A REVIEW OF FACTORS AFFECTING CARBON ANODE CONSUMPTION IN THE

ELECTROLYTIC PRODUCTION OF ALUMINUM

Paul Rhedey

Abstract

Anode consumptions were determined in the laboratory in a miniature electrolytic cell in which the test electrode is fully immersed in the electrolyte. The test is carried out under conditions simulating those of industrial reduction cells, and the results parallel those of plant-scale tests. The correlation between the laboratory and plant con-sumption data is demonstrated. Laboratory studies led to better under-standing of many factors affecting anode consumption. The mechanism is reviewed. Results are presented for (1) anode materials, (2) anode processing variables, and (3) cell operating practices. Of considerable interest are the consumption rates obtained with special cokes such as needle, fluid, and high-temperature cokes, and with coal-tar and petroleum pitches containing very low amounts of quinoline-insolubles. Anode consumption exhibits a minimum with increasing binder content. It can be significantly modified by the use of certain additives. Major changes in aggregate size distribution have marked effects on consumption in both the prebaked-type and Soderberg electrodes. The effect of electrolyte temperature and composition and some of the reduction cell variables on anode consumption are briefly discussed.

Paul Rhedey is head of the Carbon Section of Alcan Research and Develop-ment Limited's Electrometallurgical Division, Arvida, Quebec, Canada

Introduction

Alcan R & D: Arvida developed a laboratory test cell and has been using it over the past ten years for the determination of baked carbon anode consumption.[1] The laboratory anode consumption is measured on cored or machined samples of baked electrodes fully immersed in the electrolyte. The laboratory results therefore do not include the amount of carbon consumed by air oxidation or by secondary causes inherent to plant operation such as paste leaks or mechanical losses. A small amount of air oxidation of the sample occurs when it is withdrawn from the cell after the test. This was found to be 2% of the theoretical consumption and could be applied to the results as a standard correction. The laboratory baked anode consumption results may be expressed as a percentage of the theoretical consumption, theoretical being that corresponding to formation of CO_2 at 100% current efficiency (0.112g/Ah, or 0.247 lb/kAh).

The plant anode consumption may be considered as the sum of the following quantities: carbon consumed in the electrolytic reduction process at the anode face, carbon consumed by secondary reactions such as CO_2 permeation, eroded carbon dust, mechanical losses through cracking and breakage, paste leaks or other losses, and carbon lost by air oxidation of the hot anode surface. It is believed that a major part of the excess consumption is usually due to the eroded carbon dust, while the role of secondary reactions is small. Air oxidation under certain conditions is appreciable. It is well known that the difficulty in determining the effect of any one variable on anode consumption in a plant-scale test lies in maintaining the numerous other operating variables at a constant value in a series of cells over a sufficiently long period of time. In order to achieve adequate accuracy a statist-ically designed experiment is necessary involving two sets of randomly selected operating cells, one set with the anodes to be evaluated, and another set with "control" anodes. The number of cells per set should be at least 24 or more, and the duration of test from 3 to 6 months. Under these conditions, provided that the smelter is equipped for such tests, a difference of 1 to 2% in anode consumption can be detected with acceptable confidence limits.

Many investigations have been carried out over the past ten years at Alcan R & D: Arvida on the different aspects of the laboratory baked anode consumption, and factors affecting it. Similarly many plant-scale tests have been conducted or observations made otherwise at the Alcan smelters and affiliates with regard to anode raw materials, manufacturing and operating conditions. The paper gives an up-to-date review of factors affecting anode consumption based on both laboratory and plant-scale measurements.

Results

Effect of Anode Materials on Consumption

For commercial calcined cokes from various sources, baked anode

consumption was found to decrease with increasing Collier bulk density. Table I gives the results. The rate of decrease is 0.45% consumption per 0.01 density units for both prebaked and Soderberg test electrodes.

The effect of degree of calcination on anode consumption is small. Consumption decreased with decreasing temperature of calcination at a rate of 0.8% per 100°C over the calcination temperature range of 1100 to 1400°C. Figure 1 shows the results, including those obtained on prebaked test electrodes where baking temperature was either 1100°C or the same as the calcination temperature. Plant tests confirmed the tendency of anode consumption to increase with increasing coke calcination temperature.

TABLE I

Effect of Coke Bulk Density on Anode Consumption

Test electrode type	Bulk density g/cm³	Anode Consumption %
Soderberg	0.775	125.0
	0.804	126.5
	0.828	121.5
	0.879	123.1
	0.886	121.4
Prebaked	0.840	125.5
	0.889	124.9
	0.905	124.6
	0.905	122.8
	0.923	123.6
	0.932	121.7
	0.934	121.1

NOTE: Bulk density by Collier method on 20 x 35 Tyler mesh sample.

The effect of partial oxidation and surface oxygen content was investigated in Soderberg test electrodes. There was no significant effect on consumption over a range of 5 to 25 wt% burn-offs. The effect of cooling the coke in inert gas (nitrogen) in contrast to direct water quench after calcination was also examined. No effect on anode consumption appeared.

Anode consumption of Soderberg test electrodes decreased with increasing sulphur content at a rate of 2.5% per 1% sulphur over the range of 1 to 4% sulphur in the calcined coke. A similar, but less significant correlation was found for prebaked test electrodes. The rate of decrease in consumption was 1.2% per 1% sulphur in the coke. The laboratory results are shown in Figure 2. Similar results were found in plant-scale tests, although the effect of sulphur appeared less pronounced there than in the laboratory.

Several types of petroleum cokes have been evaluated in the laboratory. The properties of the cokes are given in Table II. Needle coke gave slightly lower anode consumption (1 to 2%) in both Soderberg and prebaked test electrodes than sponge coke. The reduction in consumption clearly would not justify paying a premium usually associated with this type of coke, for the aluminum industry. Substitution of fluid coke in the aggregate decreased anode consumption of Soderberg test electrodes significantly. As Figure 3 shows the rate of decrease is 2% per 25% fluid coke addition. A 22-cell, 6-month, plant test of fluid coke additions to Soderberg paste was made. The results obtained agreed with the laboratory prediction, and it was concluded that use of fluid coke of acceptable purity is advantageous in Soderberg paste. At the present time such fluid coke is not available to Alcan. High-temperature fluid coke (coke deposited in a fluidized bed at high temperature) gave very high consumption results in the laboratory. The use of 25 to 60% unground or ground high-temperature fluid coke in the aggregate increased the consumption of Soderberg test electrodes by 10 to 15%. In prebaked-type test electrodes anode consumption was 15% higher than for regular delayed coke. The high consumption is attributed to the low reactivity of high-temperature fluid coke.

