

THE UNIVERSITY OF MINNESOTA

GRADUATE SCHOOL

Report
of
Committee on Thesis

The undersigned, acting as a Committee of the Graduate School, have read the accompanying thesis submitted by Wesley John Roberts for the degree of Chemical Engineer. They approve it as a thesis meeting the requirements of the Graduate School of the University of Minnesota, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Chemical Engineer.

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Properties of Metals and Alloys used
for Chemical Equipment

A Thesis
Submitted to the Faculty of the
Graduate School of the
University of Minnesota

by

Wesley John Roberts

In Partial Fulfillment of the Requirements

of the degree

Chemical Engineer

June

1922

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Properties of Metals and Alloys Used for
Chemical Equipment.

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Object:- In the working out of this thesis an attempt has been made, first, to collect and put in comprehensive form all available data concerning the commercial metals and alloys with particular reference to their ability to withstand the corrosive action of chemical used in the chemical industry; and second, to perform corrosion tests on the alloys for which no data are available.

In the first instance, it was found that, out of the large number of alloys used in the chemical industry published data could be found for only a few of them. In some cases the data which ~~was~~ ^{were} published ~~was~~ ^{were} so vague as to be useless for the purpose intended. In other cases, however, the tests that had been carried out by others were very thorough and the data obtained reported in excellent form.

In the second place, difficulty was experienced in obtaining samples of the alloys on which to run corrosion tests. The difficulty was in not being able to locate the firm that manufactured the alloy. In a few cases the firms did not respond to a request for samples but in most instances they were very accommodating, not only sending the samples at once but gladly offering further service.

As a consequence the field of alloys is only partially represented in the twenty-one on which tests were made. More corrosive agents for different lengths of time and at different temperatures and concentrations should be included before a working knowledge of any given alloy could be obtained.

Feb 29 1938 B. d. u. g. m.

Mechanical and physical properties are required in addition to make the research complete.

Introduction: - The corrosion problem is a very large one, being nearly unlimited in its scope. When we consider the metals such as zinc, copper, nickel, aluminum, iron and tin, which are the most commonly used metals and then consider the nearly endless chain of alloys which can be made by combining those with each other and with other elements such as chromium, cadmium, uranium, vanadium, tungsten, silicon, molybdenum, titanium, manganese, and others in all combinations which are possible and each alloy formed having its peculiar characteristics, we begin to realize what a large field it really covers. And one peculiar thing about the phenomena of corrosion is that the result cannot be predicted. By adding one metal to another to form an alloy, we may expect to get an alloy that is very resistant to the action of a certain solvent but when it is tried it may increase the solubility of the first metal.

W. D. Richardson in his article "The Solutions of Metals in Acids" in the Transactions of the American Electrochemical Society, vol. 38 p. 245 says that the inconsistent behavior of the metals in corrosion and acid solution phenomena on the basis of the electro-chemical series can only be explained by taking into consideration a number of factors.

"The principal factors are solution tension, the hydrogen influence, the oxygen influence, the carbon dioxide influence, the cathode influence and the halogen influence.

"Corrosion and solution of metals in acids may be considered as actions tending to go forward at rates proportion-

al to solution tension and hydrogen ion concentration, but subject to the accelerating and retarding influence of many substances acting as catalyzers.

"Indications of the sensitiveness of various metals to the H_2 and O_2 influences can be obtained by their behavior when treated as couples in dilute acids and neutral salts and connected through a sensitive voltmeter or galvanometer.

"Studying the behavior of metallic catalyzers on the rates of solution of copper-bearing iron, pure open-hearth iron, grey cast iron and semi-steel in normal sulphuric, hydrochloric and nitric acids at 16 C., with several metallic catalyzers, it was found that the rolled metals in general showed different behavior to that of the cast metals.

" Under conditions of corrosion the cast metals are relatively less attacked in the presence of much oxygen than the purer rolled metals. They are also relatively less attacked by an oxidizing acid, such as nitric acid, than by the non-oxidizing acids, sulphuric and hydrochloric. The catalyzers silver, copper and formaldehyde all reverse this action and cause the rates of the cast metals in nitric acid to be increased and the rates of the copper bearing in pure open-hearth iron to be reduced. Platinum while catalyzing the rolled metals negatively in nitric acid, catalyzes them positively in sulphuric and hydrochloric and is without action on the cast metals in any acid. The failure of platinum to catalyze the cast metals is probably due to the evolution of poisons from the impure metals by the action of the acids."

The above statements of Mr. Richardson have been cited to bring out a few of the factors that must be considered when

dealing with the phenomena of corrosion or solution of metals. "Corrosion is known to be electrolytic in many cases, and purely chemical in others. It is generally recognized that chemical and electrolytic corrosion are practically identical and recently this has been shown by Turrentine, in the case of the action of nitric acid on copper. Hence, in the corrosion of alloys by means of the electric current, the amount of corrosion which it would take years to obtain chemically, can be obtained in a few hours electrochemically." - A. T. Lincoln Tr. A. E. S. 11, 43.

