sensitization in the temperature range 800-1650 F, are susceptible to intergranular attack in nitric acid. For this reason the columbium-stabilized alloys, Types 347, 309Cb, and 310Cb, are used in equipment fabricated by welding. Molybdenum additions, as found in Types 316 and 317, do not improve resistance to corrosion by nitric acid.

425-  
900C

Because of the susceptibility of sensitized stainless steel to intergranular attack in nitric acid, boiling 65 per cent nitric acid frequently has been used to detect the existence of a sensitized condition<sup>15</sup>. This test is sometimes used as an indication of unbalanced composition. However, the results of the test must not be used indiscriminately to predict the behavior of the steels in service other than nitric acid.

The presence of nitric acid in some mixtures of acids leads to very low corrosion rates of the stainless steels. Mixtures of nitric acid and sulfuric acid have already been mentioned. The corrosivity of several other acids, including phosphoric and acetic, is also reduced by the presence of nitric acid. On the other hand, mixtures of nitric acid with hydrochloric acid or hydrofluoric acid are corrosive to all stainless steels, the rate of attack depending upon the concentration and temperature. Nitric-hydrofluoric acid mixtures are regularly used for descaling stainless steels.

Table XI contains representative data from corrosion tests in nitric acid.

## Phosphoric Acid

The good resistance of stainless steels to practically all concentrations of phosphoric acid at moderate temperatures has made them very useful and economical materials for equipment in the production and handling of this acid. Corrosion rates in pure phosphoric acid solutions under a variety of concentration and temperature conditions are shown in Table XII. Types 302 and 304 are satisfactory with most concentrations at room temperature. At higher temperatures, particularly with strong solutions, Type 316 is required. The limiting temperature for the latter alloy is about 225 F. If fluorides or chlorides are present in hot plant phosphoric acid solutions, corrosion of the stainless steels may be increased considerably. If solutions contain nitric acid, corrosion will be reduced. Phosphoric acid can cause intergranular corrosion in sensitized material. Hence the low-carbon versions of the stainless steels are preferred for welded equipment.

107C

## Sulfurous Acid

Sulfurous acid will cause pitting of Types 302 and 304 stainless steel but has only a slight corrosive action on the stainless steels containing molybdenum. As a result, Type 316 is quite useful for ducts and stacks handling flue gases which contain sulfur dioxide.<sup>26</sup> When the gases or solutions are hot, wet, and contain some sulfuric acid, stainless steels containing copper may be necessary<sup>24, 27</sup>. In the sulfite pulp paper industry Type 316 and 317 are used for heat exchangers, digester linings, and circulating systems handling the hot sulfite liquors. Where conditions are not as severe, as in steam injectors and blow pit linings, Types 304, 308, and 347 may be used. In more severe

TABLE XI

## Corrosion of Stainless Steels in Nitric Acid

| AISI Type          | Acid Concentration, % | Temperature, °C    | Corrosion Rate, mpy/year | Source (see below) |
|--------------------|-----------------------|--------------------|--------------------------|--------------------|
| 302                | All <sup>a</sup>      | 60 16              | <0.1 <3                  | <sup>d</sup>       |
| 302                | 10                    | Boiling            | 0.3 7.5                  | <sup>e</sup>       |
| 308                | 65                    | Boiling            | 9.6 244                  | <sup>f</sup>       |
| 309                | 65                    | Boiling            | <12 <300                 | <sup>f</sup>       |
| 309Cb              | 65                    | Boiling            | <4.8 <120                | <sup>f</sup>       |
| 310                | 65                    | Boiling            | <12 <300                 | <sup>f</sup>       |
| 302 <sup>b</sup>   | 65                    | Boiling            | 12 300                   | <sup>e</sup>       |
| 316 <sup>b</sup>   | 65                    | Boiling            | 20 500                   | <sup>e</sup>       |
| 347 <sup>b</sup>   | 65                    | Boiling            | 12 300                   | <sup>e</sup>       |
| 316Cb <sup>b</sup> | 65                    | Boiling            | 25 635                   | <sup>e</sup>       |
| 302 <sup>c</sup>   | 65                    | Boiling            | 228 5,790                | <sup>e</sup>       |
| 316 <sup>c</sup>   | 65                    | Boiling            | 540 3,700                | <sup>e</sup>       |
| 347 <sup>c</sup>   | 65                    | Boiling            | 50 1,270                 | <sup>e</sup>       |
| 316Cb <sup>c</sup> | 65                    | Boiling            | 85 2,160                 | <sup>e</sup>       |
| 304                | 93                    | 90 32              | 0.6 15                   | <sup>b</sup>       |
| 304                | 93                    | 110 43             | 2 50                     | <sup>b</sup>       |
| 304                | 93                    | 130 54             | 8 200                    | <sup>b</sup>       |
| 304                | 95                    | 90 32              | 1.1 28                   | <sup>b</sup>       |
| 304                | 97                    | 90 32              | 8.7 218                  | <sup>b</sup>       |
| 304                | 97                    | 110 43             | 15 380                   | <sup>b</sup>       |
| 304                | Red Fuming            | 50-80<br>70-27     | 0.4 10                   | <sup>i</sup>       |
| 304                | Red Fuming            | 250-300<br>120-150 | 1300<br>33,000           | <sup>i</sup>       |
| 316                | Red Fuming            | 250-300<br>120-150 | 2500<br>63,500           | <sup>i</sup>       |

