Production of Standard-Grade Ferromanganese in an Electric Arc Furnace

John P. Hager

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PRODUCTION OF STANDARD-GRAGE FERROMANGANESE
IN
AN ELECTRIC ARC FURNACE

by

JOHN F. HAGER

A Thesis
Submitted to
The Department of Mineral Dressing
In Partial Fulfillment of the Requirements
for the
Degree of Bachelor of Science in Metallurgical Engineering
Mineral Dressing Option

MONTANA SCHOOL OF MINES
Butte, Montana
May 20, 1958
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PRODUCT OF STANDARD-GRDAE FERROMANGANESE
IN AN ELECTRIC ARC FURNACE

I. INTRODUCTION

Essentially, the investigation reported herein was conducted to determine the adequacy of a laboratory-sized electric arc furnace for the production of ferromanganese. The question is: What factors should be considered in the design of a laboratory furnace in order that the results of laboratory testing be applicable to industrial operations?

For continuity the importance and use of standard-grade ferromanganese for present day steelmaking is briefly reviewed.

A. Ferromanganese in Steel-Making

Steelmaking requires the addition of various chemical elements to obtain the desired results. These results may include deoxidation of the molten metal to the desired degree, control of grain size, improvement of the mechanical and physical properties, increase the resistance to corrosion, and to increase the response of the steel to subsequent heat treatment. These elements are quite often added as an alloy of iron and hence the name ferroalloy.

The ferroalloy that is of concern to this thesis is known as standard-grade ferromanganese. The chemical requirements of standard ferromanganese as set forth by the National Stockpile Materials Purchase Specification are as follows:

1
### Manganese
- **Minimum**: 75%

### Carbon
- **Maximum**: 7.5%

### Silicon
- **Maximum**: 1.25%

### Phosphorus
- **Maximum**: 0.35%

### Sulfur
- **Maximum**: 0.05%

### Iron
- **Remainder**

In addition to standard-grade ferromanganese, low-carbon and medium carbon ferromanganese are produced. The use of these products is dictated by the maximum carbon allowed in the steel.

The ferromanganese is added either to the furnace or ladle, and in some cases to both. The lump size should be between 5 to 2 inches depending on whether the addition is to the furnace or ladle; the larger size is suitable for the furnace and the smaller for the ladle. The time of addition to either is dependent upon the following factors:

1. **Effect of the addition on temperature of the bath,**
2. **Ease of solution,**
3. **Susceptibility to oxidation,** and
4. **Formation and elimination of reaction products.**

One specific use of ferromanganese as an addition agent is illustrated by its application to the problem of hot working steel. If sulfur is present in steel, as iron sulfide, brittleness will occur during hot working operations. The addition of manganese prevents the formation of iron sulfide and thus eliminates brittleness during hot working.

**B. Ferromanganese Production**

The direct smelting of ferromanganese from manganese and iron ore
is accomplished in either a blast furnace or an electric arc furnace. Because of the smaller proportion of solid fuel required by the latter and because of the increasing availability of cheap electric power, the electric furnace is becoming more popular.

The charge used in the electric arc furnace consists of manganese ore or concentrates, iron ore or scrap, limestone, and coke. The manganese concentrates or ore can be nodulized prior to smelting.

The charge is placed in an electric arc furnace and smelted until there is a separation of the metal phase from the impurities (slag). The furnace is then tapped and the melt poured into trays. After sufficient time for cooling, the slag is chipped from the surface of the ferromanganese. The ferromanganese is then crushed and sorted to the desired size and sent to the steel plant.

II. PURPOSE OF INVESTIGATION

The original purpose of this thesis was to determine the feasibility of producing standard-grade ferromanganese from the Cuban concentrates using an electric arc furnace. This purpose was later changed since it became necessary to study the adequacy of a laboratory electric arc furnace for comparability with commercial operations.

Since the original purpose of the investigation had been changed while the area of investigation had not, the research work was then continued with the purpose of collecting information on ferromanganese production as a background for anticipated future work in pyrochemical research at the Montana School of Mines. Thus, the work was directed primarily towards the design of a furnace that could be used for laboratory and pilot-plant
investigations.

During the background studies a joint agreement was made with the Anaconda Company for the investigation of ferromanganese production in a small, 50 pound, electric arc furnace which was recently purchased by that company. The Anaconda Company was primarily concerned in obtaining a procedure for furnace operation and at the same time an attempt to reduce the manganese content in their slag. The arrangement allowed not only an opportunity to conduct tests, but also a chance to evaluate the capabilities and limitations of this furnace.

III. BACKGROUND FOR THE INVESTIGATION

The background research was developed into two stages. The first of these was an analysis of the methods available for ferromanganese production, and the second was directed towards design of a furnace.

A. Analysis of the Methods of ferromanganese Production

The smelting of manganese and iron ore for the production of ferromanganese requires the presence of a strong reducing agent that will reduce the manganese and iron oxides to their elemental forms, while at the same time the non-reduced oxides or impurities must form a slag that will be immiscible and unreactant with the metal phase. This then requires the necessary temperature for;

1. The reduction to take place, and
2. The formation of a suitable slag.

The thermodynamics of the system requires a temperature of about 1500° C for the reduction to take place. The slag used with ferromanganese
must be a monosilicate or basic slag, since an acid slag will have an affinity for MnO thus causing a subsequent loss of manganese. The melting point of a monosilicate slag in the CaO-SiO₂ system is about 2000° C. This temperature will then be the lower limit for successful smelting. With the lower temperature limit determined, the features of electric arc furnaces that will produce this temperature must receive consideration.

On the basis of temperature requirements, the two most obvious choices would be the blast furnace and the electric arc furnace. Since both of these furnaces will produce the required temperature, the choice between the two must be made on the basis of economics, with consideration of other features as merely secondary. According to Sully³, "The essential difference between the production of ferromanganese in the blast and electric furnace is that the proportion of solid fuel is very much less in the latter, the ratio being about 3:1." This is one of the reasons for the widespread adoption of the electric furnace in the United States and Europe. Some of the secondary features of the electric furnace are:

1. The very effective reduction zone obtained around the carbon electrode, and

2. The higher degree of control that can be exercised with the electric arc furnace.

Having decided on an electric arc furnace, the next step would be to determine the design of a furnace that would be suitable for ferromanganese production.