The corrosion of non-ferrous alloys may, according to H. S. Rawdon, belong to one of four distinct types - namely, (a) Selective attack of certain constituents, (b) inter-crystalline brittleness, (c) internal oxidation and (d) the simultaneous action of stress and corrosion. As examples of each type he gives the following:

- Type (a) Brass (60% Cu. 40%Zn) was exposed to sea water for several years. The alpha constituent, (65% Cu.) was untouched, while the beta constituent (50% Cu.) was corroded by a bleaching out of the Zn.
- Type (b) Cable sheath of lead exposed underground became brittle due to the destruction of the inter crystalline material (usually non-miscible impurities as Fe, Cu, Ni, Zn or miscible eutectic forming elements as Sn or Sb). This type of corrosion can be induced by immersion in lead acetate solution.
- Type (c) Boiler safety plugs of Sn deteriorated by change of metal to infusible oxide under influence of moist heat. The same type of change is found with Al-Zn alloys. In this case moist heat causes the oxidation and swelling of the eutectic matrix.
- Type (d) Brass and lead under combined stress and corrosion will fail far below normal stress. This is due to selective corrosion of the alpha constituent in the former, and to inter crystalline brittleness in the latter.

Although the four illustrations have been described

as distinct types for convenience, it is quite evident that they are distinct types only so far as appearance is concerned. Fundamentally, they are all very similar.

The increased corrosion due to internal strains or flaws as in the case of the lead pipe will probably account for the failure of the cast iron acid egg which was reported to have been in service for six months for handling mixed nitration acids when it suddenly cracked.

Thus, we are constantly confronted with instances where the unexpected has happened. Men have attempted to explain those happenings and have propounded theories to explain them. Those theories suggest possibilities but they have not been accepted generally. A great many men who have spent much time on this subject do not agree wholly with the statements of Mr. Richardson, Lincoln, and Rawdon as given above but have propounded theories of their own. Although those explanations of what corrosion really is seem to differ widely. In general they are very similar. Where the chief difficulty lies is in the fact that the various experimenters have worked on different types of alloys and under different conditions and have naturally obtained different results. For example, one man may work on the corrosion of brasses using all possible combinations of zinc and copper with possibly the addition of a third element and get all possible data. He would then feel competent to theorize on what corrosion was and he may do it very well for this class of alloys. Another man may work on chromium steels, for instance, and after having obtained all possible data, may try to put his findings in the form of a theory. Each one's theory may work very well as far as his class or type of alloy

went, but would fall down miserably when applied to the other class.

What is needed is a more comprehensive study of all alloys and under conditions as nearly similar as possible to actual conditions which structural metals are called upon to resist. We also need a universal or standard unit to designate the rate or amount of corrosion.

Experimental: - The samples as obtained were mostly in the form of sheets. These had to be sawed or ground into sizes that could be conveniently handled. After getting the samples into pieces about an inch square and polished, the area was carefully measured and recorded. The object in measuring the area was to obtain the loss in weight per unit of area exposed. Some of the data published is given as percentage loss in weight. This doesn't mean anything unless the size of ~~the size of~~ the sample corroded is given. For example, a given weight of metal in the form of a sphere corroded for a given time in a given chemical would have a smaller percentage loss in weight than would the same weight of the same metal in the form of a thin plate corroded for the same length of time in the same chemical; because in the first instance the area exposed would be far less than in the second. But the loss in weight per unit area exposed would be the same in the two cases.

The samples were then subjected to a treatment of hot sodium hydroxide to remove grease, dipped in dilute hydrochloric acid, except in the case of lead and lead alloys, washed with water, alcohol, and ether in succession and quickly dried over a flame and placed in a desiccator. After a few minutes in the desiccator the samples were carefully weighed and the

weights recorded. The sample was then placed in a beaker, tilted upon a glass bead and covered with about 100 cc. of the corrosive agent. The beaker was then covered with a glass plate and allowed to stand at a constant temperature of about 22 centigrade for a given length of time. The length of time was determined by the rate at which the sample was attacked by the chemical. In most instances the period of time was taken as 21 days, but in the case where concentrated nitric acid was used many of the samples were rapidly attacked and were removed. These tests proving conclusively that this particular alloy was not fitted for use with this chemical. Other instances of this type were also found.

The sample was tilted up on a glass bead to reduce the area of contact of sample with the beaker to a minimum. This gave a point contact with the bead and one edge of the sample with the beaker.

After corrosion, the sample was taken out, washed with water and the scale removed by means of a wire brush, care being taken not to remove any of the metal. The sample was then washed successively in water, alcohol, and ether, quickly dried and weighed. The weight was recorded and the loss in weight in grams per square centimeter surface exposed calculated. The data along with the published data ~~was~~^{were} tabulated in one large table.

The solutions of the corrosive agents were made up and the concentration determined by means of a hydrometer. This is not an altogether accurate method but the variation was not sufficient to make any perceptible difference in the loss in weight of the sample being corroded. There was, of course, some

evaporation of the solution during the time of corrosion but this was so slight as to be negligible as shown by actual measurement of the liquid from time to time.

Data obtained: -

ALUMINUM BRONZE - TEMPERATURE 32° C

Corrosive	D Duration of test	Area in Sq. cm.	Initial Wt. Grams	Final Wt. Grams *	Loss Gms./sq.cm.
90% H ₂ SO ₄	21 days	15.388	25.4926	15.3392	.6598
50% H ₂ SO ₄	21 days	14.94	14.3296	14.3270	.00017
25% H ₂ SO ₄	21 days	13.390	12.1395	12.11	0022
60% HNO ₃	30 min.	14.774	14.6027	Dissolved	
30% HNO ₃	100 min.	14.554	14.27	4.8968	.64403
10% HNO ₃	12 days	13.390	12.11	7.8243	.32006
35% HCL	21 days	14.660	14.5628	12.8909	.11405
10% HCL	9 days	15.5	14.4640	13.9375	.03396
35% NaOH	15 days	14.94	14.3270	14.327	.00
25% NaOH	28 days	15.5	15.1138	15.1122	.000103
Glacial Acetic	33 days	15.3	15.7151	15.5281	.01222
Con. NH ₄ OH	21 days	15.5	15.1122	14.464	.04182
3% NaCL	21 days	14.12	14.64	14.6106	.00208
Tap Water	21 days	13.86	14.7105	14.7128	.000169 ⁽¹⁾
1% NaOH	21 days	14.616	14.49	14.4622	.001902

