

the present work; but it may be instructive to assume for purposes of illustration a critical temperature of $1,300^{\circ}$,* between the melting point of the iron and that of the slag, and adopting Professor J. W. Richards'† estimates of the combustion temperature (*i. e.*, the initial temperature of the gases after their combustion in the hearth, before any of their heat has been given up to the surrounding solid and molten materials), as $1,965^{\circ}$ for dried blast and $1,861^{\circ}$ for moist blast, to see what effect ought to be caused by changing from dried to moist blast.

When the combustion temperature is $1,965^{\circ}$, the margin between it and the critical temperature is 665° ; but this margin is only 84 per cent as great, or 561° , when the combustion temperature is $1,861^{\circ}$. But with this lower combustion temperature and this narrower margin, just as much heat must be supplied above the critical temperature to do the critical work as when the combustion temperature was higher. But how can this be brought about? Either by restoring the combustion temperature to its old level and thus getting the old greater margin between combustion temperature and critical temperature, or by burning more fuel.

The combustion temperature could be restored to its old level by any one of several expedients, such as raising the temperature of the blast, and so directly raising the temperature

* The critical work of melting the slag must indeed be carried out at the melting point of that slag, which is much above $1,300^{\circ}$; but if we were to confine our attention to this higher temperature we should seem unfair, because we should neglect the fact that, of the heat left in the gases after supplying the heat absorbed by the melting of the slag, much could still be used, not only in the uncritical work of heating the solid materials up to this temperature, but in the critical work of melting the iron at its lower melting point of, say, $1,200^{\circ}$. If on the other hand, we confined our attention to this lower critical point, we should manifestly understate the case, by making no provision for the critical work of melting the slag. The critical temperature of $1,300^{\circ}$ to which we shall confine our attention, then, is to a certain degree *pro forma*. My aim is, not to show accurately just how great the saving due to drying the blast should be, but rather to show that, on any reasonable assumption, this saving ought to be very great, far out of proportion to the heat directly needed for heating and dissociating the moisture.

† "The Application of Dry-Air Blast to the Manufacture of Iron," to appear probably in Vol. XXXVI, *Trans. American Inst. of Mining Engineers*.

level from which combustion starts; or by lessening the quantity of nitrogen in the blast, and so diminishing the denominator of the right-hand side of the temperature equation,

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

or by using a fuel of greater pyrometric intensity, which may either increase the numerator or lessen the denominator of that side. Of course the combustion temperature is not affected by increasing the quantity of fuel, which simply increases in like proportion the numerator and denominator of this side of the equation.

But to get by means of extra fuel as much heat available above the critical temperature with moist blast, when the margin is only 561° , as when it is 665° , means burning $665 \div 561$ or 1.19 times as much fuel per ton of iron, or 19 per cent more fuel, than with dried blast. That this number happens to agree with the actual saving, which Mr. Gayley effects, is of course no indication that my estimates are accurate. The agreement is wholly accidental; indeed, I could easily have framed those estimates so as to bring about such an apparent agreement.

But is as much as 19 per cent of extra fuel really needed? To simplify our discussion, let us divide the heat generated, whether by the extra fuel or what we may call the regular fuel (that is to say, the quantity of fuel which would be needed even with dried blast), into the heat represented by the margin between the combustion temperature and $1,300^{\circ}$, and that represented by the margin between $1,300^{\circ}$ and 0° ; or, in short, into the heat above $1,300^{\circ}$ and the heat below $1,300^{\circ}$. The gases from our extra fuel, which supplies the extra heat needed above $1,300^{\circ}$, must, when they have cooled from $1,861^{\circ}$ to $1,300^{\circ}$, a distance of 561° , still contain $1,300 \div 561 = 2.3$ times as much heat as they have given out above $1,300^{\circ}$.

Now, will not some of this extra heat below $1,300^{\circ}$ be recovered by the descending solids in the upper part of the furnace as the rising gases sweep past them? And will not the extra carbon monoxide generated by burning the extra fuel at the tuyères be in part oxidized to carbon dioxide in the upper part of the furnace, there doing useful work and generating usable heat?

Apparently not. Three aspects of the case may be considered. First, is any of the extra carbon monoxide later oxidized to carbon dioxide, and if so, is any useful work thus done? Second, of the heat above $1,300^{\circ}$, from the extra fuel, is a larger proportion available for the critical work above $1,300^{\circ}$? Third, of the extra heat below $1,300^{\circ}$, can any part be recovered and put to useful work?

To the first question the answer is probably "No." It is true that, as the gases pass upwards through the furnace, a great quantity of their carbon monoxide is oxidized to carbon dioxide by the oxygen of the ore; but this quantity is fixed per ton of iron. A ton of ore contains only just so much oxygen, with which it can oxidize only just so much carbon monoxide; and increasing the quantity of carbon burnt and carbon monoxide generated in the hearth per ton of iron made, which is the same as saying per ton of ore charged, does not add one atom to the oxygen in that ore, or to the quantity of carbon monoxide which that oxygen can oxidize to carbon dioxide. Thus nothing more is to be got out of the descending column of solids in the way of further oxidation of carbon monoxide to carbon dioxide.

