This thesis is submitted for partial satisfaction of the requirements for the degree of Engineer of Metallurgy

By

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June, 1954
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INTRODUCTION

This thesis is a description of an effort to adapt rotary kilns to a new process. The rotary kiln is the largest piece of moving equipment available to industry. All the intricacies of its mechanical operation are known, but adapting the rotary kiln to a new process poses many problems. It is difficult to interpolate data from other processes using rotary kilns and the basic technology has not advanced to the state where one can use a set of standard formulas.

The first section covers laboratory and pilot plant work, with the conclusions drawn from this work. The next section deals with the theoretical concepts of heat transfer and illustrates typical examples of the type of process calculations that were made during the months of plant design. Considerable effort was expended in an attempt to correlate the work of others so it would be applicable to our problem. The final section contains drawings and some calculations, which, in general, deal with the mechanical aspects of kiln design.
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<td></td>
</tr>
</tbody>
</table>
SECTION 1

PROCESS DEVELOPMENT
AN ACCEPTABLE PRODUCT WAS FIRST MADE IN THE LABORATORY IN A SINTERING POT. THE FIRST LINE OR REASONING DICTATED THE USE OF CALCIUM CHLORIDE TO VOLATILIZE THE LEAD AS LEAD CHLORIDE. THE FOLLOWING IS A TYPICAL RESULT:

<table>
<thead>
<tr>
<th>SINTERING POT</th>
</tr>
</thead>
<tbody>
<tr>
<td>CaCl₂</td>
</tr>
<tr>
<td>6%</td>
</tr>
</tbody>
</table>

These tests were followed by a series of tests using an induction furnace with charge in a combustion tube. The furnace was charged at 700°C and the temperature raised to 1100 - 1150°C. For these tests 3% - 5% calcium chloride was the addition agent. These tests were conducted for periods of one hour and two hours. The following is a typical result:

<table>
<thead>
<tr>
<th>INDUCTION FURNACE</th>
</tr>
</thead>
<tbody>
<tr>
<td>Concentrate</td>
</tr>
<tr>
<td>CaCl₂</td>
</tr>
<tr>
<td>6%</td>
</tr>
<tr>
<td>5%</td>
</tr>
</tbody>
</table>

From the laboratory results it appeared that a Dwight Lloyd machine would be the best machine to accomplish the job as outlined. The 12" x 72" Dwight Lloyd sintering machine at the Boulder City Station, U.S. Bureau of Mines, was rebuilt so as to provide a bed depth of ten and one-half inches to duplicate commercial practice.

The feed was pelletized in a revolving drum which had a trommel screen (1/2 in. openings) attached to it. The screen undersize was a round pellet. The additions to the charge were 5% calcium chloride and 10% minus 8 mesh petroleum coke. The concentrate had about 35% moisture.
The draft fan did not pull sufficient draft for a ten inch bed and the bed had to be reduced to six inches. Several tests were made using this six inch bed. The analysis of the sinter indicated a high loss of manganese, ostensibly by volatilization. Due to these unsatisfactory results the sintering tests were discontinued.

**Dwight Lloyd Sintering Machine**

<table>
<thead>
<tr>
<th>CHARGE</th>
<th>SINTER</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn %</td>
<td>Pb %</td>
</tr>
<tr>
<td>40.3</td>
<td>2.71</td>
</tr>
</tbody>
</table>

It was then apparent that the problem could best be solved by use of a rotary kiln.

A great number of heat balances were made, using various combinations of feed, varying percentages of water in the feed, different feed rates, etc. After studying these balances it was decided that the operation should be accomplished in two passes for these reasons:

1. If the raw feed with an excess of combustible material were to be fed to a single kiln which would nodulize and calcine in one step, there would be a high temperature zone in the center of the kiln which would cause ringing of the material on the refractory lining.

2. If the fusion temperature of the charge should vary as the composition of the charge might vary, the kiln would be difficult to hold stable, due to ringing in zones not adjacent to the boring bar.

3. In the case of a single pass the exit gas temperatures would be high and the gas velocities would also be very high, making a gas difficult to handle, with a high dust loading.

The calcine operation can be likened to the incineration of hard-to-burn carbonaceous material. There is enough calorific value in the raw feed to evaporate the water contained in the feed and to keep the material at sufficient temperature to fully burn or volatilize all of the combustibles.
SECTION 1
Part A

PILOT PLANT (Continued)

As such the kiln used for this purpose is not a furnace in which we are interested in transferring heat to the charge from an exterior source, such as a burner, but an incinerator in which we are trying to burn the whole feed. The critical points are not heat transfer rates, but mass velocity, gas velocity, volume, etc.

On the other hand, the nodulizing kiln will require "process" heat to be transferred to the charge. It is in this phase of operation where complex chemical reactions take place and the concentrate is heated to incipient fusion and nodulized.

It was on this basis that the pilot plant tests were undertaken at the Bureau of Mines, Boulder City Station, Boulder City, Nevada. The appended table is a condensation of the various combinations of tests that were made and the assay results. A typical log of one test run is also appended to illustrate the means of obtaining data.

There were several considerations made when using this kiln, one of them being that the gas velocity and the mass velocity were very low. These low velocities gave very light dust loadings in the exit gases which might not be true in a big machine. Because of the small diameter (22 inches) heat transfer due to radiation would be different than in a machine with a large diameter and a greater ratio of length to diameter. However, it was attempted to keep the percentage loadings, by volume, comparable to a commercial machine, as well as to control the atmosphere above the charge. The following engineering data was used for direct interpolation to a large machine: retention time of charge, physical state of charge, nature and chemical composition of the dust, and optimum furnace atmosphere. Previous work accomplished by the U.S. Bureau of Mines was used as a guide.
SECTION 1
Part A

TYPICAL DATA SHEET

from

PILOT RUN

Test No. 1 - NODULIZING

Date of Test: 19 October 1951


Frank Trotter Joel Morris Carl Merrill

Kiln Data:

Length - 23' - 0"
Ins. Dia. - 1' - 10"
RPM - .5
Retention Time - 1 hour
Peripheral Speed = 2,80 ft./min.
Fuel - P.S. 200
Draft - Stack
Loading = 6% feed 4% discharge
Charge Temp. - 160°F
Feed Rate - 350 lbs./hr.
TYPICAL DATA SHEET from PILOT RUN (Continued)

TEMPERATURES:

<table>
<thead>
<tr>
<th>Gases above Charge</th>
<th>Nodules</th>
<th>Sta. 1</th>
<th>Sta. 3</th>
<th>Exit Gas</th>
<th>Time</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>1860°F</td>
<td></td>
<td></td>
<td></td>
<td>11:07</td>
</tr>
<tr>
<td></td>
<td>2100°F</td>
<td>1950°F</td>
<td>500°F</td>
<td></td>
<td>11:50</td>
</tr>
<tr>
<td>Roof</td>
<td>2100 F</td>
<td></td>
<td></td>
<td></td>
<td>11:55</td>
</tr>
<tr>
<td>2300°F</td>
<td>2150°F</td>
<td></td>
<td></td>
<td></td>
<td>12:00</td>
</tr>
<tr>
<td>2700°F</td>
<td>2175°F</td>
<td></td>
<td></td>
<td></td>
<td>12:10</td>
</tr>
<tr>
<td></td>
<td>1400°F</td>
<td>525°F</td>
<td></td>
<td></td>
<td>12:30</td>
</tr>
<tr>
<td></td>
<td>2050°F</td>
<td>1350°F</td>
<td></td>
<td></td>
<td>12:35</td>
</tr>
<tr>
<td></td>
<td>1950 F</td>
<td></td>
<td></td>
<td></td>
<td>12:50</td>
</tr>
<tr>
<td></td>
<td>2050°F</td>
<td>1500°F</td>
<td>550°F</td>
<td></td>
<td>1:45</td>
</tr>
<tr>
<td>2600°F</td>
<td>2075°F</td>
<td></td>
<td></td>
<td></td>
<td>3:20</td>
</tr>
</tbody>
</table>

LOG:

11:07 Feed
11:55 Fuming at 2000°F
12:10 Stack smoke clear - nodules forming well
12:50 Will not nodulize at 1950°F
1:45 Nodulizing at 2100°F some fines - nodules tough some MnO
2:10 Changed feed to charge 2 - coke mixed dry 36#
2:30 Pb fuming 1700° - 1875°F
3:20 No ringing at 1600°F - some ringing at 1850°F
SECTION 1
Part A

TYPICAL DATA SHEET from PILOT RUN (Continued)

GAS ANALYSIS:

<table>
<thead>
<tr>
<th>Time</th>
<th>CO₂</th>
<th>O</th>
<th>CO</th>
</tr>
</thead>
<tbody>
<tr>
<td>11:50</td>
<td>5%</td>
<td>13.4%</td>
<td></td>
</tr>
<tr>
<td>12:45</td>
<td>4.6%</td>
<td>15.6%</td>
<td>0.1%</td>
</tr>
<tr>
<td>2:10</td>
<td>6.2%</td>
<td>13.6%</td>
<td>0.2%</td>
</tr>
</tbody>
</table>

ASSAY OF NODULES:

<table>
<thead>
<tr>
<th></th>
<th>Mn</th>
<th>S₁₀₂</th>
<th>Al₂O₃</th>
<th>Pb</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.805</td>
<td></td>
<td>10.90</td>
<td>3.96</td>
<td>.66</td>
</tr>
<tr>
<td>1.815</td>
<td></td>
<td>10.94</td>
<td>3.59</td>
<td>.91</td>
</tr>
</tbody>
</table>

OBSERVATIONS & CONCLUSIONS:

1. The temperature range for the fuming of Pb is 1650°F - 1950°F.

2. It is necessary to reach 2100°F to nodulize. The charge will definitely not nodulize at 2000°F.

3. Nodules produced were hard and tough with a small percentage of fines. When nodules were quenched in H₂O, some MnO was formed. However, when nodules were air-cooled no MnO was indicated.