* After removing scale

(1) Gain in Weight

TOBIN BRONZE - TEMPERATURE 22°C

Corrosive	Duration of test	Area in Sq. cm.	Initial Wt. Grams	Final Wt. Grams *	Loss Gms./sq.cm
90% H ₂ SO ₄	21 days	17.3	25.3105	24.795	.02979
50% H ₂ SO ₄	21 days	15.840	23.1531	23.15	.00019
25% H ₂ SO ₄	21 days	17.413	24.4192	24.372	.00271
60% HNO ₃	30 min.	15.98	22.8033	00.00	Dissolved
30% HNO ₃	100 min	15.39	18.0335	6.393	.75633
10% HNO ₃	12 days	17.413	24.3720	18.954	.31115
35% HCL	21 days	16.882	24.394	22.926	.08696
10% HCL	9 days	15.931	22.208	22.00	.01305
35% NaOH	15 days	15.84	23.15	23.15	.000
25% NaOH	28 days	15.931	23.2976	23.2965	.000069
1 % NaOH	21 days	16.410	23.2284	23.155	.00447
Glacial Acetic	33 days	16.5	24.6271	23.982	.0391
Con.NH ₄ OH	21 days	15.931	23.2965	22.2080	.06833
3 % NaCL	21 days	14.924	22.9079	22.8634	.00298
Tap Water	21 days	15.697	23.721	23.721	.00

* After removing scale

Ampco - Temperature 22° C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Grams	Final Wt. Gms.*	Loss Gms./sq.cm.
90% H ₂ SO ₄	21 days	14.608	14.7242	14.4910	.00911
50% H ₂ SO ₄	21 days	13.971	13.9312	13.9270	.00030
25% H ₂ SO ₄	21 days	15.894	16.174	16.1590	.00094
60% HNO ₃	30 min.	15.358	15.4067	Dissolved	
30% HNO ₃	100 min.	14.175	13.6106	5.3068	.59946
10% HNO ₃	6 days	15.894	16.159	12.0310	.25972
35% HCL	21 days	15.637	16.0336	13.873	.13814
10% HCL	9 days	14.07	14.0344	13.9640	.005003
35% NaOH	15 days	13.971	13.927	13.9268	.000014
25% NaOH	28 days	14.07	14.361	14.3592	.000127
1% NaOH	21 days	14.320	14.2646	14.2280	.00255
Glacial Acetic	33 days	15.666	16.1687	16.1030	.00431
Con NH ₄ OH	21 days	14.07	14.3592	14.0344	.00189
Tap Water	21 days	14.704	14.6284	14.6280	.000027

* After removing scale

MECO - TEMPERATURE 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms.	Final Wt. Gms. *	Loss Gms./sq.cm.
90% H ₂ SO ₄	21 days	27.042	44.8437	44.6808	.00602
50% H ₂ SO ₄	21 days	19.382	24.0551	24.0520	.00016
25% H ₂ SO ₄	21 days	22.682	26.6100	26.5320	.00343
60% HNO ₃	10 min.	23.413	19.7470	Dissolved	
30% HNO ₃	100 min.	11.415	14.5804	4.3450	.89662
10% HNO ₃	6 days	22.682	26.5320	22.0914	.19578
35% HCL	21 days	26.391	37.2585	27.9864	.35951
10% HCL	9 days	26.130	44.4200	43.9710	.01718
35% NaOH	15 days	19.382	24.0520	24.0699	.000923 ⁽¹⁾
25% NaOH	28 days	26.130	44.7400	44.7350	.00019
15% NaOH	21 days	26.850	45.0245	45.0220	.00009
Glacial Acetic	33 days	27.044	44.6774	44.2240	.01676
Con. NH ₄ OH	21 days	26.130	44.7350	44.4200	.01205
3% NaCL	21 days	26.78	43.6370	43.6320	.000186
Tap Water	21 days	11.501	16.4380	16.4380	.00000

* After removing scale

(1) Gain in weight.

CLEBRIUM - TEMPERATURE 22° C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Grams.	Final Wt. Gms. *	Loss Gms./sq.cm.
90% H ₂ SO ₄	21 days	29.130 m	33.5251	33.3631	.00556
50% H ₂ SO ₄	21 days	31.140	36.7320	36.7270	.00016
25% H ₂ SO ₄	21 days	30.378	35.9551	35.8846	.00232
60% HNO ₃	30 min.	27.90	32.1748	Dissolved	
30% HNO ₃	90 min.	30.06	36.4620	25.1838	.37518
10% HNO ₃	6 days	30.378	35.8846	30.6492	.17234
35% HCL	21 days	28.980	33.4524	18.6290	.51149
10% HCL	9 days	27.90	31.5854	31.1673	.01498
35% NaOH	15 days	31.14	36.7270	36.7288	.000057 ⁽¹⁾
Glacial Acetic	33 days	30.060	34.8263	34.3675	.01526
Con. NH ₄ OH	21 days	27.90	31.8102	31.5854	.00805
3% NaCL	21 days	30.832	35.8560	35.8420	.000454
Tap Water	21 days	31.14	36.2700	36.2720	.000063
1% NaOH	21 days	28.404	31.8192	31.8192	.00000