A comparative laboratory testing of samples of horizontal stud Soderberg paste made with pitch coke and petroleum coke revealed very little difference in anode consumption. The former gave slightly, but not significantly, lower (around 1%) laboratory baked anode consumption.

A considerable amount of work was carried out on coal-tar pitch binders, both in the laboratory and in the smelters. The range of properties of coal-tar pitches tested in the laboratory is given in Table III. An increase in softening point was found to decrease the laboratory consumption of Soderberg paste and green prebaked electrodes. The decrease in paste consumption was 2% per 10°C increase in softening point over the range of 100 to 125°C. Paste binder requirement did not change with increasing softening point. It appears that quinoline-insoluble content between 6 and 16% does not affect consumption. Good

TABLE III

Range of Properties of Pitch Binders Tested

Property		Coal-tar pitch Minimum	Coal-tar pitch Maximum	Petroleum Pitch Minimum	Petroleum Pitch Maximum
Softening pt.(cube-in-air (Alcan))	°C	70	130	118	118
Coking value (Alcan)	%	38.4	64.0	46.6	58.9
C/H ratio (atomic)		1.24	1.95	1.27	1.62
C/H x CV		50	118	59	89
Quinoline-insoluble	%	2.5	16.0	0.1	16.8
Benzene-insoluble	%	12.0	34.0	4.0	30.5
Beta-resins (BI-QI)	%	9.0	21.5	1.3	20.1
C/H (atomic) of QI		2.7	4.9	1.8	12.1
Density	g/cm³	1.25	1.34	1.22	1.29
Ash	%	0.10	0.60	0.02	0.12
Sulphur	%	0.30	0.70	0.80	1.60
Viscosity*: EVT_{15}		120	190	145	170
EVT_{1015}		85	145	105	125
T_c		22	30	20	30
Soderberg paste binder requirement**: 60% elong.	%	26.5	33.0	27.5	30.0
150% elong.	%	29.0	34.0	28.5	34.5
Typical laboratory baked Soderberg anode consumption	%	124	130	122	125

* EVT_{15} and EVT_{1015} = equivalscous temperature for 15 and 1015 poises, respectively;

$$T_c = 1000/(EVT_{15} - EVT_{1015})$$

** With Alcan reference coke and aggregate size distribution.

TABLE II

Typical Properties of Petroleum Cokes Tested

Property		Type of Coke Delayed Sponge	Delayed Needle	Regular Fluid	High Temperature Fluid
Hydrogen	%	0.09	0.11	0.07	0.02
Sulphur	%	2.17	1.80	5.38	0.40
Ash	%	0.38	0.30	0.44	0.56
Real density	g/cm³	2.06	2.04	1.94	1.82
Mean crystallite thickness	L-Å	27.0	34.5	20.0	55.0
Electrical resistivity	10^{-4} ohm.cm	450	480	550	700
Reactivity to CO_2*	cm³/g.sec	0.190	0.03	0.066	0.004
Porosity **	%	25.2	25.0	15.0	10.0
Bulk density (20 x 35 mesh)***	g/cm³	0.880	0.880	0.940	0.980
Hardgrove grindability index		40.5	45.0	32.0	25.0
Vanadium	%	0.016	0.010	0.100	0.010
Iron	%	0.040	0.030	0.040	0.020
Silicon	%	0.025	0.010	0.020	0.020
Nickel	%	0.014	0.010	0.008	0.010
Calcium	%	0.017	0.010	0.020	0.020
Typical laboratory baked Soderberg anode consumption	%	126.0	124.5	120.0	138.0

* Flow rate per gram of coke at which 20 vol % of CO_2 is converted to CO at 1000°C.

** Mercury porosimetry, 20 x 35 Tyler mesh.

*** By Collier method

results have been obtained both in the laboratory and in the plant in horizontal stud anodes with coal-tar pitches containing as low as 6% quinoline insoluble and 14% beta-resins. A pitch with higher C/HxCV tends to give superior test electrode properties, but not lower baked anode consumption. Heat or pressure-treated pitches are disliked by Alcan because of the increased Soderberg paste binder requirement associated with these pitches. Anode consumption does not seem to be affected by treatment. During laboratory investigations a promising correlation was found between anode consumption and the coking value of acetone-soluble fraction, showing a decrease in baked anode consumption with increasing CV of the acetone-soluble fraction.

The petroleum pitches tested have shown a wide range of properties as can be seen in Table III. Some of the pitches gave several percent lower laboratory baked anode consumption than regular coal-tar pitch. Generally speaking petroleum pitches appear to be satisfactory in the laboratory and usually have a lower paste binder requirement than coal-tar pitch. The suitability of petroleum pitch as binder for prebaked anodes has already been demonstrated by others. So far only semi-quantitative tests have been carried out by Alcan in horizontal-stud anodes. The results of these tests have been encouraging. A plant-scale test showed that petroleum pitch makes a satisfactory anode in HS cells. Overall paste consumption for 20 cell-months was 0.349 lb/kAh. This was 4.9% lower than consumption of regular paste at the time of the test. It has not yet been established whether or not petroleum pitch would meet the more severe thermal stability requirement of vertical-stud anodes.