4. No ringing was observed at 1600°F; some indications at 1950°F.

5. It is quite difficult to cool nodules by spraying with H₂O as the larger ones retain considerable heat. Feeding this material on a belt would be difficult due to temperatures.

6. Weight of one cubic foot of nodules - 130# angle of repose = 45°

7. In the course of nodulizing it is evident gas temperatures above the charge exceed charge temperatures by 400°F.
### RESUME OF TEST DATA

#### ROTARY KILN

<table>
<thead>
<tr>
<th>Coke</th>
<th>CI Heads</th>
<th>CALCINE</th>
<th>NODULE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Time</td>
<td></td>
</tr>
<tr>
<td>5%-3/16&quot;</td>
<td>3.1% 36.8%</td>
<td>3.25% 44.1%</td>
<td>30 min.</td>
</tr>
<tr>
<td>5%-3/16&quot;</td>
<td>3.08% 36.2%</td>
<td>2.45% 40.7%</td>
<td>40 min.</td>
</tr>
<tr>
<td>2-1/2%-3/16&quot;</td>
<td>3.24% 36.6%</td>
<td>2.81% 42.1%</td>
<td>60 min.</td>
</tr>
<tr>
<td>5%-3/8&quot;</td>
<td>2.74% 36.3%</td>
<td>2.87 41.5%</td>
<td>60 min.</td>
</tr>
<tr>
<td>5%-3/8&quot;</td>
<td>2.74% 36.3%</td>
<td>2.54% 40.8%</td>
<td>60 min.</td>
</tr>
<tr>
<td>4%-1/4 1/8&quot;</td>
<td>2.78% 36.8%</td>
<td>2.97% 40.0%</td>
<td>60 min.</td>
</tr>
<tr>
<td>7-1/2%-3/8&quot;</td>
<td>2.63% 37.3%</td>
<td>2.13% 40.0%</td>
<td>60 min.</td>
</tr>
<tr>
<td>4%-3/8 1/8&quot;</td>
<td>2.62% 36.4%</td>
<td>2.52% 40.2%</td>
<td>60 min.</td>
</tr>
<tr>
<td>3-1/2-1/8&quot;</td>
<td>2.62% 36.4%</td>
<td>2.52% 40.2%</td>
<td>60 min.</td>
</tr>
<tr>
<td>CaCl 1.5%</td>
<td>2.63% 37.0%</td>
<td>2.66% 40.5%</td>
<td>60 min.</td>
</tr>
<tr>
<td>HCl 4%</td>
<td>2.63% 37.0%</td>
<td>2.53% 40.25%</td>
<td>60 min.</td>
</tr>
<tr>
<td>4%</td>
<td>2.63% 37.0%</td>
<td>2.53% 40.25%</td>
<td>60 min.</td>
</tr>
</tbody>
</table>
CHEMISTRY OF THE PROCESS

The finished nodulized product must meet the following specifications: 3/

1. Maximum of 15% combined Alumina and Silica
2. Maximum of 12% Phosphorus
3. Minimum of 45% Manganese
4. Maximum of 14% Iron
5. Maximum Iron to Manganese ratio 1:10
6. Maximum Copper, Lead and Zinc = 1%
7. Maximum Copper = 25%
8. Not more than 5% - 20 mesh
9. Be agglomerated into solid masses

The concentrate as it comes from flotation will not meet these specifications, as it contains about 24% Lead, and it is from 40% - 42% Manganese.

The rotary kilns have six principal functions which result in the production of a satisfactory product. They are as follows:

1. Evaporation of water
2. Removal of reagents by combustion
3. Fusing the fine concentrate into nodular masses
4. Partial reduction of manganese mineral
5. Reduction of the gypsum contained in the concentrate
6. Reduction and volatilization of the lead contained in the concentrate

The last three functions are chemical in nature and are outlined in further detail.

A. REDUCTION OF MANGANESE

The manganese in the concentrate is in the wad form. It is mostly manganese oxide with some percentages of the other oxides of manganese present. When in a reducing atmosphere, as provided by coke, and at temperatures of about 700°F and above, the minerals of manganese that are present are reduced to form a series of manganese oxides, including MnO, MnO₂, and MnO₂. There is a limited amount of MnO formed. It can readily be identified by its bright green color.
CHEMISTRY OF THE PROCESS (Continued)

B. DECOMPOSITION OF GYPSUM

Gypsum is decomposed to form calcium oxide at 1200°C. This same reaction can be accomplished by the addition of coke at about 800°C. This calcination results in a weight loss of almost 50%, and inasmuch as there is sometimes 10% by weight of gypsum present, the concentrate is upgraded considerably by this reduction.

C. VOLATILIZATION OF LEAD

The lead in the concentrate probably exists in a complex mineral form. It could be loosely bonded with silica or alumina. It is the author's opinion that the lead is reduced or partially reduced, and reacts with the gypsum and other sulfate minerals and is volatilized as lead sulfate.

Due to these reactions the manganese concentrate is upgraded from 115% to 120% of the manganese assay of the concentrate,
CONCLUSIONS OF PILOT PLANT WORK

A. BURNING OF FLotation REAGENTS

No difficulties were encountered in burning reagents and evaporating water. It is necessary to maintain a supply of preheated air above the charge to be calcined to insure combustion of reagents. At times it was impossible to operate the kiln with the burners off, only using the fuel in the charge for heat to evaporate water. It may be possible to operate the large kiln without a burner for similar periods. It appears that a temperature of about 650°F must be maintained to keep the volatilized hydrocarbons burning. By calculation, if a slurry of 60% water is fed to the kiln, the burners will have to be used and this would require about 2 GPM of fuel. Unless a kiln is purchased especially designed for handling slurry, the slurry might run half way down the kiln, as was experienced in the pilot kiln. This would cut the retention time in half and create an intolerable operating condition.

B. TEMPERATURES REQUIRED

The base nodulizing temperature was between 2000°F and 2100°F for the sample nodulised. If the silica and alumina exist in a higher percentage than 11% - 12% in the feed, we would expect that the fusion temperature would be lower. Temperatures which exceeded 2000°F produced a nodule which was completely fused and more brittle than nodules produced at lower temperatures. The gas temperatures exceeded the charge temperature by approximately 700°F.

Calcining may be accomplished in the range of 1000°F without detrimental effect (see coke sizing). On the calcining operation it seemed necessary to raise the charge to about 1000°F before it was oil free. The oil elimination, of course, depends on sufficient retention time for combustion. A retention time of thirty-five to forty minutes yielded an oily product. With a sixty-minute retention time, the cake was discharged clean, dry, and oil-free.

C. EXCESS AIR

Preliminary runs were made without considering the percentage of excess air. It was decided to control the atmosphere so as to duplicate actual operating conditions. For economic reasons about 20% excess air would be optimum, but the percentage excess air is a question of fuel oil economies and the capacity of the gas handling and cleaning system.
SECTION 1
Part C

CONCLUSIONS OF PILOT PLANT WORK (Continued)

D. EFFECT OF COKE SIZING

When the coke was screened, and fine coke eliminated (minus 1/8"), lead losses in the calcine were reduced to a minimum. It is indicated that sized coke, for example, minus 3/8", plus 1/8", could be added to the calcine kiln without volatilizing lead, but without a doubt, a percentage of coke would be consumed. Generally speaking, with the exclusion of fine coke in the calcine kiln, the question of whether coke should be added to the nodulizer or calciner is a mechanical problem and should not effect the process. There are certain economic studies which could best be made in regard to coke during actual plant operation.

