CALCULATION OF FURNACE CHARGES.

By the calculation of a furnace charge is usually meant the adjustment by computation of fluxes to the ore (and sometimes to the ash of the fuel) in a smelting furnace, so as to secure, so far as calculation goes, the formation of a slag of required composition.

It is rarely possible to figure the outcome with precision, even granting the conditions of good sampling and smooth running.

The best approach to theoretical results is found in iron smelting. The reason is obvious enough. The only "variants" in this case are:

1. The iron which may enter the slag.

2. Variation in amount of silica which may enter the metal, as silicon.

It is otherwise in lead and copper smelting, where the difficulties of fumes and of the absorption of undesired metal in the slag are complicated by very uncertain factors such as the oxidation of sulphides to a degree greater or less than estimated.

The total absence of "matte" from the iron furnace—nothing being allowed to enter the charge which goes to the formation of that product, constitutes of itself a simplification sufficient to make a "class" of iron smelting as distinct from that of any metal whose ores are charged wholly or partly as sulphides.

Although it is not possible to dispense with intelligent calculations for slag and matte formation, nothing but special experience at a given plant and on given ores and fuel can enable the practitioner to "discount" the inevitable variations.

This fact has been made the basis for countless sneers against the scientific calculation of metallurgical operations. The novice will often be assured that a certain "run" was made without any computation of charges, and numberless are the tales told of the "theorist" who spent a week in calculating his charge and then froze his furnace the first day.

This means that there are many things to learn about smelting other than the computation of correct charges.

That a "run" was made without any calculation may be absolutely true. If the average composition of the material is fairly constant, there is no reason why a charge once established should not continue to serve for an indefinite time. Also to quote from Professor Peters in his "Copper Smelting," "It is almost as hard to damage an improving furnace as it is to better a sickly one." Under first class conditions, then, a considerable variation in slag composition may take place without damage.

Nevertheless there is no better safeguard against mishaps other than those purely mechanical, than a knowledge, clean-cut and scientific, of what you are working for, and of the material with which you are to accomplish your object.

It is futile to pretend that you have any such knowledge unless you are clear as to the composition of your charges, and the theory upon which you are mixing them.

Gone, let us hope, are the days of the old rule: "A lot of ore, a lot of coke, and about a quarter of a lot of limestone."

The author confesses to having seen certain iron furnaces run upon this luminous dictum. He feels bound to add that it was "several" years ago.

By a "slag" is always meant a fusible silicate. No other case at least is considered in these pages.

By a "flux" is meant any substance which, added to a charge, produces fluidity, usually by chemical combination with certain non-metallic ingredients of the ore.

However, an ore may be "self-fluxing." That is, no additions, such as limestone or iron oxide, are needed for successful smelting. In such a case the "flux" is still present, but as a constituent of the ore instead of an artificial addition to it.

A "matte" is a combination of metals with sulphur (also to a less extent with other elements) which settles under the slag in the hearth.* It is frequently the only commercial product of a furnace.

A "speiss" is a basic arsenide of iron, often containing a variety of other metals also. It forms under the same conditions as "matte." Speculations, however interesting as to the

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* That is to say, which should do so.

essential nature and composition of matte, are out of place in this work.

The "charge" of a furnace includes ore, fuel and fluxes. When the composition of all of these is known, we may roughly determine in advance what portions of each will go into metal, matte, slag, fumes or gases.*

Complete "reduction" implies the elimination of the non-metallic portion of a compound, and the production of the metal as such.

$$2PbO + C = 2Pb + CO_2$$
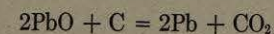
According to this equation the lead oxide is "reduced" and the carbon is "oxidized," the chemical operation being in fact a mere transfer of oxygen. Metallurgically such an operation is spoken of as "reduction," since the "reduced" product (the metallic lead) is the commercial one.