Effect of Processing Variables on Consumption

In laboratory work five different aggregate size distributions have been used as shown in Figure 4. The results revealed a good correlation between the calculated cumulative surface area of the aggregate and laboratory baked anode consumption. Figure 5 shows the correlation. It was concluded that for Soderberg paste a "straight line" aggregate size distribution, concave at the coarse end, and, not containing more than 30% fines minus 200 mesh is the most favourable. For prebaked anodes a coarser aggregate, similar to A-2 in Figure 4, appeared to be preferable. It further appeared that size distributions which give best packing with minimum of voids such as the "hole-in-middle" distribution, A-4 in Figure 4, do not necessarily give low consumption. The laboratory results have been confirmed in plant-scale tests. In a half-line changeover experiment paste with A-1 size distribution was compared with paste made with a coarser size distribution (between A-1 and A-2 in Figure 4). The coarser aggregate required less binder, and anode paste consumption was 4.6% lower than that of A-1 paste, the difference being highly significant.

Consumption of Soderberg test electrodes decreased by 1.7% when paste elongation was decreased from 150 to 25%, a decrease of 0.35% per 25% elongation. When Soderberg paste was vibrated and binder content

reduced by 2% in a plant test, consumption decreased by 2.8%. In pressed prebaked-type test electrodes consumption decreased at a rate of 1.5% per 1% increase in binder content over the range of 13 to 19% binder. Binder coke density showed a good correlation with anode consumption, when binder coke density was defined as follows:

$$\text{Binder coke density, } d_b = \frac{1}{V_b} \times \frac{p}{100} \times \frac{C}{100}$$

C = apparent binder coke yield.
p = parts of binder by weight per 100 parts by weight of filler coke.
V_b = total volume of baked carbon which contains 1 g of filler coke.

A similar correlation was found for vibrated test electrodes and on core samples of vibrated prebaked anode blocks. Laboratory test electrode studies have shown that anode consumption exhibits a minimum at a binder content which is just enough to fill the calculated voids of the aggregate in the green body. This is shown in Figure 6.

Pitch impregnation and subsequent rebaking of prebaked-type test electrodes improved physical properties but did not reduce anode consumption significantly.

In the laboratory preheating of coke or pitch prior to mixing had no effect on consumption. Preheating is usually applied when continuous mixers are used. Some preheating of the coke occurs even in batch mixers. Preheating conceivably shortens mixing time, but there is no evidence that anode consumption would be affected.

No difference was found in the laboratory anode consumption between batch and continuous-mixer pastes from Alcan smelters.

Consumption of prebaked-type test electrodes was found to decrease with increasing forming pressure at a rate of 1.8% per 1000 psi over the range of 3000 to 6000 psi.

A relatively new forming method, vibration, gave prebaked-type test electrodes with the same consumption as pressing, under properly chosen vibrating conditions. A semi-quantitative comparison of vibrated and pressed prebaked anodes was made at Alcan's Arvida Works. In five cells 300 anodes of each type were tested. The performance of vibrated anodes was found to be the same as that of pressed anodes. Also, comparable consumption results were obtained in the laboratory on a set of core samples from pressed and vibrated anode blocks baked in the Arvida Works ring furnace.

Presence of air during baking of prebaked-type test electrodes resulted in significantly increased anode consumption. The increase in consumption of 1.5 inch diameter test electrodes was as high as 8%.

The effect of baking temperature previously reported (1) was confirmed. In Soderberg test electrodes consumption decreased at a rate of 8% per 100°C increase in baking temperature over the range of 940 to 1050°C. In prebaked-type test electrodes anode consumption decreased at a rate of 3.5% per 100°C increase in baking temperature between 975 and 1300°C. A decrease of from 3 to 5% in anode consumption per 100°C increase in baking temperature has been reported in the literature for prebaked anodes of pilot-plant and production cells. (2,3) A recent plant-scale test at Arvida Works confirmed the improvement in anode consumption with increasing baking temperature. Anode consumption decreased by 4.1% when mean anode baking temperature was raised from 1050 to 1200°C.

Several additives have been tested in the laboratory and on plant-scale tests. Addition of 3 to 5% aluminum chips to Soderberg paste gave 2 to 3% reduction in the consumption of test electrodes, expressed on an aluminum-free basis. In a 20-cell, six-month plant test the presence of 5% aluminum saw chips in Soderberg paste reduced paste consumption by 5.8%. In the laboratory air oxidation was also found to decrease with addition of aluminum metal. Since in the electrolytic cell the aluminum added to the paste is oxidized to alumina and then reduced again, this would not be an economical way of reducing paste consumption.

Sulphur added to paste in amount of 1 to 4 g per 100 g coke had no effect on the baked anode consumption of Soderberg test electrodes. Due to an increase in coking value of the pitch, however, and because sulphur permits the use of a lower binder content for a given paste elongation, there would be a decrease in green paste consumption. This is expected to be in the range of several percent, but has not been quantitatively determined. Additions of 1% sulphur were made to the paste of an HS cell. The result was a 4% reduction in binder requirement confirming findings in the laboratory. Due to objectionable odours in the mixing and smelting operation, however, it was not possible to conclude the test.

Other additives such as Al_2O_3 in different particle sizes, H_3BO_3, H_3PO_4, $Na_2B_4O_7$, $Na\ AlF_6$, and NaF significantly increased the consumption of Soderberg test electrodes. The use of B_2O_3 was beneficial.

Reclaimed anode butts might be referred to as a necessary additive to prebaked anodes. Laboratory anode consumption of prebaked-type test electrodes increased as the amount of butts was increased in the aggregate. Over the range of 0 to 25% butts and with a "straight-line" intermediate size distribution (A-1 in Figure 4) consumption increased by 0.3% for each 1% butts used in the aggregate. With coarse size distribution (A-2 in Figure 4) the increase in consumption was smaller, 0.2% for each 1% butts used. The rate of air oxidation also increased significantly with increasing butts content. The effect of using reclaimed crushed butts in prebaked anodes was not determined in the plant. The laboratory results including a correction for plant air oxidation are in qualitative agreement with results reported for the same range of additions by others.(4)

Additions of 5 to 20% of crushed scrap cell lining to Soderberg paste increased consumption of test electrodes considerably. Recovery of materials in scrap cell lining via the anode is therefore not recommended.

Effect of Operating Variables on Consumption

The effect of electrolyte temperature, electrolyte composition and anode current density on the laboratory anode consumption has already been reported. (1) In more recent plant-scale tests the effect of electrolyte temperature on Soderberg paste consumption was confirmed. Paste consumption decreased by 0.0006 lb/kAh per 1°C, or about 1% per every 5°C decrease in electrolyte temperature over the range of 965 to 985°C. The agreement between laboratory and plant data is excellent.