E. ADDITION REAGENTS

In the event it is necessary to add chlorides to effect volatilization of the lead, HCl as a source of chlorine should be seriously considered in preference to calcium chloride. Hydrochloric acid could be combined with the manganese oxides to form manganese chloride, which would provide a source of chlorine without diluting the nodule as calcium chloride would do. Hydrochloric acid as such has proven effective in laboratory tests for volatilization of the lead. Due to the free energy of the components and their respective heats of combination, manganese chloride will react more readily with lead than calcium chloride.

F. VOLATILIZATION OF LEAD

An analysis of the fume collected identified the lead fume as about 70% lead sulfate; the other portion being lead oxide, chloride, hydroxide, etc. The identity of these compounds is not surprising because at no time during any nodulizing tests were the temperatures high enough to eliminate any quantity of lead in any form other than chloride or sulfate. In order of vapor pressures, lead chloride is first followed by sulfate, then oxide. We can safely conclude that the lead in the Three Kids concentrate will have to be eliminated as chloride or sulfate. It should be noted here when chloride additions were made to the kiln, pink fumes of manganese chloride were observed at the stack. This volatilization of manganese could not be tolerated from the standpoint of lowering the product grade and also a product loss.
CONCLUSIONS OF PILOT PLANT WORK (Continued)

F. VOLATILIZATION OF LEAD (Continued)

When considering critical temperatures, in reference to lead volatilization, it should be remembered that at about 1900°F incipient fusion of the mineral surfaces begins. At this point the charge is changing from a mixture of solids to a molten solution and at this temperature or point selective volatilization of lead stops. This is, of course, due to the fact that the lead is occluded in the molten mass and there is no longer great surface for the fume to escape from. The fact that the fusion point is a function of the chemical constituents of the charge, which at times may vary, probably accounts for the erratic results obtained in lead elimination. A time of an hour and a half to two hours was required for proper lead elimination without a chloride addition.
ELECTRON MICROPHOTOGRAPH - LEAD SULFATE FUME - 25,000 DIAMETERS MAGNIFICATION
SECTION 11

PROCESS ENGINEERING
SECTION 11

PROCESS ENGINEERING

The process calculations necessary to evaluate the equipment and establish operating criteria are described in this section. Part A, a theoretical discussion of heat transfer in rotary kilns, is an attempt to correlate the work of many investigators and apply them to this specific problem.

The calculation sheets on the calcine kilns, Part B, include a heat balance and other data, such as mass velocity. The calculation sheets on the nodulizing kiln include a heat balance and make use of the equations developed in the discussion of heat transfer in rotary kilns to ascertain if the equipment is of correct size, Part C. It is the author's opinion that with this information an engineer who has general acquaintance with chemical and metallurgical problems could rate and judiciously select equipment for any process using rotary kilns.
The technology of heat transfer in rotary kilns is limited in scope. This, of course, is partially due to the fact that the greatest percentage of these furnaces have been used in the cement industry. The technology of making cement has been developed from an Edisonian approach and, therefore, selection of equipment has largely been done with that philosophy. Furthermore, the kiln has had rather limited application and difficulty has been experienced in accumulating design data with universal application. In the case of a new problem, as in the calcining of manganese concentrates from the Lord Process, in which there is no previous operation to consult, the kiln must be tailored to fit the problems of a special occasion.

In essence, a rotary kiln is a rotating furnace, consisting of a large tubular steel shell, lined with refractory, operated at high temperatures. Heat is generated from fuel, such as oil, coal, or natural gas. These hot gases impart heat to the furnace charge and to the refractory linings. The refractories in turn radiate their captive heat to the exposed surface of the furnace charge and, by contact, give heat to the bottom of the charge bed.

The exchange of heat in a rotary kiln is then effected in three ways: radiation, convection, and conduction. These phenomena are complicated in our case by secondary combustion of the charge bed and by the complicated reactions of reduction of the manganese mineral, reduction of the gypsum, etc., and the series of reactions which end in the volatilization of the lead. The formula of Fourier, Stefan-Boltzman and others, require considerable thought before they may be used to estimate heat transfer rates. The usual formula used in stationary furnaces do not conveniently lend themselves to this problem.

Heat transfer in rotary kilns used in the cement and lime industry has been studied in great detail by Gygi and Gilbert. There have been several other engineers who have evaluated these rates, both theoretically and practically. Unfortunately the equations in the literature are not readily adaptable to other materials than cement, such as manganese. Most people who operate kilns take no data and are chiefly concerned with their own problems and prefer to solve them in an empirical fashion.
The following is an attempt to set up enough equations and empirical comparisons to determine the capacity and size of the kilns for calcining and nodulizing the manganese concentrate. No attempt was made to confine these criteria to close limits, but only to use them as a yardstick by which to take intelligent measure of the problem. In the first kilns, which act as dryers and incinerators, some of the more complex problems of transfer by radiation, etc. are not too critical as there is an excess of heat in the combustibles contained in the charge. The great problems are the nature of the kiln atmosphere, mass rate, gas velocity, etc. In the kiln which is used for nodulizing and reduction heat is transferred at high temperatures and all the considerations of heat transfer are important.

As one would expect, at high temperatures the greatest percentage of heat is transferred by radiation. Gilbert 11/ and Cygi 9/ found that approximately 50% to 70% of the heat transferred to the charge in cement kilns was by radiation.

Hottel 15/ has described the phenomena of radiation between gases and furnace linings and his equations evaluating this transfer is adapted here for use in estimating radiation between the surface of the charge and the hot gases in the kilns.

\[ Q = 0.17 A_c E_c \left[ E_G \left( \frac{T_G}{100} \right)^4 - e_G \left( \frac{T_c}{100} \right)^4 \right] \]  (1)

The quantity of heat transferred as evaluated by the equation is for a foot-long section of kiln, where \( A_c \) is the chord length of charge surface in square feet.

Hottel 15/ states that furnace surfaces considered have emissivities from 0.7 to 1.0. \( E_c \) the apparent emissivity of the charge surface is approximately the average of the charge emissivity and one. \( E_G \) is the emissivity of gases at flowing temperatures and \( e_G \) is the emissivity of gases as evaluated by Hottel. 15/

Equation 1 may be used to determine heat transfer from gases to refractory lining by substituting the area of refractory exposed to the gas and lining temperatures. The exchange of heat from the refractory to the charge can be evaluated by the following equation:
SECTION 11
Part A

HEAT TRANSFER IN A ROTARY KILN (Continued)

\[ Q = 0.17 A_c \left( \frac{1 - \frac{E_g}{e_c}}{\frac{1}{e_c} + \frac{A_c}{A_R} \left( \frac{1}{e_c} - 1 \right)} \right) \left[ \left( \frac{T_R}{100} \right) \frac{H}{T_T} - \left( \frac{T_C}{100} \right) \frac{H}{T_T} \right] \]  \hspace{1cm} (2)

These equations evaluate the heat exchanged in one foot sections, perpendicular to the horizontal axis of the kiln. Heat could also be transferred by the hotter gases and surfaces being in proximity to the cooler surfaces. This is considered to be of small magnitude as the ratio of diameter to length of kilns is large and the absorptive power of the combustion gases is great.

The refractory lining of the kiln is heated by the gases of combustion as they flow through the kiln. This heating continues until equilibrium temperatures are reached. The bricks are then cooled when contact is made with the material. As the kiln rotates the cooled walls again reach equilibrium with the gases. There is of course heat lost through the walls.

It seems reasonable to make certain simplifications to eliminate extraneous factors. It can be observed that a layer of charge remains almost stationary in relation to the adjacent lining until it cascades. By Schmidt's graphical method it was calculated that the penetration of heat into manganese calcine is about 2 inches. As the kiln diameter is large, the surface of this layer, for practical purposes, can be treated as flat.

These assumptions indicate that transfer by conduction in a kiln is similar to the heat exchange occurring when a wall at temperature \( T_1 \), comes in sudden contact with a surface at temperature \( T_2 \). A derivation based on the application of Fourier's formula to this type of problem is:

\[ Q = 2K \left( \frac{T_R - T_C}{T_T} \right) \sqrt{\frac{H}{\pi D_T}} \]  \hspace{1cm} (3)

where \( Q \) is equal to BTU's per hour per square foot of charge surface contacting the lining in \( H \) hours. The circumference area requires about one revolution to complete one heating cycle. The total surface completing a circuit in an hour is the circumferential area divided by the revolutions per hour. By proportion, since the total area of surface under the charge is \( A_v \), this area makes \( \frac{1}{H} \) circuits per hour

\[ Q = 2K A_v \left( \frac{T_R - T_C}{T_T} \right) \sqrt{\frac{\pi D_T H}{\pi D_T}} \]  \hspace{1cm} (16)
HEAT TRANSFER IN A ROTARY KILN (Continued)

The transfer of heat by convection is relatively unimportant in a rotary kiln. Several investigators have calculated $2/10\%$ from 1\% to 6\% of the total heat is transferred by convection.

