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"How to Use U.S. Coals in Cokemaking"
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Selecting Coal Blends for Coke Making

The object of making good coke is simple, generate a high quality product that will not damage the oven chambers, while keeping productions cost minimal. This makes the selection of coals used to manufacture metallurgical coke the critical first step in the coke making process. Most of the metallurgical coals used in the U.S. are from the Eastern Region, and Eastern coals are synonymous with high pressure and hard pushing. The shrinkage associated with these coals is not linear, but unpredictable and not easily controlled. Prior to 1970, the solution to oven damage was to rebuild an oven every 20 or so years, or to slow down the operation. Since neither are viable alternatives, the selector must use some knowledge of gas dynamics and material structure to remove the by-product gases, keep the pressure minimal, and provide sufficient shrinkage.

In order to get an easy push, two conditions are required:

(1). After coking, coke size should be large and rectangular in shape, and form two columns inside the oven. The presence of coalescing forces between the coke blocks will aid the integrity of the mass as it leaves the oven chamber thereby exposing the walls to a minimal amount of pressure. Even when the correct blend is used, oxidized coals can cause a deterioration of normal binding, causing separation, and hard pushes.

(2). There should be enough shrinkage, so the ill-perfect oven wall will not hinder the pushing. The best laboratory scale method to estimate coal shrinkage during the coke making is the sole-heated oven test (SHO). However, one must remember during blend formulation that the blends SHO result is not linear. Brysch and Ball (1) reviewed sole-heated oven data of U.S. coals from the U.S. Bureau of Mines and noted that the relationship between volume change and the percentage of a given coal in a binary blend was not a straight line. The inflection point occurred at a different percentage for various blends. In addition, the actual shrinkage in a binary blend, as well as blends of three or more coals, is less than the theoretical value.

For any given blend, coke size and shrinkage is a function of coking time. A longer time (slower heating rate) allows more time for gases to escape and for coke shrinkage during the final solidification phase. The slower heating rate also provides more time for the plastic layer to agglomerate the inert ingredients and form large coke size.

Among the properties of a desirable coal blend are that the fluidity (the liquidation of the coal) is between 400 and 1000 d.d.p.m. the ash (the material left after incineration) less than 5.5 %, the sulfur content less than 1%, the volatile matter (V. M. the organic matter driven off during coking) less than 26 %, the SHO test between 8 % and 12 %, the Mean Maximum Reflectance (MMR) is between 1.1% to 1.22%, and the correct particle size (92 % of the coal should pass through ¼ inch screen with 80% passing through an 1/8 inch screen).

Each coal used in the blend brings it's own positive and negative effects to the mix. . High volatile (HV) coal offers good shrinkage but the stability suffers. U.S. Low-Volatile (LV) coal makes strong coke (high in coke stability), however, these thin wall bubble structures are also stable enough to trap by-product gases and lower the actual shrinkage. The combination of the two actually accentuates the problems, trapping even more by-products gas. Western Canadian coals contain less V.M. and more oxygen; while carbon textures are nucleated from certain oxygen compounds. More oxygen content makes these carbon textures finer and shorter in length. Thus, it makes bubble structure less stable and traps less by-product gas. The V.M. of petroleum coke ACME uses is usually around 12 to 15%. Less V.M., no bubble structure, and less-satisfactory binding make petroleum coke another ideal filler for a predominately U.S. coal blend. The performance of the blends

with Western Canadian Coals but without petroleum coke is almost as poor as the blends with U.S. coals only -- unpredictable and low in actual shrinkage. The reason is simple. The microstructure of a coke portion made from Canadian L.-V. coal suddenly became thin-wall bubble structure, same as the U.S. L.-V. coals. The high blend fluidity, which was rich in hydrogen, rejuvenated the Western Canadian coals, changed the carbon texture, and was able to trap more by-product gases. The combination of the U.S. coals, Canadian coals and the petroleum coke produced results close to their theoretical values.