Passing now to the second question, of the heat above $1,300^{\circ}$ only a part will actually be used for the critical work above $1,300^{\circ}$, because that work has to be done in a very limited part of the furnace, just in the region of highest temperature. Through this region the very expanded gases rush at very great speed, so that they leave it before giving up all of their heat which is above $1,300^{\circ}$, just as the gases of a boiler fire must necessarily sweep past the boiler to the feed-water heaters, before they have given up to the boiler all of their heat above the boiling point. Now, the present question is this: of the heat above $1,300^{\circ}$, is a larger or a smaller proportion actually used for the critical work above $1,300^{\circ}$, in case of moist blast, than in case of dried blast? If a larger proportion, then this would make for lessening the extra fuel really needed to something below the 19 per cent apparently needed; if a smaller proportion, this would make for increasing the extra fuel needed.

The proportion must be smaller in case of moist blast for two evident reasons. First, the transfer of heat from the gases to the solid and molten bodies which they are heating (the temperature of which is assumed to be the same in both cases) is

slower, because the combustion temperature in case of moist blast is much lower than in case of dried blast, and because, the less the difference in temperature between any two bodies, the more slowly will heat pass from one to the other. Second, the time available for this heat transfer is much shorter in case of moist blast, because of the greater quantity of gases resulting from the greater weight of fuel which must be burnt, and their consequent more rapid passage through the hearth. This greater weight of gases outweighs, in its influence on their volume, their initial lower temperature.

Passing now to the third question, we at once meet the fact that, even with dried blast, the gases escape hot from the top of the furnace, which means that the descending solids are unable to absorb and recover even the smaller quantity of heat in the smaller volume of more slowly moving gases formed with dried blast. If they cannot absorb and recover the whole of this smaller quantity of heat, how are they to absorb any of the extra heat in the larger volume of gases generated with moist blast, especially in view of their traveling faster because there is so much more of them, and thus having less opportunity for heat transference? The only extra heat-absorbing capacity which the descending solids now have is that caused by their containing the extra 19 per cent of coke, which will have to be burnt at the hearth to compensate for the narrowed margin between combustion temperature and critical temperature. It is only in virtue of their containing this extra 19 per cent of coke that the descending solids have any extra heat-absorbing power; and they can absorb extra heat solely for heating up the extra coke which is the source of the extra quantity of gas, and is in weight only a small fraction of the weight of those extra gases the heat of which this coke is to absorb. But this cannot be regarded as contributing to the useful work of the furnace, which consists in deoxidizing iron ore, silica, and lime, dissociating limestone, and melting and superheating the iron and slag. All that can be said is that part of the heat developed by the extra fuel can be utilized in heating that fuel itself. But of the extra heat present in the products of its combustion after they have cooled to the critical temperature, none appears to be available for the useful work of the process.

In short, the fact that, even with dried blast, the gases still

escape hot from the top of the furnace, leaves us without strong reason to think that with moist blast the descending solids can recover for any of the useful work of the furnace any of the extra heat below $1,300^{\circ}$ due to the extra fuel.

Thus we find no escape from the conclusion that the large excess of coke apparently needed in the hearth, in case of moist blast, is actually needed; that of all the heat which its combustion develops, only that represented by the narrowed margin between combustion temperature and critical temperature can be utilized, with the exception of that used in heating the coke itself to the critical temperature, so that the rest of this heat is wasted.

How great is the contrast between the small usefulness of this extra fuel and the very great usefulness of the fuel used with dried blast! Most of the heat which this latter fuel develops is well utilized in the useful work of deoxidizing, preheating, dissociating, melting, and superheating.

What has been said of the extra heat developed by the extra fuel needed to make good the narrowing of the temperature margin, is equally true of the extra heat needed to make good the heat absorption in the dissociation of the moisture.

This reasoning, then, seems to make good the first three reasons given in the beginning of § 339.

If our judgment, which looks always to find some great cause for a great effect, revolts at the idea that taking a little moisture out of the blast should save 19 per cent of the fuel in the blast-furnace, consider again the cases given in § 340; consider especially that raising the combustion temperature from 101° to 105° , or by only four per cent, theoretically increases the proportion of heat available above the critical temperature of the boiling of water by 400 per cent. Consider a stream of water four feet deep, the upper surface of which is one inch above the level of the waste weir; raise the upper surface of the stream by ten per cent, or 4.8 inches, and the flow over the waste weir increases 480 per cent. Consider the swimmer whose entangled feet let him stretch his mouth to within an inch of the surface; he might as well be a mile below. His last inch, if he can gain it, is worth infinitely more than the ten fathoms he has already risen.

The reason why the relation of the initial or combustion temperature to the critical temperature has not hitherto received

due attention, is probably that in most of our familiar operations the margin between the two is so great that the usual variations in that margin are not of very great importance. So far as I have noticed, Mr. J. E. Johnson, Jr.,* was the first to point out clearly the importance of the critical temperature in the blast-furnace process.