The standard formula given for convection between a gas and its bounding surface is:

$$ Q = U A_c \left( t_g - t_c \right) $$

$$ U = 0.04 \frac{C_p (a)}{D' \cdot 2} $$

$U =$ Coefficient of convection heat transfer (BTU per sq. ft. per °F per hour)

$A_c =$ Area chord surface of charge (sq. ft.)

$t_g =$ Average temperature of gas

$t_c =$ Average temperature of charge

$C_p =$ Specific heat. BTU per lb. per °F.

$G =$ Mass rate lbs. per sq. ft.

$D'$ = The effective diameter equal to four times the open area divided by the periphery.

The equations developed in the above discussion on heat transfer in rotary kilns will be used in the heat and material balances of Parts B and C to estimate the capacities of the various kilns.
SECTION 11
Part B

CALCINE KILNS

HEAT BALANCE

Data Given:

Feed - 21.95 T/H ea. Kiln

Feed Composition - (Flotation Concentrate)

<table>
<thead>
<tr>
<th>Component</th>
<th>Rate (T/H)</th>
<th>Rate (lbs./min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mineral (40% Mn)</td>
<td>11.55</td>
<td>385.0</td>
</tr>
<tr>
<td>Oil, Soap, Oronite</td>
<td>2.45</td>
<td>81.7</td>
</tr>
<tr>
<td>Water</td>
<td>6.95</td>
<td>232.0</td>
</tr>
<tr>
<td>Coke</td>
<td>1.00</td>
<td>33.3</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>21.95</strong></td>
<td><strong>732.0</strong></td>
</tr>
</tbody>
</table>

Reagent Composition

<table>
<thead>
<tr>
<th>Component</th>
<th>Rate (lbs./min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diesel Oil</td>
<td>57.5</td>
</tr>
<tr>
<td>Tall Oil Soap</td>
<td>19.2</td>
</tr>
<tr>
<td>Oronite (Sodium Sulfonate)</td>
<td>5.0</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>81.7</strong></td>
</tr>
</tbody>
</table>

Temperatures

(a) Feed 70° F

Product 1000° F

(b) Gases

Inlet to Burner 70° F

Flame - None intermittent

Exit - To be Calculated

Specific Heats

<table>
<thead>
<tr>
<th>Component</th>
<th>Specific Heat (BTU/# °F)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Gases</td>
<td>.26</td>
</tr>
<tr>
<td>Mineral</td>
<td>.15 @ 70° F, .21 @ 1000° F</td>
</tr>
<tr>
<td>Oil</td>
<td>.50 @ 70° F</td>
</tr>
<tr>
<td>Water</td>
<td>1.00 @ 70° F</td>
</tr>
</tbody>
</table>

Bulk Gravities

<table>
<thead>
<tr>
<th>Component</th>
<th>Bulk Gravity (#/cu.ft)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feed</td>
<td>85</td>
</tr>
<tr>
<td>Calcine</td>
<td>53</td>
</tr>
</tbody>
</table>
SECTION 11
Part B

CALCINE KILNS (Continued)

Particle Size
80% minus 200 mesh

Type Kiln
Counter - Current

Kiln Size
Shell Diameter = 8' 0", 7' 0" I.S. Refractory
Shell Length = 150' 0"
Volume = 5780 FT^3
Refractory 6" thick

Heat Gain
Diesel Oil (18,000 BTU/#) 57.5 #/min 1,030,000 BTU/min
Soap (6,000 BTU/#) 19.2 #/min 115,000 BTU/min
Oronite (4,000 BTU/# est.) 5.0 #/min 20,000 BTU/min

Result: 1,165,000 BTU/min

Heat Losses
(a) Evaporation of Water
232 #/min  70° F to 212° F
(1150.2 BTU/# - 38 BTU/#) = 1112.2 BTU/#
(1112.2 BTU/#) (232 #/min) = 258,000 BTU/min

(b) Shell Radiation
Log Mean Temp. Diff. Estimated
@ 400° F

Area Shell (150') (7') (8') = 3770 FT^2

Combined Coefficient
Chart 113 A 50 (Std. Steel Corp.)
5.5 BTU/FT^2 HR °F

(3770 FT^2)(5.5 BTU/FT^2 °F HR)(400° F) =
8,300,000 BTU/HR

or 138,000 BTU/Min

(19)
SECTION 11
Part B

CALCINE KILNS (Continued)

Heat Losses (Continued)

(c) Loss to Product

\[(385\#/\text{Min})(0.24 \text{ BTU/##°F})(1000\#^\circ \text{ F})\] - 92,000 BTU/Min

Summary

Heat Gain

(a) Combustion of Reagents

1,165,000 BTU/Min

Heat Loss

(a) Evaporation of Water 258,000 BTU/Min
(b) Shell Radiation 138,000 BTU/Min
(c) Loss to Product 92,000 BTU/Min
(d) Loss to Gases (by difference) 677,000 BTU/Min

Temperature of Gases

81.7#/Min Fuel

@ 30% Excess Air 18#/ Air/# Fuel *

* Fan Engineering Buffalo Forge Co.

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\[(61.7#/\text{Min})(18#//#) = 11470 \# \text{ Air/Min}\]

\[235 \# \text{ Water/Min}\]

\[677,000 \text{ BTU/Min} = (11470\#)(0.26 \text{ BTU/##°F})(T) + (235\#)(0.50 \text{ BTU/##°F})T\]

\[T \text{ exit gases} = \frac{677,000}{499} = 1360^\circ \text{ F}\]
SECTION 11
Part B
CALCINE KILNS (Continued)

Temperature of Gases (Continued)

This temperature may be high as it is calculated on the basis of complete oxidation of the hydrocarbons. We could expect some distillation, etc., and therefore estimate the exit gas temperatures at

1000°F to 1400°F

Volume of Gases

Assume 1200°F
Altitude 1800 Ft.

\[ V_{\text{AIR}} = \left( \frac{1.170\% \text{ Prod. of Comb. & Air}(1000°F + 460°F)}{30°F/\text{mol}} \right) \times \left( \frac{359 \text{ ft}^3/\text{mol}}{28.02} \right) \]

\[ V_{\text{AIR}} = 59,700 \text{ CFM} \]

\[ V_{\text{H}_2\text{O}} = \left( \frac{235\% \text{ H}_2\text{O}(1000°F + 460°F)(359 \text{ ft}^2/\text{mol})(29.92)}{460°F} \right) \]

\[ V_{\text{H}_2\text{O}} = 15,800 \text{ CFM} \]

Total \( V = 75,500 \text{ CFM} \)

Mass Velocity

\[ \text{Kiln Area} = \pi \times 3.50^2 = 38.5 \text{ ft}^2 \]

\[ \text{Mass Vel.} = \left( \frac{1.170\%/\text{lin} + 235\%/\text{lin}}{38.5 \text{ ft}^2} \right) \times 60 \text{ Min/hr} \]

\[ \text{Mass Vel.} = 2680\%/\text{ft}^2/\text{hr} \]

This is a high mass velocity. 1200%/ft^2/hr would be about a normal value.

Gas Velocity

\[ G_v = \frac{75,500 \text{ CFM}}{38.5 \text{ ft}^2} \]

\[ G_v = 1950 \text{ ft/min} \]

This is a high value and will promote high dust loadings. A normal velocity should be below 1000 ft/min.
Calculation of saturated volume & saturation temperatures calcine kiln gases after leaving scrubbing tower

**Given:** 75,000 CFM @ 1400° F which is equivalent to 11470# Air & 235 # H2O

**Required:**
- Saturated Volume, Saturation Temperature, Volume to I.D. Fan

1. **Humidity of Hot Gas**
   \[ H = \frac{235\# H_2O}{11470\# Gas} = 0.16 \# H_2O/\# Dry Gas \]

2. **Total Heat Content/# Hot Gas**
   - Water Vapor
     \[ Q = (C_P)(H)(T)(W) = 0.46(0.16)(1400 - 32)(1) = 106 BTU/# \]
   - Latent Heat Water Vapor
     \[ Q = (1400 - 32\#)(0.16) = 220 BTU/# \]
   - \( \Delta H \) Dry Gas
     \[ Q = (C_P)(W)(H)(T) = 0.26(1)(1/#)(1400 - 32) = 354 BTU/# \]
   - **Total Heat**
     \[ 680 BTU/# \]

*At adiabatic conditions the heat content of 680 BTU/# dry gas corresponds to a saturated gas at 179.2° F. At 179.2 a saturated gas has a volume of 324 ft³ per pound of dry gas, therefore (11470# dry gas)(324) = V @ 179.2° F

\[ V @ 179.2° F = 47,600 CFM \]

This is the volume of gas leaving wet scrubber & entering fan.

