PERFORMANCE OF HIGHLY ALLOYED MATERIALS IN CHLORINE DIOXIDE BLEACHING

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ABSTRACT

Wensley and Reid have called attention to the importance of the general corrosion rate of nickel base alloys for D stage bleaching service. Earlier investigators had assumed that resistance to localized corrosion would qualify an alloy for long term service and in many instances purposely avoided reporting general corrosion rates so as to focus attention and alloy selection on resistance to pitting and crevice corrosion. The unusually high general corrosion rates that Wensley and Reid reported for the nickel base alloys suggested that TAPPI data be re-examined. Accordingly the authors have re-examined the TAPPI Phase I and Phase II data and were able to develop general rate data on nickel base alloys to supplement the earlier reported data on resistance to localized corrosion.

In addition to Phase I and II data, new data from test racks exposed by Haynes International in D stage environments, and new data from Ingersoll Rand are also reported.

These data now show the general corrosion rates for alloy C276 to be < 0.9 mpy for exposure periods of 6 months or more in those mills which carry the acidic environment of the tower through to the vat without additions. The general corrosion rate for alloy C276 in those few mills that do add NaOH, as did the mill reported on by Wensley and Reid, is < 2.9 mpy for exposure periods of 6 months or more. The 2.9 mpy maximum rate is substantially lower than the higher rates for alloy C276 reported by Wensley and Reid. The higher rates reported by Wensley and Reid are believed to be due to their short 2 month exposure period which was not long enough to measure the long term steady state rate. Contrary to the Wensley and Reid data, the extensive data in this report indicate nickel base alloys to be promising candidates for D stage environments where localized corrosion limits the usefulness of other highly alloyed materials.

Wensley and Reid[1]

The practice at Wensley and Reid's mill was to add caustic between the tower and the vat bringing the pH up into the 6-7 range. The temperature was reported at 70C (158F), residuals at 20-200 ppm $Cl\ 0_2$ (as active chlorine) and chlorides at 600 ppm. These conditions are reasonably representative of those few mills that neutralize with caustic. The normal practice for most mills, however, is to carry the acidic conditions through to the vat without additions.

General corrosion rates for alloy C276 were reported to range from 4.3 - 10.6 mpy in earlier 2 month tests, from 2.2 to 2.8 mpy in Test 321 and as 5.2 mpy in Test 325. Tests 321 and 325 were also 2 month exposures. Higher mpy corrosion rates were reported for alloy 625 and Hastelloy® alloy C22. General corrosion rates for alloy G3, Hastelloy® alloy G30, and the stainless steels were < 0.5 mpy although some of these alloys suffered localized corrosion.

TAPPI PHASE I & II

MILLS THAT NEUTRALIZE WITH CAUSTIC
(Similar to Wensley and Reid)

Using TAPPI Phase I weight loss and specimen area information, the general corrosion rates for alloy G, C276 and the cast nickel base alloy Illium® 98 in mills which neutralize with caustic were calculated and are shown in Table 2[2]. Previously published depth of localized corrosion data are also shown for type 317L, the alloy of reference. Localized corrosion in this and following tables is shown as maximum depth of pitting in base plate (BP) material and maximum depth of crevice corrosion in the creviced sites of a serated spacer. In the Phase I program two test racks with two specimens of each alloy were installed below the liquid level on the inlet side of the vat. It was intended that one rack be removed at 6 months and one at 12 months. As can be seen the exposure periods were not uniform for all mills. The first exposure time was less than 6 months at three mills, but the second exposures ranged from 5 months to 16 months.

Table 3 summarizes the general corrosion rate for alloy C276 from the data in Table 2.

Table 3

BEHAVIOR OF ALLOY C276 IN D STAGE

NEUTRALIZED

TAPPI PHASE I

MILL	EXPOSURE TIME MONTHS	CORROSION RATE mpy	
D	2	0.9	
	5		0.5
Q	3	4.3	
	7		2.9
K	8.6	2.0	
	16.1		2.0
E	3	2.4	
	6		2.3

The corrosion rate is lower for the longer period of exposure in each case except for Mill K where the first removal of the specimens was made only after 8.6 months. These data indicate corrosion rate is sensitive to the time of exposure and that the corrosion rate decreases during the first few months of ex-

* Arthur H. Tuthill, Consultant, Blacksburg, VA ** Donald E. Bardsley, IMPCO Div. of Ingersoll Rand Co., Nashua, NH

posure until it reaches its long term steady state rate after about 6 months. The general corrosion rate for alloy G was < 1 mpy in these mills, though there was slight crevice corrosion reported on 4 of the 8 specimens exposed. The general corrosion rates for the cast nickel base alloy, Illium 98 were higher, up to 15.4 mpy.