In the laboratory the addition of 5% lithium fluoride to the electrolyte did not affect anode consumption at constant temperature. In a 34-cell, 12-month plant-scale test with 2.5% lithium fluoride addition paste consumption decreased from 0.355 to 0.347 lb/kAh, with an accompanying decrease of 11°C in electrolyte temperature. The reduction in paste consumption is fully attributed to the decrease in electrolyte temperature.

Various operating practices have been evaluated in plant tests. Hot stud planting increased paste consumption by 2%. Anode baking contours and baking rates were measured at one of Alcan's smelters on anodes with single-row and double-row studs on power. No difference in paste consumption was indicated. The effect on anode consumption of plugging stud holes with alumina-cryolite paste was also studied. The reduction in anode consumption was not significant. It was concluded that the small saving effected by this practice would not pay for the extra labour involved.

In a plant-scale test at Alcan's Shawinigan smelter a 4-inch average increase in anode height resulted in a 1.7% reduction in paste consumption. The effect of open versus closed paste compartment doors was studied in a plant-scale test of short duration. It was found that anode baked height decreased by 1.5 inch when paste compartment doors were open or removed, but the difference in paste consumption was not significant.

To assess the extent of anode side oxidation in HS cells the anodes in all lines of the Shawinigan smelter were measured once per month for one year. Total side and end oxidation was found to vary between 5 and 7%. In the same year a test was run in the smelter with an anode equipped with aluminum frames. Paste consumption in the test cell was 10% lower than the consumption for the line, 0.328 vs 0.365 lb/kAh. The difference appeared highly significant and it was mainly attributed to the absence of air oxidation, and uniform current density.

From *Light Metals 1971*, Thomas G. Edgeworth, Editor

Comparison of Laboratory and Plant Consumption Data

Samples of Soderberg paste were obtained from different smelters and tested in the laboratory. The aggregate size distributions used in the pastes are given in Figure 7. Other details and the laboratory anode consumption results are given in Table IV. In order to compare the data with those reported by smelters, the laboratory baked anode consumption results were converted to paste consumption figures using the following equation.

$$\text{laboratory baked anode consumption, \%} \times \frac{0.247}{yB + (100 - B)} = \text{calculated anode paste consumption, lb/kAh}$$

where B = binder content in the green mix, wt %

y = binder coke yield = (% coking value of pitch/100) + 0.10

The calculated consumption data were corrected for carbon consumed by air oxidation. This was based partly on measurements and partly on estimates and ranged from 2 to 7% for the different anodes. A correction for carbon consumed by secondary reaction with carbon dioxide was not made as this is not beleived to be appreciable.

The calculated laboratory consumption figures are plotted versus plant consumption data in Figure 8. With one exception the points fall on a straight line indicating a good correlation between the laboratory and plant data. The laboratory consumption results are however 3.7% higher than the plant consumption figures. It might be that the coke yield values used in converting percent baked anode consumption to lb paste per kAh are too low. Another possible explanation for the discrepancy is the faster baking in the laboratory which under laboratory conditions might result in a higher rate of baked anode consumption. Still another plausible explanation might be current leakage in the plant through points or lumps of carbon under the anode. It is also possible that high-temperature baking at anode effects decreases the overall consumption rate in the smelters.

The unusually high plant consumption figure for S-1 paste is attributed to the unfavourable aggregate size distribution which resulted in poor physical properties of the operating anode and consequent mechanical losses. Test electrodes prepared with the paste samples gave low compressive strength, high air permeability, high electrical resistivity and high rate of air oxidation.

Review of Mechanisms of Anode Consumption

Several possible mechanisms have been proposed in the literature for anode carbon consumption in the electrolytic production of aluminum.

It has been suggested that an interaction exists between the two components in the aggregate-binder binary system and the porosity and

TABLE IV

Laboratory Anode Consumption Data Obtained on Samples of Soderberg Paste from Different Smelters

Aggregate size distrib. See Fig. 7	Type of anode	Type of coke (1) aggregate	Coal-tar pitch binder content %	Baked anode consumption (2) %	Calculated anode paste consumption (3) lb/kAh
S-1	VS	SPC	29.5	132.8	0.360
S-2	VS	DPC	31.6	129.4	0.359
S-3	VS	DPC	33.5	127.3	0.350
S-4	HS	DPC + FPC	27.2	123.0	0.336
S-5	HS	DPC	28.1	128.0	0.368
S-6	HS	SPC	30.9	128.9	0.359
S-7	HS	DPC	33.2	129.3	0.362

(1) DPC = Delayed petroleum coke; FPC = Fluid petroleum coke; SPC = Slot-oven pitch coke

(2) Percent of theoretical corresponding to primary formation of CO_2; includes 2% air oxidation

(3) Corrected for air oxidation

thermal expansion of the aggregate greatly affect the microporosity of the binder coke which develops during baking.(5) The microporosity, in turn, determines the dusting tendency of the anode. It was shown that the low binder coke microporosity in the anode gives little dust formation and low anode carbon consumption.

Several investigators postulate that the mechanism of electrolytic consumption is similar to the mechanism of the carbon-carbon dioxide gas reaction, thus the weight loss and amount of dust which results in the latter may be taken as a measure of electrolytic consumption and dusting. (6,7) By careful selection of temperature, gas flow, reaction time, and sample dimensions, the authors established conditions similar to those prevailing in a reduction cell, and recommended the carbon dioxide gas reaction for the study of factors affecting anode consumption.