*From a standard psychrometric chart.*
SECTION 11
Part C

NODULIZING KILN

HEAT BALANCE

Given:

Feed – Dry Calcine 838#/min, 53#/FT³ @ 800°F
Petroleum Coke 66.6#/min

Discharge – Nodules 750#/min, 130#/FT³ @ 2100°F

Required:

Heat loss to product, radiation
Exit gases
Burner Fuel Requirement
Mass & Gas Velocity
Determine if kiln is correct size for heat transfer

Heat Gain

1. Calcine
   \[(838#/\text{min})(24 \text{ BTU/# °F})(800 \text{ °F}) = 161,000 \text{ BTU/min}\]

2. Coke (assume 25% combustion)
   \[(66.6#/\text{min})(12,000 \text{ BTU/#}) = 200,000 \text{ BTU/min}\]

3. Burner Fuel
   To be calculated

Heat Loss

1. Shell Radiation
   Log Mean Temp. Diff. Est. @ 500°F
   Area Shell = \[(150')(7')(10') = 4710 \text{ FT}^2\]
   Combined Coefficient
   Chart 113 A 50 (Std. Steel Corp.)
   \[5.5 \text{ BTU/FT}^2 \text{ HR °F}\]
   \[H = (4710 \text{ FT}^2)(5.5 \text{ BTU/FT HR °F})(500 \text{ °F}) = 12,900,000 \text{ BTU/HR} = 216,000 \text{ BTU/min}\]

2. Nodules
   \[H = (750#/\text{min})(26 \text{ BTU/# °F})(2100 \text{ °F}) = 409,000 \text{ BTU/min}\]
Weight of Air for Combustion

Assume 50% Excess Air

\[(20\# \text{ Oil}/\text{Min})(21.5 \# \text{ Air}/\# \text{ Oil}) = \# \text{ Air}/\text{Min}\]

\[\# \text{ Air}/\text{Min} = 430\]
SECTION 11
Part C

NODULIZING KILN (Continued)

Volume Gas at Max. t and at Exit t

\[ V_{@\text{Max}} = \left( \frac{\text{W/h}}{\text{Min}} \right) \left( \frac{359 \text{ FT}^3/\text{MOL}}{30\#/\text{MOL}} \right) \left( 300^\circ \text{F} \right) \left( \frac{29.92'' \text{ Hg}}{\text{Hg}} \right) \]

\[ V_{@\text{Max}} = 3000 \text{ CFM} \]

\[ V_{@\text{Exit}} = 17,000 \text{ CFM} \]

Kiln Sizing

Assume 10' Diameter

6'' Kiln Block = 9'0'' I.D.

Area Kiln Section = (4.5^2) \pi

\[ = 63.5 \text{ FT}^2 \]

Mass Velocity

\[ \frac{25,800 \# \text{ Gas/Hr}}{63.5 \text{ FT}^2} = \text{Mv} \]

\[ = 406#/\text{FT}^2 \text{ Hr} \]

This is a low value and will give low dust loadings in exit gases.

Gas Velocity

\[ V_G = \frac{17,500 \text{ CFM}}{63.5 \text{ FT}} \]

\[ V_G = 275 \text{ FT/Min} \]

A low value which will create low dust loads in exit gases.
SECTION 11
Part C
MODULIZING KILN (Continued)

Kiln Length

Using formulas developed in the section on heat transfer in rotary kilns, we will evaluate the quantity of heat that can be transferred in a chosen machine. In order to do this we will evaluate the heat transferred at 25 ft. stations in the kiln. The following is a profile of the gas and charge temperatures in a 10' diameter by 150 ft. long kiln:

<table>
<thead>
<tr>
<th>Station</th>
<th>Charge Temp.</th>
<th>Gas Temp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>25</td>
<td>2100°F</td>
<td>3000°F</td>
</tr>
<tr>
<td>50</td>
<td>1810°F</td>
<td>2600°F</td>
</tr>
<tr>
<td>75</td>
<td>1580°F</td>
<td>2200°F</td>
</tr>
<tr>
<td>100</td>
<td>1320°F</td>
<td>1800°F</td>
</tr>
<tr>
<td>125</td>
<td>1060°F</td>
<td>1400°F</td>
</tr>
<tr>
<td>150</td>
<td>800°F</td>
<td>1000°F</td>
</tr>
</tbody>
</table>

For example we will evaluate the transfer at station 25 here:

1. Heat Transfer by Radiation - Gases to Charge

\[ Q_1 = 0.17 \times A_C \times \epsilon_c \times \left( \frac{e_G}{100} \right)^{1/4} \times \left( \frac{T_G}{100} \right)^{1/4} \]

\[ Q_1 = 0.17 \times (7.0) \times (0.92) \times \left( \frac{3160}{100} \right)^{1/4} \times \left( \frac{2560}{100} \right)^{1/4} \]

\[ Q = 38,800 \text{ BTU/hr} \]

2. Heat Transfer by Radiation - Walls to Charge

\[ Q_2 = 0.17 \times A_C \left( \frac{1 - \epsilon_G}{\epsilon_c} + \frac{A_C}{A_W} \left( \frac{1}{\epsilon_c} - 1 \right) \right) \times \left( \frac{T_R}{100} \right)^{1/4} \times \left( \frac{T_c}{100} \right)^{1/4} \]

(26)
SECTION 11
Part C

Heat Transfer by Radiation - Walls to Charge (Continued)

\[ Q_2 = (0.17)(7.0) \left[ \frac{1 - 0.38}{\frac{1}{2} + \frac{7}{20.5} \left( \frac{1}{2} - 1 \right)} \right] \left[ \left( \frac{3460}{100} \right)^4 - \left( \frac{2560}{100} \right)^4 \right] \]

\[ Q_2 = 650,000 \text{ BTU/Hr} \]

3. Heat Transfer by Conduction - Walls to Charge

Kiln speed 1 RPM

Area refractory in contact with charge = 7.8 \text{ FT}^2

Inside circumference = 28.3 \text{ Ft}

\[ H = \frac{(7.8)(1)}{(28.3)(60)} \]

\[ H = 0.046 \text{ Contact time charge particle with refractory} \]

\[ D_T = \frac{K}{E_G C_p} \]

\[ D_T = \frac{0.20}{(53)(26)} \]

\[ D_T = 0.045 \]

\[ Q_3 = 2 K A_v (T_R - T_C) \frac{1}{\sqrt{11 H D_T}} \]

\[ Q_3 = \frac{(2)(0.20)(7.8)(900)}{\sqrt{11 (0.046)(0.046)}} \]

\[ Q_3 = 93,000 \text{ BTU/Hr} \]

4. Heat Transfer by Convection

\[ Q_4 = U A_c (t_G - t_C) \frac{0.014 C_p (0)^{0.8}}{D^{0.2}} \]

\[ Q_4 = \frac{(0.014)(0.26)(388)^{0.8}}{(7.5)^{0.2}} \frac{(7)(3460 - 2560)}{(7.5)^{0.2}} \]

\[ Q_4 = 5,600 \text{ BTU/Hr} \]
Heat Transfer (Continued)

<table>
<thead>
<tr>
<th>STATION</th>
<th>RADIATION</th>
<th>RADIATION</th>
<th>CONDUCTION</th>
<th>CONVECTION</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Gas - Charge</td>
<td>Wall - Charge</td>
<td>Wall - Charge</td>
<td></td>
</tr>
<tr>
<td>25</td>
<td>38,800</td>
<td>650,000</td>
<td>93,000</td>
<td>5,600</td>
</tr>
<tr>
<td>50</td>
<td>23,000</td>
<td>372,000</td>
<td>76,000</td>
<td>4,700</td>
</tr>
<tr>
<td>75</td>
<td>12,500</td>
<td>210,000</td>
<td>62,000</td>
<td>3,800</td>
</tr>
<tr>
<td>100</td>
<td>6,150</td>
<td>104,000</td>
<td>48,000</td>
<td>3,000</td>
</tr>
<tr>
<td>125</td>
<td>2,480</td>
<td>43,500</td>
<td>34,000</td>
<td>2,100</td>
</tr>
<tr>
<td>150</td>
<td>660</td>
<td>13,000</td>
<td>20,000</td>
<td>1,200</td>
</tr>
<tr>
<td></td>
<td>83,590</td>
<td>1,392,500</td>
<td>333,000</td>
<td>20,400</td>
</tr>
</tbody>
</table>

Average Transfer Per Foot: 14,000 BTU/hr 232,000 BTU/hr 55,500 BTU/hr 3,400 BTU/hr

Then from the table the total heat that can be transferred per foot of run is 304,900 BTU/hr.