ASH - Initially, Western Canadian coals were a deterrent to metallurgical coal users, due to their high ash contents. This is because of the mineral matter distribution difference between Western Canadian coals and U.S. coals. Western Canadian coals contain lots of fine mineral matter, which is very difficult to wash away. These ashes are high in Al_2O_3 and SiO_2, and low in Fe, K, Na, and Ca; they actual reduce the reactivity (2,3). So, they should be considered "necessary evils".

Oxygen Content - Western Canadian coals always contain more oxygen than the U.S. counterparts with similar V.M. content. Oxygen produces linkages during heating. This explains why the fluidity of Western Canadians is low.

Amount of Reactive Material - Both Western Canadian coals, and petroleum coke have less reactive material. Thus, it makes gases easier to escape during coke making.

Carbon Textures - This is the major factor to decide the Coke Strength After Reaction (CSR) and reactivity (2,4,5). Carbon textures produced by a coal is determined by its rank MMR, not its V.M. content. No Western Canadian coal generates isotropic carbon texture. All commercially available Western Canadian coals generate desirable anisotropic carbon texture.

Because of the Western Canadian coals high oxygen content, (compared to U.S. coals), the end product is a coke with finer carbon texture. U.S. L.-V. coals have more reactive material/less oxygen content, and eventually end up with long fiber carbon textures. A long fiber texture is usually very strong along the fiber direction. With such strong fiber and high viscosity during coking, gases inside have a difficult time to escape the coking mass. This is why U.S. L.-V. coal is very expansionary during coke making. Shorter fibers are not as strong along the fiber direction. That is why Western Canadian L.-V. coal has more of a chance to form a thick-wall bubble structure and shrink during coke making. This thick-wall bubble structure should be much stronger than thin-wall structure in either stability or CSR.

Binding and Interaction - Western Canadian coals usually bind very well with any U.S. coals. Sometimes, they even react with U.S. coals. Interaction produces extremely strong binding. Petroleum coke, on the other hand, can only have reasonably fair binding.

Petroleum Coke - It boosts up the apparent specific gravity of coke, and increases the CSR as well.

Yield - With petroleum coke and Western Canadian coals in the blend, coke yield increases.

Conclusion - Using a blend comprised of U.S. coals, petroleum coke, and Western Canadian coals, enables production of high quality metallurgical coke with minimal damage to the oven.

References

1. Brysch, O.P. and Ball, W.E., Inst. Gas Tech., Research Bull., No. 11, p. 60, 1951

2. Goscinski, J. S. and Patalsky, R. M., Ironmaking Conference Proceeding., p. 53-73, 1990

3. Valia, H. S., Transaction of the ISS, p 77-78

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How to use U.S. Coals in Cokemaking

C. C. Lin

ABSTRACT

U.S. coals from Appalachian region, similar to German coals, were famous for their high pressure and hard push during cokemaking. The actual shrinkage of coal blend by using only U.S. coals is not linear to its ingredients. There is a famous proverb within ironmaking people----shrinkage of a coal blend is unpredictable and uncontrollable.

The solution to oven damage, prior to 1970, was usually to rebuild an oven every 20 years. This was extremely expensive. After 1980, due to the international competition, steel mills in the U.S. were no longer able to afford that kind of expense. The only alternative is to slow down the operation, which, in term, was not practical. For the past 20 years, U.S. coke ovens have been damaged one by one and eventually this country became an coke-importing country. Actually, cokemaking is a gas dynamics as well as a material structure problem. This problem should be very easy solved by an experienced material scientist. As long as by-product gases can be removed on time, it should have minimal pressure and provide enough shrinkage. As long as coke is structurally sound, its quality should be guaranteed.

Addition of petroleum and Western Canadian coals successfully met these requirements. Moreover, they also boost the CSR, yield, and stability. Coke petrography can be a very useful tool here.