<sup>a</sup> Includes concentrations from 5% to concentrated acid.  
<sup>b</sup> 1100-1150 C <sup>c</sup> Annealed 5 minutes at 2010-2100 F and then air cooled.  
<sup>d</sup> 1100-1150 C <sup>e</sup> Annealed 5 minutes at 2010-2100 F, air cooled, then reheated for 4 hours at 1200 F.  
<sup>f</sup> 650 C

<sup>g</sup> Hudson <sup>10</sup>  
<sup>h</sup> Sosir <sup>11</sup>  
<sup>i</sup> Sands <sup>12</sup>

<sup>j</sup> Sargent and Middleham <sup>13</sup>  
<sup>k</sup> Franks, Binder and Bishop <sup>14</sup>  
<sup>l</sup> Kaplan and Andrus <sup>15</sup>

sulfurous acid environments, usually involving the presence of sulfuric acid, the copper-containing stainless alloys with 29 to 41 per cent nickel, 20 per cent chromium and 2.3 to 3 per cent molybdenum may be required. The low-carbon grades will be more satisfactory if welding is involved.

TABLE XII

## Corrosion of Stainless Steel in Phosphoric Acid

| AISI Type | Acid Concentration, % | Temperature, °C | Exposure Phase | Corrosion Rate, mpy μ/year |
|-----------|-----------------------|-----------------|----------------|----------------------------|
| 302       | 5                     | 68 20           | Liquid         | Nil                        |
| 302       | 75                    | 68 20           | Liquid         | Nil                        |
| 316       | 90.4                  | Room            | Liquid         | Nil                        |
| 316       | 5                     | 200 93          | Liquid         | 0.1 3                      |
| 316       | 20                    | 200 93          | Liquid         | 2.0 50                     |
| 316       | 60                    | 200 93          | Liquid         | 5.0 125                    |
| 316       | 85                    | 208 98          | Liquid         | 28 710                     |
| 316       | 10                    | 225 107         | Refluxing      | 1.0 25                     |
| 316       | 50                    | 242 117         | Refluxing      | 21 530                     |
| 316       | 85                    | 235 113         | Liquid         | 52 1,320                   |
| 316       | 85                    | 255 124         | Liquid         | 110 2,800                  |

## Carbonic Acid

Carbonic acid has no effect on stainless steels. As a result, Type 304 gives good performance in fabrication of carbonating equipment and is resistant to practically all types of steam condensate.

## CORROSION BY BASES

The 18-8 stainless steels have excellent resistance to corrosion by weak bases such as ammonium hydroxide and organic compounds like aniline, pyridine, and the aliphatic amines. Type 304 can be used for such equipment as ammonia stills and for certain types of amination reactions.

The performance of stainless steels in solutions of strong bases may be illustrated with results of tests in sodium hydroxide solutions, as summarized in Table XIII. The 18-8 steels usually show very slight attack in solutions up to 50 per cent NaOH concentration at temperatures up to about 220 F. In higher concentrations and temperatures corrosion rates are likely to be appreciable. 104 C

Under conditions of stress, stress corrosion cracking of stainless steels may occur in hot sodium or potassium hydroxide solutions. Hot metal surfaces wetted by dilute solutions may be so affected due to concentration of the caustic by evaporation.