A "matte," although its formation is usually accompanied by both oxidizing and reducing agencies, is properly the resultant of neither. It may be either a "residual" or a direct union compound. For example (1st case):

$$2CuS + O_2 = Cu_2S + SO_2$$
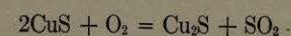
Or, by merely heating:

$$2CuS \text{ (heated)} = Cu_2S + S$$
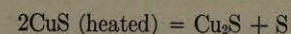
Here the matte (Cu_2S) may be called a "residual" compound, being what is left of the cupric sulphide after the reaction is over.

2nd case: $2Fe_2O_3 + 7PbS = 7Pb + 4FeS + 3SO_2$
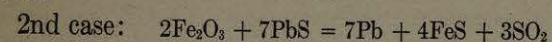
Here the matte (FeS) is evidently no mere "residual," but is formed by a complex chemical interchange.

Let us suppose that we are to smelt a partly roasted (oxidized) ore, containing lead sulphide, zinc sulphide and some oxides of both of these metals, also iron pyrites (FeS_2) copper and silica.

We have limestone ($CaCO_3$) for flux, also hematite (Fe_2O_3).

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* By "fumes" we understand substances dissipated in a gaseous state, but condensing to solids at ordinary temperatures (e.g., PbO; ZnO).

Gases proper do not condense at ordinary temperatures. The usual gaseous products of a furnace are known as "permanent" gases (CO_2; SO_2).

The fuel may be taken as simply carbon.

Special cases with figures will be found later. We have here merely to indicate the general problem, which is to estimate which of these constituents will yield metal, and which matte, slag, fumes or gases. The case is introduced chiefly to point out the somewhat indeterminate nature of the problem, showing that it is not practicable to make accurate predictions as to the relative proportions of these products.

Let us take them singly.

Metal.—Lead is supposed to be the only metallic product here, the theory of the operation being to get all of that metal, *as* metal, while the copper and other elements go into the matte. But no smelting operation will reduce *all* the lead, or at least will not bring it all on the hearth as metallic lead. Some of it will remain in the matte as sulphide, a little will go into the slag, and a variable amount will be dissipated as fumes, either lost or collected as "flue-dust." We start, then, with elements of uncertainty in our calculation-data. If the assumption is made, however, that the whole of the lead will be "tapped," our calculations will not be materially affected.

Matte.—This is a difficult product to figure, regarding probable correspondence of computations to results. It is a very easy matter to throw together (in our calculations) the supposed elements which might go to matte formation, if that were all. For example, take all of the sulphur with so much of the metals as might be supposed to meet chemical formulæ rationally, but this will not do, for there are influences at work to modify so simple a process as the "melting down" of the sulphur with its chosen proportion of metals, to form the matte.

Study of these would lead us astray. We may mention only the variable oxidation of the blast, controlled by temperature, pressure, shape of the furnace and composition of the charge. These variations may result in greater or less oxidation of sulphur and of metals, thus causing change in ratio of matte and slag. It is evident that the more oxidation of metals takes place the more probable it is that these will find their way into the slag instead of the matte. This is often the desired result as to iron, it may be to a limited extent as to zinc, but copper is of course too valuable to waste in the slag, and whether the

operation be one for metal and matte, or for matte alone, copper is always desired in the latter.

Various rules have been given for estimation of composition and amount of matte, *i.e.*, in advance of the operation. Thus Professor Peters in his "Modern Copper Smelting," tenth edition, page 82, says:

"Taking the contents of copper in the charge as a standard for comparison, sufficient sulphur should be allotted to it to form a subsulphide, excess of sulphur remaining being supplied with sufficient iron to form monosulphide of that metal. If other metals are present, such as lead, zinc or manganese, three-fourths of the former, one-half of the second, or one-fourth of the latter substance may be first considered as forming a monosulphide with the sulphur. . . . If the rate of smelting be slow and considerable lime or magnesia be present, 5 per cent. of the sulphur should be deducted before beginning the calculation; and if the furnace is a reverberatory the resulting matte will average 8 per cent. higher in copper than is found by this formula."