How to Use U.S. Coals in Cokemaking

C. C. Lin

This paper will demonstrate how ACME Steel overcame the fundamental weaknesses of Eastern U.S. coals and is still able to make good metallurgical coke with high productivity. There are several kinds of coals in the U.S. (For example; Colorado coal, Illinois coal, Alabama coal, Kentucky coal and Eastern coal). U.S. Coals are not quite suitable to make top-notch metallurgical coke. It is also economically not feasible to import all coals from overseas. Eastern U.S. coals, in fact, make relatively better coke than those from other regions. Most of the metallurgical coals used in the U.S. are from the Eastern Region; that is the topic we are going to discuss in the following. That is why Eastern U.S. Coals, in general, also mean U.S. Coals.

However, Eastern U.S. Coals are famous for their high pressure and hard pushing. Before 1970, U.S. steel mills usually rebuilt their coke ovens every 20 years. Nowadays, they can no longer afford to do this. The author will illustrate how coke petrography and the knowledge borrowed from material science are successfully applied here.

Introduction

ACME Steel Company's coke plant is located on the Southeast side of Chicago. It operates two 50 oven batteries. These batteries were constructed in 1956-57, and were through wall repaired in 1978-79. The current maximum production rate is 123 ovens per day (19 hour coking cycle) with 18.4 tons of coal blend being charge into each oven. They should be considered as middle-age ovens. Some defects pre-existed or developed on these re-conditioned ovens after years of usage. Some walls are not straight (bowed and curved); some have recesses (insets). Using these ovens to produce coke at high production rate is not an easy job.

One of ACME's operation criteria is to use coal blends that pose no risk to the oven chambers. Coals that can generate high wall pressures are avoided and blends must possess good shrinkage to ensure easy pushing. The second criterion is the coke quality. Nowadays, more and more coke users emphasize coke strength after reaction (high temperature strength, CSR) due to the PCI or gas injection. CSR seems to be even more important than coke stability (room temperature strength). The use of blends that contain Western Canadian coals, Eastern U.S. coals, and petroleum coke help ACME achieve its cokemaking goals. Actually, ACME Steel Company was the first U.S. steelmaker to introduce both petroleum coke and Western Canadian coals into the U.S. cokemaking society.

Oven Pushing Problem

The worst scenario is after coking the oven requires extremely enormous forces to push. In order to get an easy push, two conditions are required:

(1). After coking coke size should be large and rectangular in shape, and form two columns inside the oven (Figure 1). The presence of coalescing forces between the coke blocks will aid the integrity of the mass as it leaves the oven chamber which thereby exposes the walls to the least amount of pressure. That also means a deterioration of normal binding during cokemaking will be a disaster(For example: Oxidized coals).

(2). There should be enough shrinkage, so the ill-perfect oven wall will not hinder the pushing. The best laboratory scale methods to estimate coal shrinkage during the cokemaking is through the sole-heated oven test(SHO). However, one must remember during blend formulation that the blend SHO result is not additive. Brysch and Ball (1) reviewed sole-heated oven data on U.S. coals from the U.S. Bureau of Mines and noted that the relationship between volume change and the percentage of a given coal in a binary blend was not a straight line. Also, the inflection point occurred at a different percentage for various blends(Figure 2). In addition, the actual shrinkage in a binary blend is almost always less than the theoretical. The so-called theoretical shrinkage is assuming they are linear. The same situation happens in the blend that includes three or more coals.