B. Design of an Electric Arc Furnace for the Production of Ferromanganese

An extensive literature survey was conducted in an attempt to obtain a design of a furnace that would be suitable for laboratory and pilot-plant
work. A great deal of information concerning electric arc furnaces that are used in steel production was found, but there was a conspicuous absence of material on the design of electric arc furnaces used in ferromanganese smelting. An attempt was made, therefore, to correlate the information on steel furnaces to its application on ferromanganese furnace design.

Most of the steel furnaces are built as tilting-type furnaces. Since ferromanganese production lends itself to continuous operation, there is no need to have the furnace tilt. Indeed, the charge can be continuously fed at the top with a periodic tapping at the bottom. In most steel furnaces, the heat is developed by a direct arc between the electrodes which are situated above the bath, but in ferromanganese smelting the electrodes can be placed in the slag. In ferromanganese smelting, there is a higher slag to metal ratio so that the arcing can take place between the electrodes and the high resistance slag; thereby, reducing heat losses from the arc.

Perhaps the biggest difference between the two types of furnaces is in electrical design. The electrical load on the ferromanganese furnace differs from that on the steel furnace. Since ferromanganese furnaces are charged continuously, the load is fairly steady and the power factor can be maintained around 90 per cent. The voltages used are lower than in the steel furnaces, but the current densities greater. These requirements necessitate a careful design of the secondary circuits to keep reactance to a minimum.

In design features common to both steel and ferromanganese furnaces, are certain variables peculiar to an electric arc furnace. It is these variables that determine the successful operation of the furnace. These
variables include:

1. **Furnace body and lining**: As previously mentioned, the body of the ferromanganese furnace should be non-tilting and, in general, of simpler mechanical design than the steel furnace. The body is usually round and quite commonly without a top. The hearth lining should be made out of carbon blocks and the unsmelted charge will later form a lining around the carbon blocks. Between the carbon blocks and the steel shell, a paste of fireclay, magnesite, or chrome is rammed in and will serve as insulation. It is common for the ferromanganese producer to build his own furnace body; this is exemplified by the Anaconda Company who used old copper convertors for furnace bodies.

2. **The number of phases**: Most ferromanganese furnaces are either single or three phase. The single phase furnaces are characterized by the one or two electrodes, and are more commonly used for small furnaces. The single electrode furnaces have a conducting bottom which gives high localized temperatures and the smelting can be controlled very closely. The double electrode furnace is characterized by the Lectromelt size-W furnace. The three phase furnace is, by far, the most popular and is built with either six or, more commonly, three electrodes. The three electrodes are arranged in the shape of an equilateral triangle, thus permitting a complete balancing of the phases and resulting also in much lower reactance.

3. **Electrodes**: Two types of electrodes are generally used in ferromanganese furnaces. These are the graphite and the carbon electrodes. Of the two, the amorphous carbon electrode is more frequently used. This is because of its insusibility, insolubility, chemical inertness, electrical conductivity, mechanical strength and resistance to shock. The graphite electrode costs twice as much as the amorphous carbon electrode. Since
the consumption and performance characteristics are about the same for both, the carbon is cheaper than the graphite. Soderberg self-baking electrodes are available for ferromanganese furnaces, but their main field of usefulness is in medium and large sized furnaces which require electrodes from 16 to 20 inches to a maximum diameter of 8 feet. 4

As an electrode is consumed in operation, a threaded nipple is inserted in the top and a new electrode is screwed down on the exposed end of the nipple. A carbon paste can be used on the joint to improve electrical conductivity.

The electrode consumption varies with the size of the furnace, electrode composition, and certain operating conditions. A representative figure for electrode consumption, according to Anaconda 5, is 30 pounds of carbon per long ton of ferromanganese. This figure was obtained from a 2500 Kva furnace.

4. The electrical circuit and furnace control: Because of arc irregularities and the changing condition of the bath, some method must be available for adjusting the power requirements. These various power requirements can be met by two means, applied either individually or combined: by a change of voltage and / or a change of current. The voltage is adjusted by changing the taps on the transformer while the current can be changed by simply adjusting the resistance of the arc which is proportional to its length.

On many furnaces, regulation can be carried out by voltage tap changing. If only one product is manufactured in a furnace and the voltage requirements are well known, a range of six taps, two below and four above normal
voltage, about 5% apart, will be sufficient. This practice is, however, not usual, most regulation is performed by controlling electrode travel; most furnaces being designed to give 3 to 4 feet of electrode travel.

The electrodes can be raised or lowered automatically by electrically operated winches. The electrical load is quite uniform, which minimizes load fluctuations. As a result the automatic regulators can be of the slow acting type.

An external reactor is not required in ferromanganese furnaces since the load is substantially steady, but impedance must receive consideration due to the high currents; thus, it is essential to specify the lowest inherent impedance in the transformer. For this reason many transformers are built of the shell type.

IV. EXPERIMENTAL WORK

The first experimental work was conducted on the Cuban flotation concentrates, but after five tests the work was discontinued. The remaining test work was conducted in the Research Department of the Anaconda Reduction Works at Anaconda, Montana. The charge constituents were obtained from the storage bins at Anaconda's ferromanganese plant.

A. Ceramic Furnace Tests on the Cuban Flotation Concentrates

A series of five tests were conducted on the flotation concentrates of the Cuban ores. The tests were discontinued because the ceramic furnace would not produce the required temperature for reduction and proper slag formation.
B. Tests Conducted in Anaconda

A total of twelve tests were conducted on the charge materials used by Anaconda in their ferromanganese furnaces. The tests were conducted in a Lectromelt, 50 pound, ladle-type laboratory furnace. The carbon electrodes are manually operated and the power requirements are rated at 50 Kva.

An analysis of the thermodynamics of reduction and slag formation together with stoichiometric calculations were made prior to the actual testing. This work was an attempt to analyze temperature requirements and slag composition as a first approximation towards successful ferromanganese smelting. Considerations on furnace design and operation were made as the tests progressed, and any changes in design were made between tests.