From TAPPI Phase II data, the general corrosion rates for alloy G, G3, C276, and 625 specimens in mills which neutralize with caustic are shown in Table4[3]. In the Phase II program there were so many specimens that two identical racks were installed in each vat. Both racks were removed at the end of the exposure periods which ranged from just under 6 months to 7 1/2 months. Corrosion rates in these longer exposure periods for alloy C276 ranged from 0.1 to 1.3 mpy and for alloy 625 from 0.1 to 3.9.

The general corrosion rates of alloy C276 in both the Phase I and Phase II longer term exposures in mills neutralizing with caustic are significantly lower than the rates reported by Wensley and Reid in their shorter 2 month exposure periods. The authors believe the lower rates can be attributed to the longer periods of exposure and that these lower rates are more representative of probable long term behavior.

In the mills that neutralize with caustic general corrosion rates for alloy G and G3 were quite low and similar to rates reported by Wensley and Reid.

MILLS THAT DO NOT ADD CAUSTIC (Acidic)
(Typical of Current Practice in Most Mills)

Table 5 shows general corrosion rate data from the TAPPI Phase I program for mills that do not add caustic. General corrosion rates from Table 5 are summarized below.

Alloy C276	0.1 - 0.7 mpy
Alloy G	0.4 - 0.9 mpy
Illium® 98	0.4 - 1.3 mpy

Table 6 shows the general corrosion rate data from the TAPPI Phase II program for the mills that do not add caustic. These data are summarized below for the shorter and longer periods of exposure.

	3 month	6-7 month
Alloy C276	0.8 - 1.7	0.2 - 0.9
Alloy 625	1.0 - 7.0	0.6 - 1.8
Alloy G	0.8 - 2.0	- - 0.9
Alloy G3	1.0 - 1.3	1.3 - 1.4

The general corrosion rates for nickel base alloys are higher and more variable in the three month exposures than in the 6-7 month exposures.

The corrosion occurring in D_2 stage of mill AA was so severe that corrosion product bridged across some of the stainless steel specimens in the 6 month exposure. Spare racks were therefore installed for 90 days only in D_2 and the results from these racks were the results originally reported. Since bridging did not occur on the nickel base specimens or those adjacent to them, it was felt that the results from the longer term exposure in D_2 stage should be included in this report. No other results from this rack had been previously reported because of the bridging phenomenon.

The TAPPI Phase I and Phase II data support Wensley and Reid's findings on the importance of the general corrosion rate in evaluating nickel base alloys, but also show that it is the long term rate from 6 month or longer exposure periods that should be used in evaluating such alloys. These data also support Wensley and Reid's observation that the NiCrMO alloys G and G3 have very low general corrosion rates and should be considered and evaluated for these D stage environments, especially in those mills that neutralize with NaOH.

DATA FROM HAYNES INTERNATIONAL EXPOSURES
(Acidic D Stages)

Haynes International has made available previously unpublished corrosion data from their field exposure test program in D stage environments. These data are shown in Table 7. It happens that these five exposures were made in mills that do not add caustic and have low pH in the vats. Type 317L, the alloy of reference, suffered < 5 to 31 mils of base plate pitting attack indicating very low service life for 317L in D stage which has been borne out by mill experience. Only in mill 4 where there was < 5 mil depth of base plate attack and no crevice corrosion, would 317L appear to be capable of long term performance. This may be due to the near zero residual chlorine reported at this mill. 904L which is used in Europe in lieu of 317L, also suffered > 5 mil depth of base plate pitting attack as it did in the TAPPI Phase II exposures. The rather high residuals may account for the 15-30 mil depth of base plate pitting reported in the three mills in which a 6% Mo alloy was exposed. The base plate pitting of 6% Mo in these D stage environments emphasizes the need to carefully evaluate the higher alloyed materials in each D stage environment as there is considerable mill to mill variation in the degree of corrosion attack experienced by the 6% Mo alloys.

The duplex stainless steel, Ferralium® alloy 255 suffered less than < 5 mil depth of base plate attack in two mills, but >5 mils in the other three mills, two of which had high residuals. This indicates the duplex alloy 255 would be a somewhat marginal selection for D stage washers under acidic conditions. Wensley and Reid reported that the duplex stainless steel alloy, 2205, was the material of construction for the washer in the mill where their tests were run (caustic conditions).