**TABLE XIII**  
Corrosion of Types 302 or 304 Stainless Steel in Sodium Hydroxide

| NaOH Concentration, % | Temperature, °C |         | Corrosion Rate, mpy $\mu$ /year |             |
|-----------------------|-----------------|---------|---------------------------------|-------------|
|                       | F               | C       | mpy                             | $\mu$ /year |
| 100                   | 750             | 400     | 68                              | 1,730       |
| 60 to 100             | 300-500         | 149-260 | 20                              | 500         |
| 73                    | 248-320         | 120-160 | 113                             | 2,825       |
| 73                    | 230             | 110     | 45                              | 1,140       |
| 73                    | 221             | 105     | 8.4                             | 210         |
| 70                    | 194-239         | 90-115  | 27                              | 675         |
| 50                    | Boiling         |         | 15                              | 375         |
| 50                    | 149             | 65      | 0.1                             | 3           |
| 50                    | 136             | 58      | <0.1                            | <3          |
| 30                    | 149             | 65      | <0.1                            | <3          |
| 30                    | 68              | 20      | <0.1                            | <3          |
| 22                    | 131             | 55      | <0.1                            | <3          |
| 14                    | 190             | 88      | <0.1                            | <3          |

#### CORROSION BY ORGANIC COMPOUNDS

Organic compounds give rise to no corrosion problems with the stainless steels except in a few specific cases involving organic acids and organic halides. The pure halogenated organic compounds will not attack the stainless steels but upon standing in the presence of water a halide may hydrolyze to yield the corresponding halogen acid which can cause serious pitting, stress corrosion cracking, or general corrosion.

#### Acetic Acid

The number of instances where stainless steels are satisfactory for organic acids far outnumber the few cases where they fail. As a result, the stainless steels are widely used in the food, petroleum, soap, pharmaceutical and chemical industries where organic acids are common. The equipment used in the production of acetic acid and in its many industrial applications typifies the usefulness of stainless steels for these acids. Representative corrosion rates are shown in Table XIV. Types 302, 304 and 347 stainless have very good resistance to all concentrations of acetic acid at moderate temperatures but not to hot concentrated acid. Consequently, they are used to a considerable extent for storage of the acid and its utilization in processing such materials as cellulose acetates and foods. Types 316 and 317 are more resistant to boiling acid solutions of intermediate concentration and are used for

**TABLE XIV**  
Corrosion in Acetic Acid

| Acid Concentration, % | Temperature, F | Duration of Test, days | Corrosion Rate, mpy $\mu$ /year |          |
|-----------------------|----------------|------------------------|---------------------------------|----------|
|                       |                |                        | Type 302                        | Type 316 |
| 0 to glacial          | Room           | Up to 157              | <0.1 <sup>a</sup> <3            | <0.1 <3  |
| 1                     | Boiling        | —                      | <0.1 <sup>a</sup> <3            | <0.1 <3  |
| 2.2 <sup>b</sup>      | Boiling        | 45                     | >31 <sup>a</sup><br>>790        | 7.7 195  |
| 10                    | Boiling        | 7                      | 70 1,750                        | —        |
| 10                    | Boiling        | 5                      | —                               | 0.3 8    |
| 20                    | Boiling        | 112                    | 2.6 <sup>a</sup> 66             | 0.7 18   |
| 50                    | Boiling        | 4                      | 130<br>3,250                    | <1 <25   |
| 80-100 <sup>c</sup>   | Boiling        | (80) <sup>d</sup>      | 7.6 190                         | 0.15 4   |
| 80-100                | Boiling        | (80) <sup>d</sup>      | 12 305                          | <0.1 <3  |
| 99 <sup>c</sup>       | Boiling        | 82                     | >66<br>>1650                    | 2.5 64   |
| Glacial               | Boiling        | 21                     | 31 790                          | 0.8 20   |

<sup>a</sup> Type 304.

<sup>c</sup> Vapors.

<sup>b</sup> Contains other organic compounds.

<sup>d</sup> 80 operating hours.

such equipment as stills, columns, and heat exchangers in acetic acid production.

#### Formic Acid

Formic acid is a good reducing agent and is capable of causing severe corrosion of the straight 18-8 stainless steels when hot. Types 316 and 317 usually are resistant and are applied to such applications as rapid-aging of textiles and distillation of formic acid alone or mixed with other organic materials. Typical corrosion rates from plant tests are given in Table XV.

