The New Compound Electrode: Current Situation and Thermoelectric Studies

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Abstract

The Spanish ferroalloys company, FERROATLANTICA, has been using a new type of electrode at its silicon plant since 1991. This is a compound electrode consisting of a graphite core and an external lining of Soderberg paste, extruded through a steel casing.

Since 1994 this electrode has been installed and has been working at the factories of other silicon companies. Thus, at present, it is working in three different continents, at different factories built using different technologies, and without any previous contact among themselves, which means different knowledge in all running procedures.

In this presentation we will speak about the history of the project from its beginnings, the main technical points to be taken into consideration before starting on the project and the results of the mathematical model called "Thermoelectric studies of the ELSA electrode" carried out in collaboration with Santiago de Compostela University in Spain.

The history of the project

This project was initiated in 1991 in the only furnace in production at that time at our factory. This furnace had been working with prebaked electrodes from its construction in 1976. It was and is an 18 MW furnace, with an Elkem column and is 1.2 metres in electrode diameter. The efficiency of the factory in the main parameters as electrode consumption, recovery of silicon, energy consumption per metric ton and operating time was at a high level in the sector at that time.

During the changeover and in the first years many problems of all types cropped up. Until halfway through 1993 positive results were not obtained. When they were, however, it lead to us starting up our second furnace, installing the same system in it, now notably improved technically. Since 1994 we have again got back to the same values of efficiency and production time in the furnaces as we had with the prebaked electrodes.

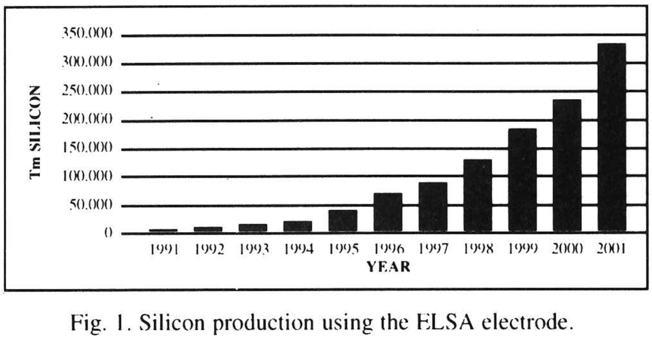

Fig. 1. Silicon production using the ELSA electrode.

Since 1994 we have sold our technology to different silicon plants around the world. There are factories of very important companies with the ELSA electrode in operation and the number is increasing every year owing to the big advantage compared to the prebaked electrode. Fig. n° 1 shows the present silicon production with the ELSA electrodes and our estimate for the coming years.

Basic principles of the "ELSA electrode"

This electrode consists of a central column of baked carbonaceous material, graphite or similar, which acts as a central mechanical support, and an outside steel casing with the same outside diameter as the prebaked electrodes currently in use in the world. A special Soderberg type paste is introduced between the central column and the casing and this flows down the length of the column until it finishes up being baked in the area of the contact clamps. A scheme is included as fig. n° 2.

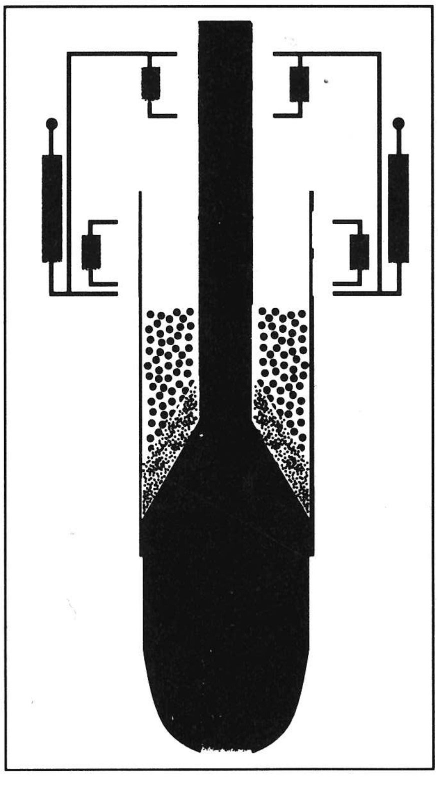

Fig. 2. Diagram of the ELSA Electrode.