Alloy C276 and G3 both had very low general corrosion rates of 1 mpy or less and slight localized corrosion indicating both alloys should perform well in these environments. Hastelloy alloy C22 behaved in a manner quite similar to alloy C276 in the two mills where it was included in the testing.

INGERSOLL RAND COMPANY

Long term data from laboratory testing of nickel base alloys and stainless steels in a simulated acidic D stage environment are shown in Table 8. These results again show 317L, the reference material, to be subject to localized corrosion. Both 904L and 254SMO™ performed better than 317L. Hastelloy® alloy C22 had an order of magnitude lower volume loss than the 6% Mo alloy in this test. The general corrosion rate for alloy C22™ was <0.01 mpy.

SHORT SEQUENCE BLEACHING

As early as 1958,[4] it was reported by Rapson and Anderson that 88 brightness could be achieved in three stages of bleaching by combining chlorine dioxide with chlorine in the first stage, hypochlorite with caustic in the second stage and chlorine dioxide in the last stage. This process did not gain acceptance until about two decades later when oxidative extraction using oxygen instead of hypochlorite in the second stage became popular because of the low cost of oxygen compared to hypochlorite. Mill experience of adding oxygen to the extraction stage has been reported by Enz and Hallenbeck.[5].

In 1985, IMPCO started the first short sequence C/D - E/O - D low level bleach plant in North America at Mead Paper in Chillicothe, Ohio. This state-of-the-art technology which utilized Compaction Baffle Filters and short sequence bleaching would now operate at temperatures above those normally seen in the chlorination and caustic extraction stages of a conventional five stage bleach plant. Because the Compaction Baffle Filter is completely sealed so the process liquid and vapor is totally contained by the vat and hood, it was decided to expose coupon test racks in the inlet box and in the hood area of each of these filters to establish the corrosivity of these environments.

Preparation For Field Testing

Test racks containing several different welded metal coupons were made. For the purpose of this discussion, 317L will be used as a bench mark. The 6%-7% molybdenum super stainless steels, which contain higher nickel than 317L stainless, were included along with a nickel base alloy Hastelloy® alloy C-22.

After welding, the coupons were pickled in a hydrofluric/nitric acid bath following the ASTM A380 procedure.

During assembly of the test racks, all coupons were insulated from each other by a teflon washer on one side of the sample and a serated teflon washer on the opposite side.

Two test racks were exposed inside the IMPCO Compaction Baffle Filter. One rack was in the inlet box and the other rack was in the hood (see Figure 1 for locations). Table 9 lists the operating conditions of these two locations and the data results.

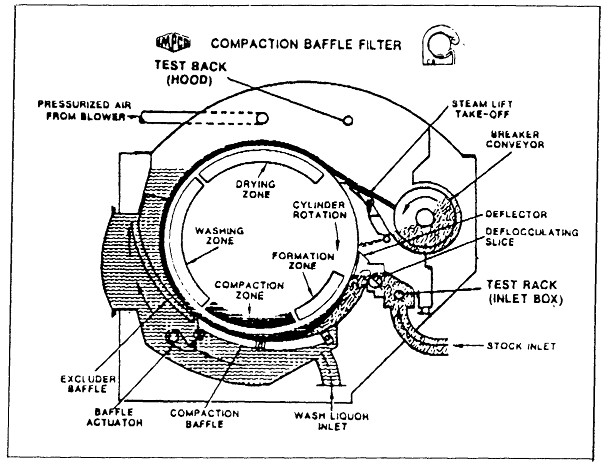

FIG. 1 LOCATION OF COUPON TEST RACKS

Discussion;

In the inlet box, which is acidic with a pH of 2.5-3.5, the 317L base plate pitted > 5 mils and suffered 8 mils crevice attack. The base plate of the three of 6% Mo alloys was resistant to pitting in the inlet box and suffered only 2 mil depth of crevice attack on one of the three alloys. There was some, but < 5 mil base plate and crevice attack on all three 6% Mo alloys in the vapor phase. These data and the low volume loss indicate 6% Mo alloys should perform quite satisfactorily in this D stage environment. Alloy C22™ had higher volume loss in the inlet box, but the corrosion rate was only 0.01 mpy. This compares to 0.03 mpy for the 6% Mo alloys. These low corrosion rates indicate that alloy C22™ and the 6% Mo alloys should perform quite satisfactorily in this D stage.