It is generally accepted that excess carbon consumption and dusting in reduction cells is the result of selective oxidation in the anode. The binder coke being the more reactive component of the anode oxidizes more rapidly, causing the aggregate (petroleum coke) particles to erode from the anode face. It has been confirmed experimentally that carbon particles collected from the surface of the electrolyte consist exclusively of aggregate coke.(1) This suggests that excess anode consumption and dusting can be reduced by decreasing the inhomogeneity of the anode mass, preferably by improving the crystallite structure of the binder coke. The above also implies that excess consumption can be reduced by increasing the amount of binder coke in prebaked anodes for a given bulk density of the dry aggregate. While the latter method is obviously limited by pitch exudation of the formed anode block, further improvement is possible through the use of pitch binders with high coking yield. In addition to the above, more nearly homogeneous anodes with more uniform crystallinity and reactivity may be obtained by several other means, such as high baking temperature or the use of additives.

Most of the effects on anode consumption reported here can be explained by the selective oxidation mechanism. Some of the results such as the effect of coke bulk density and use of fluid coke, however, indicate that structural properties of the aggregate coke might be a contributing factor to electrolytic consumption. It is conceivable that some erosion of the aggregate coke particles occurs during electrolysis which is governed by such properties of the particles as porosity and cell wall structure. It would appear that high bulk density, low porosity, or a very dense cell wall structure consistent with a desirable reactivity may reduce the electrolytic consumption (dusting) by about 4%.

Experimental work carried out at Alcan R & D has not resulted in an acceptable correlation between microporosity or carbon dioxide reactivity and direct electrolytic consumption. It is concluded that the latter is the most reliable measure of anode performance in the laboratory which correlates well with anode consumption in reduction cells. It should be remembered that the laboratory anode consumption test measures the electrolytic consumption only. In addition to this carbon is consumed in

TABLE V

Break-down of Total Baked Consumption for
Soderberg and Prebaked Anodes

(Typical Figures)

Item	Soderberg HS lb/kAh	HS % of F	Soderberg VS lb/kAh	VS % of F	Prebaked 1100°C baking temperature lb/kAh	Prebaked % of F
Faraday consumption	0.247		0.247		0.247	
Excess electrolytic consumption or dusting as determined in the laboratory cell (corrected for air oxidation)	0.065	26.3	0.065	26.3	0.031	12.6
Excess carbon consumption due to CO permeation (estimate)	0.004	1.6	0.001	0.4	0.005	2.0
Excess carbon consumption due to air oxidation	0.018	7.3	0.005	2.0	0.031	12.6
Total baked carbon consumption	0.334	35.2	0.318	28.7	0.314	27.2

reduction cells by other mechanisms such as secondary reaction with carbon dioxide and air oxidation. It is estimated from permeability measurements on core samples of production anodes that carbon consumed by the carbon dioxide reaction would be in the vicinity of 1.5% and 0.5% of the electrolytic consumption for 60kA, 50 inch wide HS and 120kA, 100 inch wide VS Soderberg anodes, respectively. Based on measurements and estimation air oxidation is believed to be 1 to 2% in VS, and 4 to 7% in HS anodes. Only indirect indication is available of the air oxidation of prebaked anodes. Core samples taken from anodes baked in a ring furnace at 1100°C and used in a plant-scale test gave a laboratory electrolytic consumption of 0.278 lb/kAh after correction for air oxidation. This was in excellent agreement with results obtained in laboratory test electrodes baked to the same temperature. The plant consumption result for the group of anodes was 0.314 lb/kAh. It is assumed that the difference is due mostly to air oxidation. Carbon consumed by the carbon dioxide reaction was estimated to be between 1.5 and 2% of the electrolytic consumption. Table V shows the breakdown of total baked carbon consumption for Soderberg and prebaked anodes based on the above data.

Conclusion

Significant improvements have been effected in the laboratory electrolytic anode consumption by using high bulk density coke and fluid coke in the aggregate, relatively low calcination temperature, high softening point pitches, relatively coarse aggregate size distribution with optimum binder content, high baking temperatures in non-oxidizing atmosphere, and by additions of aluminum metal chips, sulphur, or boron oxide to paste. The use of low reactivity, high-temperature coke, anode butts or scrap cell lining, addition of alumina, cryolite, or sodium fluoride to paste, and the use of low forming pressure and oxidizing baking temperature for prebaked anodes were detrimental. Most of the results can be explained by the selective oxidation mechanism of the binder coke in the anode. Many of the factors found to affect anode consumption have been tested in the plant. Laboratory and plant consumption data have been found to correlate well, thus it is concluded that the laboratory electrolytic anode carbon consumption test satisfactorily predicts the performance of the carbon for reduction cell anodes.

Acknowledgment

References

(1) Hollingshead, E.A., and Braunwarth, V.A., "Laboratory investigation of carbon anode consumption in the electrolytic production of aluminum", Extractive Metallurgy of Aluminum, Vol. 2, 31-50, Interscience Publishers, New York, 1963.

(2) Lewis, R.A., "Design and operating of experimental 10 kA scale cells for aluminum reduction process research and development." AIME Operating Metallurgy Conference, Philadelphia, December 1966.

(3) Harvey, P.R., and Van Dyne, L.A., "Effects of operational variables on the physical properties of baked anodes," AIME Annual Meeting, Chicago, February 1965.

(4) Hildebrandt, R.D., "Carbon and coke aggregates in relation to aluminum cell anode quality." AIME Annual Meeting, Washington, February 1969.

(5) Bowitz, O.T., Eftestol, T. and Selvik, R.A. "New methods for testing raw materials for anode carbon paste." Extractive Metallurgy of Aluminum, Vol.2, 331-348, Interscience Publishers, New York, 1963.

(6) Scalliet, R., "A test of anode reactivity with carbon dioxide". Extractive Metallurgy of Aluminum, Vol. 2. 373-384, Interscience Publishers, New York, 1963.