#### Lactic Acid

The stainless steels are used widely for handling lactic acid solutions as they occur in food and dairy products. The regular 18-8 varieties commonly are used for this purpose. Hot concentrated solutions of lactic acid can cause severe pitting of the alloys which do not contain molybdenum, as shown in Table XVI which gives the results of a plant corrosion test in a lactic acid evaporator. In such an application Types 316 and 317 are preferred materials of construction.

#### Miscellaneous Organic Acids

Table XVII presents additional results from tests in a number of plant processes involving miscellaneous organic acids. It may be noted that all of these may be handled and stored at room temperatures in the simple 18-8 alloys such as Types 302 and 304. At higher

TABLE XV

Corrosion of Stainless Steels in Mixtures of Acetic and Formic Acids

| AISI Type | Acid Content, % |                | Temperature, F C |     | Corrosion Rate, mpy $\mu$ /year |             |
|-----------|-----------------|----------------|------------------|-----|---------------------------------|-------------|
|           | Acetic          | Formic         | F                | C   | mpy                             | $\mu$ /year |
| 304       | 99.7            | 0.02           | 248              | 120 | 5.0                             | 125         |
| 316       | 99.7            | 0.02           | 248              |     | 0.4                             | 10          |
| 317       | 99.7            | 0.02           | 248              |     | 0.5                             | 13          |
| 347       | 99.7            | 0.02           | 248              |     | 7.3                             | 185         |
|           |                 |                | 99-118           |     |                                 |             |
| 302       | 50              | 2 <sup>a</sup> | 210-245          |     | destroyed                       |             |
| 347       | 50              | 2 <sup>a</sup> | 210-245          |     | destroyed                       |             |
| 316       | 50              | 2 <sup>a</sup> | 210-245          |     | 0.7                             | 18          |
| 316       | 50              | 2 <sup>a</sup> | 210-245          |     | 8.4                             | 215         |
| 317       | 50              | 2 <sup>a</sup> | 210-245          |     | 0.3                             | 8           |
|           |                 |                | 93-110           |     |                                 |             |
| 302       | 25              | 4              | 200-230          |     | destroyed                       |             |
| 316       | 25              | 4              | 200-230          |     | 3.3                             | 84          |
| 317       | 25              | 4              | 200-230          |     | 2.0                             | 50          |
| 347       | 25              | 4              | 200-230          |     | 20                              | 500         |
|           |                 |                | 275              |     | destroyed                       |             |
| 302       | 30              | 8              | 275              |     | 4.5                             | 114         |
| 316       | 30              | 8              | 275              | 135 | 1.8                             | 46          |
| 317       | 30              | 8              | 275              |     | 42                              | 1,070       |
| 347       | 30              | 8              | 275              |     |                                 |             |
|           |                 |                | 212              |     | 85 (vapor)                      | 2,160       |
| 302       | 0               | 90             | 212              | 100 | 1.8 (vapor)                     | 46          |
| 316       | 0               | 90             | 212              |     |                                 |             |

<sup>a</sup> Contains also 23% acetaldehyde and 5% low boiling material.

temperatures, these same types are satisfactory in some acids while a few acids require the molybdenum-containing Type 316 or 317 alloy. The latter materials are used for such equipment as fatty acid stills and evaporators for maleic and phthalic acid anhydrides.

In the petroleum field and in the production of resins and plastics, phenol is successfully distilled in equipment constructed with Type 316 stainless steel. Simple storage of phenol is accomplished in Type 304 containers. Type 316 also gives good service in contact with hot naphthenic acids.

#### CORROSION BY FOODS

Foods containing acids such as acetic, citric, malic, tartaric, and lactic are processed in equipment made of Type 304 or 316 stainless steel. Where salt is added during the processing of foods, Type 316 is preferred. A series of plant corrosion tests in the processing and handling of a wide variety of foods showed the corrosion of austenitic stainless steel to be so low as to be negligible<sup>22</sup>. Other tests have also demonstrated that corrosion is so slight that contamination of foods during cooking and cold storage in stainless steel vessels is of no consequence<sup>23</sup>. Tests by the Federal Food and