OLSSON AND FRIGREN[6]

Olsson and Frigren reported considerable field experience with 6% Mo alloys in D stage in their excellent review presented at the 6th International Seminar on Corrosion in the Pulp and Paper Industry in Helsinki September 1989. They report good performance of 6% Mo washers and filtrate piping. Severe corrosion of 6% Mo piping around the mixers and some corrosion in 6% Mo vats was also reported in the same mills where the 6% Mo washers were performing well. Their data and the data in this report suggest that nickel base alloys may prove useful in D stage piping around the mixers where vibration and temperature greatly limit the usefulness of FRP.

FIELD EXPERIENCE

There has been limited use of nickel base alloys in D stage to date. One mill has reported good experience with a partial liner of alloy C276 sheet in the inlet section of a Cronifer® alloy 1925hMo vat where the 6% Mo alloy suffered severe crevice attack under pulp pads which adhered to the surface in areas of low velocity in the vat. Except under the pulp pads the

6% Mo alloy was resistant and has performed well for 5 years. The alloy C276 liner was inspected three years after installation and found free of localized corrosion under the pulp pads which create these severe crevice areas.

EVALUATION OF CORROSION DATA - BLEACH PLANTS

Localized Corrosion

When the corrosion data from the Phase I TAPPI program became available for analysis, it was apparent that comparisons based on weight loss/corrosion rate would be meaningless as the weight loss for most specimens was from localized pinhole type pitting or crevice corrosion. Useful comparisons would have to be based on relative depth of localized attack. This created a second problem as up until that time corrosion engineers had tended to analyze localized corrosion on a go or no go basis; the alloy was either resistant to localized corrosion and satisfactory for use, or it was susceptible and unsuitable. There was little or no precedent for useful ranking of alloys based on relative depth of localized corrosion. It was therefore decided to consult with the mills where the exposures had been made and review their experience with the type 317L washers then in service. This was done and the following results were published[7].

Maximum depth of localized corrosion on 317L specimens exposed in vat	Service life of 317L washer in same vat where specimens were exposed
2 - 15 mils	> 20 years
17 - 50 mils	4 - 16 years

What this study showed was that these stainless steels were more resistant to the propagation and proliferation of localized corrosion in actual service than had been previously appreciated. This was not so startling a finding as it first seemed. It was common knowledge among engineers who inspect alloy equipment that some areas of localized corrosion were often found. These areas are ground out, sometimes weld repaired, but only rarely affect the normal service life of the equipment.

The Phase I data also showed some, but markedly less, depth of attack for the 6% Mo austenitic alloy. It seemed reasonable to interpret the lesser depth of attack as an indication of order of magnitude better resistance than the 317L then in use.

Four years later when the Phase II data became available, alloys were classified into three groups according to the maximum depth of localized corrosion[8]:

Superior	< 5 mils Base Plate Pitting and	< 5 mils Crevice
Useful	< 5 mils Base Plate Pitting and	< 15 mils Crevice
Unsatisfactory	> 5 mils Base Plate Pitting or	> 15 mils Crevice

These somewhat more restrictive criteria were adopted in part because it was realized that the > 20 year service life reported for some D stage washers included a number of years under less severe conditions than prevailed in 1976-79 when the specimens were exposed. Also 317L D stage washers continued to fail under these more severe conditions.

While these criteria are somewhat arbitrary they did predict that 904L would perform only marginally, if any, better than 317L. Field experience has certainly proven this to be the case. These criteria also predicted that the 6% Mo alloys would have an order of magnitude better resistance than either 317L or 904L. Again experience with over 75 6% Mo washers placed in service since 1982 have proven this to be case also.

General Corrosion Rate Data

The Phase I and Phase II TAPPI programs did not report corrosion rate since most of the alloys were ranked on the depth of localized attack. This omission is addressed in this report for the three nickel base alloys in the Phase I program and the four nickel base alloys in the Phase II program as well as the new data from Haynes International and Ingersoll Rand.