Calculations on similar rules will be found among the illustrations.

This calculation, viz: estimating the amounts of metal in matte by combination with sulphur, and then removing the whole combination from subsequent consideration, is called "taking out the matte," and is a necessity in slag calculation.* *What remains after the matte is "taken out" is the basis for slag computation.* There are cases where no matte is "taken out;" these are confined to iron smelting or to those rare cases in other metals where sulphur is entirely absent.

Slag.—Having disposed of these subtractions of metal (if there is any to be allowed for) and matte, the remaining elements, so far as they are solids, are to be combined into a "slag." Illustrations of the procedure will be found in the pages following. Since the subtractions for metal or matte are from the ore alone, no figuring on slag is attempted until these subtractions have been made, so that, practically, "slag calculation"

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* The above quotation from Professor Peters' work applies to smelting for copper matte, not at all to smelting on "lead basis" with matte as an incidental. Practitioners, however, regard their own trial runs as of far greater importance than any set "rules" for matte estimation.

is made not (as a rule) upon the original ore, but only upon the ore "prepared" (on paper) for the calculation, *by the elimination of all except its slagging constituents.*

Fumes.—Probably no metallurgist would attempt to "figure out" in advance the losses by fumes. It has been elsewhere said that in actual running the results by analysis of matte and slag may indicate, although somewhat roughly, the fume losses. These may be important enough to lead to re-calculation of charges.

Fumes may include oxides of lead, zinc, arsenic and several other metals. It is a matter of common knowledge that many substances not particularly volatile in themselves will be carried, and that in no inconsiderable quantities, by more volatile compounds. The phenomenon is by no means confined to smelting operations, but is well known to every laboratory chemist.

Certain compounds of gold, when heated by themselves, decompose readily, the non-metal dissipating, the gold remaining behind. Mix the same compound of gold with others which are entirely volatile, the curious phenomenon is now presented of the gold compound partly resisting decomposition, so that gold will be found in very notable quantity in the collected fumes.

The same is true of every metal. It is useless, then, to assume that a certain constituent will not be found in the fumes, so far as the mere fact goes that it is not *of itself* volatile. Here we have a factor even more uncertain than matte, in forming our estimates.

Gases.—Gases are mainly formed in two ways, first, from combustion of the fuel, and second, from expulsion of carbonic acid gas from limestone. We have also, in many cases, SO_2 gas from combustion of sulphur. They present no obstacles in any case to slag computation. Assume, whenever limestone is charged, that all of its evolved gas is "out" of the computation. Silica unites with CaO. Gas escapes.

The present treatise being almost wholly confined to calculations for slags already assumed, we do not go into the physical properties of their numerous varieties. It is fairly presumable that any person who has use for slag calculations has at hand sufficient data of either reference or experience to know what he should figure for.

There are, however, certain considerations which must be taken into account, on the physical side, brief mention of which is not altogether out of place.

Fusibility is the chief desideratum. As for fusibility at a stated temperature, it is evident that in an iron furnace, with temperature hundreds of degrees above that of any matting or lead furnace, the question of temperature in relation to slag fusion is less important. Hence a very great variation in silica percentage is allowable. No general rule can apply except the statement that nice adjustment of fusibility to estimated temperature is not a practicable idea, but that when it is known that the temperature, from whatever causes, will be low, slags of low-fusion point should be figured for.

Here may come in a complication. Fusibility is not the only requisite. If the more fusible of two possible slags should also be much the heavier, the question of separation of the matte becomes important. It is obvious that separation, *other things being equal,* will be better accomplished when there is a marked difference in specific gravity between slag and matte. Broadly, the more iron oxide, the heavier the slag, while lime lightens it. Unfortunately, iron usually adds fusibility.

