A Method of Studying Søderberg Electrode Consumption

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Abstract

Estimate of the electrode consumption in cm/MWh (or kg/MWh) is calculated as the ratio of slightly filtered values of total slipping and energy consumption for each electrode recorded each day. To compare the consumption of the electrodes individually or in different periods of time, the standard Student's t-test is used. Data within a period of about three months are included in the tests.

Control charts for individual values, covering two different periods of time, are supplied as a visual check of the consumption in the two periods.

The new method is used to study the quality of different types of electrode paste. Practical use of the method in full-scale tests is presented.

Introduction

Electrode performance is closely connected to and a very important part of the smelting furnace operation. An extensive effort has therefore been made to ensure a simple and safe operation of the selfbaking Søderberg electrode.

In the following survey, the work concerning improved electrode performance has focused on important regions of the electrode. The regions have been selected by the methods and possibilities of investigations, the temperature being the most important factor:

- 50 to 300°C are the temperatures of the region where the solid electrode paste is liquefied and gradually heated before the baking. Temperatures inside the electrode as well as at the boundaries can easily be measured. Simulation of the paste softening can also be made with models in the laboratory. Therefore, in most cases the softening is regulated, and an acceptable soft paste quality is obtained in the upper electrode part.

- 300 to 500°C are the temperatures of the so-called paste baking zone. In many electrodes the position of the baking zone has been measured. Using computer simulations with mathematical models the baking can easily be controlled (Ref. 1), especially if an on-line computer is used for furnace control. Soft paste breakage will very seldom occur.

- 500 to above 1600°C are the temperatures of the baked or solid electrode part conducting the electric current. The electrode materials are exposed to thermal stresses, which may cause a breakage in the baked part of the electrode. Hard breakages probably constitute the most common electrode problem. As the load on electrode materials in these conditions can not be measured, mathematical models compute thermo-mechanical stresses (Ref. 1, 2). Data from furnace shut-downs have been statistically treated and procedures for transient electrode conditions worked out.

- 1600 to above 3000°C are the temperatures at the electrode tip, somewhat dependent on the smelting process. In this region, most of the electrode consumption takes place, mostly reflected by the electrode slipping. Consumption mechanisms and causes are difficult to investigate and little material has been published. Some research has been carried out, however, and a short review of the results is given in the next chapter.

The goal of the present paper is to present a suggested approach to Søderberg electrode consumption, where the consumption of each electrode is estimated based on the slipping and energy consumption. A statistical treatment is an important part of the study to compare estimated consumption figures. The method is used to study how different electrode pastes influence the consumption.

Electrode Consumption Studies

Previous Studies

At the smelting furnaces the electrode consumption is observed on a daily basis. The normal procedure is to register the slipping more or less continuously, and then calculate the consumption as cm or kg electrode paste per MWh. If MWh per electrode is recorded, the consumption per electrode may be calculated. However, the figures most commonly reported are the total consumption in cm or kg paste per MWh. The total consumption in kg paste per ton of product is also a common value.

The electrode material is a relatively expensive carbon source. Consumption data collected from various furnaces indicate that there may be a large potential at some plants if an optimal electrode consumption can be obtained. To point at clear connections between the consumption and the actual parameters is therefore of great interest and is discussed in the following.

There are several consumption mechanisms depending on the smelting process, and if the usage takes place at the electrode tip, the surface or as a breakage, or splitting of the column.

The consumption may also be retraced to several causes:

- Operational furnace conditions (carbon stoichiometry, raw material segregation, etc.)
- Electrode conditions (current load and variations, furnace shut-downs, etc.)
- Electrode paste quality (physical properties, carbon reactivity, etc.)

A modern smelting furnace is normally characterized by good electrical control. During stationary operation the electrode current (or resistance) and the total furnace power are kept quite constant. However, to change electrical parameters over a period of sufficient length to study their influence on electrode consumption is hardly permitted in any plant.