Alloys that resist localized corrosion and corrode uniformly, are generally preferred to those that are subject to localized corrosion, primarily because their performance is more easily predicted. Figure 2 summarizes the long term corrosion rate from the TAPPI Phase I, TAPPI Phase II, Haynes International and Ingersoll Rand Co. testing for alloy C276 on a generalized weight loss vs. time curve. Corrosion rate is the tangent to the weight loss vs. time curve. For alloy C276 in D stage it takes about 6 months for the weight loss vs. time curve to reach its long term steady state rate in both acidic and neutralized chlorine dioxide bleaching environments. The tangent to the curve and the corrosion rate for shorter exposure periods is greater than the actual long term steady state rate.

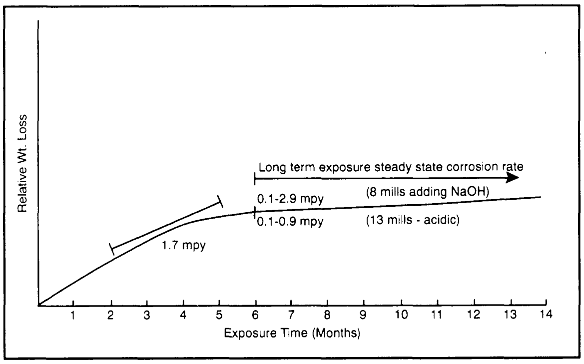

Figure 2. Range of Corrosion Rates for HASTELLOY® alloy C-276 in D Stage.

Once the true long term rate of metal loss or thinning is known, it can be allowed for in the original design. For example a 1 mil per year corrosion rate indicates a loss of 20 mils from the surface during a 20 year life. This amount of metal loss is generally tolerable for most tanks, piping and heavier structural elements. It is marginal, but probably tolerable, for heat exchanger tubing and some thin sheet applications, provided the rate is known and understood in the original equipment design. The designer always has the option of providing a little extra thickness for a corrosion allowance when he feels it is desirable to do so in order to maintain the structural soundness of his equipment throughout the desired lifetime.

All the designer needs to know is what the long term steady state corrosion rate actually is. Fortunately this rate is easy to determine, the primary need being a long enough exposure time for the long term steady state rate to be determined. It cannot be determined from short term data. Also fortunately, the general corrosion rate does not vary as greatly as does localized corrosion with excursions from target or "normal" conditions.

In the Tables general corrosion rates were not calculated or shown for alloys with > 5 mils Base Plate Pitting or 15 or more mils of crevice corrosion.

The data indicate that nickel base alloys appear to have low long term general corrosion rates of < 1 mpy in D stage environments of mills that do not neutralize with NaOH. The good performance at low pHs suggests that as chlorine dioxide substitution for chlorine in C stage increases, nickel base alloys should also be evaluated for these C stage as well as D stage environments.

Nickel base alloys exhibit somewhat higher long term general corrosion rates of up to about 3 mpy in D stage environments where NaOH is added. Since a major purpose of the NaOH addition is to reduce corrosion, it would be best not to add NaOH when the D stage environment is severe enough to require the use of nickel base alloys.

CONCLUSIONS

1) Although nickel base alloys have not been widely considered for D stage environments these data indicate that nickel base alloys may be very useful materials for those D stage environments where the 6% Mo alloys suffer extensive localized corrosion.

2) Alloy C276 exhibits long term general corrosion rates of 0.3 to 0.9 mpy in D stage in those mills that do not neutralize with NaOH.

3) Alloy C276 exhibits long term general corrosion rates of 0.1 to 2.9 mph in D stage in those few mills that still neutralize with NaOH. This compares with rates that ranged from 2.2 to 10.6 mpy in a similar D environment as reported by Wensley and Reid for their shorter exposure times.

4) The Phase I and Phase II data indicate that it requires at least 6 months exposure to develop the true long term general corrosion rate of nickel base alloys in D stage environments. Shorter exposure periods are likely to give variable and higher rates that are not indicative of long term performance.

5) Alloy 625 has a slightly higher general long term corrosion rate than Alloy C276. Based on limited data Hastelloy® alloy C22 appears to have resistance approaching that of alloy C276. The cast nickel base alloy, Illium® 98, has an order of magnitude higher general corrosion rate than wrought alloys C276 and 625 and is also subject to localized attack in some D stage environments.

6) The Phase I and Phase II data confirm the good resistance of the G class alloys in those mills that still neutralize with NaOH as reported by Wensley and Reid.

ACKNOWLEDGEMENT

The authors would like to express their appreciation to Haynes International and Ingersoll Rand Co. for making data from their test programs available for publication in this paper.