Unfortunately, that is, as regards conflict between two desirable properties. The metallurgist has not unfrequently to decide between two slags one of which is the lighter, the other the more fusible.

Still another consideration comes in, in matte separation. It has been remarked * that an "acid" (siliceous) slag lets fall a matte better than an equally light and much "thinner" basic slag, *containing principally alkaline and earthy bases.*

The combination of these principles for the effective separation of slag and matte belongs to the tentative practice of actual operations.

The special conditions of heat and blast, with probably several others, come in to modify slag practice. Rare, indeed, would be the case in which it would be possible to establish all of these conditions in advance.

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* Peters' "Modern Copper Smelting," page 231, tenth edition. The observation is also found elsewhere, though I am unable to quote the work.

In charge calculations we shall assume one hundred pounds of ore as basis of computation. This has been objected to on the grounds (1) of "custom," (2) of "difficulty."

If a "custom" is good it should be retained; if bad, it should be dropped.

As to "difficulty," it is both easier and safer to figure on the 100 basis, and afterward multiply by whatever factor is called for.

This applies especially to our method of "representative equations."

As for starting with "total" charge and then subdividing into ore, fuel and flux, it is so much more "difficult" that argument is uncalled for.

The methods of slag calculation (furnace charges) hitherto used seem to the author to lack generality. However, before introducing a general method, we demonstrate the usual calculation by excess and deficiency. The substance of this has already been given in the stoichiometric part of the work.

A few tables of silicates familiar to all metallurgists are given, as reference matter, also some problems hardly to be classified under any heading in Part I.

Slags having been roughly divided (on the arithmetical side) as either "formulistic" or "percentage," we here point out that while every formula can be readily transformed into a percentage analysis, the converse of this proposition is rarely true.

Nevertheless, the best "recipes" which state percentages are either directly derived from formulistic compounds (Problem III) or they are close approximations to such formulæ.

Computations regarding excess, whether of one constituent over another in the same substance, or as adjustments of one material in the charge to another, have to do mainly with formulistic considerations. In the method finally recommended as the most general, the usage will be to settle upon the formula if such be demanded, *and then reduce to the "percentage" basis.*

In order to familiarize the student with the handling of chemical ratios some examples are introduced in advance of slag calculations proper. They involve metallurgical operations to some extent, but are given as exercises rather than as practical cases.

No new principles are introduced. Every problem falls under one or another case already given.

The calculation of a charge may be made upon the sole basis of *percentages* of the ingredients of the resulting slag. But the student knowing no other method is ill equipped. He should not only recognize chemical relations, but should be ready to figure by their means, in any computation called for.

A few of the examples are purely "stoichiometric," having little connection with practical metallurgy, although involving reasoning of the same character. They will aid in apprehension of the elements of the subject, which are, by the way, easier to grasp and apply than is commonly supposed.

Slags are formulistically classed as "Singulo," "Bi-" and "Sesqui-" silicates.* These terms refer to the ratio of the oxygen in the silica to that in the bases.

Examples.—$2CaO,SiO_2$ is a singulo silicate because oxygen in silica *equals* oxygen in base.

CaO,SiO_2 is a bisilicate because oxygen in the silica is *double* that in the base.

In a sesqui-silicate the oxygen in the silica is *half as much again* as oxygen in the base. Thus: $4CaO,3SiO_2$.

Here we have four atoms of oxygen in the lime and six in the silica, *i.e.*, oxygen in silica is to oxygen in base as $1\frac{1}{2}$ to 1.

This nomenclature is a return to the old "dualistic" form of chemical formulæ. It might perhaps better be called a retention of it.

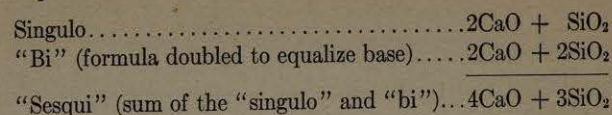See problem III, "Given formula of a compound to deduce its analysis."