During furnace operation the other parameters mentioned above will vary, more or less uncontrolled, and in many cases several factors change simultaneously. Even if the weighing of raw materials is rather accurate, variation in moisture content and chemical analysis as well as segregation may cause internal operational variations in the furnace. Therefore, it is difficult to study the effect of the various consumption parameters and literature on consumption, in particular the Søderberg electrodes, is rather scarce. However, some relevant results are reported:

- Vorob'ev and Zhuchkov (Ref. 3) have studied a 14.5 MVA SiCr-furnace with 900 mm diameter electrodes and found how the electrode consumption depended on electrode diameter and density, charge stoichiometry and electrical power.
- Westly (Ref. 4) has studied total consumption figures from a series of Si and FeSi-furnaces and found relations between consumption and certain electrical parameters.

New Consumption Studies

Elkem Carbon is a major producer of Søderberg electrode paste, but the company is also working on improving electrode performance. Therefore, one investigation has focused on developing a method of determining how different paste qualities affect electrode consumption. Laboratory tests of the paste are of course carried out. Thermal shock resistance, segregation tendency, and reactivity measurements give important information, but full-scale tests in industrial furnaces are necessary for the final conclusions.

When testing a new type of electrode paste, the plant may charge the test paste to all electrodes in the furnace for a period of time. The total consumption will then be compared with the "standard" paste during a new test period (or with old operational numbers). Reliable results are not obtained as the furnace and electrode conditions normally will vary too much during the two test periods.

Even if the two paste types are charged to two different electrodes in the same furnace and during the same period, the electrodes may behave differently and any difference in consumption may be due to other internal conditions in the furnace. One electrode may be close to the tapping hole, another to the stack or influenced by segregation of the furnace raw materials.

The present method developed by Elkem reduces these uncertainties to a minimum:

- One paste type (the test paste) is charged to one of the electrodes, while another electrode, charged with another paste (the standard paste), is used as a reference. This is done at the same period of time.
- To eliminate possible individual electrode effects, caused by the position in the furnace, the paste being charged to the two electrodes will after two to three months be exchanged.
- Total testing time lasts four to six months, somewhat depending on the furnace conditions. The third electrode may also be included in the test.

To measure the consumption a special procedure is applied, which makes it possible to use a standard statistical method to compare consumption numbers.

Recording Consumption

The only practical way to obtain an estimate of the electrode consumption is based on measurement of the electrode slipping. Over a reasonably long period of time the electrode usage in cm must approximately correspond to the slipping of the electrode. Approximately because the length of an electrode below the contact clamps or the electrode holder is unknown and may vary as much as plus or minus half a meter.

It is generally accepted that the electrode consumption is proportional to the energy consumption, and a reasonable measure of