Kiln is 150'-0" long, therefore (150)(304,900) = 45,735,000 BTU/hr can be transferred to surfaces which is considerably greater than the heat required per hour as calculated. We can safely assume that a 10' X 150' kiln will be large enough from a heat transfer standpoint.
SECTION 11

NOMENCLATURE

\( A_c \) Area of chord surface of charge - sq. ft.

\( A_r \) Area of refractory exposed to gas - sq. ft.

\( A_v \) Area of refractory in contact with charge - sq. ft.

\( B_g \) Density lbs. per cubic ft.

\( C_p \) Specific heat at constant press. BTU/# °F

\( D \) Diameter kiln - ft.

\( D' \) Effective diameter kiln - ft.

\( D_T \) Thermal diffusivity - sq. ft./hr.

\( G \) Mass rate - lbs. per sq. ft.

\( E_c \) Emissivity of charge surface

\( K \) Thermal conductivity - BTU per sq. ft. per hr. per °F per ft.

\( H \) Time of contact of charge particle with refractory - hr.

\( E_g \) Emissivity of gases

\( e_c \) Emissivity of charge surface re-absorption considered

\( e_g \) Emissivity of gases at flowing temperature

\( T_c \) Temperature charge surface °R

\( T_g \) Temperature gases - °R

\( T_R \) Temperature refractory - R

\( U \) Coeff. of convection heat transfer - BTU per sq. ft. per °F per hr.
SECTION III
PHYSICAL PLANT

SPECTRAL LINE

#424060
15.00 ft
30.00 ft
20 ft. per sec.
200 ft.
2 hours
72.00 - 75.00
1.0000 - 1.0005
2.0000 - 2.0005
2.0000 - 2.0005
2.0000 - 2.0005
17,900 CFM
245 ft./min
404 pounds per sq. ft. per hour
See Plate No. 3.
200 connection, 72.4 ft. constant
700 flushing pipe
2.25" diameter, 25.44. constant
See Section 2B Specifications.

SPECTRAL LINE

#424060
15.00 ft
30.00 ft
20 ft. per sec.
200 ft.
2 hours
72.00 - 75.00
1.0000 - 1.0005
2.0000 - 2.0005
2.0000 - 2.0005
2.0000 - 2.0005
17,900 CFM
245 ft./min
404 pounds per sq. ft. per hour
See Plate No. 3.
200 connection, 72.4 ft. constant
700 flushing pipe
2.25" diameter, 25.44. constant
See Section 2B Specifications.
### SPECIFICATIONS

#### NODULIZING KILN

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln Diameter</td>
<td>10½&quot;-0&quot;</td>
</tr>
<tr>
<td>Kiln Length</td>
<td>150' 0&quot;</td>
</tr>
<tr>
<td>Kiln Slope</td>
<td>1/2&quot; per ft.</td>
</tr>
<tr>
<td>Kiln Speed</td>
<td>1/2 to 1.2 RPM</td>
</tr>
<tr>
<td>Retention Time</td>
<td>2 hours</td>
</tr>
<tr>
<td>Burner Fuel</td>
<td>2.5 GPH - PS 400</td>
</tr>
<tr>
<td>Burner</td>
<td>Pressure Atomizing (500 PSI)</td>
</tr>
<tr>
<td>Exit Gas Temp.</td>
<td>10000°F</td>
</tr>
<tr>
<td>Flame Temp.</td>
<td>3000°F</td>
</tr>
<tr>
<td>Material Temp. in</td>
<td>800°F</td>
</tr>
<tr>
<td>Material Temp. out</td>
<td>21000°F</td>
</tr>
<tr>
<td>Gas Volume out</td>
<td>17,000 CFM</td>
</tr>
<tr>
<td>Exit Gas Velocity</td>
<td>275 FT/Min</td>
</tr>
<tr>
<td>Mass Velocity</td>
<td>4,06 pounds per sq. ft. per hour</td>
</tr>
<tr>
<td>Total HP @ RPM</td>
<td>See Plate No. 3.</td>
</tr>
<tr>
<td>Kiln Drive</td>
<td>20&quot; diameter, 20 ft. penetration</td>
</tr>
<tr>
<td>Boring Bar</td>
<td>70% alumina brick</td>
</tr>
<tr>
<td>Refractory</td>
<td>super-duty fire clay - 6&quot;</td>
</tr>
<tr>
<td>First 50'</td>
<td>kiln block</td>
</tr>
<tr>
<td>50' - 150'</td>
<td>See Brickwork Specifications</td>
</tr>
</tbody>
</table>

#### CALCINE KILNS

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Kiln diameter</td>
<td>8' 0&quot;</td>
</tr>
<tr>
<td>Kiln Length</td>
<td>150' 0&quot;</td>
</tr>
<tr>
<td>Kiln Slope</td>
<td>9/16&quot; per ft.</td>
</tr>
</tbody>
</table>
SECTION III
Part A

SPECIFICATIONS (Continued)

Calcine Kilns (Continued)

<table>
<thead>
<tr>
<th>Kiln Speed</th>
<th>6 to 2.0 RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Retention Time</td>
<td>60 Min.</td>
</tr>
<tr>
<td>Burner Fuel</td>
<td>When needed</td>
</tr>
<tr>
<td>Burner</td>
<td>Mechanical Atomizing</td>
</tr>
<tr>
<td>Exit Gas Temp.</td>
<td>1400° F</td>
</tr>
<tr>
<td>Material Temp. in</td>
<td>70° F</td>
</tr>
<tr>
<td>Material Temp. out</td>
<td>1000° F</td>
</tr>
<tr>
<td>Gas Volume out</td>
<td>75,000 CFM</td>
</tr>
<tr>
<td>Exit Gas Velocity</td>
<td>1950 FT/Min.</td>
</tr>
<tr>
<td>Mass Velocity</td>
<td>2680 lb. per sq. ft. per hr.</td>
</tr>
<tr>
<td>Total HP @ RPM</td>
<td>14.40 @ 1.4 RPM</td>
</tr>
<tr>
<td>Kiln Drive</td>
<td>See Plate No.</td>
</tr>
<tr>
<td>Refractory</td>
<td>1500 High Duty Fire Clay</td>
</tr>
<tr>
<td></td>
<td>6&quot; Kiln Block</td>
</tr>
<tr>
<td></td>
<td>(See Brick Specifications)</td>
</tr>
</tbody>
</table>

COOLER

<table>
<thead>
<tr>
<th>Cooler Diameter</th>
<th>8.0&quot;</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cooler Length</td>
<td>98.0&quot;</td>
</tr>
<tr>
<td>Cooler Slope</td>
<td>7/16 in. per ft.</td>
</tr>
<tr>
<td>Cooler Speed</td>
<td>1.58 RPM</td>
</tr>
<tr>
<td>Retention</td>
<td>40 Min.</td>
</tr>
<tr>
<td>Nodule Temp. in</td>
<td>2100° F</td>
</tr>
<tr>
<td>Nodule Temp. out</td>
<td>600° F</td>
</tr>
</tbody>
</table>
SECTION 111
Part B

CALCULATION OF SLOPE AND SPEED

of the

NODULIZING KILN

\[ T = \frac{1.77\sqrt{Q}}{(S)(D)(N)} \]

* U.S.B.M., Tech. Paper
No. 384, 1927

\[ T = \text{Retention time of material (mins.)} \]
\[ Q = \text{Angle repose material (degrees)} \]
\[ L = \text{Length shell (feet)} \]
\[ D = \text{Diameter inside lining (feet)} \]
\[ S = \text{Slope shell (degrees)} \]
\[ N = \text{Speed shell (RPM)} \]

<table>
<thead>
<tr>
<th>Slope per Ft.</th>
<th>S</th>
</tr>
</thead>
<tbody>
<tr>
<td>1/4&quot;</td>
<td>1.19°</td>
</tr>
<tr>
<td>5/16&quot;</td>
<td>1.49°</td>
</tr>
<tr>
<td>3/8&quot;</td>
<td>1.79°</td>
</tr>
<tr>
<td>7/16&quot;</td>
<td>2.087°</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>2.39°</td>
</tr>
<tr>
<td>9/16&quot;</td>
<td>2.68°</td>
</tr>
<tr>
<td>5/8&quot;</td>
<td>2.98°</td>
</tr>
</tbody>
</table>

\[ Q = 45° \]