For a given blend, coke size and shrinkage is a function of coking time. A longer time (slower heating rate) allows more time for gases to escape and longer time for coke to shrink during the final solidification phase. The additional time also provides more time for the plastic layer to agglomerate the inert ingredients and form large coke size. At ACME, our target SHO contraction of 8-10% generally provides us with coke that pushes with minimal force. The lower actual shrinkage in Eastern U.S. coal blends is a nightmare to every U.S. cokemaker. For decades, U.S. coke ovens, one by one, were damaged before knowing the cause or solution.
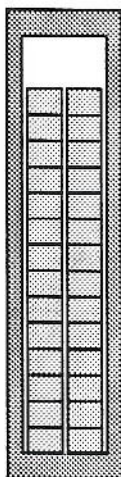

Figure 1 - Two Columns of Rectangular Shape
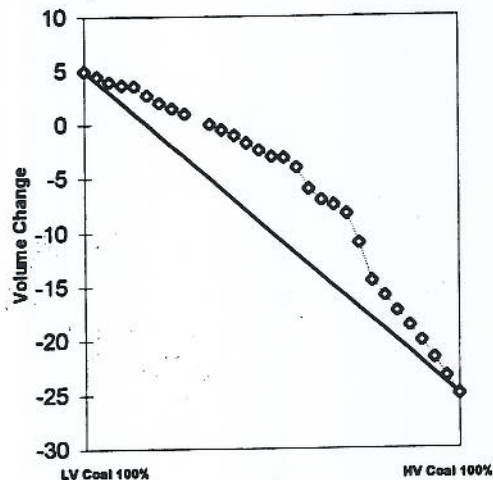Coke Inside Coke Oven.

Figure 2 - Shrinkage of a Blend of H.-V.
and L.-V. Eastern U.S. Coals.

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Table I - <u>Characteristics of Eastern U.S. Coals and Coke Made from Them</u>

<u>Coal</u>

Ash:	Low
Sulfur:	High
Alkaline:	High
Oxygen:	Low
Fluidity:	High
Hydrogen:	High

<u>Coke</u>

CSR:	Average
Reactivity:	Average
Coke Stability:	Average

Table II - <u>Properties of Desirable Coal Blend (ACME Standard)</u>

Fluidity:	400 - 1000 d.d.p.m.
Ash:	<5.5%
Sulfur:	<1.0%
V.M.:	<26%
MMR:	Between 1.10% to 1.22%
SHO Test:	>8.0%, <12.0%
	Prefer 8 - 10%
Particle Size:	Approx. 92% Pass 1/4"
	Approx. 80% Pass 1/8

Table III - <u>Properties of Desirable Coke (ACME Standard)</u>

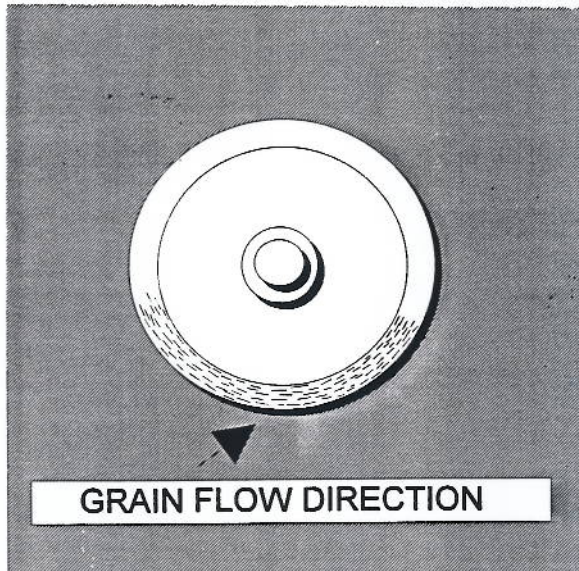|	
Ash:	<8.0%
Sulfur:	<0.9%
V.M.:	<0.7%
Coke Size:	Approx. 50% plus 2"
Stability:	Approx. 62%
CSR:	Approx. 67%

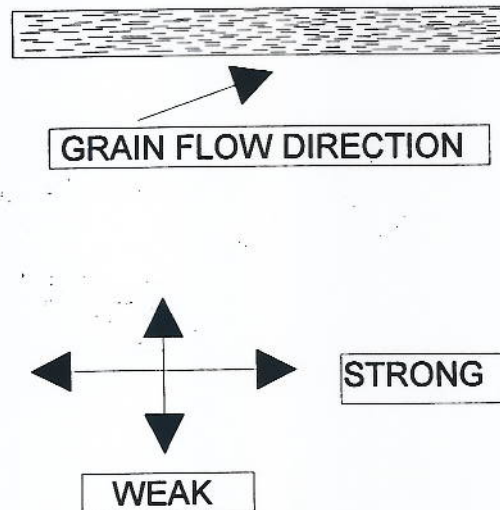Figure 3(a) - Grain Structure of a Railroad Wheel.