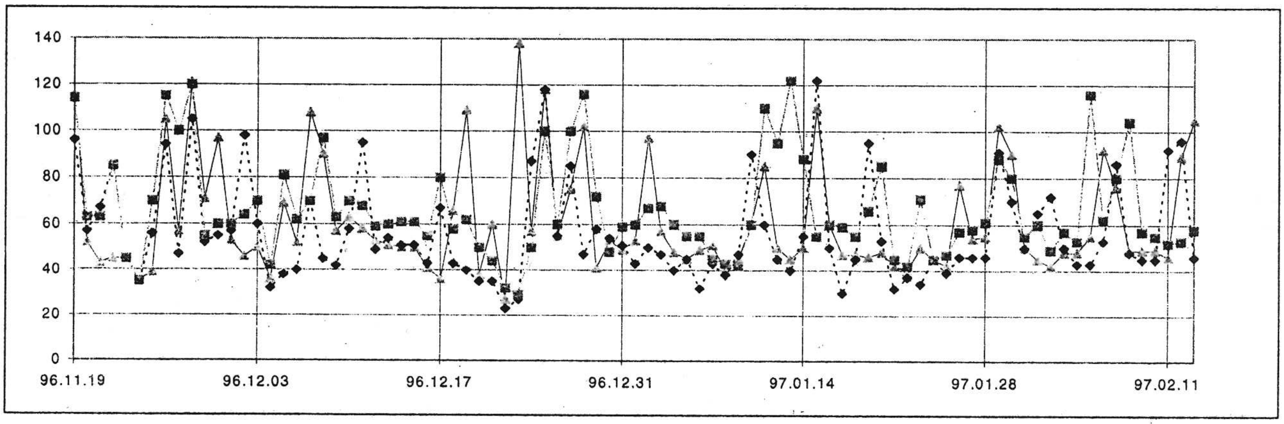

Fig. 1. Electrode slipping recorded each day

electrode consumption may then be expressed in cm/MWh. In addition to slipping, it is therefore required to measure the energy consumption of each electrode.

Electrode consumption is also related to the density of the electrode paste. In any case, since the paste is bought according to weight, it is of interest to compare the consumption in kg/MWh. Therefore, if electrodes of paste with different density are to be compared, consumption given in kg/MWh is used. This unit is not directly dependent on the electrode size, and may therefore more readily be used to compare the electrode consumption of different furnaces.

Electrode consumption is frequently given as kg/ton (kg paste per ton furnace product). This is a commercial measure and is not suitable for comparing the consumption of individual electrodes.

Slipping of electrodes is in principle used to compensate for the electrode usage. However, the electrode consumption is not exactly known, and over some time even a small error accumulates and causes electrode length variations. Too low slipping rate will give short electrodes, and due to the electric control the electrode holder will move down and vice versa for too high slipping. The slipping rate is therefore adjusted either automatically or manually by the operators, to maintain the holder in a reasonable midrange position.

Unfortunately other conditions than high or low slipping influence the holder position. The variation in daily slipping is probably more influenced by the operating conditions in the furnace itself than by actual variations in electrode consumption. The slipping therefore shows rather large variations from day to day or even from week to week. This is clearly illustrated in Fig. 1, which shows the recorded slipping per day for the three electrodes of a ferrosilicon furnace over a period of nearly three months.

CALCULATING CONSUMPTION

Total electrode slipping and energy consumption are measured rather accurately. The ratio of these two figures over a period of some months will give a value for the consumption i cm/MWh. This method gives a single value for the consumption, and no information in the recorded data is used to determine the accuracy of the calculated figure. Therefore, another approach is used to estimate the consumption.

A value for the consumption is calculated for each day. However, to reduce the effect of the extreme values for slipping that sometimes occur, a common exponential filter (EWMA- Exponential Weighted Moving Average) is used on the daily recorded data for slipping and energy consumption for each electrode. A value for "electrode consumption" in cm/MWh is calculated for each day as the ratio of the filtered values for slipping and MWh. The estimate of the consumption during the period is the average of the daily values in the period. The variations in these values (the standard deviation) may then be used to estimate the accuracy of the consumption figure.

Actually the procedure is only correct (equal to the ratio of the total values for the period) if the MWh values are constant each day. During normal operation the variations observed are rather small, and the error made is negligible. However, during two to three months of operation, the furnace may be shut down for shorter and longer periods. Low MWh-values may be observed and even slipping during shut-down periods. To avoid too extreme daily values, a certain preparation of the daily data is made before filtering:

- Days with no operation (both slipping and MWh equal zero) are rejected.
- Days with very low MWh-values are also left out, but the slipping and MWh-values are added to the values from the previous or next day.

The calculation of a daily "electrode consumption", based on the prepared data, is as follows:

$$\overline{S}_i = \alpha \cdot S_i + (1-\alpha) \cdot \overline{S}_{i-1} \qquad (1)$$

$$\overline{E}_i = \alpha \cdot E_i + (1-\alpha) \cdot \overline{E}_{i-1} \qquad (2)$$

where

S_i - *recorded slipping in cm on day i*

E_i - *recorded energy consumption in MWh on day i*

α - *filter constant*

$\overline{S}_{i-1}$ and $\overline{E}_{i-1}$ mean filtered values on day *i-1*.

A suitable value for the filter constant is found to be 0.5, which corresponds to an averaging over three days. To minimize any effect due to a high or low initial value, the value for day 1 is taken to be the average of the first three days.