Two different slipping systems exist, one for the casing and the other for the central column, and the combination of both systems is necessary so as to slip the casing as little as possible and to also carry out the correct extrusion of the carbon electrode with the central column slipping rings.

The result is that the furnace works in an identical way to that with prebaked electrodes and there is no appreciable contamination in the silicon metal. There are many small details to be taken into account to get similar results, but we can now say that the technology is sufficiently well-known and has been tested in quite different types of furnaces and factories.

The procedure is patented in all silicon producing countries all over the world.

Advantages and disadvantages using the ELSA electrode

The main advantage is the economic one. With present prices, the cost of the electrode can be reduced down to more or less a third of the cost of the prebaked electrode depending on the diameter of the latter. Simplifying with a hypothetical example, the difference in costs between the two systems could be as follows:

Prebaked electrode: 1 Tm= $ 2.250

ELSA electrode:

1 Tm graphite	$3.200
6 Tm paste	$2.820
7 Tm electrode	$6.020 → 1 Tm= $ 860

The above is the most powerful reason why we think that in the near future all silicon factories will change over to this type of electrode. On average, the cost reduction in silicon metal production is around 12-16 %. But, there are also a number of other advantages which, although not so spectacular must be taken into account.

One of these advantages, is one of logistic supply since there are many more factories in the world making graphite electrodes and Soderberg paste than those making prebaked electrodes, where transport costs have always been a major factor.

Yet another advantage is the reduction of electrode breakages normally due to long stoppages; even in the case of the special conditions which the FERROATLANTICA Sabón furnaces must run under, with six hour daily stoppages every weekday.

The major inconvenience is that, as in whichever new project, one has to learn the functioning until the necessary index of regularity is reached to be able to make high quality silicon. In our case, we can say that the testing has been very hard since there was no previous experience in the field, and the running with this new electrode has not been the same as with traditional prebaked electrodes. In this project, we have managed to change not only the new raw materials, such as Soderberg paste and graphite electrode, but also nearly all the essential elements in an electrode column such as contact clamps pressure and slipping rings, etc. However, now, with all the experience we have acquired from the different changeovers we have carried out in the furnaces at different factories of different companies, we use this experience to find the best solution to all the technical problems at the plants involved.

Another inconvenience is that the speed of slipping is not free as with a prebaked electrode since this new type of electrode evidently has to be baked, and this causes a minimum period of time between slipping. Thanks to the graphite core, it is possible to do all the necessary slipping speed at normal furnace running time, but, of course, in the case of faults, start-ups, breakages etc. one has to wait until the electrode is baked, which is almost the same as with whichever conventional Soderberg electrode.

Summing up, we should like to say that the new type of electrode is going to become very important within the very near future for economic reasons, since in the rest of the parameters and running procedures of the furnaces the advantages and disadvantages of the new electrodes against the old ones are very close and, in both cases, similar running results in the furnace and in the quality of the silicon are obtained.

Thermoelectric studies. The beginning

In order to understand the working of the electrode and to be able to adapt the technology to different diameters and working systems throughout the world, it has been necessary to study in depth the different raw materials and, in collaboration with the Applied Mathematics Department of Santiago de Compostela University (Spain), to create a mathematical model called "Thermoelectric Study of the ELSA Electrode". The following aspects have been taken into account in said study:

Paste is one of the fundamental elements in this electrode. Unlike a normal Soderberg electrode, the casing does not have fins to bake the paste more easily. The inside of the casing is absolutely smooth to allow the slippage of the electrode throughout the casing. The casing is really an extrusion sleeve of the electrode and, thus, the paste does not have any help from the casing to carry out baking. On the other hand, the transmission of heat from the furnace through the central electrode determines that the outline of the baked paste is much more conical than with a normal Soderberg electrode. This gives rise to segregation problems in the paste that have to be taken highly into account.

The baking of the paste is a crucial point in the working of this type

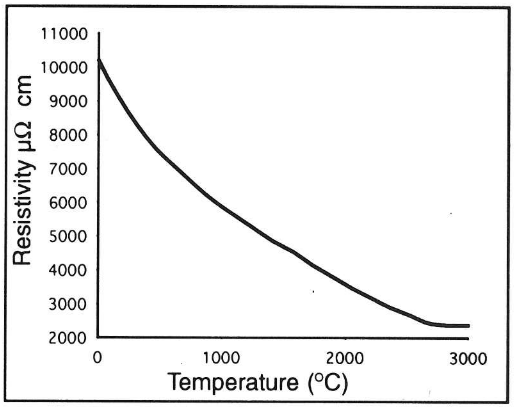

Fig. 4. Paste electrical resistivity.

