the iron richer in sulphur and poorer in silicon, by impeding the removal of sulphur and the deoxidation of silicon, both of which need a high temperature. But that the gain to be had by drying the blast could be as great as Mr. Gayley has shown not only was unforeseen but, when reported with every detail and warrant of veracity, was promptly rejected by many learned metallurgists as absurd.

339. Reasons for the Fuel Saving. — That removing the variations in the cooling effect of the moisture in the blast by removing the moisture itself should remove a grave cause of irregularity in the working of the furnace, needs no explanation. And that removing a refrigerating substance like moisture from the blast should bring about a fuel-saving far greater than that immediately due to saving the heat needed for its decomposition and heating, becomes clear enough on careful study. The several causes which combine to bring about this at first sight surprising effect can be understood best by looking backwards, taking first the condition of the furnace when using dried blast, and then seeing how this condition is affected by changing from dried to common moist blast. Looking at the subject in this way, it seems to me that the chief reasons why the presence of moisture in the blast increases the fuel consumption so very greatly are these:

First, that, by lowering the temperature developed by combustion in the hearth, it cuts out a large fraction of the relatively narrow margin between the combustion temperature and the "critical" temperature at and above which much of the "critical" work of the furnace (a term to be explained shortly) must be done, and thus lessens proportionately the heat available for that critical work.

Second, this combustion temperature is further lowered, the margin between it and the critical temperature is further narrowed, and the heat available for the critical work thereby further lessened, by the lowering of the temperature of blast which the use of moist blast itself brings about. In Mr. Gayley's case this lowering of the temperature appears to be due to the greater quantity of blast to be heated in stoves of a given size, and not to any increase in the ratio of the weight of blast to be heated to the weight of gas which is to heat it, because there appears to be no material change in the percentage of nitrogen in the waste gases. Indeed the facts seem to indicate that, with moist blast,

his hot blast stoves are overloaded, because, although the ratio of heating gas to blast to be heated seems almost the same with dried as with moist blast,* and although the heating gas is much richer in carbon monoxide, yet the blast was not heated so hot in case of moist as in that of dried blast. This seems to show that an important part of the saving brought about by drying the blast could have been effected by increasing the size of the hot blast stoves.

Third, that, to supply the extra heat which is needed, not only for making good the loss just noted in the heat available for the critical work of the furnace, but also to make good the heat abstracted by the dissociation of the moisture, calls for an altogether disproportionate increase in the fuel consumption, because only a small proportion of the heat developed by this extra fuel can be utilized, with the consequence that so much of this heat as is not utilized must still be present in the waste gases when they escape from the top of the furnace and thus be lost: hence the lowering of the temperature of these gases which Mr. Gayley causes by drying the blast.

Fourth, that this increase, due to moisture in the blast, in the temperature of the gases escaping from the furnace top necessarily causes them more vigorously to attack, dissolve, and carry away the incoming coke by the reaction

$$(27), CO_2 + C = 2CO,$$
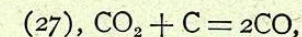
to meet which robbery of coke additional fuel must be charged.

---

* This is easily shown. The composition of the waste gases escaping from the top of the furnace was as follows:

	WITH DRIED BLAST	WITH MOIST BLAST
Carbon monoxide	19.9 per cent	22.3 per cent
Carbon dioxide	16.0 "	13.0 "
Nitrogen and hydrogen, by difference	64.1 "	64.7 "
Total	100.0 per cent	100.0 per cent
Gas temperature	376° F.	538° F.

Thus the quantity of nitrogen per 100, or per unit, of gas was not changed by changing from moist to dried blast, which is the same as saying that the quantity of gas per unit of nitrogen was not changed. But as the nitrogen comes wholly from the blast, and as the quantity of nitrogen per unit of blast is constant, this is the same as saying that the quantity of gas per unit of blast to be heated by that gas was not changed.