F_i, the "electrode consumption" in cm/MWh on day *i*, is then calculated as

$$F_i = \frac{\overline{S}_i}{\overline{E}_i} \qquad (3)$$

An estimate of the consumption during the period is taken to be the average of the daily consumption figures, F_i. However, to further avoid any initial effects due to filtering, the first five values are not included in the calculated average.

COMPARING ELECTRODE CONSUMPTION

Student's t-test

To determine if there really is a difference in consumption between two periods (or two electrodes), the natural variations in the estimated consumption figures must be taken into account. Different statistical methods may be used, but for our purpose the Student's t-test has been selected.

The Student's t-test is a standard statistical method to determine whether the average values of two data series are significantly different. The risk of making a mistake when concluding that there is a significant difference, is given as the significance level. A commonly used value is 5%. The Student's t-test is described in most introductory books on statistics.

Referring to the "Summary and Conclusions" sheet shown in Fig. 5, a very short explanation of the figures presented is necessary. The table at the top shows the comparison of the consumption in two different periods for three electrodes. The "Average difference" is the difference between the estimated consumption, kg/MWh, for the first and second period. Based on the variations in the daily values and the number of days within each period, it is possible to calculate the probability that the average difference might be obtained, even if the real (true) consumption has not changed between the periods. This "Probability" is given in the next column. Since the probability is less than 5%, ("Level of significance"), the conclusion is that there is: "Significantly less consumption in the first period". For the other two electrodes the probability is larger than 5%, and the conclusion is then: "No significant difference".

It should be noted that even if the conclusion of a comparison is that no significant difference exists, this is not necessarily true; however, based on the available data and the given significance level, it is not possible to discover any difference. The risk of making this type of mistake is larger than the significance level of 5%.

The possibility of distinguishing between the consumption of individual electrodes, depends on how large the real difference is, the number of observed values, and on the variations observed in the daily consumption values, i.e. the standard deviation. The smaller the variation and the more values that are included, the better the sensitivity of the test.

Control Chart from Statistical Process Control

To compare the electrode consumption of one electrode within two different time periods another method is to use a control chart. Data from the first period is used to calculate the average value, and the control limits and the data from both periods are plotted on the same chart.

An example of a control chart of this type is given in Fig. 2. There are standard rules to determine if the "process" (the consumption) is in statistical control, i.e. that no real changes have occurred. Using these rules, the consumption values do not show statistical control in any of the periods. This makes the comparison of the consumption within the two periods less reliable. However, it may be assumed that the electrode consumption in the 2. period is larger than in the 1. period. Most of the points in the 2. period seem to be above the average value (from the 1. period). However, the conclusion based on the control chart in this case requires a certain measure of personal judgment.

At furnaces where the slipping is more consistent, the daily consumption values will show better statistical control, and a more standard interpretation of the control charts may be used.

A PRACTICAL EXAMPLE

Furnace Test

The described method has been used for experimental runs on smelting furnaces. In the following example, results from a test of a new type of electrode paste, based on different raw materials, are presented. The furnace used produces 75% ferrosilicon and the electrode diameter is 1.7 m. The experiment was run over more than six months. During the first three months electrode 1 was charged with the new paste, while electrode 2, selected as a reference, was charged with the standard paste. After about three months the charging of paste was switched and electrode 2 received the new paste and standard paste was charged to electrode 1. Standard paste was used for electrode 3 throughout the experiment. Slipping and energy consumption for each electrode were recorded each day during the experiment.

A short period at the start of the second period was discarded because of operational problems with the furnace. Obviously the initial days in each of the two periods, before the new paste had reached the electrode tip, were not used.

During the experimental period the furnace was operated at about 40 MW and with the electrode current around 130 kA. The operation of the furnace was reasonably good, but some shut-downs of notable length were encountered. The data have therefore been prepared as explained earlier, by removing days with zero values and combining days with low energy consumption. This leaves two periods of data to be used as basis for the method:

1. period:	96.11.19	to	97.02.13
2. period:	97.03.10	to	97.06.04.