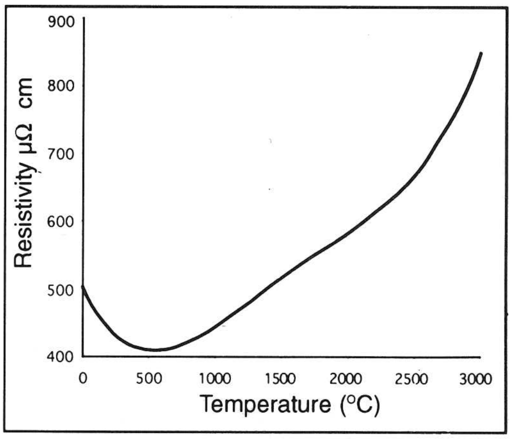

Fig. 3. Graphite electrical resistivity.

of electrode and so we considered it necessary to carry out a mathematical model of the paste baking. This is, in the ELSA electrode, different to the normal Soderberg type electrode due to its central core, and to the fact that the casing does not have fins. It was also necessary to check the results obtained with actual measurements carried out in the different furnaces in operation.

In order to know the paste baking profile temperature we have put thermocouples on the graphite and on the casing and we have done a lot of laboratory tests, studying the adhesion between paste and graphite on one hand and between paste and casing on the other.

Using the information obtained, as study data we have introduced the following resistivity curve of the paste in accordance with the temperature, where it can be seen that as the temperature increases the paste resistivity decreases.

As far as graphite is concerned, the situation is indicated by the following data where the graphite resistivity falls between 0ºC and 600ºC but after that, and because of a special property in graphite, it increases in relation to the temperature.

The paste resistivity is very high before baking and at around 0ºC can be about 20 times greater than the graphite one. This ratio of 20:1 is maintained until 500ºC. Above this temperature the ratio decreases and at 2500ºC the relationship is that the paste is approximately 3 times greater than the graphite. This is shown in figures nº 3 and 4.

Skin effect and the current distribution on this electrode

We have observed that concerning the current distribution two opposite effects take place: skin effect, which is due to alternating current, leads the current to go to the outer part of the electrode, i.e. to the paste. However, the fact that the electrical resistivity of graphite is much lower than the resistivity of paste when the temperature of the latter is below 1500º C leads the current to "prefer" the graphite. Actually, results obtained by the numerical model show that the two effects are balanced to some extent. On the other hand, as the temperature at the bottom of the electrode is about 2500º C, the resistivity of the paste approaches that of the graphite and then the skin effect is the most important one in that part of the electrode. In other words, at the tip of the electrode most of the current goes through the paste.

When we represent the vectorial fields of the electrical current we can see, a great deal of the electrical energy "prefers" the graphite and goes through the paste in said area to reach the graphite. This is a consequence of the fact that the electrical conductivity in the graphite in the area of the contact clamps is around 20 times less than that in the paste. As the current flows down the electrode the resistivity of the graphite tends to increase whilst that of the paste tends to diminish. This, together with the skin effect causes an important part of the electrical energy to go from the graphite to the paste at the bottom of the electrode. Thanks to this, the necessary areas of furnace reaction are maintained and this means that similar metallurgical results are obtained with this electrode as with prebaked ones.

We can see the results obtained in figure nº 5 which represents the distribution of the real part of the current density throughout the electrode. The most relevant aspect is the abrupt jump produced between the outer graphite surface and the inner paste surface.

It must be mentioned that the boundary conditions obtained experimentally on the electrode paste surface have been introduced into the model according to experiments carried out in the different factories where the electrode is in use.

As was to be expected, the slope of the curve of the baking of the paste is much greater than with a Soderberg-type electrode owing to the better thermal conductivity of graphite, and so the paste bakes firstly near the graphite core at an elevated height. This must be taken into account in order to avoid segregation problems.