* After removing scale

(1) Gain in weight

FANOSITE - TEMPERATURE 22° C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms.	Final Wt. Gms. *	Loss Gms./sq.cm.
90% H ₂ SO ₄	67 hrs.	9.252	4.4700	4.4118	.005209
50% H ₂ SO ₄	21 days	5.800	2.2265	1.4990	.12543
25% H ₂ SO ₄					
60% HNO ₃	21 days	8.356	3.7151	2.3520	.16255
30% HNO ₃					
10% HNO ₃					
35% HCL	5 min.	8.806	4.3922	3.6571	.08348
10% HCL					
35% NaOH					
25% NaOH	28 days	8.074	3.5561	Dissolved	
1% NaOH	67 hours	8.386	4.6600	3.7151	.11267
Glacial Acetic	33 days	7.955	3.7310	3.7225	.00106
Con. NH ₄ OH	21 days	7.955	3.7225	3.7268	.00054 ⁽¹⁾
3% NaCL					
Tap Water					

* After removing scale

(1) Gain in weight

NICKEL - TEMPERATURE 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. gms.	Final Wt. Gms *	Loss gms./sq.cm.
90% H ₂ SO	21 days	13.328	8.2344	8.1757	.00440
50% H ₂ SO	21 days	12.667	7.1607	7.1270	.00266
25% H ₂ SO	21 days	13.848	8.3650	8.2785	.00639
60% HNO ₃	21 days	12.106	8.7007	2.0144	.55230
30% HNO ₃	6 days	13.181	7.2995	0.0000	
10% HNO ₃	12 days	13.848	8.2785	3.7190	.32907
35% HCL	21 days	14.282	8.5656	3.6464	.34444
10% HCL	9 days	13.913	8.3504	8.1410	.01505
35% NaOH	15 days	12.667	7.1270	7.1282	.000094 (1)
25% NaOH	28 days	13.913	8.3729	8.3729	.00000
1% NaOH	21 days	14.006	8.4179	8.4184	.000035 (1)
Glacial Acetic	33 days	14.224	8.4167	8.0390	.02655
Con NH ₄ OH	21 days	13.913	8.3729	8.3504	.00161
3% NaCL	21 days	21.76	7.9678	7.9678	.00000 (1)
Tap Water	21 days	14.466	8.5924	8.5936	.000083 (1)

* After removing scale

(1) Gain in weight.

Monel Metal -- Temperature 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Grams	Final Wt. Grams*	Loss gms/sq. cm.
90% H ₂ SO ₄	21 days ^m	14.770	16.5652	16.5130	.00285
50% H ₂ SO ₄	21 days	13.936	3.1702	3.1676	.00018
25% H ₂ SO ₄	21 days	15.75	18.0270	17.9815	.00 88
60% HNO ₃	30 min.	13.000	2.9452	Dissolved	
30% HNO ₃	6 days	15.22	17.4300	4.5100	.84888
10% HNO ₃	12 days	15.75	17.9815	14.9958	.18956
35% HCl	21 days	13.971	15.8785	13.7485	.15246
10% HCl	9 days	15.77	17.9385	17.7963	.009017
35% NaOH	15 days	13.936	3.1676	3.1688	.000086 ⁽¹⁾
25% NaOH	28 days	15.77	17.9872	17.9870	.000012
1% NaOH	21 days	17.804	17.2640	17.2640	.00000
Glacial Acetic	33 days	13.860	15.6535	15.5258	.00921
Con NH ₄ OH	21 days	15.77	17.9870	17.9385	.00307
3% NaCl	21 days	13.665	15.5232	15.5210	.00016
Tap Water	21 days	15.22	17.5200	17.5230	.000197 ⁽¹⁾

* After Removing scale

(1) Gain in weight.

NICKEL SILVER - TEMPERATURE 22° C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Grams	Final Wt. Grams *	Loss Gms./sq.cm.
90% H ₂ SO ₄	21 days	13.612	4.8645	4.7560	.00797
50% H ₂ SO ₄	21 days	13.478	4.9848	4.9830	.00013
25% H ₂ SO ₄	21 days	13.944	4.7550	4.7230	.00247
60% HNO ₃	30 min	12.988	4.6420	Dissolved	
30% HNO ₃	90 min	6.873	4.8544	Dissolved	
10% HNO ₃	3 days	12.944	4.7230	0.7172	.30947
35% HCL	21 days	17.760	4.5316	3.1168	.08895
10% HCL	9 days	14.301	5.1816	5.1110	.004937
35% NaOH	15 days	13.478	4.9830	4.9830	.00000.0001
25% NaOH	28 days	14.676	5.3300	5.3285	.000102
1% NaOH	21 days	14.676	5.3854	5.3840	.000095
Glacial Acetic	33 days	14.030	5.0936	4.9030	.01358
Con. NH ₄ OH	21 days	14.676	5.5285	5.1816	.01001
3% NaCL	21 days	12.48	4.4204	4.4220	.000128 ⁽¹⁾
Tap Water	21 days	13.663	5.0200	5.0220	.000146 ⁽¹⁾

* After removing scale

(1) Gain in weight

ATERITE - 6 TEMPERATURE 22°C

Corrosive	Duration of test	Area in Sq. cm.	Initial Wt. Gms.	Final Wt. Gms.*	Loss Gms./sq.cm.
90% H ₂ SO ₄	21 days	8.692	13.2420	13.1782	.00734
50% H ₂ SO ₄	21 days	8.330	13.1733	13.1733	.00000
25% H ₂ SO ₄					
60% HNO ₃	1 hr	9.07	14.0477	Dissolved	
30% HNO ₃	10%				
10% HNO ₃					
35% HCL					
10% HCL	9 days	8.380	12.3952	12.2270	.02007
35% NaOH	15 days	8.330	13.1733	13.1720	.00156
25% NaOH	28 days	8.380	12.4334	12.4346	.0014 ⁽¹⁾
Glacial Acetic					
Con. NH ₄ OH	21 days	8.380	12.4346	12.3952	.00470
3% NaCL					
Tap Water					

* After removing scale if any has formed.