(7) Gray, C.F. and Metrailer, W.J., "Comparative reactivities of petroleum cokes." Ind.Eng.Chem., Prod.Res.Dev., Vol. 2, No. 2, 152-155, 1963.
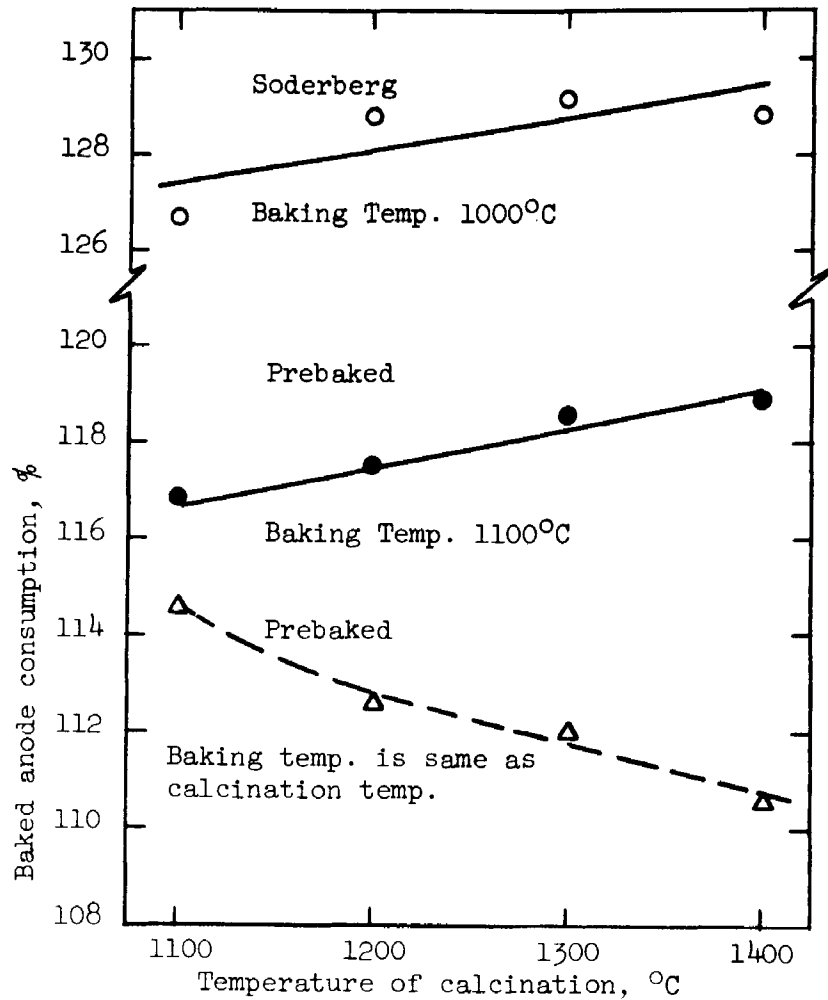
Figure 1. Effect of Coke Calcination Temperature on the
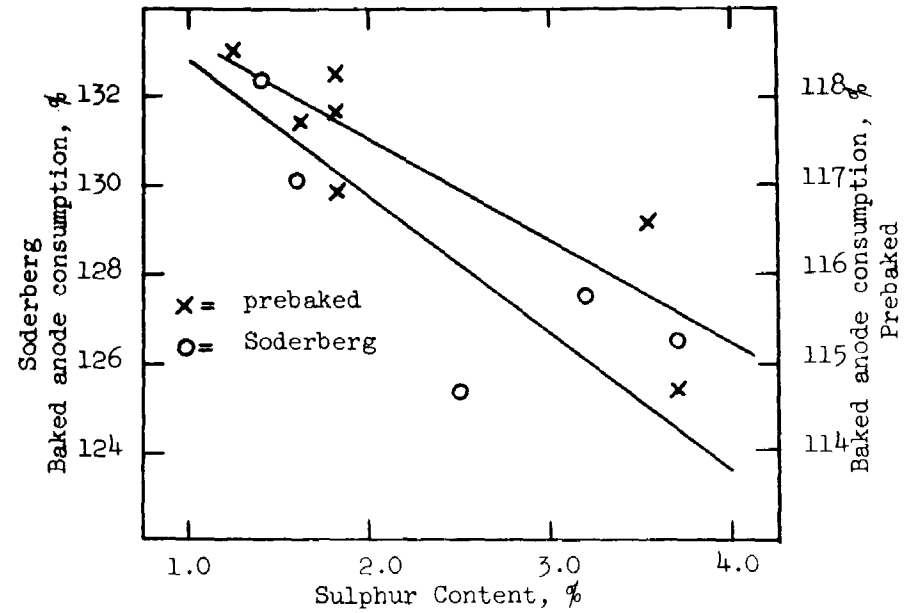Baked Anode Consumption of Test Electrodes

Figure 2. Correlation between Sulphur Content
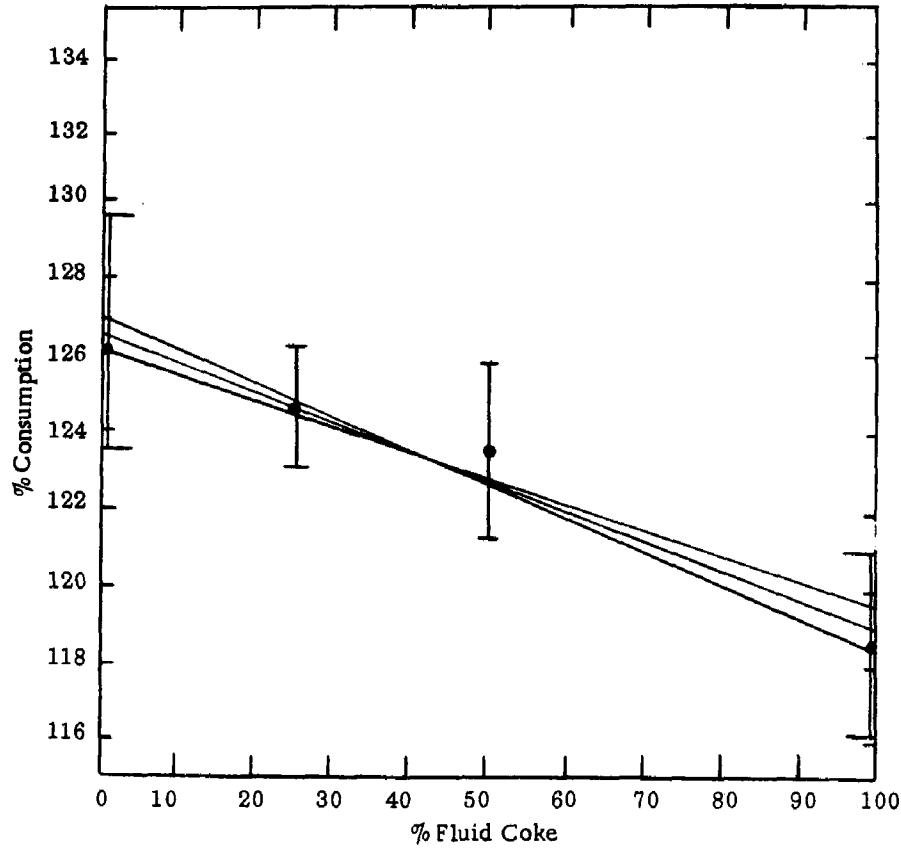of Coke and Anode Consumption