1. The thermodynamics of ferromanganese reduction: The mechanism of ferromanganese reduction is that of an oxidation-reduction reaction. The manganese oxides are reduced by elemental carbon which is subsequently oxidized to carbon monoxide or carbon dioxide. Since carbon dioxide does not exist at the temperatures experienced in ferromanganese reduction, carbon will oxidize only to carbon monoxide. The iron oxides are also reduced by carbon to give elemental iron and carbon monoxide.

The thermodynamic concept of free energy is the means by which a reaction, if written as a chemical equation, can be determined to take place. The decrease of free energy accompanying a process at constant temperature and pressure is defined as the maximum work, i.e., maximum work other than the work of expansion, obtainable from a process. This means that all spontaneous processes taking place at constant temperature and pressure are accompanied by a decrease of free energy. If the free energy change of a reaction is positive, the reaction will not proceed, but if
it is negative the reaction will take place.

The free energy calculations are based on standard free energy changes. This assumes that the solids and liquids are at unit activity, and that the gases are at unit fugacity. While this may not be the conditions under which ferromanganese reduction reactions actually take place, no other information is available. While only a first approximation, standard free energy calculations are very reliable.

Although free energy will determine if a certain reaction can take place, it will not give any positive indication of the rate at which the reaction will proceed. This concept of reaction rates is known as chemical kinetics, and because of the lack of information no consideration of reaction rates was made.

Before any free energy calculations could be made, an analysis was made of the oxide forms of manganese and iron. The assays that Anaconda furnished indicated the presence of MnO, MnO₂, Mn₃O₄, and FeO. The temperature above which reduction takes place was calculated for each of these oxides.

The standard free energy change (Δ\(F^0\)) of any reaction is equal to the sum of the standard free energies of formation of the products minus the sum of the standard free energies of formation of the reactants, i.e.,

\[
\Delta F^0 = \Delta F^0 \text{ (products)} - \Delta F^0 \text{ (reactants)}.
\]

The free energy function is dependent on temperature so that the free energy of formation of various compounds is represented as a function of temperature. The function may be represented as a curve on a graph or as a transcendental equation. The free energy of formation of the elements is taken by convention to be zero.
The temperature at which the reaction will proceed is determined by the temperature at which the sum of the standard free energies of formation of the products is more negative than the sum of the standard free energies of formation of the reactants. In the reduction of manganese and iron oxides by carbon, only the standard free energy of formation of the metal oxide and carbon monoxide need be considered; the remainder of the products and reactants are elemental, hence the free energy change is zero. This simplifies the calculations; and, the temperature at which the reaction will go can be read directly from a graph. If the standard free energy of formation of the metal oxide and carbon monoxide are plotted against temperature, the temperature at which the carbon monoxide curve crosses the metal oxide curve is the temperature above which the reaction will proceed, provided that with increasing temperature the standard free energy of formation of the carbon monoxide becomes and remains more negative than the standard free energy of formation of the metal oxide.

Two graphs of standard free energy of formation versus temperature were plotted. The first graph (Fig. 1) contains the curves for the formation of MnO, MnO₂, Mn₂O₃, CO, and CO₂. The temperatures required for reduction are indicated in a summary (page 15) following the curves. The curves for the formation of FeO, CO, and CO₂ are plotted on a second graph (Fig. 2); the results are also indicated in the summary.

The free energy curves for the formation of various oxides were obtained by two methods. The curves for MnO, FeO, CO, and CO₂ were obtained from Hopkins, and the remaining curves were obtained by calculating the \( \Delta F^0 \) values, from the equations given by Thompson, at various temperatures. The calculations for the curves MnO₂ and Mn₃O₄ are included in Appendix I.
A graph of the free energy of formation of various manganese and carbon oxides as a function of temperature. 8

Figure 1
A graph of the free energy of formation of iron and carbon oxides as a function of temperature.

Figure 2
<table>
<thead>
<tr>
<th>Metal Oxide</th>
<th>Reaction</th>
<th>Point on graph (Fig. 1 &amp; 2) indicating the temperature at which the reaction will proceed.</th>
<th>Minimum required temperature - °C.</th>
</tr>
</thead>
<tbody>
<tr>
<td>MnO</td>
<td>$2\text{MnO} + 2\text{C} = 2\text{Mn} + 2\text{CO}$</td>
<td>A</td>
<td>1430</td>
</tr>
<tr>
<td>MnO</td>
<td>$2\text{MnO} + \text{C} = 2\text{Mn} + \text{CO}_2$</td>
<td>B</td>
<td>2425</td>
</tr>
<tr>
<td>MnO₂</td>
<td>$\text{MnO}_2 + 2\text{C} = \text{Mn} + 2\text{CO}$</td>
<td>C</td>
<td>730</td>
</tr>
<tr>
<td>MnO₂</td>
<td>$\text{MnO}_2 + \text{C} = \text{Mn} + \text{CO}_2$</td>
<td>D</td>
<td>730</td>
</tr>
<tr>
<td>Mn₃O₄</td>
<td>$\frac{1}{2}\text{Mn}_3\text{O}_4 + 2\text{C} = \frac{1}{2}\text{Mn} + 2\text{CO}$</td>
<td>E</td>
<td>1080</td>
</tr>
<tr>
<td>Mn₃O₄</td>
<td>$\frac{1}{2}\text{Mn}_3\text{O}_4 + \text{C} = \frac{1}{2}\text{Mn} + \text{CO}_2$</td>
<td>F</td>
<td>1455</td>
</tr>
<tr>
<td>FeO</td>
<td>$2\text{FeO} + 2\text{C} = 2\text{Fe} + 2\text{CO}$</td>
<td>G</td>
<td>725</td>
</tr>
<tr>
<td>FeO</td>
<td>$2\text{FeO} + \text{C} = 2\text{Fe} + \text{CO}_2$</td>
<td>H</td>
<td>700</td>
</tr>
</tbody>
</table>
The minimum temperatures for the reduction of the various oxides were calculated on the basis of the carbon oxidizing to CO and CO$_2$. There is some question whether the reactions involving CO$_2$ will take place, since CO$_2$ is unstable above 1000° C. Consequently, the temperature analysis was made on the basis of CO formation.