(1) Gain in weight.

ATERITE - 16 Temperature 22°0

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms.	Final Wt. Gms.*	Loss gms./sq.cm.
90% H ₂ SO ₄	21 days	8.769	14.2504	14.1058	.01649
50% H ₂ SO ₄					
25% H ₂ SO ₄					
60% HNO ₃					
30% HNO ₃					
10% HNO ₃					
35% HCL	21 days	8.627	14.6359	5.4965	1.05915
10% HCL					
35% NaOH					
25% NaOH					
1 % NaOH Glacial Acetic	21 days	8.291	12.8276	12.6717	.01880
5on. NH ₄ OH					
3% NaCL	21 days	8.354	12.5735	12.5697	.000454
Tap Water	21 days	8.357	14.0935	14.0590	.004128

* After removing scale

ATERITE - 136 Temperature 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms	Final Wt. Gms.*	Loss gms./sq.cm.
90% H ₂ SO ₄	21 days	8.346	14.1461	14.1004	.00547
50% H ₂ SO ₄					
25% H ₂ SO ₄	21 days	8.456	12.1236	12.1126	.00130
60% HNO ₃					
30% HNO ₃	100min.	8.680	13.4250	5.6705	.89336
10% HNO ₃	12 days	8.456	12.1126	7.9238	.49537
35% HCL					
10%HCL					
35% NaOH					
25% NaOH					
1% NaOH	21 days	9.257	13.5208	13.5214	.000064 (1)
Glacial Acetic	33 days	8.807	13.5190	13.4252	.01065
Con. NH ₄ OH					
3% NaCL					
Tap Water					

* After removing scale

(1) Gain in weight

ACIMET

Temperature 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms.	Final Wt. Gms. *	Loss Gms./sq.cm.
90% H ₂ SO ₄	21 days	13.476	18.6870	18.4294	.01911
50% H ₂ SO ₄	21 days	11.388	13.1014	13.0957	.00012
25% H ₂ SO ₄	21 days	12.174	18.2760	18.2256	.00414
60% HNO ₃	21 days	12.174	18.7088	9.7350	.73713
30% HNO ₃	6 days	12.330	19.8850	5.1574	1.1954
10% HNO ₃	3 days	12.174	18.2256	4.0935	1.0587
35% HCL	21 days	11.545	14.9925	11.6614	.28852
10% HCL	9 days	11.938	17.8500	17.6113	.01999
35% NaOH	15 days	11.388	13.0957	13.0861	.000843
25% NaOH	28 days	11.938	17.9337	17.9320	.00014
1% NaOH	21 days	12.381	15.2056	15.0308	.01444
Glacial Acetic	33 days	11.781	17.2415	15.0410	.19113
Con. NH ₄ OH	21 days	11.938	17.9320	17.8500	.00687
3% NaCl	21 days	10.555	15.0386	14.8925	.01384
Tap Water	21 days	12.174	17.7140	17.6850	.003606

* After removing scale

4% ANTIMONIAL LEAD - Temperature 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms.	Final Wt. Gms.*	Loss Gms./sq.cm.
90% H ₂ SO ₄	21 days	15.48	22.2866	21.9462	.02198
50% H ₂ SO ₄	21 days	14.40	19.9990	19.9912	.00054
25% H ₂ SO ₄	21 days	14.10	19.3558	19.2960	.00424
60% HNO ₃	21 days	15.21	21.7648	18.3523	.22436
30% HNO ₃	6 days	15.75	22.2302	10.2095	.76317
10% HNO ₃	3 days	15.100	19.2960	5.3403	.98972
35% HCL	21 days	14.228	19.6461	14.1280	.38757
10% H CL	9 days	15.604	19.5088	19.3380	.01169
35% NaOH	15 days	14.40	19.9912	19.9817	.000659
25% NaOH	28 days	14.604	19.6250	19.6200	.00034
1% NaOH	21 days	14.340	19.9138	19.7036	.01466
Glacial Acetic	33 days	15.880	20.2164	19.8676	.04715
Con. NH ₄ OH	21 days	14.604	19.6200	19.5088	.00761
3% NaCL	21 days	15.504	21.6228	21.4646	.010207
Tap Water	21 days	14.78	19.2615	19.2311	.002057