Aggregate	Crushed Butts		Rod Mill Coke			Ball Mill Coke	
Size Fractions (Tyler Mesh)	3x4	4x10	10x20	20x48	48x100	100x200	-200

A_1 = intermediate
A_2 = coarse
A_3 = fine
A_4 = hole-in-middle
A_5 = rich-in-middle

Figure 3. Correlation between Anode Consumption and Percent Fluid Coke in the Aggregate of Soderberg Paste
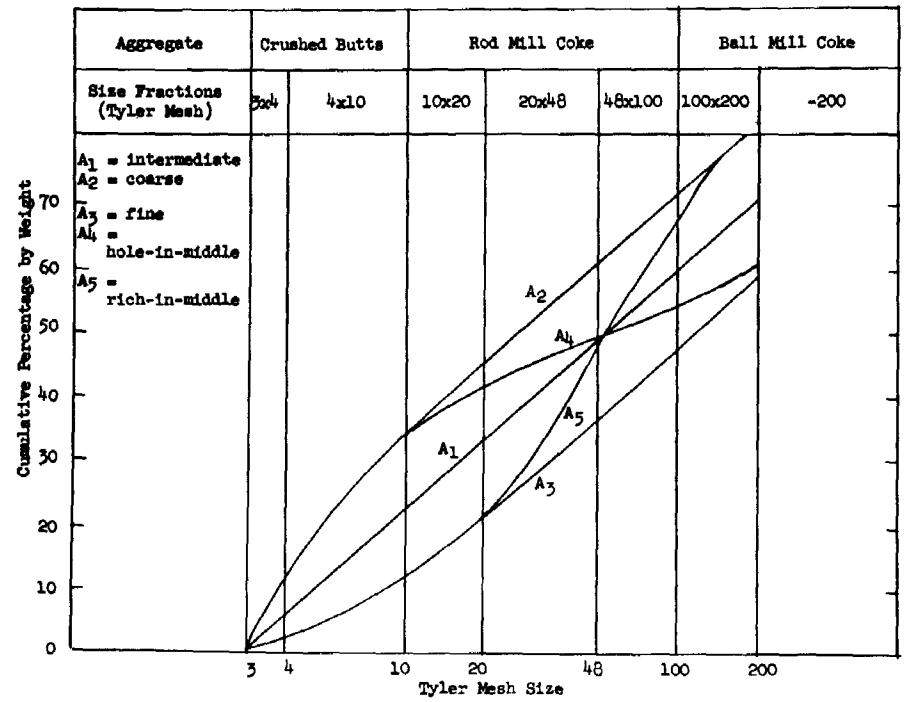
Figure 4. Cumulative Logarithmic Diagram of Aggregate Size Distributions
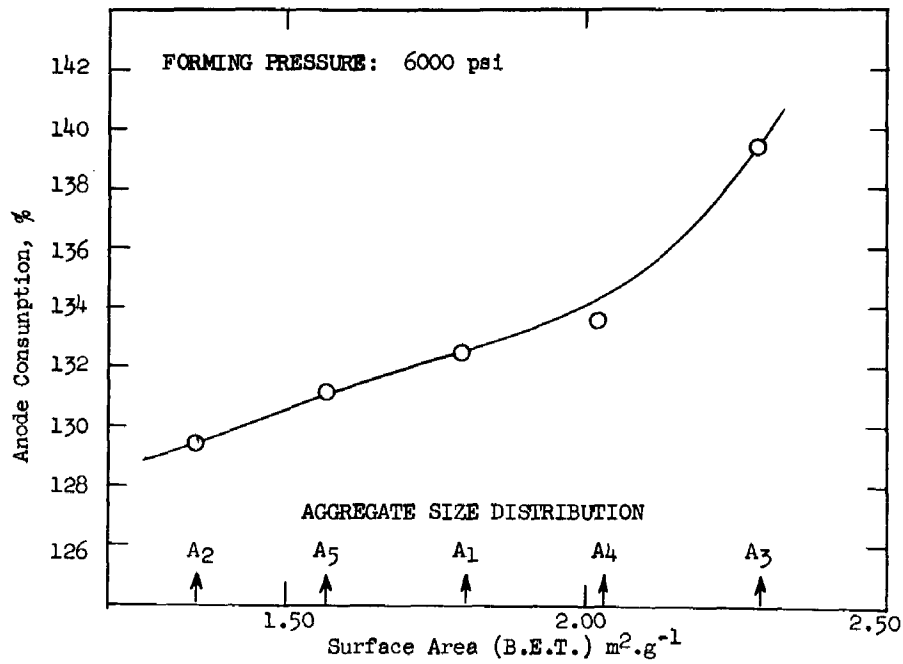
Figure 5. Anode Consumption as a Function of
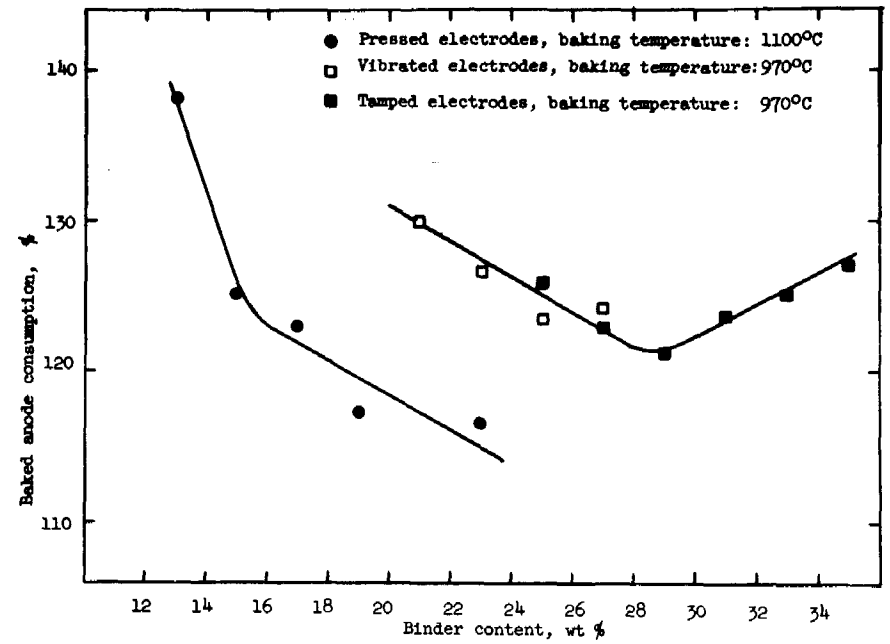Calculated Cumulative Surface Area
of Aggregate