From the summary (page15), the minimum temperature for reduction is 1430° C. Since CO$_2$ is unstable at this temperature there is no need to further consider reactions involving CO$_2$. This temperature becomes the lower limit for successful reduction, so the next step is to determine a lower temperature limit for formation of a suitable slag. The higher of the two temperatures will be the minimum temperature for successful ferromanganese smelting.

2. Analysis of the formation of ferromanganese slag: The composition of the slag used in ferromanganese smelting is essentially CaO and SiO$_2$. Other oxides such as Al$_2$O$_3$, MgO, FeO, and MnO will be present in the slag, but they should be in minor quantities in comparison to CaO and SiO$_2$. The SiO$_2$ is the acid constituent of the slag and the CaO is the basic constituent. The general formula for slag composition is written as XCaO-SiO$_2$; where X represents the number of moles of CaO that are combined with one mole of SiO$_2$. If X is less than 2.00 the slag is acid and if X is greater than 2.00 the slag is basic.

According to Figure 3, the free energy of formation of a neutral slag is more favorable than an acid slag, so if the slag becomes acid it will have an affinity for CaO. Controlling the slag neutrality is very important because MnO will act as a CaO equivalent and combine with an acid slag to produce a neutral slag. Therefore, the presence of an excess of CaO will
A graph of the free energy of formation of various slag compositions as a function of temperature.  

Figure 3
promote the formation of 2CaO-SiO$_2$ which will form in preference to MnO-SiO$_2$
or 2MnO-SiO$_2$. From this reasoning, it should be clear that an excess of limestone should force the MnO out of the slag and cut manganese slag losses to a minimum.

The results obtained by the Bureau of Mines in smelting siliceous manganese ores (Fig. 4) indicates the importance of controlling the basicity of the slag.

3. **Stoichiometric calculations:** The calculations for the formation of ferromanganese from nodules, iron ore, limestone and coke, were based on the production of 25 pounds of standard-grade ferromanganese and a slag with a 37% SiO$_2$, 63% CaO composition. The 37% SiO$_2$, 63% SiO$_2$ composition was chosen because, according to the CaO-SiO$_2$ phase diagram (Fig. 5), this is very nearly the composition of a neutral slag. The melting point of a slag of this composition is 2000° C. This temperature then becomes the minimum temperature for successful smelting, since the temperature necessary for reduction was only 1430° C.

On a basis of 25 pounds of ferromanganese, the following weights of feed materials were calculated:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>32.3</td>
</tr>
<tr>
<td>Iron Ore</td>
<td>3.86</td>
</tr>
<tr>
<td>Coke</td>
<td>9.80</td>
</tr>
<tr>
<td>limestone</td>
<td>7.45</td>
</tr>
</tbody>
</table>

Smaller or larger charges may be calculated by simply multiplying these weights by a suitable factor.

The calculations together with the assays of the feed materials are contained in Appendix II.
A graph of the relationship between slag basicity and manganese recovery in the smelting of siliceous manganese ores.  

Figure 4
Phase diagram for the CaO-SiO₂ system

Figure 5
4. **Furnace design and operation**: The furnace used for the testing work was a Lectromelt, size-W, 50 Kva, single phase, double electrode, electric arc furnace (Figures 6 and 7). The furnace body was constructed in the shape of a ladle (Fig. 8) which could be lifted from the furnace frame to facilitate easy pouring.

The electrodes were held in position by electrode holders (Fig. 7) which provided for vertical movement of both the holder and electrode, and which also allowed the electrode to slip through the holder when the holder remained stationary. The electrodes project downward through the furnace (Fig. 9) roof into the bath. The distance between the electrode tips could be adjusted from above and outside the furnace. Cooling glands for each of the electrodes were set in the furnace roof and permitted easy movement of the electrodes during adjustment. Of course, the primary purpose of these glands was to cool the upper portion of the electrodes. The bottom edge of the roof was also lined with a cooling element, and the two were connected in series with a water tap. A schematic diagram of the furnace is provided in Figure 10.

The roof is made of alusite and the ladle is a steel shell with a carbon crucible inserted. The carbon crucible is cemented with a chrome refractory which is both a cementing and insulating material. The ladle was originally lined entirely with refractory material, but the life of the refractory was short. This was the reason that the carbon crucible was inserted in the ladle.

The electric power comes into the building at 458 volts and is subsequently changed to 200 volts for the furnace transformer. The furnace
Fig. 6 Lectromelt, size-W, ladle type, electric arc furnace.

Fig. 7 Body and electrode arrangement of the furnace.
Fig. 8 Furnace ladle together with handles.

Fig. 9 Roof and electrode arrangement.
Fig. 10 Schematic diagram of the Lectromelt furnace.
transformer converts the 220 volts to 110 volts for furnace consumption. The power is transferred from the transformer to the electrodes by heavy multi-wire cables. The current comes into one electrode and leaves by the other. Figure 11 shows the furnace transformer together with the circuit breaker. The furnace is also provided with an ammeter and a wattmeter. The Lectromelt corporation suggests that the readings on the ammeter and wattmeter should read 160 and 100 respectively when the electrodes are placed together and the furnace is in a dead-short condition.\(^{10}\) In actual operation, this was not the case since the ammeter went off scale and the wattmeter went over 100. Apparently, the transformer did not have enough impedance and this factor might account for the difficulties to be mentioned later, since according to the instruction manual,\(^{10}\) "The impedance is the greatest single factor for efficient furnace operation." A schematic diagram of the electrical circuit is provided in Figure 12.

The time required to melt a 20 to 23 pound charge was found to be about one hour. Some difficulty was experienced in maintaining a steady arc at the beginning of the melt, but as soon as slag began to form the furnace ran rather smoothly.

One problem that was experienced was the frequent occurrence of unsmelted charge remaining in the ladle after pouring. This was a result of the very localized heating around the electrodes, and the inability of the charge to conduct sufficient heat to melt the charge next to the hearth.

As will be observed from the outline of tests which follows, the size of feed materials was very important in furnace operation. The original materials came from the storage bins in the ferromanganese plane and ranged in size from 1 to \(1/2\) inch. This size proved to be too large for efficient
Fig. 11 Furnace transformer and circuit breaker.