* After removing scale

6% Antimonial Lead - Temperature 22° C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Grams	Final Wt. Grams*	Loss Gms.sq/cm.
90% H ₂ SO ₄	21 days	15.68	23.3261	23.0890	.01512
50% H ₂ SO ₄	21 days	14.724	22.3440	22.3370	.00047
25% H ₂ SO ₄	21 days	15.276	22.2974	22.2286	.00450
60% HNO ₃	21 days	15.70	23.2251	16.7858	.41015
30% HNO ₃	6 days	16.46	23.9745	7.1280	1.02344
10% HNO ₃	3 days	15.276	22.2286	7.1200	.98900
35% HCL	21 days	13.8800	20.3929	12.3380	.58880
10% HCL	9 days	15.108	21.6910	21.5034	.01242
35% NaOH	15 days	14.724	22.3370	22.3265	.000713
25% NaOH	28 days	15.108	21.7725	21.7690	.00023
1% NaOH	21 days	15.386	22.9000	22.6605	.01557
Glacial Acetic	33 days	14.068	20.059	18.1200	.14117
Con. NH ₄ OH	21 days	15.108	21.7690	21.6910	.00516
3% NaCL	21 days	15.900	23.6090	23.4780	.008239
Tap Water	21 days	14.436	21.5048	21.4785	.001822

* After removing scale

8% Antimonial Lead - Temperature 22°C

Corrosive	Duration of test	Area in sq.cm.	Initial Wt. Grams	Final Wt. Gms. *	Loss Gms.sq.cm.
90% H ₂ SO ₄	22 days	14.718	20.6978	20.4558	.01644
50% H ₂ SO ₄	22 days	14.940	21.1494	21.1458	.00024
25% H ₂ SO ₄	22 days	15.306	21.9535	21.9520	.000098
60% HNO ₃	22 days	15.560	22.0492	18.1985	.24747
30% HNO ₃	6 days	16.635	23.8865	6.8090	1.02658
10% HNO ₃	9 days	14.718	20.4558	1.1685	1.31648
35% HCL	22 days	15.612	22.2630	12.2946	.63851
10% HCL	9 days	14.607	20.9845	20.8514	.009116
35% NaOH	15 days	15.190	21.0497	21.0455	.000276
25% NaOH	22 days	14.607	20.9851	20.9845	.00004
1% NaOH Glacial Acetic	22 days	15.084	21.7096	19.8782	.12142
Con.NH ₄ OH	22 days	14.67	20.7840	20.7880	.00027 ⁽¹⁾
3% NaCL	21 days	16.800	21.2344	21.1314	.006131
Tap Water	21 days	16.284	23.4950	23.4755	.00119

* After removing scale

(1) Gain in weight

10% Antimonial Lead - Temperature 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms.	Final Wt. Gms. *	Loss Gms.sq./cm.
90% H ₂ SO ₄	21 days	11.425	18.1660	17.9780	.01645
50% H ₂ SO ₄	21 days	16.196	19.9166	19.8895	.00167
25% H ₂ SO ₄	21 days	15.971	20.7345	20.6809	.00352
60% HNO ₃	21 days	15.28	19.4258	15.6973	.24399
30% HNO ₃	6 days	14.100	18.3200	.999	1.22837
10% HNO ₃	8 days	16.196	19.8895	3.3026	.81980
35% HCL	21 days	13.568	17.5970	3.1420	1.06565
10% HCL	8 days	14.502	18.4005	18.2287	.01185
35% NaOH	15 days	14.238	18.1188	18.1160	.000196
25% NaOH	21 days	16.547	21.7700	21.7459	.00145
1% NaOH					
Glacial Acetic	21 days	15.578	19.6680	17.7800	.12120
Con. NH ₄ OH	21 days	14.502	18.4540	18.4005	.00368
3% NaCL	21 days	15.351	19.8526	19.7600	.00603
Tap Water	21 days	14.208	18.2147	18.2000	.001035

* After removing scale

Chemtal - Temperature - 22° C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms.	Final Wt. Gms *	Loss Gms. Sq. Cm.
90% H ₂ SO ₄	21 days	15.370	29.6521	29.4312	.01437
50% H ₂ SO ₄	21 days	17.20	34.2208	34.2220	.00007 ⁽¹⁾
25% H ₂ SO ₄	21 days	21.916	31.4730	31.4110	.00282
60% HNO ₃	21 days	16.256	32.6837	11.1969	1.35256
30% HNO ₃	6 days	16.668	31.8750	12.8800	1.13960
10% HNO ₃	3 days	21.916	31.4110	14.5540	.76916
35% HCL	21 days	16.144	31.9348	25.7544	.38284
10% HCL	9 days	15.068	28.7334	28.4865	.01638
35% NaOH	15 days	17.20	34.2220	34.2085	.000784
25% NaOH	28 days	15.068	28.8080	28.8015	.00043
1 % NaOH	21 days	15.512	32.9625	32.7380	.01447
Glacial Acetic	33 days	16.780	33.6806	30.8784	.16700
Con NH ₄ OH	21 days	15.068	28.8015	28.7334	.00457
3% NaCL	21 days	14.509	35.2300	35.0926	.00947
Tap Water	21 days	13.655	31.5340	31.5030	.00227

* After removing scale

(1) Gain in weight.