340. DISCUSSION. IMPORTANCE OF INITIAL GAS TEMPERA-
TURE IN HEATING PROCESSES WITH A CRITICAL TEMPERATURE.—
Let us now study these reasons, and first let me explain the mean-
ing of " critical " as here used, by the case of the boiling of water.

Here the heating work naturally falls into two distinct parts,
that of heating the water from its initial temperature, say 0° C.,
to its boiling point, which requires relatively little heat; and second
that of boiling it at atmospheric pressure, by making good the
heat made latent by the boiling, which calls for 5.36 times as
much heat. The boiling point may here be called a critical point,
and the work of boiling the water critical work; it is work which
has to be done by heat supplied from above this critical
temperature.

The importance of the idea may be seen by comparing this
operation of boiling water with one which has no critical temper-
ature, such as heating a column of copper balls enclosed in a
vertical shaft with adiabatic walls (i. e., walls through which
absolutely no heat escapes), to 1,000° by means of a stream of
heated gas passing up through that column. Let us assume that
each ball is withdrawn as soon as it reaches 1,000°, but not before.
Ignoring here and throughout this discussion the variations of
specific heat due to variations in temperature, the same quantity
of heat is required to raise a gramme of copper through one
degree at a low temperature as at a high temperature; the same
quantity is needed for each and every degree rise of temperature.

Here recognize clearly that efficient heating, i. e., thorough
utilizing of the heat contained in the heating gases, means that
the conditions are such that the heat initially in the heating gases
is transferred nearly fully to the copper balls, so that those gases,
before leaving the balls, have their heat thoroughly removed by
those balls, i. e., become thoroughly cooled. Note carefully these
last three words. The heat in the escaping gases proves as
clearly that it has not been utilized as the cake in my hand proves
that it has not been eaten. What I still hold I have not parted with.

Now, in order that this transfer of heat from gas to balls
under these conditions shall be nearly complete, the only require-
ment as far as the initial temperature of the gas is concerned is
that it shall be above 1,000°. If it is but little above 1,000°, much
gas and much opportunity for heat transference, i. e., very pro-
longed contact, are needed; if it is very far above 1,000°, pro-

portionally less are needed. Here quantity of heat can make up
for what temperature lacks, provided only that there is some
margin between the initial temperature of the gas and the final
temperature which the balls must reach.

A large margin is indeed somewhat better than a small one,
but a small one will suffice. Lot 1 of 50 grammes of gas at 1,100°
contains as much heat as lot 2 of 25 grammes at 2,200°, and
theoretically and roughly speaking, the heat contained in lot 1
should be nearly as well utilized as that in lot 2, in passing
through the column of copper balls, i. e., nearly as great a pro-
portion of that heat should pass into the copper balls in the up-
ward journey between them, in case of lot 1 as in that of lot 2.
Quantities of heat are here of chief importance, and initial gas
temperature is of secondary moment, provided only that it is
above the temperature to which the copper must be heated.

Of course, to recover the heat of lot 1 needs a longer column
of balls than would suffice to recover the heat of lot 2 with equal
thoroughness, because if the same quantity of balls is to be heated
per hour, the quantity per hour of gas of lot 1, and therefore the
rate of travel, must be twice as great as those of lot 2. Further,
cooling these two lots of gas to the same temperature, say 110°,
would still leave unrecovered, and therefore unused, twice as
large a percentage of the initial heat in lot 1 as in lot 2. In
short, the recovery of the heat from lot 1 cannot readily be made
quite as thorough as from lot 2; and in order to make it even
approximately as thorough, there must be much greater opportu-
nity for heat transference.

But the influence of initial temperature may be of a wholly
different order of magnitude in operations with a critical temper-
ature; in these, initial temperature may be as important as quan-
tity of heat. Thus, not even an infinite quantity of gas at 99°
can boil one single gramme of water at atmospheric pressure. If
the work of heating and boiling is to be done by the heat contained
in a stream of gas, for instance in the gaseous products of the
combustion of a boiler fire, it is only by as much as that gas is
above 100° that it can boil water.