Fig. 13 Carbon crucibles used for cooling the molten ferromanganese and slag.
1. Supply 220V-1Ph-60 cycle
2. Line SW. 2 Pole single throw 250V 400A fuse
3. Oil circuit breaker
4. Current trip coil - 5 A (Time delay)
5. Shunt trip coil 40-110V - 60cycle
6. Power transformer - 50KVA & Reactor
7. Manual tap changer - 3 position
8. Interlock SW. - Tap change & O.C.B. (Normally open)
9. Current trans. - Ratio 800/5A
10. Ammeter 5A, scale 0-200% (100% = 400A)
11. Heatmeter, (Wattmeter) 500watt, (scale 0-200% 80KW (100% 40KW)

Fig. 12 Schematic diagram of the electrical circuit of the furnace.
operation in the laboratory furnace, and the materials were subsequently crushed to 3/8 to 1/2 inch. The size of coke was particularly important in determining the amount of reduction obtained, i.e., the smaller the size of the coke the better the reduction.

While operating the furnace produced a great amount of fumes, and the color of the fume indicated that manganese was present.

It should be mentioned here that the ladle was lifted from the furnace frame to facilitate pouring. The charge was then poured into carbon crucibles (Fig. 13) which permitted rapid cooling of the slag and metal.

5. Outline of tests: A total of twelve tests were conducted on the materials obtained from the bins in the ferromanganese plant. The data from these tests is tabulated as follows:

Test # 1
Weight of charge materials:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>6.46</td>
<td>lb.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron ore</td>
<td>.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coke</td>
<td>1.56</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>1.49</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Products wt.-lb.  
Ferromanganese 1.45 11.1 61.2  
Slag 5.75 36.1  
Fumes  

Comments  
The power consumption was very irregular and an excess of coke was noted. The next test will be conducted with a smaller addition of coke.

Test # 2
Weight of charge materials:

<p>| | | | | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>6.46</td>
<td>lb.</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Iron ore</td>
<td>.77</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Coke</td>
<td>1.00</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Limestone</td>
<td>1.50</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Comments  
The test ran smoother than the previous test, but the coke continued to remain in excess. The slag was black indicating high manganese content.
Product wt.-lb. Mn Fe Mn recovery
Ferromanganese 0.40 11.8 52.8 1.185
Slag 9.88

Test # 3

Weight of charge materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>6.46</td>
</tr>
<tr>
<td>Iron ore</td>
<td>0.77</td>
</tr>
<tr>
<td>Coke</td>
<td>1.00</td>
</tr>
<tr>
<td>Limestone</td>
<td>1.50</td>
</tr>
</tbody>
</table>

Product wt.-lb.
Ferromanganese 0.10
Slag 7.50

Comments
The slag continued to be black and a large amount of material remained in the ladle. There was considerable arcing between the electrodes, and the power consumption was very irregular.

No assays

Test # 4

Weight of charge materials:

<table>
<thead>
<tr>
<th>Material</th>
<th>Weight (lb)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>13.00</td>
</tr>
<tr>
<td>Iron ore</td>
<td>1.54</td>
</tr>
<tr>
<td>Coke</td>
<td>2.00</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.00</td>
</tr>
</tbody>
</table>

Comments
The charge weights were doubled and this resulted in steadier power consumption. The color of the slag was a dark green which indicates the presence of a considerable amount of manganese.

Products wt.-lb.
Ferromanganese 1.52
Slag 8.20
Fumes

Product wt.-lb.
Ferromanganese 1.15

Test # 5

Comments
The materials were crushed prior to smelting and the ladle was relined with a carbon crucible. Conductivity increased, but the slag continues to be dark green.

No assays
Test #6

Weight of charge materials:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>13.00 lb.</td>
</tr>
<tr>
<td>Iron ore</td>
<td>1.54</td>
</tr>
<tr>
<td>Coke</td>
<td>2.00</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.00</td>
</tr>
</tbody>
</table>

Products wt.-lb.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>.70</td>
</tr>
</tbody>
</table>

Comments

The slag was black and the smelting results were very poor.

Test #7

Weight of charge materials:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>13.00 lb.</td>
</tr>
<tr>
<td>Iron ore</td>
<td>1.54</td>
</tr>
<tr>
<td>Coke</td>
<td>2.00</td>
</tr>
<tr>
<td>Limestone</td>
<td>4.50</td>
</tr>
</tbody>
</table>

Products wt.-lb.

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>1.90</td>
</tr>
</tbody>
</table>

Comments

The limestone was increased to 4.5 pounds, but this did not help. The slag was dark green and considerable material remained in the ladle.

Test #8

Weight of charge materials:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>13.00 lb.</td>
</tr>
<tr>
<td>Iron ore</td>
<td>1.54</td>
</tr>
<tr>
<td>Coke</td>
<td>4.00</td>
</tr>
<tr>
<td>Limestone</td>
<td>2.50</td>
</tr>
</tbody>
</table>

Products wt.-lb.

<table>
<thead>
<tr>
<th></th>
<th>%Mn</th>
<th>%Fe</th>
<th>%CaO</th>
<th>%SiO2</th>
<th>%Mn recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>4.80</td>
<td>62.2</td>
<td>29.5</td>
<td></td>
<td>37.2</td>
</tr>
<tr>
<td>Slag</td>
<td>8.16</td>
<td>20.9</td>
<td>1.9</td>
<td>27.3</td>
<td>21.3</td>
</tr>
<tr>
<td>Fumes</td>
<td></td>
<td></td>
<td></td>
<td>20.8</td>
<td>41.5</td>
</tr>
</tbody>
</table>

Comments

The crushed materials were pulverized prior to smelting, the weight of coke was increased, and the weight of limestone decreased. The results were a light to dark green slag, smooth power consumption, and no materials remaining in the ladle.