CORROSIRON - TEMPERATURE 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Grams	Final Wt. Gms. *	Loss Gms.sq.cm.
90% H ₂ SO ₄	21 days	50.894	85.7387	85.7361	.00005
50% H ₂ SO ₄	21 days	18.296	21.4250	21.3848	.00219
25% H ₂ SO ₄	21 days	44.447	54.2829	53.4611	.01849
60% HNO ₃	21 days	49.064	85.1651	85.1651	.00000
30% HNO ₃	21 days	48.694	84.1330	84.1140	.00039
10% HNO ₃	12 days	44.447	53.4611	53.4508	.00029
35% HCL	21 days	44.447	58.8862	54.3130	.10289
10% HCL	9 days	19.000	21.1570	20.9616	.01028
35% NaOH	15 days	18.296	21.3848	21.3692	.000853
25% NaOH	28 days	19.000	21.1415	21.1556	..00742 ⁽¹⁾
1% NaOH	21 days	47.551	78.2017	78.1944	.000153
Glacial Acetic	33 days	18.68	21.2081	21.1944	.00073
Con. NH ₄ OH	21 days	19.000	21.1556	21.1570	.00007 ⁽¹⁾
30% NaCL	21 days	49.489	85.1600	85.1415	.000373
Tap Water	21 days	18.680	21.1940	21.1710	.00123

* After removing scale

(1) Gain in weight

DURIRON - Temperature 22°C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. Gms	Final Wt. Gms. *	Loss Gms. sq. cm.
90% H ₂ SO ₄	21 days	22.890	52.7964	52.7961	.00001
50% H ₂ SO ₄	21 days	21.645	52.1269	52.1200	.00032
25% H ₂ SO ₄	21 days	22.973	52.3055	52.1460	.100694
60% HNO ₃	21 days	8.170	8.4745	8.4736	.00011
30% HNO ₃	21 days	8.403	8.5625	8.5590	.000416
10% HNO ₃	12 days	22.973	52.1460	52.1454	.000026
35% HCL	21 days	8.955	9.0396	8.5622	.05331
10% HCL	9 days	6.496	5.9798	5.9310	.007512
35% NaOH	15 days	21.645	52.1200	52.1120	.000369
25% NaOH	28 days	6.496	5.9765	5.9765	.00000
Glacial Acetic	33 days	29.828	13.0060	12.9930	.00132
Con. NH ₄ OH	21 days	6.496	5.9765	5.9798	.00050 (1)
30% NaCL	21 days	9.330	12.9525	12.0226	.003204
Tap water	21 days	8.170	8.4735	8.4760	.000428
10% NaOH	21 days	22.908	52.9677	52.9641	.000157

*After removing scale

(1) Gain in weight

Corrosion - Temperature 22°C

BUFLOKAST - TEMPERATURE 22° C

Corrosive	Duration of test	Area in sq. cm.	Initial Wt. in gms.*	Final Wt. Gms.	Loss gms./sq.cm.
90% H ₂ SO ₄	21 days	15.4	20.9318	20.9314	.000025
50% H ₂ SO ₄	21 days	13.255	16.4695	16.4695	.000000
25% H ₂ SO ₄	21 days	10.238	11.3900	11.3730	.00166
60% HNO ₃	21 days	8.980	9.3729	9.3724	.0000556
30% HNO ₃	21 days	15.40	20.0050	19.9995	.000357
10% HNO ₃	12 days	10.238	11.3730	11.3890	.00156 ⁽¹⁾
35% HCL	21 days	10.238	11.8688	11.3900	.04676
10% HCL	9 days	9.06	9.8740	9.8164	.00635
35% NaOH	15 days	13.255	16.4695	16.4676	.000128
25% NaOH	28 days	9.06	9.8725	9.8720	.000055
1% NaOH	21 days	8.972	9.8806	9.8740	.00073
Glacial Acetic	33 days	10.726	11.1738	11.1730	.000076
Con. NH ₄ OH	21 days	9.06	9.8720	9.8740	.00022 ⁽¹⁾
3% NaCL	21 days	9.36	11.1694	11.1764	.00074 ⁽¹⁾
Tap Water	21 days	8.900	9.3735	9.3760	.000272 ⁽¹⁾

* After removing scale

(1) Gain in weight.

Discussion:- As before stated, more corrosive agents should have been employed. Between five and ten different strengths of each sulphuric, nitric, hydrochloric, and acetic acids and sodium hydroxide should have been used along with such other reagents as ammonium hydroxide, phenol, lactic acid, boric acid, ammonium chloride, sodium chloride, sodium chloride, water and many others. Those actually used were: three strengths each of sulphuric and nitric acids and sodium hydroxide, two of hydrochloric, and one each of acetic acid, ammonium hydroxide, and sodium chloride and water.

Duplicate samples in the various corrosives should have been used also but a scarcity of samples prevented this.

Conclusion:- From the data obtained in the corrosion tests the following facts were noticed. The alloys were divided into five classes; namely, lead alloys, brasses, bronzes, nickel alloys, and silic~~on~~cast irons. The brasses and bronzes, however, may be classed together as far as their general characteristics to withstand corrosion are concerned. Taking each class separately it was found that the lead alloys are very unstable in nitric acid and dissolve at a more rapid rate in dilute than in concentrated except the alloy chental which is more stable in dilute than in concentrated acid. In sulphuric acid. In sulphuric acid it was found that they are quite resistant to the 50% acid but do not resist the 90% or the 25% acid so well, being more stable in the latter than in the former. In hydrochloric they are quite stable in the dilute acid but corrode rather rapidly in the concentrated. Sodium hydroxide has very little effect in this class of alloys, the 25% solution having the least effect and the

very dilute solution having the greatest. They do not resist glacial acetic acid very well but are not appreciably effected by concentrated ammonium hydroxide, sodium chloride solution, or water.

The brasses and bronzes are very resistant to sulphuric being more resistant to the weaker acid. They are badly corroded in nitric acid, the strongest acid having the greatest effect. They are fairly resistant to hydrochloric acid, especially the weaker acid. Sodium hydroxide has little or no effect on them, they being less affected by the more concentrated solutions. They resist glacial acetic fairly well as they do ammonium hydroxide and corrode very slightly in sodium chloride solution and are practically unaffected by water.