Figure 3(b) - Tensile Strength vs. Grain Flow Direction.

Cokemaking is a Branch of Material Science Plus Gas Dynamics

Figure 3(a) shows the grain structure of a railroad wheel. This is the only way to make railroad wheel strong. The same goes for the grain structure of a wooden board (Figure 3(b)). This is why U.S. L.-V. coal makes U.S. coke strong (High in coke stability). However, these thin wall bubble structures (Figure 4) are also stable enough to trap lots of by-product gases and lower the actual shrinkage.
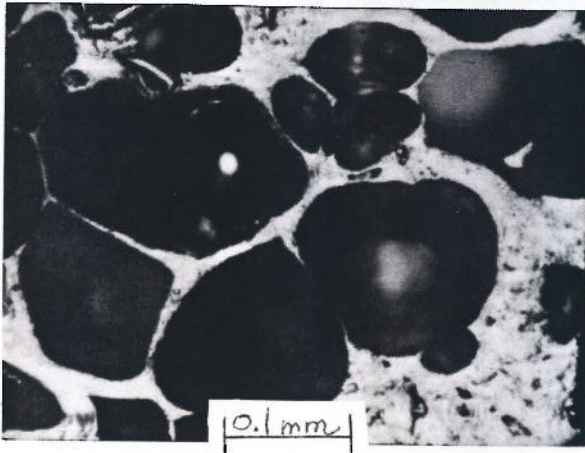

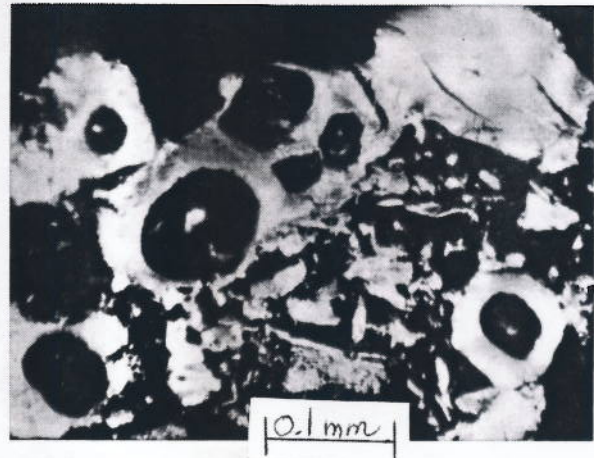Figure 4 - Crucible Coke Made by U.S. L.-V. Coal.   Figure 5 - Crucible Coke Made by Western Canadian L.-V. Coal.

High V.M. in H.-V. coal and high viscosity in L.-V. makes the problem worse. Usually, the volume of gases generated during cokemaking is proportional to the blend's V.M. That is the reason why U.S. coals are unsafe. In order to alleviate this issue, opposite action has to be taken. That means (1). We have to reduce the amount of U.S. L.-V. coal, and (2). We have to reduce the amount of V.M. in the blend. In other words, we have to look for some other kinds of coals, or fillers, in order to accomplish this goal. Figure 5 is a crucible coke made by a Western L.-V. coal. Only few thin wall bubble structures were observed. Chunks and Thick-wall bubble structures were plenty. This kind of structure should be in favor of both stronger coke and easier for the escape of by-product gases, which, in tern, reduces the oven pressure and provides easy push.