REFERENCES

1) Wensley, D.A., and Reid, D.C., "Corrosion of Nickel - Base Alloys in Chlorine Dioxide Washer Service" NACE 90 Las Vegas April 1990

2) Tuthill, A.H., "Progress Report Corrosion Test Results - Phase I Bleach Plant, C, D & H Stages" TAPPI Engineering Conference, New Orleans, Nov. 1979 TAPPI Press Report - 84

3) Tuthill, A.H., "Corrosion in Aggressive Bleach Plant Environments - Phase II" TAPPI Engineering Conference, Dallas, TX, Sept. 1983

4) Rapson, W.H. and Anderson, C.B. TAPPI, 41(19): 486 (1958)

5) Enz, S.M. and Hallenbeck, M.R. TAPPI, 67(6): 54 (1984).

6) Ollson, J. and Frigren, E. "Experiences from the Use of the Stainless Steel UNS 31254 in Finnish and Swedish Bleach Plants", 6th International Symposium on Corrosion in the Pulp and Paper Industry" Helsinki, Finland, Sept. 1989.

7) Tuthill, A.H., "Localized Corrosion of AISI 316/316L and 317/317L: Short-Term Tests vs. Experience" MP July 1983 pgs 45-51

8) Tuthill, A.H., "TAPPI Phase II Corrosion Test Program - Part I Resistance of 26 Candidate Materials to Aggressive C, D & H Stage Bleach Plant Environments" Proceedings Fourth International Symposium on Corrosion in the Pulp & Paper Industry Stockholm, Sweden May 30 - June 2, 1983

APPENDIX

Tables 1	Composition of Alloys
2	Behavior of Nickel Base Alloys in D stage - NaOH added Phase I
4	Behavior of Nickel Base Alloys in D stage - NaOH added Phase II
5	Behavior of Nickel Base Alloys in D stage - Acidic - Phase I
6	Behavior of Nickel Base Alloys in D stage - Acidic - Phase II
7	Behavior of Alloys in D stage - Acidic - Haynes International Exposures
8	Behavior of alloys in simulated chlorine dioxide bleaching environment - Acidic Ingersoll Rand Co.
9	Exposure in Acidic D stage with (SO_2) of Short Sequence Bleach Plant - Ingersoll Rand Co.

Table 1 Composition of alloys in this report

	Cr	Ni	Mo	Mn	Co	Other	
317L	18	14	3.5	1.5			
904L	20	25	45	1.5		1.5 Cu	0.05 N
AL6XN™	21	25	6.5	0.5		0.20N	
254SMO™	20	18	6	0.5		0.7Cu	0.2 N
Cronifer® alloy 1925 hMo	20	25	6.4			0.22N	0.8 Cu
Ferralium® alloy 255	25.5	5.5	3	1.5		2 Cu	0.18 N
Alloy G	22	45	6.5	1.0	2.5	1 W	2 Cu
Alloy G3	22	42	7	1.0	5	1.5 W	2 Cu
Alloy C276	15.5	56	16	1.0	2.5	3.7 W	5.5 Fe
C22™	22	58	13	0.5		3 W 3 Fe	0.35 V
Alloy 625	22	61	9	0.4		3 Fe 3.5 Cb + Ta	
Illium® 98	27	57.5	8	2		5.5 Cu	

Trademarks	
254SMO™	Avesta AB
Cronifer®	VDM
AL6XN™	Allegheny Ludlum
C22™	Haynes International
Ferrallium®	Langley Alloys Ltd.
Illium®	Stainless Foundry and Engineering

Table 2 Behavior of nickel base alloys
D stage - NaOH added - Phase I
Gen. Corrosion Rate - MPY & Max. Depth Attack - mils

Mill	D	D	E	E	K	K	Q	Q
Rack	6566	6567	6667	6668	6614	6615	6663	6664
pH	6.5-7		6.5		8-8.5		5.4-7.3	
ClO_2* ppm	20-90		300-500		1,000		30	
Temp F	140-150		140-165		113-122		140-145	
Cl ppm	480		1,700		Low		780	
Time Days	60	163	91	181	258	486	89	217
317 mpy	NR	NR	NR	NR	NR	NR	NR	NR
BP	0	24	P	37	7	7	26	47
CC mils	7	10	32	12	19	20	33	40
G mpy	<0.1	<0.1	0.1	0.1	<0.1	0.1	1.5	1.1
BP	0	0	0	0	0	0	0	0
CC	0	3	0	<1	0	0	<1	<1
I** 98 mpy	0.9	1.0	15.4	11.3	4.4	4	9.5	8.9
BP	0	0	0	0	0	3	0	0
CC	0	0	1	0	0	0	0	1
C276 mpy	0.9	0.5	2.4	2.3	2.0	2	4.3	2.9
BP	0	0	0	0	0	0	0	0
CC	0	0	0	0	0	0	0	0