The nickel alloys are readily dissolved in nitric acid, the more concentrated acid having the greatest effect except in the case of pure nickel where the more dilute acid had the greatest effect. They are fairly resistant to hydrochloric acid especially the weaker acid. Sulphuric acid has very little effect the 50% acid showing the least effect. Sodium hydroxide has very little or not effect. The alloys are fairly resistant to acetic acid and resist ammonium hydroxide very well. In sodium chloride there is very little or no loss or even a gain in weight as in the case of nickel silver. Pure nickel, monel metal and nickel silver all gain in weight in water and ~~al~~terite loses very little.

The silicon cast irons are the most resistant of all showing the greatest loss in concentrated hydrochloric acid but being fairly resistant to even that and quite resistant to the dilute hydrochloric. The next best corrosive being dilute sulphuric acid but that has but little effect. In quite a number

of the other cases there was a gain in weight as in the case of concentrated ammonium hydroxide all three samples showed a gain in weight.

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Loss of weight in grams per square centimeter per day.

Material	Temp.°C	Concentration of Sulphuric Acid					Concentration of Hydrochloric Acid				Concentration of Nitric Acid					Acetic Acid			Sodium Hydroxide			Sodium Chloride	Ammonium Hydroxide			Water					
		10%	25%	35%	50%	90%	10%	20%	25%	35%	50%	10%	25%	30%	60%	70%	10%	50%	98%	1%	25%	35%	3%	10%	35%		Con.				
Metals																															
Nickel	22°		.000304		.000126	.00020	.00167							.27422						.000803	.0000016*	.000000	.0000062*	.000000				.000076	.000039*		
Copper																															
Aluminum																															
Lead																															
Zinc																															
Brasses																															
Clebrium	22°		.000110		.0000076	.000265	.00166																								
Meco	22°		.000163		.0000076	.000287	.001908							.02435	.28723		6.0028			.000462	.000000	.0000016	.0000038	.0000216				.000384	.000003*		
														.01710	.3263		12.98			.000507	.000004	.0000006	.0000067*	.0000088				.000574	.000000		
Bronzes																															
Ampco	22°		.000043		.000014	.000434	.000556																								
Aluminum	22°	.00007	.000104		.0000081	.03140	.00377	.0000613						.00658	.04328		8.6256			.000130	.000123	.0000045	.0000009	.0000901				.001098	.0000012		
Tobin	22°		.000129		.0000090	.001416	.00145							.00544	.02667		10.2736			.000371	.00009	.0000037	.000000	.0000992				.001088	.000008*		
H	22°	.000205			.000096	.000156	.01277							.00414	.02592		10.8911			.001183	.000213	.0000024	.000000	.000142				.00784	.000000		
B	22°	.000070			.000025	.0000133								.00577						.000127	.00022		.0000095					.00305	.00472	.000000	
Manganese		.0001383																		.000188	.000363								.00100	.002013	
Lead Alloys																															
Acimet	22°		.000197		.0000057	.000989	.00222							.01373	.3529		.1992	.03510													
4% Antimonial	22°		.000202		.000025	.001048	.00129							.01842	.3299		.1271	.01558											.000328	.000171	
6% Antimonial	22°		.000214		.0000224	.00072	.00138							.02801	.32966		.1712	.01480											.000362	.000097	
8% Antimonial	22°		.0000044		.0000109	.000745	.001013							.02910	.14627		.1711	.01122											.000246	.000086	
10% Antimonial	22°		.000167		.0000795	.000784	.00148							.05049	.10247		.2045	.01159											.00012*	.000056	
Chemtal	22°		.000134		.0000033	.000681	.00182							.01823	.25638		.1885	.06450											.000175	.000049	
Nickel Alloys																															
Aterite-6	22°				.000000	.000349	.00223																								
Aterite-16	22°					.00078								.05042							.000009*	.000005*	.0000104						.000224		
Aterite-36	22°		.000062			.00026															.000896				.000028					.000195	
Monel Metal	22°	.0002015	.000137		.0000085	.000135	.001002	.0020305						.00726	.15796		.1412			.000323	.000003										
Nickel Silver	22°		.000117		.0000062	.000380	.000548							.003708	.10315					.000279	.000000	.0000004	.0000057*	.0000076				.000146	.000093		
																				.000412	.0000045	.0000036	.000000	.0000061					.000477	.0000069	
Al Alloys																															
Fanosite	22°				.00597	.00186								24.04224						.000032	.04023								.000025		
Silica Cast Irons																															
Buflokast	22°		.000079		.000000	.0000011	.00070							.002226	.00013*		.000017	.0000026											.000104	.000129*	
Corrosiron	22°		.000881		.000104	.000002	.00114							.004899	.000024		.0000186	.000000											.000033*	.0000586	
Duriron	22°		.000330		.000015	.0000004	.000834							.00254	.0000021		.0000198	.000052											.0000238*	.0000203*	
Duriron	82°-88°	.0000762	.000045											.17810	.000125	.0000193				.0000079											
Miscellaneous																															
Copper Steel	Room	.011377					.031186										.32953														
High Cr Steel	Room	.19561					.067781										.0000155														
High Cr-Ni Steel	Room	.01625					.071734										.000041														
High Cr-Si Steel	Room																.0000775														
25% Ni Steel	Room	.001705					.003456										.260865														
38% Ni Steel	Room	.000635					.002945										.638345														
Wrought Iron	Room	.07595					.040532										.265825														

* gain in weight.