90 Mins. Retention

\[ 90 = \frac{1.77\sqrt{45}}{(150)} \]

\[ SN = 2.2 \]

(32)
CALCULATION OF SLOPE & SPEED OF THE NODULIZING KILN (Continued)

120 Mins. Retention

$$120 = \frac{1.77\sqrt{15}}{(9)(5)(N)}$$

$$SN = 1.63$$

<table>
<thead>
<tr>
<th>Slope</th>
<th>90 Min. Retention RPM</th>
<th>120 Min. Retention RPM</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/8&quot;</td>
<td>1.23</td>
<td>.91</td>
</tr>
<tr>
<td>7/16&quot;</td>
<td>1.10</td>
<td>.78</td>
</tr>
<tr>
<td>1/2&quot;</td>
<td>.92</td>
<td>.68</td>
</tr>
<tr>
<td>9/16&quot;</td>
<td>.82</td>
<td>.60</td>
</tr>
<tr>
<td>5/8&quot;</td>
<td>.74</td>
<td>.55</td>
</tr>
<tr>
<td>1/4&quot;</td>
<td>1.05</td>
<td>1.36</td>
</tr>
<tr>
<td>5/16&quot;</td>
<td>1.47</td>
<td>1.10</td>
</tr>
</tbody>
</table>

It appears from chart that a slope of 1/2" per foot will give reasonable speeds and consequently the power required to drive kiln will not be excessive.
SECTION 111
Part C

CALCULATION OF
TOTAL HORSEPOWER REQUIRED
TO DRIVE NODULIZING KILN

Total Horsepower = Load Horsepower + Friction Horsepower

(1) Friction Horsepower

\[ HP = \left( \frac{W}{rd} \right) (bd)(td)(N)(F)(0.0000110) \]

\[ W = \text{Vertical load on roller shaft bearings - in lbs,} \]
\[ bd = \text{Roller shaft bearing diameter - in inches} \]
\[ rd = \text{Roller diameter - in inches} \]
\[ td = \text{Riding ring diameter - in inches} \]
\[ F = \text{Coefficient friction oil lubricated bearings} \]
\[ N = \text{RPM shell} \]

(2) Load Horsepower

\[ HP = (D \times \sin\theta)^3(N)(L)(K) \]

\[ D = \text{Inside diameter (inside refractory)} \]
\[ \sin\theta = \text{Vertical axis of kiln intercepted at center of kiln by a line which originates at the point where the charge surface touches the kiln lining bounds} \]
\[ N = \text{RPM kiln shell} \]
\[ L = \text{Length of shell - in feet} \]
\[ K = 0.00110 \text{ based on angle of repose of approximately 45} \]
SECTION 111
Part C

CALCULATION OF TOTAL HORSEPOWER REQUIRED TO DRIVE NODULIZING KILN

(1) Friction Horsepower

\[ HP = \left( \frac{713,000 \#}{12'} \right) \left(\frac{1\frac{1}{4}'}{12'}\right) \left(0.92\right) \left(0.018\right) \left(0.0000110\right) \]

\[ HP = 5.35 \]

(2) Load Horsepower

\[ HP_a = \left[ (9\frac{1}{2}'' \times 0.78)^3 \times 130' \times 0.00110 \times 0.92 \right] \]

\[ HP_a = 45.0 \]

\[ HP_b = \left[ (10\frac{1}{2}'' \times 0.66)^3 \times 20' \times 0.00110 \times 0.92 \right] \]

\[ HP_b = 5.9 \]

Total Running Horsepower @ .92 RPM = 5.35 + 45.0 - 5.9 = 56.25 H.P.
APPENDICES
APPENDIX

REFRACTORY SPECIFICATIONS

SCOPE OF WORK

Work to be accomplished is as designated in the following drawings:

- EM-U535-9.6-11
- EM-U535-9.6-18
- EM-U535-9.6-19
- EM-U535-9.6-25
- EM-U535-10.6-1
- EM-U535-10.6-5
- EM-U535-10.6-6
- PA 886-1

And (2) Two 150' X 8' I.D. kilns - 6" kiln brick
(1) One 150' kiln consisting of 112'-1/2 of 10' I.D., 20' of 11'-6" I.D., and two sections 8'9" long tapering from 10' I.D. to 11'-6" I.D.

(1) One rotary cooler 68' X 8' I.D.

CONDITIONS

The bidders will quote price for labor and supervision including all miscellaneous costs as to payroll tax, subsistence, transportation, etc. Bids are to cover complete installation costs: The rotary kiln, etc., are available for inspection at the jobsite and the contractors are invited to make this inspection as no extra fees will be paid for special fitting and cutting of bricks.

All bricks are to be laid in a workmanlike manner by skilled masons and work is to be accomplished according to the following specifications

BRICKWORK SPECIFICATIONS

1. All employees shall be especially skilled for the kind of work for which they are employed and shall work under the direction of a competent foreman. All bricklayers shall be union members and belong to the local which has jurisdiction in the Las Vegas area.

2. Brick shall be dry before being laid.

3. For straight wall and sprung arch construction, brick shall be laid with dipped or buttered joints, as shown on drawings, then tapped into place with brick masons hammer to create thinnest possible mortar joint.
APPENDIX (Continued)

Brickwork Specifications (Continued)

4. In lining the rotary kilns the brick shall be laid in sections not to exceed twelve feet in length. Approximately 55% of each ring shall be laid for the twelve feet, packed in place then the kiln shall be rotated 90° for placement of additional brick. A second rotation of about 60° shall be made to complete the rings. Key brick to be cut to exact size. No metal spacers are to be used to make up for errors in cutting key brick. Brick to be grouted after laying with a mixture of fourteen (14) quarts of water and one hundred (100) pounds of fire-clay, or quick-setting cement where appropriate, this mixture swept in all cracks and voids. Bricks shall be laid in rings not spirals. Each ring independent of the other.

5. For straight walls, navy anchors will be used at appropriate spots to secure lining to steel shell.

6. Each course of brick must be laid continuously until keyed. Under no circumstances will it be permissible to have a course of brick, row or ring, remain overnight without being keyed or temporarily wedged.

7. All brick cuts to be made with a mechanical saw to proper size.

8. If bricks are to be handled by contractor they should be moved in rubber tired wheelbarrows or sprung carts.

9. Bricks will be stacked on edge with laths in horizontal joints.

10. Adequate precautions must be taken for expansion joints in the firing hoods.

11. Vertical joints to be staggered where possible to provide best bond.

12. Walls to be carried up in level courses, one at a time, rather than building opposite sides and filling in.

13. All wall openings used for instrument sleeves or peepholes should be neatly finished and packed with long fibre asbestos or similar material to prevent air leakage.
The Three Kids deposit of manganese was discovered in the fall of 1917, according to Jones. Since that time considerable energy has been spent by private industry and agencies of the Government in an effort to produce metallurgical grade manganese concentrate from the low grade ores of the deposit. All of these attempts failed to produce a metallurgical grade product economically.

The U. S. Bureau of Mines at Boulder City conducted large scale pilot runs using flotation as a means of beneficiation. They tried to de-slime the ore and float the various fractions with cationic type reagents. These runs were not successful. In 1942 the Government financed the construction of a plant at the Three Kids Mine. It was operated by the H. A. Hanna Company. This plant used a hydro-metallurgical process where the ore was leached with sulfurous acid and formed manganese sulfate. The manganese sulfate was purified, then reduced in a rotary kiln to manganese dioxide. Due to the physical and chemical nature of the ore, the plant failed to produce a product economically, and was closed.

With the benefit of this past experience, the management of Manganese, Inc. decided that the only scheme that was economically feasible was bulk flotation without sizing or de-sliming.

Southwestern Engineering Company was commissioned to develop a means of beneficiating the Three Kids ore. This work was carried out under the direction of Mr. Robert Lord, Chief Metallurgist.

After several hundred tests were made, a successful combination of reagents was developed.

The following tables give typical laboratory results on ores containing about 25% manganese and 19% manganese.