Test #9

Weight of charge materials:

<p>| | |</p>
<table>
<thead>
<tr>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Nodules</td>
<td>13.00 lb.</td>
</tr>
<tr>
<td>Iron ore</td>
<td>1.54</td>
</tr>
<tr>
<td>Coke</td>
<td>4.00</td>
</tr>
<tr>
<td>Limestone</td>
<td>3.50</td>
</tr>
</tbody>
</table>

Comments

The same procedure was used as in the previous test with the exception that the limestone was increased. The results were good: light green slag and steady power consumption.
Products

Ferromanganese 4.75 lb. 56.7 33.2 24.1 18.8 33.6
Slag 9.34 25.1 2.4 22.6 24.4 27.9
Fumes

Test # 10
Weight of charge materials:

Nodules 13.00 lb.
Iron ore 1.54
Coke 4.00
Limestone 4.00

Products

Ferromanganese 4.13 65.7 24.4 22.6 24.4 33.8
Slag 10.35 21.6 2.4 26.46 21.0 18.9
Fumes

Test # 11
Weight of charge materials:

Nodules 13.00 lb.
Iron ore 1.54
Coke 4.00
Limestone 3.00

Products

Ferromanganese 4.2 66.1 24.5 34.6
Slag 6.2 24.4 1.8 21.0 46.5
Fumes

Total smelting time was one hour
Wattmeter reading was 95
Ammeter reading was 100
Efficiency = 14.5 % (calculated in Appendix III.)

Test # 12
Weight of charge materials:

Nodules 13.00 lb.
Iron ore 1.54
Coke 4.00
Limestone 3.00

Comments

Additional limestone was added to this charge. This resulted in a darker slag and a deposit of unsmelted charge in the ladle.

The limestone weight was again adjusted, and this time the calculated 3.00 pounds was added. The slag was light green, no materials were left in the ladle, and the slag weight was the least to-date. The next test will be conducted with the same charge, but the materials will be pulverized twice, mixed, and pelletized.

This test was more conductive than all previous tests, and the furnace ran very smoothly. The slag was very fluid and the weight was the lowest of all previous tests. The only undesirable result was the presence of a large amount of dark colored fumes.
<table>
<thead>
<tr>
<th>Products</th>
<th>wt.-lb.</th>
<th>%Mn</th>
<th>%Fe</th>
<th>%CaO</th>
<th>%SiO₂</th>
<th>Mn recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ferromanganese</td>
<td>5.35</td>
<td>72.4</td>
<td>17.7</td>
<td>34.7</td>
<td>25.0</td>
<td>38.70</td>
</tr>
<tr>
<td>Slag</td>
<td>4.40</td>
<td>5.0</td>
<td>2.1</td>
<td>34.7</td>
<td>25.0</td>
<td>2.74</td>
</tr>
<tr>
<td>Fumes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>58.56</td>
</tr>
</tbody>
</table>

The following summary of the above data provides a more comprehensive evaluation of the results and effects produced by the various changes in testing procedure.

The first three tests provided an acquaintance with the operation of the furnace and the poor results were not unexpected. From Test 4 on, the weight of the charge was doubled, and Test 4 was the first test that gave a green slag and fairly steady power consumption.

Starting with Test 5, the materials were crushed to 3/8 to 1/2 inch and the carbon crucible was inserted in the ladle. Tests 5 and 6 were conducted with the charge weights of the previous test, and although the power consumption was steady, both tests resulted in black slags and little ferromanganese. Test 7 was conducted similarly except that the limestone was increased. This also failed to produce satisfactory results.

Starting with Test 8, the previously crushed materials were pulverized to about -14 mesh, the weight of coke was doubled, and a small decrease was made in the weight of limestone. This was the first really satisfactory test. Its slag was light green, 4.8 pounds of ferromanganese were produced, no materials remained in the ladle, and the conductivity of the bath increased.

Tests 9, 10, and 11 were conducted in the same manner as Test 8, and with the same weights of nodules, iron ore, and coke. The weight of limestone was changed from 2.5 pounds to 3.5, 4.00, and 3.00 pounds in Tests 9, 10, and 11 respectively. The purpose of varying the CaO was to force the MnO out of the slag. The assays showed that an increased CaO content did not improve Mn
recovery, but that the better results were obtained using the calculated value for a neutral slag. Test 12 was run using the calculated values but with a modified smelting procedure.

In Test 12, the materials were crushed, pulverized, mixed in the proper proportions, and then pelletized (Fig. 14). The charge was much more conductive than previous tests and the furnace ran very smoothly. The weights of the ferromanganese and slag were correspondingly higher and lower than the previous tests, the grade of ferromanganese higher, and the Mn assay of the slag lower than previous tests. Although the grade of ferromanganese was good and the Mn content of the slag was low, the Mn loss by fumes was around 60%.

V. CONCLUSIONS AND RECOMMENDATIONS

On the basis of the above results, several conclusions can be drawn. These are:

1. Increasing the fineness of feed materials results in improved furnace operation.

2. The addition of CaO did not produce an equilibrium shift of the manganese from the slag.

3. The loss of manganese by fumes was excessive.

4. There was no apparent control over the smelting conditions, and also a lack of ability to reproduce test results.

5. The absence of a range of voltage taps increased the power fluctuations.
Fig. 14 Apparatus used to pelletize the feed materials
6. The furnace would not give accurate determinations of power consumption.

7. There is no method available to determine the position of the electrodes in the bath, or the position of the electrodes in relation to each other.

8. The batch furnace requires that the lining of unsmelted charge be removed after every test.

9. The recovery of manganese in the ferromanganese was consistently low.

From the foregoing conclusions it becomes apparent that the Lectromelt, size-W, electric arc furnace is unsuitable for the direct reduction of manganese nodules, concentrates, or ores for the production of standard-grade ferromanganese. Although it is apparent that this furnace is unsuitable, the limitations and deficiencies of the Lectromelt furnace suggest certain corrective measures that could be incorporated in the design of an electric arc furnace for laboratory and pilot-plant studies.

Since the basic faults of the Lectromelt furnace were in design, several corrective suggestions are in order. They are:

1. The body should be non-tilting with the tap spout at the bottom.

2. An open-top furnace with continuous feeding would minimize the agitation of the slag surface and hence reduce manganese fume loss.

3. A three-phase, three electrode arrangement would produce a more even heating of the charge.

4. The furnace transformer should be provided with six taps for a
wide range of voltages.

5. Increasing the smelting capacity to 200 pounds per hour would increase the accuracy of results, eliminate fine grinding of charge materials, and remove the necessity of chipping out the unsmelted lining.

6. Automatically controlled electrodes would eliminate power fluctuations and unnecessary electrode arcing.

7. The installation of automatic recorders for power consumption, temperature, and electrode movement would provide closer control of smelting conditions, and also would provide additional data for the evaluation of the smelting characteristics of various ores.