If gas is initially at 101°, it can give up only about 1 per cent
of its heat to the work of boiling water as distinguished from
heating that water towards the boiling point; because as soon as
it has given out that one per cent and has thereby cooled to 100°,

it ceases to be able to transfer its heat to water already at 100°. If the initial gas temperature is 105°, approximately five per cent of the heat developed can thus be utilized theoretically in boiling water; if at 1,000°, 90 per cent can thus be utilized theoretically. Thus raising the initial temperature from 101° to 105°, or by only about four per cent, increases by about 400 per cent the proportion of the heat useful for boiling water.

Now, going one step farther, if the heat in a stream of gas is to be utilized thoroughly, i. e., recovered by transferring it to water, first in heating and second in boiling that water, then the initial temperature of the gas should be such that the quantity of heat which the gas gives up in cooling to 100° should bear to that which it gives up in cooling from 100° down, at least as large a proportion as that which the work of boiling bears to the work to be done in raising the water to the boiling point, in short, a proportion at least as great as 5.36 : 1. And, because (always neglecting variations in specific heat) the heat given out in cooling is proportional to the range of temperature which that cooling covers, it follows that the margin between the initial temperature and 100° should be to 100°, at least in this ratio of of 5.36 to 1; or in short that the initial temperature should be at least 100° + 536° = 636°. If it is lower than this, then in order to contain enough heat in excess of the boiling temperature, the quantity of gas must be so great that its residual heat, when it has cooled to 100°, is more than the water can utilize and recover, in being heated up to 100°; and this excess of heat must therefore remain in the gas and be lost.

To state it more generally, if we let

t_c = the critical temperature;

t_i = the initial temperature of the gas, usually its combustion temperature;

h_c = the heat which must be supplied at and above the critical temperature; and

h_b = the heat needed in bringing the body to be heated up to that temperature; then for economy the initial or combustion temperature should be as high or higher than that which the following formula calls for, $(t_i - t_c) : t_c = h_c : h_b$, **whence**

$$(35)\ t_i = t_c \left(1 + \frac{h_c}{h_b}\right)$$

To sum up, continuous heating operations which derive their

heat from passing gaseous products of combustion or other hot gases, may be divided into those which have and those which lack a critical temperature, at and above which more heat is needed because of some heat-absorbing reaction, change of state, or the like, than at the average of the temperatures below it; and these two classes differ in the following important respect as regards the initial or combustion temperature which those heating gases must have in order that their heat may be well utilized. If there is no critical temperature, then it suffices that there shall be some margin between that initial temperature and the temperature to which the objects are to be heated, and the breadth of that margin is of secondary importance; if there is a critical temperature, then that margin must be at least as great as (35) requires.

Most of our metallurgical operations have a critical temperature, or more than one. In our fusion processes it is in general the melting point of the metal treated; in the iron foundry it is the melting point of cast iron, and the critical work is supplying the latent heat of fusion of that cast iron; in the calcination of limestone it is the dissociation point of calcium carbonate, and the critical work consists in supplying the heat absorbed by that dissociation.

Simple heating processes, on the other hand, in general have no critical point. In heating copper bars in a continuous furnace like Morgan's, Fig. 113. p. 377, there is no critical temperature. In heating steel billets in such a furnace, or steel ingots in a regenerative gas furnace, there is none, unless we choose to go to the extreme refinement of considering the slight excess of heat which heating the steel through its critical range A_{c1} to A_{c3} requires.

341 A. Equation 35 Tested. — Let us test our law by applying it to three cases, of which the first has the initial gas temperature for which the law calls, while the second has a lower, and the third a higher initial gas temperature.