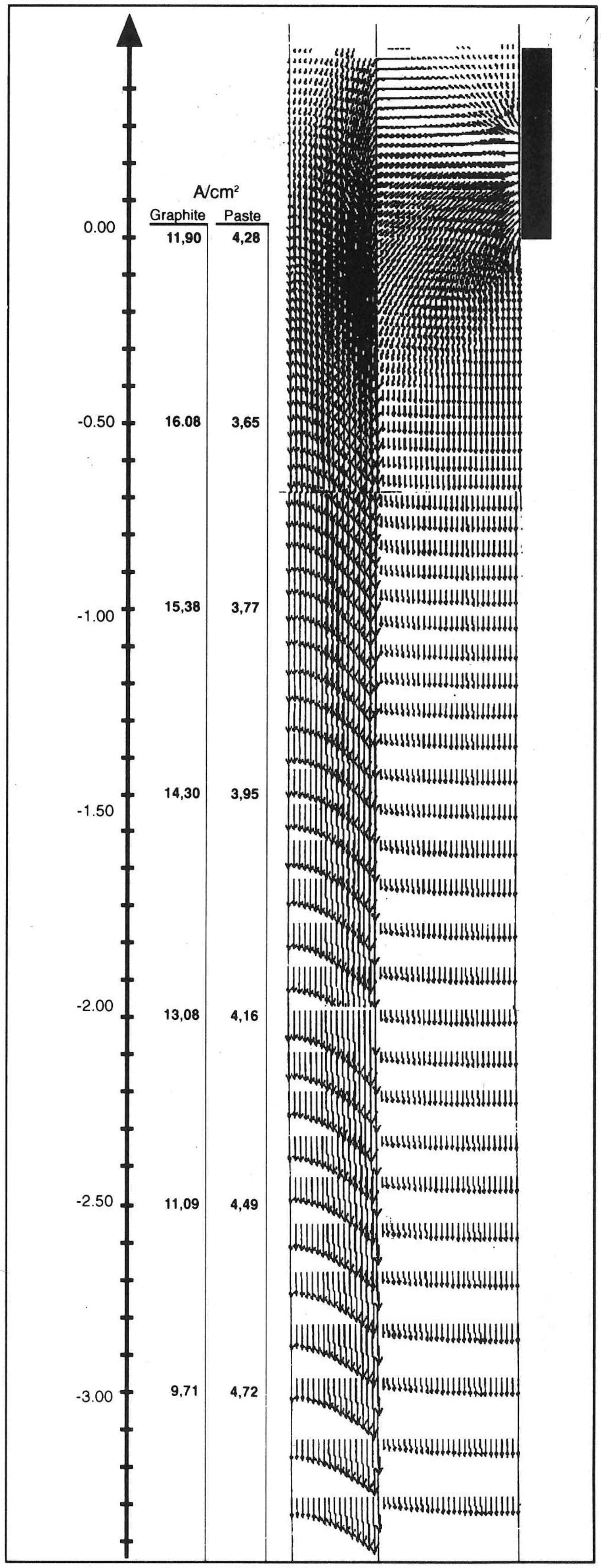

Fig. 5. Distribution of electric current.

Transient-state simulation

After having got the first results of the thermoelectric models and establishing the first conclusions, new questions arose. The slipping movement not only changes the position of the graphite but it also changes the position of the baked part of the electrode, thus deforming the temperature distribution in the electrode. However, the addition of paste to the electrode column and the part of the tip of electrode that is being burnt in the furnace are continuously changing the boundary conditions of this problem as well.

So we decided to go one step further and develop a new programme to obtain the graphic representation of the electromagnetic fields and temperatures and their variations depending on time.

In this new development, the complexity of the calculations is increased in two ways:

Firstly, as we want to estimate the time dependence of the model, we must calculate "n" stages where "n" represents the number of stages that go from the initial stage to the final transient stage, and each of these stages implies the same complexity of the stationary problem.

Secondly, some new factors appear when you want to solve non-stationary situation. The model of the transient process must be based upon the heat transmission equation, taking into account the dependence of temperature on time, and the changes produced by the movement of the electrode. A very delicate factor is to take into account the amount of energy that is consumed to change the state of the paste from the original briquettes that are put round the upper part of the electrode to the final baked electrode formed around the graphite core. This is called the latent heat.