Figure 6. Correlation between Binder Content
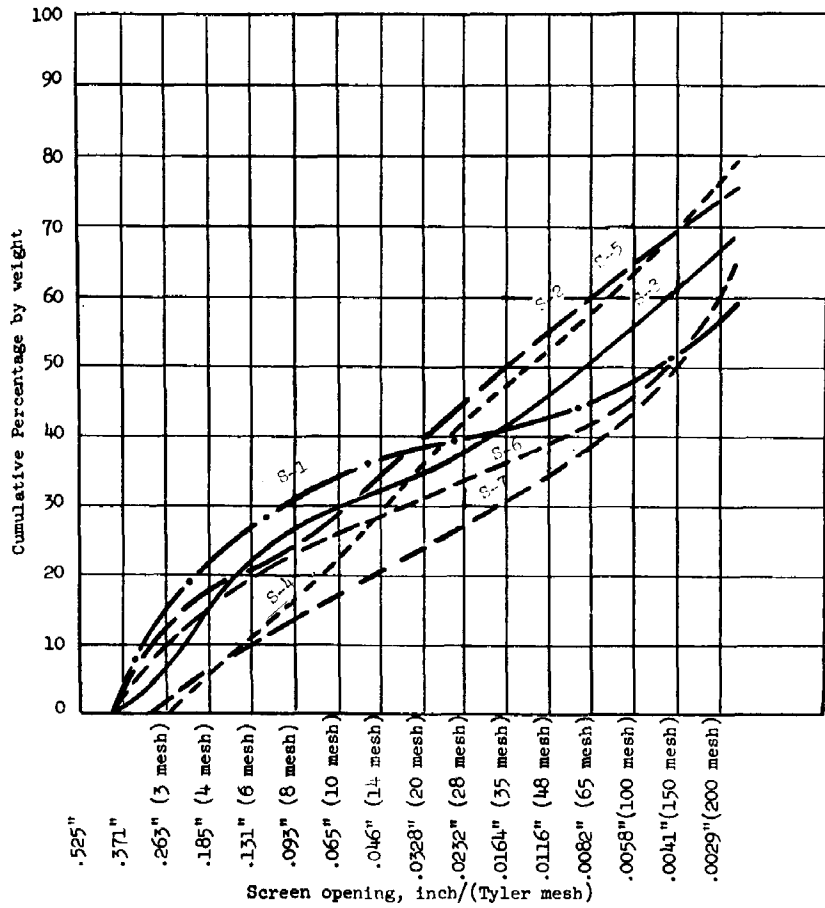of Test Electrodes and Baked Anode
Consumption

Figure 7. Size Distribution Curves of Aggregates
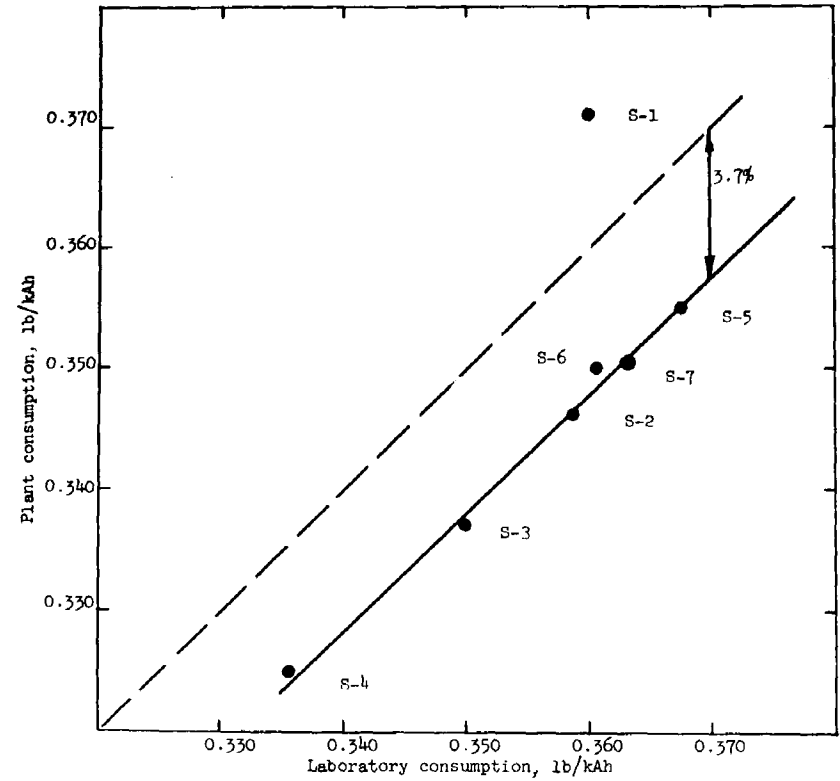Used in Soderberg Pastes

Figure 8. Correlation between Laboratory and
Plant Anode Consumption Data.
Laboratory Data Corrected for
Air Oxidation