A furnace body that incorporates these desired features is illustrated in Figure 15.

Although the Lectromelt, size-W, furnace was found to be unadaptive for the production of standard-grade ferromanganese, the limitations that were discovered have suggested a design of an electric arc furnace that could be used for the direct smelting of various ores. A furnace incorporating the features outlined above could be used for either laboratory or pilot-plant studies.

Having determined a feasible furnace design, the first step in the development of a Pyrochemical Research Program at the Montana School of Mines has been achieved.
Fig. 15 Suggested design of an electric arc furnace for laboratory and pilot-plant studies.
VI. BIBLIOGRAPHY


VII. ACKNOWLEDGMENT

The writer wishes to express his appreciation and gratitude to Professor Donald W. McGlashan, Research Professor, and Head of the Department of Mineral Dressing for his advice and assistance in this project.

Special thanks is also expressed to the Research Department of the Anaconda Reduction Works for the use of equipment, and in particular to Mr. Charles Arentzen for his assistance and cooperation on this project.
Appendix I

Calculation of the standard free energy of formation of $\text{MnO}_2$ and $\text{Mn}_3\text{O}_4$ at various temperatures.

The most common method to represent the free energy of formation as a function of temperature is to use a graphical plot. The curves for the formation of $\text{MnO}_2$ and $\text{Mn}_3\text{O}_4$ were unavailable from the literature, and in order to obtain a curve of these oxides it became necessary to calculate the standard free energy of formation of these oxides at various temperatures. This was possible by using the equations given by Thompson$^9$ for the relation between standard free energy of formation and temperature. The value of $\Delta F^0$ was calculated at three temperatures for each oxide, and a linear curve was drawn through the points.
Calculations:

For the equation $\text{Mn} + \text{O}_2 = \text{MnO}_2$ between the temperatures 0-2000° C

$$\Delta F^0 = -130,204 - 6.17T \ln T - 19.65 \times 10^{-3} T^2 + 4.95 \times 10^{-6} T^3 + 171.36 T^{1/2} + 89.50 T$$

$$\Delta F^0 \text{ at } 273^0 \text{K} = -130,204 - 3.87 \times 10^3 \log 273 - 19.65 \times 10^{-3} \times 7.45 \times 10^4 + 4.95 \times 10^{-6} \times 20.3 \times 10^6 + 171.36 \times 16.5 + 24.4 \times 10^3 = -113,859 \text{ cal.}$$

$$\Delta F^0 \text{ at } 1273^0 \text{K} = -130,204 - 18 \times 10^{3} \log 1273 - 31.9 \times 10^3 + 10.25 \times 10^3 + 6.13 \times 10^3 + 11.4 \times 10^3 = -87,624 \text{ cal.}$$

$$\Delta F^0 \text{ at } 2273^0 \text{K} = -130,204 - 3.22 \times 10^{4} \log 2273 - 10.1 \times 10^4 + 58 \times 10^3 + 8.15 \times 10^3 + 20.3 \times 10^4 = -70,054 \text{ cal.}$$

For the equation $\frac{1}{2} \text{Mn} + \text{O}_2 = \frac{1}{2} \text{Mn}_3 \text{O}_4$ between the temperatures 300-1493° K

$$\Delta F^0 = \frac{1}{2} (-340,626 + 24.61T \ln T - 18.4 \times 10^{-3} T^2 + 3.48 \times 10^{-6} T^3 - 115.6 T^{1/2} - 102.94 T)$$

$$\Delta F^0 \text{ at } 273^0 \text{K} = \frac{1}{2} (-340,626 + 37.7 \times 10^3 - 1370 + 70.8 + 19.2 + 19.2 \times 10^3 - 28,150 ) = -156,500 \text{ cal.}$$

$$\Delta F^0 \text{ at } 1273^0 \text{K} = \frac{1}{2} (-340,626 + 42.5 \times 10^4 - 83.5 \times 10^3 + 19.4 \times 10^3 + 14.4 \times 10^3 - 2.22 \times 10^5) = -92,800 \text{ cal.}$$

For the equation $\frac{1}{2} \text{Mn} + \text{O}_2 = \frac{1}{2} \text{Mn}_3 \text{O}_4$ between the temperatures 1493-1773° K

$$\Delta F^0 = \frac{1}{2} (-341,802 + 32.29T \ln T - 26.5 \times 10^{-3} T^2 + 3.48 \times 10^{-6} T^3 + 342.68 T^{1/2} - 125.05 T)$$

$$\Delta F^0 \text{ at } 1773^0 \text{K} = \frac{1}{2} (-341,802 + 42.8 \times 10^4 - 83.5 \times 10^3 + 19.4 \times 10^3 + 14.4 \times 10^3 - 2.22 \times 10^5) = -92,800 \text{ cal.}$$
Appendix II

Stoichiometric calculations to determine the charge weights for ferromanganese smelting.

Using the assays provided by Anaconda, and knowing the desired composition of slag and ferromanganese, it was possible to stoichiometrically calculate the desired weights of nodules, iron ore, coke, and limestone. The phosphorous, sulfur, and copper were disregarded in the calculations because of their small percentages. The oxides other than CaO and SiO$_2$ that remain in the slag were calculated as either CaO or SiO$_2$ equivalents. On the basis of the previous discussion, the carbon requirements were calculated as oxidizing to CO.
Calculations:

Assays:

<table>
<thead>
<tr>
<th>Nodules</th>
<th>Iron Ore</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>MnO₂</td>
</tr>
<tr>
<td>59.13%</td>
<td>4.00</td>
</tr>
<tr>
<td>MnO₂</td>
<td>FeO</td>
</tr>
<tr>
<td>4.00</td>
<td>72.30%</td>
</tr>
<tr>
<td>Fe</td>
<td>SiO₂</td>
</tr>
<tr>
<td>2.60</td>
<td>6.6</td>
</tr>
<tr>
<td>SiO₂</td>
<td>CaO</td>
</tr>
<tr>
<td>7.10</td>
<td>2.4</td>
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<td>CaO</td>
<td>MgO</td>
</tr>
<tr>
<td>4.90</td>
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<td>Al₂O₃</td>
<td>P</td>
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<tr>
<td>.80</td>
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</tr>
<tr>
<td>Zn</td>
<td>S</td>
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<td>Cu</td>
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<td>.02</td>
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<tr>
<td>H₂O</td>
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<tr>
<td>S</td>
<td></td>
</tr>
<tr>
<td>.05</td>
<td></td>
</tr>
</tbody>
</table>