TABLE XVI

Corrosion of Stainless Steels in Vacuum Lactic Acid Evaporator\*

| Type Alloy | Corrosion Rate, mpy $\mu$ /year |     |       |     | Max Depth of Pitting, mils $\mu$ |     |       |           |
|------------|---------------------------------|-----|-------|-----|----------------------------------|-----|-------|-----------|
|            | Liquid                          |     | Vapor |     | Liquid                           |     | Vapor |           |
| 302        | 1.3                             | 33  | 2.6   | 66  | 18                               | 450 | 20    | 500       |
| 304        | 3.3                             | 84  | 3.0   | 76  | 20                               | 500 | 31    | Perf. 775 |
| 347        | 0.7                             | 18  | 2.7   | 69  | 18                               | 450 | 10    | 250       |
| 321        | 0.9                             | 23  | 4.3   | 109 | 18                               | 450 | 31    | Perf. 775 |
| 309        | 0.2                             | 5   | 2.0   | 50  | 10                               | 250 | 11    | 280       |
| 310        | 0.3                             | 8   | 1.8   | 46  | 8                                | 200 | 11    | 280       |
| 311        | 5.0                             | 125 | 4.8   | 122 | 9                                | 225 | 9     | 230       |
| 316        | <0.1                            | <3  | 0.1   | 3   | Nil                              |     | 2     | 50        |
| 317        | <0.1                            | <3  | <0.1  | <3  | Nil                              |     | Nil   |           |

\* Acid concentration, 30 to 60%; temperature, 115 F; duration of test, 1000 hr. 46 C

Drug Administration have established that the extremely minute amounts of the metal components which do dissolve when food comes in contact with stainless steel utensils and equipment are of no pharmacologic significance<sup>24</sup>. This corrosion resistance, together with the ease with which it can be kept clean, makes stainless steel the preferred material for equipment which comes in contact with food in the dairy, canning, bakery, meat-packing, candy, quick-freeze, beverage, restaurant, and many other industries concerned with food.

The same reasons account for its widespread use in the manufacture and handling of pharmaceuticals. Plants for the production of aspirin (acetylsalicylic acid) and of streptomycin use stainless steel equipment throughout.

#### CORROSION BY ELEMENTARY SUBSTANCES

Among the elements which are successfully and usefully handled in stainless steel equipment are mercury and sulfur. Type 316 conveyer belts for molten sulfur are giving excellent service in a sulfur recovery process. In a process for winning mercury from its sulfide ore, stainless steel is performing well in a condenser for recovering the mercury in gases coming from an ore roaster. In this case the gases also contain some sulfur dioxide and trioxide.