The results of this program have been employed in three different lines of research, which are closely interconnected:

a. The slipping rate and slipping length: For the furnace operation it is also of the utmost importance, to determine which is the best slipping policy so as to keep good electrode baking but, at the same time, keeping the current and power parameters within the desired patterns. The model is a very interesting tool for daily normal operation. However, it can also be used to analyze some peculiar situations, as may be in the case of some types of breaks or any particular conditions that need immediate changes to the way the operator runs the furnace.

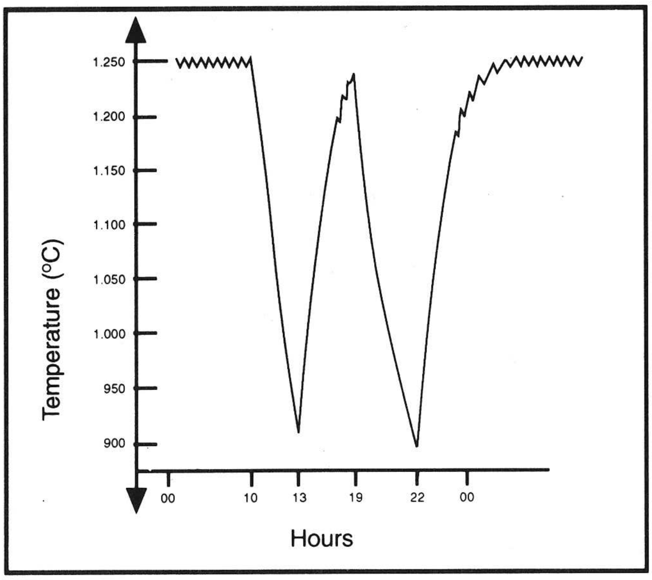

Fig. 6. Evolution of temperature in respect to time.

b. The baking rate of the paste (and consecuently the "reserve" of baked paste): According to the results of the transient model, the baking rate of the paste on the electrode has been evaluated. This finally yields a very simple equation which establishes a relationship between the height of baked paste in the electrode and the current applied to that electrode. This equation has been adjusted, employing the information taken in our furnaces. A simple linearization of this equation was also carried out and has been programmed on the PLC controlling the furnace and is working currently on-line, thus allowing the operator to know which is the amount of baked paste in each electrode.

c. In the particular case of our plant, and because of the daily furnace stoppages mentioned above, it is also very interesting to introduce these stops in the model together with the slipping pattern. The results of the model with these initial conditions are a good help to evaluate the best way to re-start the furnace after a medium-length stop, when the conditions of the furnace have changed significantly but they can still be taken back to the stationary state in a very short period of time. As can easily be inferred, such studies may be employed at any factory so as to know the furnace response after any kind of stops, no matter whatever the cause, e.g. little maintenance stops, or any kind of break-down.

The study of the mechanical stresses produced after a stoppage due to thermal expansions/contractions are also included in this model. This electrode is also peculiar in that it consists of different materials and that the support material, graphite, also supports the weight of the column. The weak points, whose study is more interesting, are the joining nipples for the different graphite elements in the column.

In the graph shown in figure nº 6 one can see the evolution of the temperature at a point on the electrode situated on the surface of the graphite and half a metre below the contact clamps which is where the Joule effect is greatest. Under the conditions of the model it can be seen that the electrode goes back to normal running conditions after stoppages. In our experience over the last few years, these stoppages do not produce breakages in the electrode.

Proximity effect of the other phases.Three-phase influence

The model referred to in the above paragraphs is axis-symmetrical.The axis-symmetry makes us neglect the so-called proximity effect; that is, the influence of the other two electrodes on the one we are studying. This effect is negligible for the conclusions we have extracted from the former models but it is very important to evaluate some other aspects of the electromagnetic behaviour of the electrodes.

When the furnaces are running normally, it can be seen that there is no axis-symmetry, but that the electrode surfaces facing the centre of the pot are those with a higher temperature. We studied the possibilities we had with mathematical modelling in order to see what the influence of proximity of the other electrodes on the distribution of the current would be and, thus, on the Joule effect.

Again, to solve the equations representing the electromagnetic fields we decided, for the sake of simplicity, to convert the model to a 2-dimensional one. The solution was to consider a cross-section of the furnace and to also make some assumptions about the direction of the current.