Modern forms of the above silicates would be:

$$Ca_2SiO_4; CaSiO_3; \text{ and } Ca_4Si_3O_{10}$$
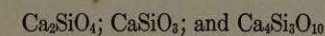
The old forms are far more convenient for the metallurgist, as they exhibit at a glance the oxygen relations of silica and base.

If, in the comparison of these forms, we so write the singulo and the bisilicate as to *equalize the bases*, their sum will then be a sesqui-silicate.

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* We have also, though rarely, some cases of "trisilicates."

Example:

Singulo................................2CaO + SiO₂
"Bi" (formula doubled to equalize base).....2CaO + 2SiO₂
                                          _____
"Sesqui" (sum of the "singulo" and "bi")...4CaO + 3SiO₂
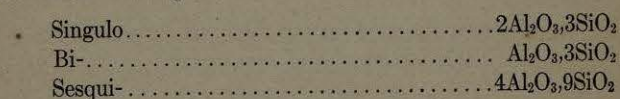
The example takes the same form as already given.

The singulo silicate is the commonest form. In the many cases where no formulæ are supposed to be figured on, but mere "percentages" of constituents are named as required, it will often be found that some "formula" was the original form. It is but a case under the problem adduced above.

It is often said that "in practice" slags are made more acid than formula calls for. They are indeed calculated to a higher percentage of silica at times, but this is to offset uncalculated bases, which come in to set the silica percentage back to its proper proportion.

As most of the metals entering into slags are bivalent, the formulæ usually show the arrangement as given above for lime. Alumina, however, has formula Al_2O_3, hence its silicates have the following formulæ:

Singulo...............................$2Al_2O_3,3SiO_2$
Bi-..................................$Al_2O_3,3SiO_2$
Sesqui-..............................$4Al_2O_3,9SiO_2$

In these formulæ, if we reduce the ratio of oxygen in base to oxygen in silica to lowest terms we still have 1 : 1, 1 : 2, and 2 : 3 as ratios of oxygen in base to oxygen in silica.

It is usually practicable, with the ordinary choice of material available, to secure a slag which shall be "formulistic" so far as regards ratio of oxygen in base to oxygen in silica. But when it comes to a demand for a certain ratio *between bases*, still retaining the oxygen ratios, the condition is quite different, and often impossible.

See example a few paragraphs below.

In showing how to provide material for "excess" and to arrange charges for slags approaching within reasonable limits to the desired formula, we do not lose sight of the fact that we are chiefly interested in showing how to compute what we may term "percentage" slags.

We should be familiar with both methods of computation. We start with the formulistic idea, and in order not to confuse

the student we do not at first introduce examples of mixed type.

Remember again that any formula may be put into analytical form, and that the transformation is made simply to facilitate calculation in the general or "representative" method, which, although we bring it last in order, *is the one recommended as of most universal application.*

We here present a case of "desired formula," giving the supposed material at command by analysis. It will be found that it is impossible to literally fulfil the theoretical requirement.

The method of calculation has been given, but in "Introductory Problems" a few pages ahead, the exact detail will be found, for which reason the case is not carried out in full, though results are indicated.

We want to produce a slag of the formula:

$$4FeO + 2CaO + 3SiO_2$$
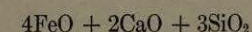
This is a "singulo." Note, however, that the requirement does not end with this proviso. We have not only the formulistic fact that the weight of all oxygen in the bases equals that of all the oxygen in the silica, but the formula calls for *twice as many molecules of iron oxide* (FeO) *as of lime* (CaO).

The following are supposed to be the only available materials at command for the charge:

1. The ore, whose only slagging ingredients are: Silica 20 per cent., and FeO (or its equivalent in other form) also 20 per cent.

2. A limestone containing five per cent. of silica and fifty-three per cent. of lime (CaO).

First, then, calculate for a "singulo" as the formula requires.

The leading results of calculation are here given; the student may verify them as an exercise.