Table IV and Table V show us the nature of Western Canadian coals. Western Canadian coals contain less V.M. and more oxygen; while carbon textures are nucleated from certain oxygen compounds. More oxygen content makes these carbon textures finer and shorter in length. Thus, it makes bubble structure less stable and traps less by-product gas. The V.M. of petroleum coke ACME used is usually around 12 to 15%. Less V.M., no bubble structure, and less-satisfactory binding make petroleum coke another ideal filler for predominated U.S. coal blend.

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Table IV - Comparison Between U.S. and Western Canadian Coals					
Coal	R_o	VM%	O_2%	SHO %	Fluidity d.d.p.m.
WC1	0.94	30.5	5.8	-8	800
US1	0.94	34.5	5.6	-25	40,000
US2	1.10	30.5	4.0	-17	20,000
WC2	1.08	27.5	5.2	-5	250
US3	1.08	30.5	4.2	-17	20,000
US4	1.17	27.7	4.0	-12	10,000
WC3	1.25	22.5	4.2	-8	100
US5	1.25	26.0	3.2	-15	18,000
US6	1.40	22.5	2.8	0	1,500
WC7	1.35	20.5	4.0	-10	30
US7	1.35	23.5	3.5	-4	2,000
US8	1.40	20.5	2.8	0	1,500
WC6	1.61	17.5	3.8	-2	2
US9	1.67	17.5	1.7	+8	100
US10	1.61	18.5	2.0	+5	200

Table V - Proximates, Fluidities, and Ash Contents of Western Canadian Coals Experienced by ACME

Proximate	WC1	WC2	WC3	WC4	WC5	WC6
V.M.	30.5	27.5	22.5	22.0	22.0	17.5
Ash, db	6.5	8.5	9.5	9.5	9.5	6.5
Sulfur, db	0.6	0.7	0.45	0.4	0.4	0.5
Gieseler d.d.p.m.	800	250	100	30	50	2
Ash Contents, %						
SiO_2	61.35	61.51	58.20	62.0	61.4	55.97
Al_2O_3	26.10	27.75	30.58	29.0	30.64	30.52
TiO_2	1.73	1.43	1.65	1.4	1.84	1.55
Fe_2O_3	4.30	3.20	3.86	2.3	2.83	2.78
CaO	1.98	1.86	1.96	2.2	0.8	3.33
MgO	0.88	0.55	0.50	0.4	0.7	1.39
Na_2O & K_2O	1.56	1.41	0.90	0.5	0.67	1.30
P_2O_5	1.50	1.68	1.52	0.6	0.48	1.17
F.S.I.	7	7	7	7	7	6

Table VI through Table IX demonstrate the way ACME approached the solution. Table VI, the actual shrinkage of the blend containing U.S. coals only has no relationship with the theoretical. The ratio can be changed any minute through the change of moisture, bulk density, particle sizes, the amount of L.V. coals.....etc. Table VII, the performance of the blends with Western Canadian Coals but without petroleum coke, is almost as bad as the blends with U.S. coals only -- unpredictable and low in actual shrinkage. The reason is simple. For example, the microstructure of a coke portion made from Canadian L.-V. coal suddenly became thin-wall bubble structure, same as what U.S. L.-V. coals did. The high blend fluidity, which was rich in hydrogen, rejuvenated the Western Canadian coals, changed the carbon texture, and was able to trap more by-product gases. Table VIII, blends with petroleum coke but without Western Canadian coals got more actual shrinkage and became more predictable. Finally, the actual shrinkage's of blends contained both Western Canadian coals and petroleum coke were not far from their theoretical values. They automatically became our top choices (Table IX).