**TABLE XVII**  
**Corrosion of Stainless Steels in Several Organic Acids.**

| Acid                              | AISI Type | Concentration, % | Temperature, |         | Exposure Phase | Corrosion Rate,   |             |
|-----------------------------------|-----------|------------------|--------------|---------|----------------|-------------------|-------------|
|                                   |           |                  | F            | C       |                | mpy               | $\mu$ /year |
| Phenol                            | 302       | 5                | 60           | 16      | Liquid         | 0.7               | 18          |
| Phenol                            | 302       | 90-100           | 302          | 150     | Vapor          | 22                | 560         |
| Phenol                            | 316       | 90-100           | 302          | 150     | Vapor          | 3.4               | 86          |
| Aspirin                           | 302       | 100              | 140          | 60      | Solid          | 0.2               | 5           |
| Citric                            | 302       | 58               | Boiling      |         | Liquid         | 0.1               | 3           |
| Naphthenic                        | 302       | 100              | 554          | 290     | Vapor          | 25                | 635         |
| Naphthenic                        | 316       | 100              | 554          | 290     | Vapor          | 0.9               | 23          |
| Tartaric                          | 302       | 5-50             | 59-212       | 15-100  | Liquid         | nil               |             |
| Oleic                             | 302       | 100              | Boiling      |         | Liquid         | <0.1              | <3          |
| Stearic                           | 302       | 100              | 410          | 210     | Liquid         | 2.3               | 58          |
| Stearic                           | 302       | 100              | 428          | 220     | Liquid         | 13                | 330         |
| Stearic                           | 302       | 100              | 446          | 230     | Liquid         | 24                | 610         |
| Palmitic                          | 302       | 100              | 439          | 226     | Liquid         | 0.2               | 5           |
| Oleic-Stearic mixture             | 304       | 100              | 440          | 227     | Liquid         | 19                | 480         |
| Oleic-Stearic mixture             | 302       | 100              | 440          | 227     | Liquid         | 16                | 410         |
| Oleic-Stearic mixture             | 347       | 100              | 440          | 227     | Liquid         | 20                | 500         |
| Oleic-Stearic mixture             | 304       | 100              | 440          | 227     | Vapor          | 14                | 360         |
| Oleic-Stearic mixture             | 302       | 100              | 440          | 227     | Vapor          | 13                | 330         |
| Oleic-Stearic mixture             | 316       | 100              | 475          | 246     | Liquid         | 1.2               | 30          |
| Oleic-Stearic mixture             | 317       | 100              | 475          | 246     | Liquid         | 0.2               | 5           |
| Oleic-Stearic mixture             | 316       | 100 (agitated)   | 475          | 246     | Liquid         | <0.1 <sup>a</sup> | <3          |
| Oleic-Stearic mixture             | 317       | 100 (agitated)   | 475          | 246     | Liquid         | <0.1 <sup>b</sup> | <3          |
| Oleic-Stearic mixture             | 304       | 100 (agitated)   | 475          | 246     | Liquid         | 14 <sup>c</sup>   | 360         |
| Phthalic Anhydride                | 302       | 100              | 438-554      | 225-290 | Vapor          | 9.2               | 23          |
| Phthalic Anhydride                | 316       | 100              | 438-554      | 225-290 | Vapor          | 0.6               | 15          |
| Phthalic Anhydride                | 317       | 100              | 438-554      | 225-290 | Vapor          | <0.1              | <3          |
| Phthalic Anhydride                | 347       | 100              | 438-554      | 225-290 | Vapor          | 11                | 280         |
| Maleic                            | 304       | 10               | 125          | 52      | Liquid         | 160               | 4,000       |
| Maleic                            | 316       | 10               | 125          | 52      | Liquid         | <0.1              | <3          |
| Maleic                            | 304       | 40               | 125          | 52      | Liquid         | 146               | 3,710       |
| Maleic                            | 316       | 40               | 125          | 52      | Liquid         | <0.1              | <3          |
| Maleic-Phthalic Anhydride mixture | 316       | 100              | 410-554      | 210-290 | Liquid         | 0.6               | 15          |
| Maleic-Phthalic Anhydride mixture | 317       | 100              | 410-554      | 210-290 | Liquid         | 0.1               | 3           |
| Maleic-Phthalic Anhydride mixture | 347       | 100              | 410-554      | 210-290 | Liquid         | 16                | 410         |

<sup>a</sup> 1 mil pitting.  
25 $\mu$

<sup>b</sup> 2 mils pitting.  
50 $\mu$

<sup>c</sup> Perforated.

315 C Considerable care must be exercised in the use of stainless steels where halogens are to be encountered. Types 304, 316 or 317 may be used for pipe lines to handle dry chlorine gas at low temperatures but are not suitable for wet chlorine gas or hot chlorine, wet or dry.<sup>31, 32</sup> Severe attack by dry chlorine may be expected at temperatures over 600 F. In some cases, calcium hypochlorite bleaching solutions, containing not more than 0.3 per cent available chlorine, can be safely handled in Type 304 vessels for short periods of time not exceeding four hours, followed by thorough washing with water. However, Types 316 and 317 generally are preferred for this type of service because of superior resistance to pitting. These materials are used to handle alkaline sodium hypochlorite bleaching solutions containing 0.3 per cent available chlorine through entire bleaching cycles.

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**Nearest Foreign Equivalents of AISI Chromium-Nickel Stainless Steels**