Case 1st. *Distribution of heat supplied by gas initially at 636°, in heating and boiling water.* To heat 1 gramme of water from 0° to the boiling point 100°, needs $1 \times 1 \times 100 =$ .... 100 calories

The latent heat of evaporation of 1 gramme of water already at the boiling point is .... 536 calories

Total heat of evaporation .... 636 calories

Applying these numbers to equation (35), the combustion temperature t_i, which the boiler fire should give to the gases resulting from that combustion, should be at least

$$t_i = 100 \left(1 + \frac{536}{100}\right) = 636°.$$

Now let us see how this heat may be used in the work of heating and boiling water.

In cooling from 636° to 100°, 50 grammes of gases, with a specific heat assumed for simplicity at 0.25, give out

$$(636 - 100) \times 50 \times 0.25 = 6{,}700 \text{ calories.}$$

If all this heat is taken up by the work of boiling the water already in the boiler and at 100°, it can boil

$$6{,}700 \div 536 = 12.5 \text{ grammes of water.}$$

There will remain in the gas, now at 100°,

$$100 \times 50 \times 0.25 = 1{,}250 \text{ calories,}$$

and if, on its way from the boiler towards the chimney, this passes through a series of feed water heaters which offer no frictional resistance to the transfer of heat from gas to feed water, the whole of this 1,250 calories might theoretically thus be transferred and so utilized in heating that feed water up to 100°. How many grammes could it thus heat? Clearly 1,250 divided by the heat needed to raise 1 gramme from 0° to 100°, or

$$1{,}250 \div (1 \times 100) = 12.5 \text{ grammes,}$$

or at the rate of 4 grammes of gas per gramme of water.

In short, the heat left in the gas after it has done its critical work of boiling 12.5 grammes of water can theoretically be fully consumed and therefore utilized in preheating up to the critical temperature a corresponding 12.5 grammes; so that the operation can go on continuously with perfect utilizing of the heat, and the escaping gases, in giving up all their heat, would be cooled to 0°.

Case 2nd. *Distribution of heat supplied by gas initially at 318°, in heating and boiling water.* Total heat in 50 grammes of gas,

$$50 \times 318 \times 0.25 = 3{,}975 \text{ calories.}$$

In cooling from 318° to 100°, 50 grammes of gas give out

$$(318 - 100) \times 50 \times 0.25 = 2{,}725 \text{ calories.}$$

This can evaporate

$$2{,}725 \div 536 = 5.1 \text{ grammes of water,}$$

or at the rate of 9.8 grammes of gas per gramme of water.

There will still be left in the gas

$$100 \times 50 \times 0.25 = 1{,}250 \text{ calories.}$$

Of this none can be used in boiling any more water, because gas at 100° can give no heat to water already at 100°; therefore the only use to which this heat can be put is to heat up towards the boiling point another lot of 5.1 grammes of water, to replace those which have just been boiled away. But this water, in thus heating, can absorb from the gases only

$$100 \times 5.1 \times 0.25 = 127.5 \text{ calories,}$$

or only about 10 per cent of the 1,250 calories left after the gas has done all the work of which it is capable in the boiling of water. The remaining, $1{,}250 - 127.5 = 1{,}122.5$ calories, because they cannot be removed from the escaping gases by the operation of heating water, must remain in them and be lost, unless perchance they can be utilized for some other purpose.

On comparing this result with that of case 1st, we see that lowering the initial temperature of the heating gases by 50 per cent, from 636° to 318°, has forced us to waste $1{,}122.5 \times 100 \div 3{,}975 = 28$ per cent of the heat initially present in the gas, instead of recovering the whole of it.

Applying the temperature equation,

$$(36) \quad t = \frac{H}{W \times S.H.}$$

in which H is the number of calories in the gases, W their weight in grammes, and S.H. their specific heat, the final temperature of the gases as they escape from the feed water heaters would theoretically be

$$t = \frac{1{,}122.5}{50 \times 0.25} = 89.8°.$$

Case 3rd. *Distribution of heat supplied by gas initially at 1272°, in heating and boiling water.* Here it is even easier than in case 1st to utilize the whole of the heat, because here, of the

total heat present, the proportion available for boiling, instead of being barely enough to do the heating work which must be done above 100°, is much greater, and this surplus can be applied either to boiling or to heating towards 100°.