Legend
BP - Base Plate Pitting
CC - Crevice Corrosion
NR - Not Reported
P - Penetrated
* - ClO_2 (Reported as active chlorine)
I** - Illium® 98

Table 4 Phase II Behavior of nickel base alloys in mills adding NaOH
Gen Corr. Rate - MPY & Max. Depth Attack - Mils

Mill	EE	DD	CC	FF
Stage	D_2	D	D	D
pH	5.2-5.8	5.5-7	6.5	6.7-7.7
ClO_2* ppm	30	<10	NR	11
Temp. F	155	169	150	166
Cl ppm	500	750	Low	1000
Time Days	227	236	216	175
317L	NR	NR	NR	NR
BP	21	39	35	41
CC	11	12	18	25
Alloy G mpy	<0.1/<0.1	0.1/0.1	0.1/0.1	<0.1/<0.1
BP	0	0	0	0
CC	3	3	1	0
Alloy G3 mpy	<0.1/<0.1	0.2/0.2	0.2/0.2	<0.1/<0.1
BP	0	0	0	0
CC	0	8	1	1
Alloy 625 mpy	1.0/1.7	2.4/2.4	3.5/3.9	<0.1/<0.1
BP	0	0	0	0
CC	1	1	1	1
Alloy C276 mpy	0.6/0.9	1.1/1.2	1.2/1.3	0.1/0.1
BP	0	0	0	0
CC	0	0	0	1

Legend
Alloy - Gen. Corr. Rate - mpy
BP - Base Plate Pitting
CC - Crevice Corrosion
NR - Not Reported
*ClO_2 (Reported as active chlorine)

Table 5 Phase I Behavior of nickel base alloys
D stage - acidic
Gen. Corrosion Rate - MPY & Max. Depth Attack - mils

Mill	B	B	H	H	T
Rack	6681	6682	6553	6552	6555
pH	3-4		3.5		2.1
ClO_2* ppm	1600		4		10-100
Temp F	122-140		100-104		144-158
Cl ppm	840		300		1,980
Time Days	185	310	138	246	258
317	NR	NR	NR	NR	NR
BP	13	18	26	32	P
CC	23	20	21	11	18
Alloy G mpy	0.6	0.6	0.5	0.4	0.9
BP	0	0	0	0	0
CC	0	0	0	0	11
I** 98 mpy	1.3	1.2	0.4	0.4	NR
BP	0	0	0	2	10
CC	0	1	0	0	1
Alloy C276 mpy	0.4	0.3	0.1	0.1	0.7
BP	0	0	0	0	0
CC	0	0	0	0	0

Legend
BP - Base Plate Pitting
CC - Crevice Corrosion
NR - Not Reported
P - Penetrated
*CLO_2 (Reported as active chlorine)
** Illium® 98

Table 6 Phase II Behavior of nickel base alloys in D stage - acidic
Gen. Corr. Rate - MPY & Max. Depth Attack - mils

Mill	AA	AA(1)	AA	GG	JJ
Stage	D2	D2	D1	D	D2
pH	3.1-3.7	3.1-3.7	3.4-4.1	2.1-3.5	3.3-5.5
ClO_2*	36	36	62	181	64
Temp F	176	176	151	157	128
Cl ppm	5600	5600	1700	1800	1550
Time Days	90	180	90	189	216
317L	NR	NR	NR	NR	NR
BP	33	NR	53	47	81
CC	7	NR	15	13	37
Alloy G	2.0/2.0	NR	0.8/0.8	0.9/0.9	NR
BP	0	0	0	0	0
CC	1	16	2	2	24
Alloy G3	1.0/1.1	NR	1.2/1.3	1.3/1.4	NR
BP	0	0	0	0	0
CC	1	15	2	13	19
Alloy 625	6.5/7.0	1.8/1.7	2.0/1.0	1.6/1.6	0.7/0.6
BP	0	0	0	0	0
CC	1	5	1	1	1
Alloy C276	1.7/1.7	0.9/0.9	0.8/0.8	0.4/0.4	0.3/0.2
BP	0	0	0	0	0
CC	0	0	0	0	0

Legend
- Alloy - Gen. Corr. Rate - mpy
- BP - Base Plate Pitting
- CC - Crevice Corrosion
- NR - Not Reported

(1) Data from the test rack exposed for 180 days was not previously reported because of bridging of corrosion products between 316L & 317L & between 316L & 825 specimens. Nickel base alloys were not affected by bridging, however.