To simplify the use of the method an Excel program has been developed. The program compares the electrode consumption, expressed in cm/MWh as well as in kg/MWh. This is done for the three individual electrodes within each of the two periods and the consumption of each electrode within the two different periods. The input data used consist of the date and the daily recording of the slipping in cm and the energy consumption in MWh per electrode for the two periods. To calculate the consumption in kg/MWh the electrode diameter and the density of the electrode paste must be entered manually as well. The input data from each period are copied into separate Excel-sheets, and all required calculations are included in the program.

The main output of the program, showing the results of t-tests performed and some characteristic values of the data from the two periods of the experiment described above, is shown in Fig. 5. The density of the new paste is measured to be 1610 kg/m^3 and for the standard paste 1575 kg/m^3. The consumption is therefore expressed in kg/MWh. A corresponding sheet with the consumption in cm/MWh is also available. In addition, control charts for the consumption of each electrode like the one in Fig. 2, are also available, at present only for consumption in cm/MWh.

Comparing Consumption within Different Periods

A printout showing a summary of result and the conslusions from the program is shown in Fig. 5. The Student's t-test is first used for comparison of the consumption of each electrode within the two periods. The result of this test is shown in the first table.

The difference in electrode consumption between the first and second period for electrode 1 is -1.12 kg/MWh, and at 5% significance level there is significantly less consumption in the first period, when the new paste was used.

For electrode 2 the corresponding difference is +0.40 kg/MWh. The calculated average consumption is less within the second period, during which the new paste was used. Compared to the first period this difference is not large enough to be significant and may have occurred only by chance. The test so far is therefore not fully conclusive concerning the consumption of the test paste compared to the standard paste.

Electrode 3 contained standard paste during both periods, and no significant difference in consumption is neither expected nor observed.

Comparing Consumption of Different Electrodes

The second table in the summary sheet shows the compared results of individual electrode consumptions within the first period. Electrode 1, with the new paste, compares favourably with electrode 2 as well as electrode 3, both with the standard type of paste.

The results from the second period, given in the next table in the summary sheet, also show significant difference between the consumption figures for the new paste in electrode 2 and the two electrodes with the standard paste. No significant difference is observed between the electrodes with standard paste in any of the periods.

The table at the bottom of the summary sheet in Fig. 5 shows some characteristic consumption values. The average value from both first and second period yields about 10% lower consumption for the test paste as compared with the reference.

USE OF CONTROL CHARTS

Control charts showing the consumption of each electrode, give a visual impression of the variation of the consumption during the test periods. The average value and the control limits are based on the data from the first period. The control chart shown in Fig. 2 shows the electrode consumption in cm/MWh for electrode 1. The corresponding charts for electrode 2 and 3 are not shown. The chart in Fig. 2 is far from being in statistical control, probably because of changing furnace conditions and inconsistent slipping routines.

To decide whether there is an average difference in consumption between the two periods, must necessarily be more or less subjective. It may appear from the chart in Fig. 2 that the consumption is higher in the 2. period. This observation does agree with the conclusions made from the t-tests above.

DISCUSSION

The basic theory behind a Student's t-test assumes that the observed data (within each period) are normally distributed and mutually independent. However, the t-test is a rather robust test, which means that it is not very sensitive to moderate deviations from the normal distribution. This is fortunate when testing the electrode consumption data, because these data in many cases show such deviations. This can be seen in the control chart in Fig. 2. Normally distributed data should in general show statistical control, especially no values should be outside the control limits.

Another way to check if data are normally distributed is to use a normal score plot of the data. In Fig. 3 and 4 two examples are shown. In a normal score plot, normally distributed data should fall approximately on a straight line. In Fig. 3 data taken from a normal distribution is plotted to show how an approximately straight line may look like. Fig. 4 shows the consumption data for electrode 1 from the first period in our example. There are clear deviations from a straight line. However, compared to the normally distributed data in Fig. 3, it may be fair to classify the deviation from a normal distribution as moderate.