| AMERICAN         | BRITISH    | FRENCH          | GERMAN                 | ITALIAN       | SWEDISH      | RUSSIAN   |   |   | JAPANESE |
|------------------|------------|-----------------|------------------------|---------------|--------------|---|---|---|----------|
|                  |            |                 |                        |               |              | GOST Specification Number   | GOST Designation Number                                   | USSR Factory Designation                |          |
| AISI             | En         | AFNOR           | VD Et                  | UNI           | SIS          |   |   |   | JIS      |
| 301              |            | Z 12 CN 18-8    | X 12 Cr Ni 17-7        | X 15 CN 1707  | 2330<br>2331 | —   | Kh17N8  | —                                       | SUS 39   |
| 302              | 58A        | Z 12 CN 18-10   | X 12 Cr Ni 18-8        | X 15 CN 1808  | 2330<br>2331 | —<br>—<br>5632-51 <sup>a</sup>  | 1Kh17N9<br>1Kh18N9<br>1Kh18N9                             | —<br>EYa-1<br>Ya-1                      | SUS 40   |
| 302B             |            |                 |                        |               |              | 4542-54 <sup>b</sup><br>—   | —<br>OKh18N9B2  | E1543<br>E1647                          |          |
| 303              | 58M        |                 | X 12 Cr Ni 18-8        |               |              |   |   |   |          |
| 304              | 58E        | Z 6 CN 18-10    | X 8 Cr Ni 18-9         | X 8 CN 1910   | 2332         | 5632-51 <sup>a</sup><br>5632-51 <sup>a</sup><br>4176-53 <sup>b</sup>                              | OKh18N9<br>OKh18N9<br>OKh18N11                            | EYa-0<br>Ya-0<br>—                      | SUS 27   |
| 304L             |            | Z 3 CN 18-10    |                        | X 3 CN 1911   |              | —   | Kh18N8  | —                                       | SUS 28   |
| 309              | 55         | Z 15 CNS 25-13  | X 15 Cr Ni Si 20-12    | X 20 CN 2412  |              | 5632-51 <sup>a</sup><br>5632-51 <sup>a</sup>  | Kh23N13<br>Kh25N15  | E1919<br>E1919                          |          |
| 309B             |            |                 |                        |               |              |   |   |   | SUS 41   |
| 310              |            | Z 15 CNS 25-20  | X 15 Cr Ni Si 25-20    | X 25 CN 2520  | 2361         | —   | Kh25N20   | E1932                                   |          |
| 310B             |            |                 |                        |               |              |   |   |   | SUS 42   |
| 314              |            |                 | X 15 Cr Ni Si 25-30    |               | 2361         |   |   |   |          |
| 316              | 58H<br>58J | Z 6 CND 18-12   | X 5 Cr Ni Mo 18-12     | X 8 CND 1712  | 2342         | —<br>5216-55 <sup>b</sup><br>4270-53 <sup>c</sup>   | Kh18N9M<br>—<br>—   | E1183<br>E1400<br>E1609                 | SUS 32   |
| 316L             |            | Z 3 CND 18-12   | X 3 Cr Ni Mo 18-13     |               |              |   |   |   | SUS 33   |
| 317              | 58J        |                 | X 5 Cr Ni Mo 17-13     |               |              |   |   |   |          |
| 318 <sup>a</sup> |            | Z 8 CNDNb 18-12 | X 10 Cr Ni Mo Nb 18-12 |               | 2343         | 5001-55 <sup>b</sup><br>—   | 1Kh16N13Mo2B<br>1Kh16N13Mo2B                              | E1405<br>E1592                          |          |
| 321              | 58B<br>58C | Z 10 CNT 18-10  | X 10 Cr Ni Ti 18-9     | X 8 CNT 1810  | 2333<br>2334 | 5632-51 <sup>a</sup><br>5632-51 <sup>a</sup><br>5632-51 <sup>a</sup>                              | Kh18N9T<br>1Kh18N9T<br>1Kh18N9T                           | EYa-T<br>EYa-1T<br>Ya-1T                | SUS 29   |
| 330 <sup>a</sup> |            | Z 20 NCS 36-18  |                        |               |              | —<br>—<br>—   | Kh15N35<br>2Kh15N35<br>3Kh15N35                           | E1613<br>—<br>—                         |          |
| 347              | 58F<br>58G | Z 10 CNNb 18-10 | X 10 Cr Ni Nb 18-9     | X 8 CNNb 1811 | 2333<br>2334 | 5050-55 <sup>b</sup><br>5632-51 <sup>a</sup><br>5216-54 <sup>b</sup><br>5632-51 <sup>a</sup><br>— | OKh18N9B<br>Kh18N11B<br>Kh18N11B<br>Kh18N11B<br>OKh18N9B2 | E1506<br>E1598<br>E1402<br>EYa-1Nb<br>— | SUS 43   |

Note: There are no foreign equivalents for AISI Types 303Bc, 305, 308, and 348.

<sup>a</sup> Not Standard Type. <sup>b</sup> State All-Union Standard. <sup>c</sup> Soviet Ministries of Metallurgy.  
<sup>d</sup> Metallurgical Industrial Technical Specification.