* ClO_2 (Reported as active chlorine)

Table 7 Behavior of stainless steels and nickel base alloys in chlorine dioxide - acidic
Haynes International Field Test Data

Mill	1	3	4	6	8
Rack	365	473	292	539	512
pH	3.1-5.5	3.5-4.5	4-5	3.1-5.5	4.1
ClO_2* ppm	20-200	0	0	20-200	0.23%
Temp F	155-160	140-145	86-149	155-160	151
Cl ppm	NR	Very low	130	N/R	Trace
Time Days	258	270	5.5 yrs	150	229
317L mpy	1.2	NR	<0.1	NR	NR
BP mils	Yes	31	<5	<30	<30
CC mils	Yes	24	0	<30	<30
904L mpy		NR	NR		NR
BP mils		13	10		<30
CC mils		26	0		<30
254SMO™ mpy	NR			NR	NR
BP mils	24			<30	<15
CC mils	32			<30	<15
255 mpy	NR	NR	<0.1	1.0	NR
BP mils	6	7	<5	<5	<15
CC mils	10	0	<2	0	0
G3 mpy	0.2	0.2	<0.1	1.0	NR
BP mils	0	4	<2	<5	<15
CC mils	4	0	<2	<5	<5
C276 mpy	0.2	0.1	<0.1	0.7	0.1
BP mils	0	3	0	<2	<5
CC mils	0	0	<2	0	0
C22™ mpy				1.2	0.1
BP mils				0	<5
CC mils				0	0

Legend
- BP - Base Plate Pitting
- CC - Crevice Corrosion
- NR - Not Reported
- YES - Attack, no depth reported
- *ClO_2 (Reported as active chlorine)

Table 8 Behavior of alloys in simulated chlorine dioxide bleaching environments - acidic - Ingersoll Rand

pH	3-4
ClO_2* ppm	100
Temp F	160
Cl ppm	2200

	317L	904L	254SMO™	C-22™
Time Days	1199	1065	1335	1650
Vol. Loss mm3	23.3	9.9	8.1	0.23
Gen. Corr. mpy	(1)	(1)	(1)	0.01

*ClO_2 (Reported as active ClO_2)

(1) Localized corrosion that occurred prevents calculating meaningful general corrosion rates.

Table 9 Exposure in acidic D stage with (SO_2) of short sequence bleach plant - Ingersoll Rand - Continued

Behavior of Weld and HAC

Type 317L and C22 specimens were welded with matching composition filler material. The three 6% Mo alloys were welded with Inconel 112 filler material.

Observations

317L	- Weld & HAZ Servere Pitting	Inlet Box & Hood
AL6XN™	- Weld - Slight Pitting	Inlet Box & Hood
254SMO™	- Weld - Slight Pitting	Inlet Box & Hood
1925hMo	- Weld - Slight Pitting	Inlet Box & Hood
C22™	No visible corrosion Weld or HAZ	Inlet Box & Hood

Table 9 Exposure in acidic D stage with (SO_2) of short sequence bleach plant - Ingersoll Rand
Volume loss - mm^3 & Max. Depth Attack - mils

	Inlet Box	Vapor Space
pH	2.5 - 3.5	5-7
ClO_2 ppm* (1)	15	-
Temp F	165	130
Cl ppm	430-780	-
Time	13 mo	4 mo
317L	NR	14.8
BP	8	3
CC	8	8
AL6XN™ mm^3	2.3	1.0
mpy	0.03	NR
BP	0	2
CC	0	2
254SMO™ mm^3	3.3	1.5
BP	0	0
CC	2	1
1925hMo mm^3	2.6	1.7
mpy	0.03	NR
BP	0	2
CC	0	0
C22™ mm^3	10.1	2.0
mpy	0.01	0.07
BP	0	0
CC	0	0

Legend	Alloy -	Vol Loss mm^3
	BP -	Base Plate Pitting
	CC -	Crevice Corrosion
	* -	Cl02 (Reported as active chlorine)

(1) The mill adds S02 but also reports a small residual indicating that the addition is not completely effective in eliminating the residual.