Table VI - Sole-Heated Oven Test Results on Blends(w/o Petcoke and w/o Western Canadian Coals)					
Blend	% of W.C.	% of P.C.	Theo. SHO %	Actual SHO %	Ratio %
A1	0	0	-20.6	-12.7	61.2
A2	0	0	-15.0	-4.3	28.7
A3	0	0	-10.5	-0.1	1.0
A4	0	0	-12.3	-2.8	22.8
A5	0	0	-13.2	-10.5	79.6
A6	0	0	-16.3	-5.8	35.6
					Avg. = 38.2

Table VII - Sole-Heated Oven test Results on Blends(w/o Petcoke & with Western Canadian Coals)					
Blend	% of W.C.	% of P.C.	Theo. SHO %	Actual SHO %	Ratio %
B1	25	0	-21.9	-18.0	82.2
B2	24	0	-13.4	-1.4	10.7
B3	24	0	-13.4	-4.7	35.8
B4	20	0	-14.8	-5.0	33.8
B5	30	0	-18.7	-9.5	50.8
					Avg. = 42.7

Table VIII - Sole-Heated Oven Test Results on Blends(with Petcoke & w/o Western Canadian Coals)					
Blend	% of W.C.	% of P.C.	Theo. SHO %	Actual SHO %	Ratio %
C1	0	15	-10.9	-6.2	56.7
C2	0	8	-15.4	-9.0	58.4
C3	0	8	-16.4	-8.5	51.8
C4	0	8	-15.3	-9.1	59.5
C5	0	9	-12.8	-9.7	75.8
					Avg. = 60.4

Table IX - Sole-Heated Oven Test Results on Blend(with both Petcoke & Western Canadian Coals)					
Blend	% of W.C.	% of P.C.	Theo. SHO %	Actual SHO %	Ratio %
D1	24	9	-11.6	-10.6	91.1
D2	14	9	-12.8	-10.0	78.2
D3	15	9	-12.2	-11.0	90.0
D4	16	9	-12.4	-10.2	82.4
D5	16	9	-11.3	-10.3	91.3
D6	17	9	-12.1	-10.5	84.5
D7	52	4	-9.1	-8.4	92.4
D8	20	9	-13.3	-11.0	82.6
					Avg. = 86.6

ASH

At the first sight, Western Canadian coals are hard to attract metallurgical coal users, due to their high ash contents (Table V). This is because of the mineral matter distribution difference between Western Canadian coals and U.S. coals (Figure 6, & 7). Western Canadian coals contain

lots fine mineral matter which are very difficult to be washed away. These ashes are high in Al_2O_3 and SiO_2, and low in Fe, K, Na, and Ca; they actual reduce the reactivity (2,3). So, they should be considered as "necessary evils".
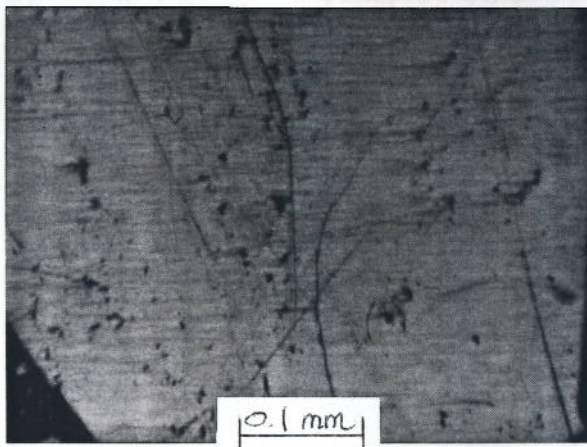

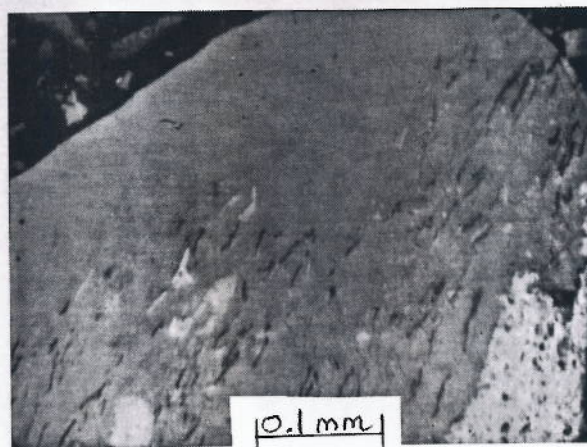Figure 6 - A Piece of Western Canadian Coal. Lots of Small Mineral Matters Included Inside the Coal.