The reasons which have now been given to explain why drying the blast causes a saving of fuel greatly out of proportion to the quantity of heat which the heating and dissociation of the moisture directly need, and why it lowers the temperature of the escaping gases, apply with equal force to explain why the saving which Neilson's invention of the hot blast effected, and every saving later made by further heating the blast, were so greatly out of proportion to the quantity of heat thus given to the blast, and why heating the blast was immediately followed by a drop in the temperature of the escaping gases and a rise in the ratio of carbon dioxide to carbon monoxide.

These reasons may be recapitulated as follows:

Adding moisture to the blast not only calls for extra fuel to supply the extra heat needed for heating and dissociating this moisture, but (like cooling the blast or diluting it with additional nitrogen) by lowering the temperature which combustion develops, narrows the already narrow margin between that temperature and the critical temperature, above which a very much larger quantity of heat is needed, to make good the absorption

*"Notes on the Physical Action of the Blast-Furnace," *Trans. American Inst. Mining Engineers*, to appear probably in Vol. XXXVI.

Mr. Johnson called my attention to the importance of this subject some years before the disclosure, but not before the invention, of the Gayley process. In this present discussion I have tried to give some needed additional precision to Mr. Johnson's definition of the critical temperature. He defined it simply as one above which certain necessary operations must be carried out. Thus defined this term applies equally to what I have called non-critical processes. His reasoning about the importance of the critical temperature is not valid, unless this is further defined as, in addition, one at or above which the heat requirement is greater, because of some special heat absorption, than at the average of the temperatures below it, a condition which he probably had in mind.

Further, I have carried the reasoning a step farther, by showing why it is that, of the heat developed by the extra fuel, probably only that which is represented by the narrowed margin between the combustion and the critical temperature can be utilized.

due to the latent heat of fusion of iron and slag, and probably of deoxidizing silica and lime, than is needed at the average of lower temperatures. The combustion temperature was in this special case further lowered and this margin thereby further narrowed, by a decided lowering of the blast temperature due to the fact that, with the hot blast stoves used, the larger quantity of blast needed could not be heated so hot, although the gas used for heating it seems to have increased in quantity proportionally, and to have improved in quality. (This part of the narrowing of the temperature margin might perhaps be made good by enlarging the hot blast stoves.)

If the narrowing of this margin is to be made good by burning more fuel, then of the heat generated by that fuel only that corresponding to the narrowed margin between the combustion and the critical temperatures can be utilized. Of that represented by the range of temperature below this we see no strong reason to expect that any important part can be recovered from the products of the combustion of this extra fuel by the descending solids, nor can the carbon monoxide generated by this extra fuel be converted into carbon dioxide by those solids, because, even with hot and dried blast, the power of those solids to absorb heat and to oxidize carbon monoxide appears to be already fully utilized, so that we have no strong reason to think that they can do more in either respect. This extra quantity of carbon monoxide and this extra heat may therefore be expected to be present in the gases when they escape from the top of the furnace, and these gases should therefore both be hotter and have a lower ratio of $\text{CO}_2:\text{CO}$. Indeed, the quantity of carbon monoxide in the escaping gases should be even greater than this would imply, because, being hotter, their carbon dioxide should react the more energetically upon the entering coke, and thereby be reduced to carbon monoxide, and further increase the fuel consumption by thus dissolving away part of the entering coke, which must be replaced by more extra fuel.

Indeed, the matter is still worse. Narrowing the margin between the combustion and the critical temperatures lessens the thoroughness with which even the heat represented by the narrowed margin can be utilized even for the critical work, first, because the cooler gases transfer their heat to the solid and molten matter which they have to heat less rapidly because of the nar-

rowed temperature margin between them, and next because, thanks to their greater weight and hence volume, they pass more rapidly by that matter. The heat transfer is slower, and the time allowed for the transfer is shorter.

Like advantages are to be expected from any further step which will widen the margin between the combustion and the critical temperatures, such as heating the blast still hotter or removing part of its nitrogen.

342. NOTE ON SORBITE AND THE OTHER STAGES OF TRANSITION BETWEEN AUSTENITE AND PEARLITE.

The greater hardness of martensite than of austenite in hyper-eutectoid steel, though it may well be due to the presence of beta iron in the martensite, can also be explained mechanically, because a first step in this transformation is that, within the austenite, cementite, which is much harder than austenite, forms. The facts (1) that martensite habitually forms along the cleavage planes of the austenite, and apparently preserves the latter's acicular structure, (2) that troostite habitually is sharply divided from martensite, and (3) that troostite, sorbite, and pearlite shade off without break into each other, are explicable by either theory, though the second suggests an essential difference, and the third a quantitative one.

Sorbite can be generated in many ways which permit the transformation to go far but not to complete itself, for instance, by quenching in oil, which cools the steel so slowly that the transformation can go beyond the martensite stage of water-quenched steel, but not slowly enough to enable it to reach the pearlite stage of slowly cooled steel; or by quenching in water after allowing the transformation to complete itself in part by cooling slowly through a part of the critical range, region V and VII; or by carrying the reheating or "tempering" of water-hardened steel nearly to A_1 .