Limestone:

| CaO     | C       |
| 49.80%  | 85.00%  |
| SiO₂    | SiO₂    |
| 6.40    | 5.50    |
| MgO     | S       |
| 1.20    | 1.00    |
| FeO     | CaO     |
| 1.00    | .45     |
| P       | MgO     |
| .02     | .30     |
| S       | P       |
| .01     | .03     |

Basis of calculations = 25 lb. of ferromanganese: Assay = 80% Mn

Manganese balance:

Mn needed = 25lb x .80 = 20 lb.
Mn from nodules = 4% x Mn/MnO₂ = 2.53% + 59.13% = 61.66%
Weight of nodules required = 20 lb/Mn/61.66 lb. Mn per 100 lb. = 32.3 lb.

Fe balance:

Sources of Fe
1. Nodules = .026 x 32.3 lb. = .84 lb.
2. Iron ore = .56 lb Fe/ 1 lb. of iron ore
Weight of iron ore required = 3.00 - .84/.56 = 3.86 pounds

Carbon balance:

1. Carbon to reduce MnO₂: MnO₂ + 2C = Mn + 2CO
\[
0.04 \times 321 \text{ lb. MnO}_2 = 0.0147 \text{ mole MnO}_2 \times 24 \text{ lb. C/mol MnO}_2 = 0.353 \text{ lb. C}
\]
2. Carbon to reduce Mn₃O₄:  \( \text{Mn}_3\text{O}_4 + 4C = 3\text{Mn} + 4\text{CO} \)

\[
\frac{.82 \times 32 \text{ lb. Mn}_3\text{O}_4}{229 \text{ lb. Mn}_3\text{O}_4/\text{mole}} = \frac{.1145 \text{ mole Mn}_3\text{O}_4 \times 48 \text{ lb. C/mole Mn}_3\text{O}_4}{5.5 \text{ lb. C}} = 3\text{Mn} + 4\text{CO}
\]

3. Carbon to reduce FeO:  \( \text{FeO} + C = \text{Fe} + \text{CO} \)

\[
\frac{.026 \times 3.86 \text{ lb. Fe}}{56 \text{ lb. Fe/mole}} \times 12 \text{ lb. C/mole Fe} = \frac{.0215 \text{ lb. C}}{12 \text{ lb. C/mole}}
\]

4. Carbon to reduce Fe₂O₃:  \( \text{Fe}_2\text{O}_3 + 3C = 2\text{Fe} + 3\text{CO} \)

\[
\frac{.80 \times 3.86 \text{ lb. Fe}_2\text{O}_3}{160 \text{ lb. Fe}_2\text{O}_3/mole} \times 36 \text{ lb C/Mole Fe}_2\text{O}_3 = \frac{.695 \text{ lb. C}}{36 \text{ lb C/Mole}}
\]

5. Carbon for the ferromanganese:  \( 25 \text{ lb} \times .06 = 1.5 \text{ lb. C} \)

Total carbon is the sum of 1 through 5 = 8.07 lb.

Coke necessary to furnish this amount of carbon = \( \frac{8.07 \text{ lb C}}{.85 \text{ lb. C/lb. coke}} = 9.8 \text{ lb. coke} \)

CaO and SiO₂ balance:

1. Nodules  \( \text{SiO}_2 = (.071+.0047) \times 32 = 2.43 \)
\( \text{CaO} = .0524 \times 32 = 1.68 \)

2. Iron Ore  \( \text{SiO}_2 = .066 \times 3.86 = .255 \)
\( \text{CaO} = .0576 \times 3.86 = .222 \)

3. Coke  \( \text{SiO}_2 = .055 \times 9.8 = .54 \)
\( \text{CaO} = .0086 \times 9.8 = .084 \)

Total SiO₂ = 3.22 lb.

Total CaO = 1.99 lb.

4. Ferromanganese  \( \text{SiO}_2 = .01 \times 25 = .25 \text{ lb.} \)

5. Limestone  \( \text{CaO available in the limestone} = (49.8+.168+.78) - \frac{63\% \text{CaO} \times 6.4\% \text{SiO}_2}{37\% \text{SiO}_2} = 41.36 \% \text{CaO available in the limestone} \)

Weight of SiO₂ in the slag = 3.22 - .25 = 2.97 lb.

Weight of slag = 2.97/.37 = 8.03 lb.

Weight of CaO in the slag = 8.03 - 2.97 = 5.06 lb.

Weight of CaO that must be added = 5.06 - 1.99 = 3.07 lb.

Weight of limestone that must be added to give the required CaO = 3.07 \text{ lb.} \times .4136 = 7.45 \text{ lb.} \)

Summary: The following weights of materials must be added to produce 25 lb. of ferromanganese.

Nodules  32.3 lb.
Iron Ore  3.86
Coke  9.80
Limestone  7.45
Appendix III

Calculation of the efficiency of power consumption of test number eleven.

The efficiency of power consumption was calculated on the basis that a 100% efficient furnace requires 3000 kilowatt-hours per long ton of ferromanganese. This value was given by Anaconda\(^5\) as the power consumption in their ferromanganese furnaces. Although this figure does not represent 100% efficiency, it will serve as a basis to compare the efficiency of the industrial furnace to the Lectromelt laboratory furnace.

Calculations:

wattmeter reading of 100 = 40 Kw

\[
\text{power input} = 0.95 \times 40 \text{ Kw} \times 1 \text{ hour} = 38 \text{ Kw-hr.}
\]

\[
\text{power consumption} = 38 \times 4.13 \text{ lb} \times 2240 \text{ lb/long ton} = 20,600 \text{ Kw-hr./l.t.}
\]

\[
\frac{3000 \text{ Kw-hr./l.t.}}{20,600 \text{ Kw-hr./l.t.}} \times 100 = 14.5\% 
\]