### TYPICAL RESULTS ON ORE OF 25% MANGANESE CONTENT

<table>
<thead>
<tr>
<th>Content</th>
<th>Wt. %</th>
<th>% Mn</th>
<th>% $S_{2}O_{3}$</th>
<th>% $Al_{2}O_{3}$</th>
<th>% Distrib. of Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assayed Head</td>
<td>100.</td>
<td>24.89</td>
<td></td>
<td></td>
<td>100.0</td>
</tr>
<tr>
<td>Calc. Head</td>
<td>92.7</td>
<td>25.02</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-Dried Concentrate</td>
<td>49.2</td>
<td>13.59</td>
<td>9.25</td>
<td>2.04</td>
<td>85.8</td>
</tr>
<tr>
<td>Cleaner Tails</td>
<td>11.5</td>
<td>11.07</td>
<td>6.73</td>
<td></td>
<td>6.4</td>
</tr>
<tr>
<td>Rougher Tails</td>
<td>29.0</td>
<td>6.73</td>
<td></td>
<td></td>
<td>7.8</td>
</tr>
</tbody>
</table>
The Plant Flow Sheet (Continued)

**TYPICAL RESULTS ON ORE OF 19% MANGANESE CONTENT**

<table>
<thead>
<tr>
<th>Content</th>
<th>Wt. %</th>
<th>% Mn</th>
<th>% S1O2</th>
<th>% Al2O3</th>
<th>% Distrib of Mn</th>
</tr>
</thead>
<tbody>
<tr>
<td>Assayed Head</td>
<td>100.0</td>
<td>18.92</td>
<td></td>
<td></td>
<td>100.0</td>
</tr>
<tr>
<td>Calculated Head</td>
<td>90.7</td>
<td>18.86</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Re-Dried Concentrate</td>
<td>33.0</td>
<td>43.6</td>
<td>7.60</td>
<td>2.15</td>
<td>75.2</td>
</tr>
<tr>
<td>Comb. Cleaner Tails</td>
<td>25.7</td>
<td>12.22</td>
<td></td>
<td></td>
<td>16.7</td>
</tr>
<tr>
<td>Rougher Tails</td>
<td>32.0</td>
<td>4.77</td>
<td></td>
<td></td>
<td>8.1</td>
</tr>
</tbody>
</table>

**CHARACTER OF THE ORE**

Practically all of the manganese oxide is porous, brown, earthy wad. The ore has tremendous surface and according to Hewet is a sedimentary deposit consisting of wad interbedded with lake or playa sediments belonging to the Muddy Creek formation of the Pliocene Age. The manganese minerals other than wad consist of minor percentage of psilomelane and magnetite. The gangue is composed of quartz, gypsum, feldspar, tuff, micas, clay, opal, strontionite. There are also small percentages of lead, copper and zinc. The table below gives an analysis of three stock piles of ore.

**ANALYSIS OF STOCKPILES**

<table>
<thead>
<tr>
<th></th>
<th>#1</th>
<th>#2</th>
<th>#3</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mn</td>
<td>29.5</td>
<td>24.1</td>
<td>18.2</td>
</tr>
<tr>
<td>Na</td>
<td>1.31</td>
<td>1.01</td>
<td>1.15</td>
</tr>
<tr>
<td>K</td>
<td>1.96</td>
<td>1.77</td>
<td>1.84</td>
</tr>
<tr>
<td>Ca</td>
<td>1.00</td>
<td>1.42</td>
<td>2.14</td>
</tr>
<tr>
<td>Mg</td>
<td>0.92</td>
<td>0.86</td>
<td>1.70</td>
</tr>
<tr>
<td>S</td>
<td>0.61</td>
<td>0.65</td>
<td>0.60</td>
</tr>
<tr>
<td>S1O2</td>
<td>25.15</td>
<td>32.25</td>
<td>42.25</td>
</tr>
<tr>
<td>Al2O3</td>
<td>5.65</td>
<td>7.00</td>
<td>8.50</td>
</tr>
<tr>
<td>Fe</td>
<td>1.35</td>
<td>2.02</td>
<td>2.07</td>
</tr>
<tr>
<td>CO2</td>
<td>0.64</td>
<td>1.23</td>
<td>1.07</td>
</tr>
</tbody>
</table>

Loss on ignition 1000 C

Stockpile 67,414 lbs. cu. ft.

The laboratory tests were followed by full scale pilot flotation tests which confirmed the laboratory results.
As indicated on the appended flow sheet the plant is sized to handle approximately 1450 tons per day of ore containing approximately 18% water.

The ore is trucked from the mine and dumped into a hopper feeding the primary jaw crusher. The five inch crusher discharge is fed to a rod deck screen where the screen undersize is fed to a belt conveyor and the over size is fed to an impact crusher. The secondary crusher product is also fed to the same belt and is conveyed to blending and bedding bins. The ore which is now crushed to 90% minus 2" is fed to rod mills in closed circuit as shown on the flow sheet.

The ground ore which is about 90% minus 200 mesh is then fed the conditioners where the following reagents are added per dry ton of mill feed:

- Diesel Oil 120#/Ton
- Tall Oil Soap 40#/Ton
- Sodium Sulfonate 7.5#/Ton
- Sulfur Dioxide 8.5#/Ton

These reagents with the exception of Sulfur Dioxide are prepared in a special plant where they are metered with proportioning pumps then emulsified as a water phase emulsion which is then pumped to reagent storage. The Sulfur Dioxide is metered to an absorption tower where sulfurous acid is made continually and added to the circuit.

The pulp is conditioned for about 15% minus at 15% solids. It is then diluted to about 10% solids and fed to rougher cells, this rougher concentrate is cleaned four times.

The reagents probably function along these lines. The sulfurous acid reacts with manganese dioxide to form manganese sulfate. The manganese sulfate reacts with the Tall Oil Soap to form an insoluble manganese soap. This soap deposits on the mineral surface, which is then in proper condition for flotation.

The soap acts as a collector, the oil as a surface conditioner, and the sodium sulfonate is an intermediate agent allowing froth formation.
PROCESS FLOW (Continued)

The concentrate is thickened, filtered, and conveyed to the kilns for further treatment. The pyrometallurgical phenomenon are fully discussed in the other sections of this thesis.
APPENDIX C

LIST OF DRAWINGS

<table>
<thead>
<tr>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLOW SHEET</td>
<td>42</td>
</tr>
<tr>
<td>PLOT PLAN</td>
<td>43</td>
</tr>
<tr>
<td>CALCINING KILNS</td>
<td>44</td>
</tr>
<tr>
<td>NODULIZING KILN</td>
<td>45</td>
</tr>
<tr>
<td>NODULE COOLER</td>
<td>46</td>
</tr>
<tr>
<td>CALCINER DRIVE</td>
<td>47</td>
</tr>
<tr>
<td>NODULIZER DRIVE</td>
<td>48</td>
</tr>
</tbody>
</table>
NOTES:
- DEEP LINES OUTLINE OUTSIDE DIMENSIONS OF CONCRETE FOOTINGS FOR BASE PLATE. BASE PLATE DIMENSIONS NOT TO EXCEED MEASUREMENTS AS INDICATED. % OF KILN FALLS ON INSIDE DIMENSION OF BASE PLATE FOOTING.

DRIVING ANGLE OF MAIN PINION IS 30° FROM THE VERTICAL.

DIRECTION OF ROTATION GIVEN WHEN OBSERVED IS FACING DRIVING END OF KILN.

SOME OF KILN 7/8" O.D. NEAR Firing END.

Firing END OF KILN

Operating Speed of KILN - 1.6 R.B.O.

KILN TURNS CLOCKWISE

KILN TURNS COUNTER CLOCKSWISE

Working End of Kiln

ST. SOM AR A. MNTOR. FRAME 50"X4
SPEED REDUCER, 115 G.P.M., 115:1
SPEED REDUCER, 115 G.P.M., 115:1
Gear, 11/2 Teeth, 4" C.R., 1/2, 40°, 12" Face
Pinion, 15 Teeth, 2" G.A.R., 12° Face
Coupling, 420 F
Coupling, 42
Coupling, 42
FALK REDUCER F.C.
KILN ENGINE NO. 11 N.
Kiln, 150'-6", 6'-1/2" O.D.
Firing End of Kiln

Operating Speed: 9 R.P.M.

Elect 15 HP A.C. Motor
650 to 1,550 R.P.M.

Speed Reducer, 12 Gears, 17:1

Coupling 280 F

Coupling 10:1

Pinion, 32" D., 3" O.A.

Gear, 17" D., 1" O.A.

Kiln Turn, 9620 F

Reducer

Kiln Engine, Mod. XAH

Kiln, 150'" 10', 10' 14" 1/2, 10'

Girth Gear

Notes:
Dotted lines outline outside dimensions of concrete footings for base plate. Base plate dimensions not to exceed measurements as indicated.

Kiln falls on inside dimension of base plate footing.

Driving angle of main pinion is 30° from the vertical.

Kiln turns clockwise when the observer is facing firing end of kiln.

Slope of kiln 1/16" per ft.

Firing End is low end.
ACKNOWLEDGMENTS

A project of this nature is always a challenge to the Engineer. The solving of these problems is generally accomplished by cooperation among a group rather than by individual effort. The greatest reward from my association with this project was not in the rich technical experience gained, but from the many friends I made from my associates. It is to those friends, the staffs of Manganese, Incorporated, and Southwestern Engineering Company, I say Thank You.
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