Once the model was programmed and tested, numerical computations were done for the ELSA electrode assuming a 3-phase system.

The results of the conclusions are shown in figure nº 7 where a lack of symmetry in this distribution of the density of the current can be seen. The greatest density of current is concentrated in a part of the electrode which curiously does not face the geometrical centre of the furnace but faces the following electrode in the same sense as the phase advance (the greatest concentration of the Joule effect is at the graphite surface).

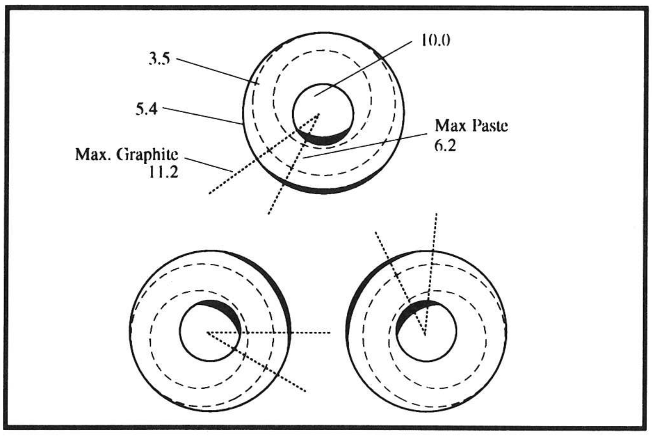

Fig. 7. Modulus of the current density (A/cm²). Three-phase current (anti-clockwise).

As a scientific curiosity, we wanted to get the results of the model where a single-phase current was introduced. In this case it could also be seen that there was a loss of cylindrical symmetry within each column but, on the other hand, it was perfectly symmetrical facing the furnace axis, the greatest amount of current being concentrated at the side of the electrode facing the outside of the furnace. These results can be seen in figure n° 8.

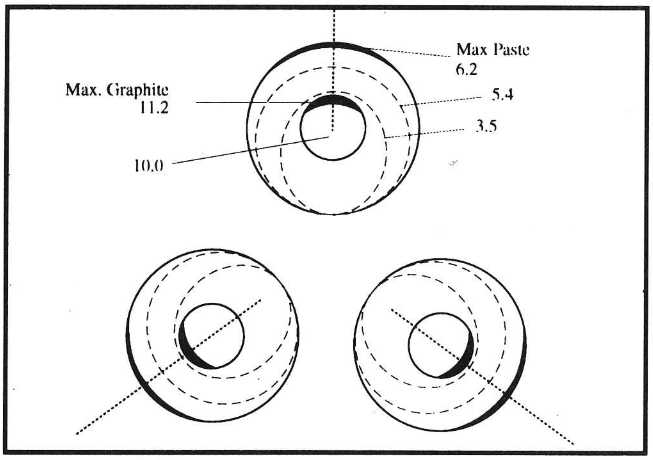

Fig. 8. Modulus of the current density (A/cm²). One-phase current.

Conclusions and future of project

The FERROATLANTICA-Sabón factory has been visited by most silicon metal producers in the world and also by makers of silicones. We explain to all of them that ELSA is the type of electrode technology in the future.

We are convinced that in the very near future all silicon furnaces, and perhaps some other ones, will work with this type of electrode based on three basic principles:

Reduction in the costs of the electrodes down to approximately a third of those which exist with normal prebaked electrodes.

Reduction of costs in transport and stocks owing to the fact that many more graphite and paste factories exist in the world than those for making prebaked electrodes.

Reduction in the number of breakages and in the costs of the same, above all under the condition of daily stoppages with which our factory works.

Furthermore, because of the cyclical character of the silicon market, we think that the ELSA electrode must be the most important argument for the silicon producers that change over their furnaces to ferrosilicon production, taking into consideration the market situation. The changeover from silicon to ferrosilicon production, and vice versa, can be made without overcost or loss of production that normally are present because of the change of the electrode columns.

As a conclusion of the different thermoelectric studies, we now dispose of a collection of programmes to "learn" about our electrode. This knowledge has been and is being not only employed since then in the design of the elements of this electrode but also in the daily operation of the furnaces, allowing us to understand the working of the electrode under different conditions better, and even to take some decisions according to this important information which we didn't have in the past.

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