In cooling from 1,272° to 0°, 50 grammes of gas give out

$$1,272 \times 50 \times 0.25 = 15,900 \text{ calories.}$$

This heat is capable of heating and boiling

$$15,900 \div 636 = 25 \text{ grammes of water.}$$

The heat absorbed in boiling this water, as distinguished from heating it towards 100°, is

$$25 \times 536 = 13,400 \text{ calories,}$$

in supplying which our 50 grammes of gas would cool through

$$13,400 \div (50 \times 0.25) = 1,072°,$$

so that their temperature would sink from 1,272° to 200°.

In order now, to recover the heat still remaining in these gases it suffices that the work remaining for them to do, *viz.,* heating to the boiling point a new lot of 25 grammes of water to replace that which they have just boiled away, should be capable of absorbing the heat which they still retain, or

$$200 \times 50 \times 0.25 = 2,500 \text{ calories.}$$

And this is just what the work remaining for them implies: for to heat this 25 grammes from 0° to 100° requires just

$$25 \times 100 \times 1 = 2,500 \text{ calories,}$$

or at the rate of 2 grammes of gas per gramme of water.

Thus, if matters are so arranged that, as soon as the gases have cooled to 200°, they sweep away from the boiler proper to the series of feed-water heaters with walls made of some substance which conducts heat perfectly, the heat left in them after they have done their work above the boiling or critical temperature can just be absorbed and utilized in heating up to that critical temperature another lot of water, just replacing that which they have boiled away, and the utilizing of the heat is perfect.

The student need hardly be told that such adjustment is impossible in practice, and that perfect conductors of heat, like

perfectly adiabatic materials, and indeed like the philosopher's stone, exist only in our imagination. Yet these ideas help to explain the limits which we work towards but can never reach.

Recapitulating these three cases,

If the combustion temperature is	the percentage of heat utilized is	the final temperature of the gases is	and for each gramme of water we need	
636°	100	0°	4	
318°	72	89.8°	9.8	grammes of gas
1272°	100	0°	2	

To sum up, the law satisfies these tests, for when (Case 1st) the initial temperature is that which the law calls for, and when (Case 3d) it is still higher, the recovery of the heat of the heating gases is complete; but when (Case 2d) it is only half what the law calls for, only 72 per cent of that heat can be recovered even theoretically.

341 B. IMPORTANCE OF THE CRITICAL TEMPERATURE IN THE BLAST-FURNACE PROCESS. — In this process there are at least two important critical temperatures, and probably more; and the critical heat, *i. e.,* the quantity of heat which must be supplied above those temperatures, is probably very large. The melting points of iron and slag, respectively, are two critical temperatures as to the existence of which there can be no question; and the quantity of heat absorbed in melting the iron and slag, respectively, their latent heat of fusion, may well be very large. Further, the deoxidation of silicon by reaction (15) $SiO_2 + 2C = Si + 2CO$ (p. 394) and the removal of sulphur, whether by reaction (30) $FeS + CaO + C = Fe + CaS + CO$ (p. 395) or by other means, very probably call for still higher temperatures and for much heat.

Let us now go on to consider the first of the reasons given in § 339 for the fuel economy of the Gayley process, *viz.,* that drying the blast greatly widens the margin between the combustion temperature and the critical temperature, and thus increases by a correspondingly large fraction the proportion of the heat developed which is available for the critical work, quite as raising from 101° to 105°, or by only four per cent, the initial temperature of the gases which are to boil water, increases the heat theoretically available for the critical work of boiling by some 400 per cent.

A complete analysis of these critical temperatures and of the heat required for each would carry us beyond the limits of