After adjusting SiO₂ and FeO *in the ore* in the required proportion by formula, we find silica excess 11.67. Adjusting also silica and lime *in the limestone* we get CaO excess 43.67. Finally we find that the limestone required will be almost exactly 50 lbs. (Ore 100.)

The slag produced will contain, for every 20 lbs. of iron oxide, no less than $26\frac{1}{2}$ lbs. of CaO. It will, in short, be very far

from the requirement of the formula, *although it will be a perfect "singulo."*

Suppose again that instead of adjusting CaO to the excess silica of the ore we took just enough limestone to yield CaO in the exact required proportion *to the iron*. Of course this could be very easily done, but the result would be that we should *no longer have a singulo silicate*. The *excess of silica* would now be a very material one over that requirement. In practice the metallurgist must now decide whether he will adhere to the "singulo" idea, or accept a more siliceous slag for the sake of the desired ratio between his bases. In all likelihood a compromise figure would be adopted, but discussions of this nature are endless, and we have assumed at the outset that they shall not be gone into to any extent.

This is a good point at which to call attention to the relation of the two oxides of iron. Slags are invariably figured as containing only the FeO form. Per contra, iron (other than sulphide) is introduced into the furnace as Fe_2O_3. To compare these, remember that we must first equalize the iron, comparing Fe_2O_3 with $2FeO$:

Molecular weight of Fe_2O_3 = ...160
Molecular weight of $2FeO$ = ...144

$160 : 144 = 10 : 9$, so that to reduce the higher to the lower oxide (*i.e.*, in passing from analyses to slag calculations) it is only necessary to multiply the percentage of ferric oxide by 0.9 to obtain the percentage of ferrous oxide. This explanation of the reason for the factor 0.9 would hardly have found a place here but for the fact that we recently saw, in actual practice, the curious error of *forgetting the equalization* of the iron in comparing the two oxides arithmetically. The operator had forgotten the factor, and tried to regain it as above, with amazing result. A similar error in other cases of stoichiometrical calculations is by no means uncommon.

INTRODUCTORY PROBLEMS.

(*a*) Ore has: Silica, 40 per cent.; alumina, 20 per cent. We are to calculate on a "singulo" basis, having a limestone analyzing: Silica, 10 per cent.; calcium carbonate, 90 per cent.

It is required to find what weight of limestone must be added to 100 lbs. of the ore, to form a lime-alumina silicate on above basis.

Solution.—We must first find silica excess in the ore itself on the "singulo" basis. Singulo silicate of alumina is $2Al_2O_3 + 3SiO_2$.

Refer here to the problems in excess and deficiency. The silica excess of the ore will be found to be *22. 36 per cent.*

We must next find the CaO excess in the limestone. Enough of the CaO must be taken out of the limestone *to satisfy its own silica*, before we can compute for the ore. In other words, we must get the *CaO excess* of the limestone, and compare it with the *SiO_2 excess* of the ore. Under the condition, this calculation of excess must be for the singulo form. (The method is illustrated for the lime here; it is of course the same as for the alumina above, where answer was given without operation.)

$$SiO_2 : 2CaO = \text{lbs. } SiO_2 : \text{lbs. CaO}$$
$$60 : 112 = 10 : 18.66$$

But the total lime in the limestone is fifty-six per cent. of ninety per cent., that is, $90 \times .56 = 50.4$ per cent. CaO.

Lime required by silica in the limestone being 18.66 per cent., we have: $50.4 - 18.66 = 31.74 =$ excess of CaO or "available" lime.

The problem is now reduced to this: An ore with 22.36 per cent. silica is to be "adjudicated" as to lime silicate with a limestone with 31.74 per cent. lime.

For the *alumina of the ore* is now out of the computation, having been set aside with its proper amount of silica in the first operation.

Also, the *silica of the limestone* is "out" of this final computation, having been set aside with its proper per cent. of lime.