Figure 7 - A Piece of U.S. Coal. Almost No Mineral Matter Included.

Oxygen Content

Table IV indicated that Western Canadian coals always contain more oxygen than the U.S. counterparts with similar V.M. content. Oxygen produces linkages during heating. This explains why the fluidity of Western Canadians is low.

Amount of Reactive Material

Both Western Canadian coals, and petroleum coke have less reactive material. Thus, it makes gases easier to escape during cokemaking.

Carbon Textures

This is the major factor to decide the CSR and reactivity (2,4,5). Carbon textures produced by a coal is determined by its rank (MMR), not its V.M. content. Table IV tells us that no Western Canadian coal generates isotropic carbon texture. All commercially available Western Canadian coals generate desirable anisotropic carbon texture.

As mentioned before, Western Canadian coals have high oxygen content. This high oxygen content, compared to U.S. coals, makes the end product a coke with finer carbon texture. U.S. L.-V. coals have more reactive material/less oxygen content, and eventually end up with long fiber carbon textures. A long fiber texture is usually very strong along the fiber direction (Figure 3 (b)).

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With such strong fiber and high viscosity during coking, gases inside have a difficult time to escape the coking mass. This is why U.S. L.-V. coal is very expansionary during cokemaking. Shorter fibers are not that strong along fiber direction. That is why Western Canadian L.-V. coal has more of a chance to form a thick-wall bubble structure (Figure 8) and shrink during cokemaking. This thick-wall bubble structure should be much stronger than thin-wall structure (Figure 4) in either stability or CSR.
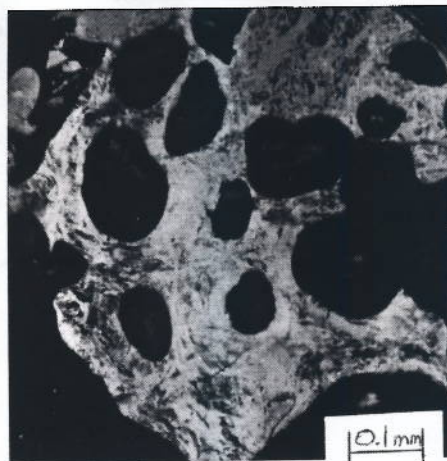

Figure 8 - Thick-wall Bubble Structure.

Binding and Interaction

Western Canadian coals usually bind very well with any U.S. coals. Sometimes, they even react with U.S. coals. Interaction produces extremely strong binding. Petroleum coke, on the other hand, can only have reasonably fair binding.

Petroleum Coke

It boosts up the apparent specific gravity of coke, and increases the CSR as well.

Yield

With petroleum coke and Western Canadian coals in the blend, coke yield increases.

Conclusion

Using a blend comprised of both petroleum coke and Western Canadian coals, enables ACME Company to produce high quality metallurgical coke with minimal damage to the oven. At the present time, ovens are still in good shape. The quality of ACME's coke is No. 1 in the U.S..

It is also the author's personal belief that 20 years from now, human beings need little research in cokemaking, if we still need coke. Cokemaking will be a routine manufacture job.

Table X - ACME's Coke Quality
(Typical, As of 10/15/98)
1. **7.5% Ash, 0.82% S, 0.50% V.M.**
2. **62.0% Stability, 67.0% CSR.**
3. **Approx. 52.0% Plus 2".**
4. **Coking Rate: 0.95 IN/HR.**

References

1. Brysch, O. P. and Ball, W. E., Inst. Gas Tech., Research Bull., No. 11, p. 60, 1951.
2. Goscinski, J. S. and Patalsky, R. M., Ironmaking Conference Proceeding., p. 53-73, 1990.
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