When performing statistical tests, it is not unusual to exclude single data which clearly falls outside the normal distribution, so called outliers, because they are assumed to be the result of some measurement error or some special situation not relevant to the test. Outliers may be found in electrode consumption data. For instance if long or forced slipping is applied, this may give a very large daily consumption. Extraordinary elongation may be used after an electrode breakage (see peaks in Fig. 2) or to compensate for too low slipping over some time. Exclusion of such data will of course be a mistake when comparing consumption data. Extreme values may, however, be reduced by adding slipping- and MWh-values for two or more days, but no values recorded should be excluded.

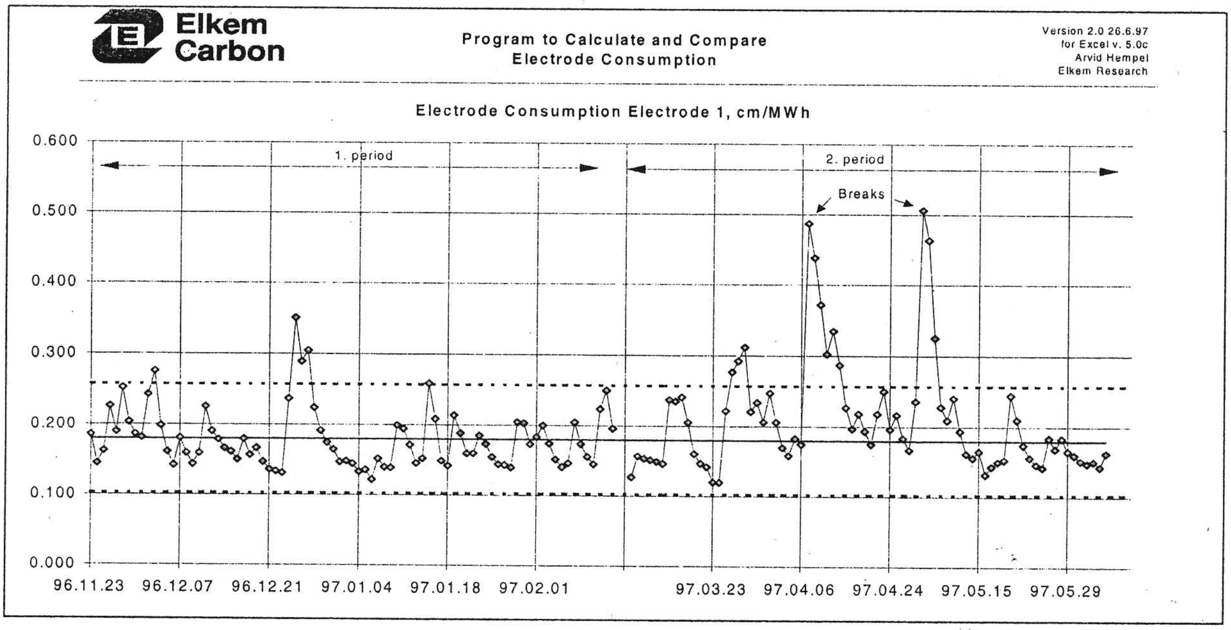

Fig. 2. An example of a control chart covering two test periods

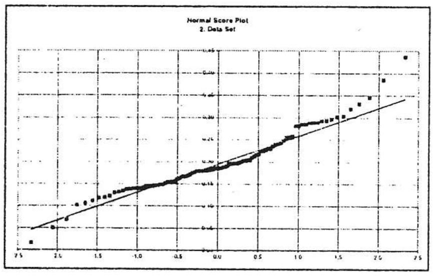

Fig. 3. Normal Score Plot
Data from a normal distribution

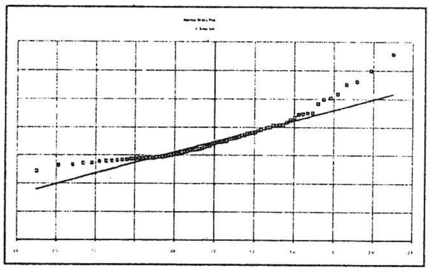

Fig. 4. Normal Score Plot
Electrode consumption data, cm/MWh

If the consumption data contain many large values, they will increase the standard deviation of the data set. The main effect of this is that the test will be less sensitive and not be able to detect a small real difference in consumption. During a test period the slipping procedure should therefore be consistent, and as far as possible follow the energy consumption of the furnace.

To apply the t-test to compare electrode consumption some care should be taken. The data should be collected from periods of at least two months, preferably longer, with a reasonably stable furnace operation, or more specific with not too many extreme daily values for the consumption.

There may be statisticians that will have objections to the method. However, it is a pragmatic method and it has the advantage that gives a straight answer when comparing consumption figures and thus to a large degree will reduce any personal arguments about the result.

CONCLUDING REMARKS

A statistical method, based on the standard "Student's t-test", has been developed in order to study the electrode consumption in smelting furnaces. Also control charts from statistical process control are valuable tools for a visual check of the consumption.

Studies have been done, employing full-scale tests of various electrode pastes. One paste type is charged to one electrode, while another electrode charged with another paste is used as a reference. To eliminate possible individual electrode effects, the paste charging to the two electrodes will be changed afterwards. Testing lasts 4 to 6 months.

An Excel program has been worked out. The input data used are the date and the daily recording of the slipping in cm and the energy consumption in MWh per electrode for the two test periods. The three individual electrodes within each of the two periods, and the consumption of each electrode in the two different periods are studied by presenting values in cm/MWh as well as kg/MWh. A comparison between the different electrodes can easily be made.

The new method is used to study different types of electrode paste: different qualities, paste charging procedures, size of solid paste, etc. The goal is to gain a better understanding of different pastes in order to optimize the electrode performance of the specific furnace and process in question. The method can also be used to obtain a connection between consumption and actual parameters. This study, however, requires stable operation and controlled changes of both electrode and operational conditions.

Elkem Carbon — Program to Calculate and Compare Electrode Consumption — Version 2.0 26.6.97 for Excel v. 5.0c, Arvid Hempel, Elkem Research

Summary and Conclusions

Company: Elkem Ferrosilicon Plant

Comparing Electrode Consumption in Different Time Periods

Electrode consumption in kg/MWh
1. period from: 96.11.19 to 97.02.13
2. period from: 97.03.10 to 97.06.04

	Average difference	Probability for equality	Conclusion
Electrode 1	-1.12	1.3 %	Significant less consumption in 1. period
Electrode 2	0.40	14.2 %	No significant difference
Electrode 3	0.23	24.6 %	No significant difference
Level of significance:		5 %	

Comparing Electrode Consumption of Different Electrodes

Comparing electrode consumption in kg/MWh
1. period from: 96.11.19 to 97.02.13

	Average difference	Probability for equality	Conclusion
Electrode 1 and 2	-0.71	1.5 %	Significant less consumption of el. 1
Electrode 1 and 3	-1.15	0.0 %	Significant less consumption of el. 1
Electrode 2 and 3	-0.44	12.6 %	No significant difference
Level of significance:		5 %	

2. period from: 97.03.10 to 97.06.04

	Average difference	Probability for equality	Conclusion
Electrode 1 and 2	0.81	4.6 %	Signficant less consumption of el. 2
Electrode 1 and 3	0.21	63.0 %	No significant difference
Electrode 2 and 3	-0.61	5.0 %	Significant less consumption of el. 2
Level of significance:		5 %	

Characteristic values for electrode consumption in kg/MWh

	1. Period			2. Period		
	El 1	El 2	El 3	El 1	El 2	El 3
Average value	6.56	7.27	7.71	7.69	6.87	7.48
Standard deviation	1.57	2.08	1.55	2.98	1.64	2.00
Max value	12.81	15.84	12.51	18.09	10.75	14.23
Min value	4.46	4.56	5.27	4.29	4.40	4.64
Number of values	87	87	87	76	76	76

Fig. 5. Summary of results and conclusions from the program

ACKNOWLEDGEMENT

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