Low CRI, High CSR Coke Trials

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ABSTRACT

To improve coke performance in the cupola, the authors discovered that coke used in blast furnaces [low Coke Reactivity Index (CRI), high Coke Strength after Reaction (CSR)] exhibits higher strength than foundry coke and may provide better performance due to larger coke pieces reaching the melt zone. Coke strength and sizing are extremely important in a cupola because the coke must reach the melt zone intact, stay in the melt zone long enough to replenish the coke bed, provide heat for melting and carbon pick-up to the liquid iron. This research evaluates the cupola performance difference between cokes of high and low CRI. In addition, efforts were made to identify differences in characteristics of these cokes.

Keywords: energy, coke, cupola, blast furnace, coke reactivity tests, coke reactivity index, CRI, coke strength after reaction, CSR, blast furnace coke, BF coke

INTRODUCTION

Higher CSR coke has higher hot strength implying that coke with those properties will travel farther down the cupola shaft which can enhance metal temperature and carbon pick up. Furthermore, the stronger coke in the presence of heat and CO_2 will better support the burden in the cupola.

The researchers discovered a technical paper presented in 1982 [1] on measuring different coke reactivity effects in cupola melting. At the time blast furnace coke (BF coke) was higher in CRI than foundry coke. Since then, BF coke was reformulated to have lower CRI and higher CSR than foundry coke. CRI of typical foundry coke today is in a range of 32 to 43 and CSR a range of 7 to 12. CRI of typical BF coke today is less than 25 and CSR is greater than 60.

Hypothesis: Lower CRI/higher CSR coke will perform better than higher CRI/lower CSR coke which is currently produced in the USA for cupola furnaces.

A test in a production cupola was proposed to substitute foundry coke in progressively higher amounts with low CRI/high CSR coke of appropriate size for the cupola (4-in x 6-in) or (100mm x 150 mm). If serious operational issues were encountered the test would be terminated. Otherwise, progressive substitutions would continue to full substitution with 100% low CRI/high CSR coke. The cupola would continue with the test coke until the supply was exhausted or operational issues that could not be corrected were encountered.

COKE DISCUSSION

DEFINITIONS

Coke Reactivity Index (CRI) – percentage weight loss of a coke sample heated for 120 minutes at 2012F (1100C) in the presence of CO_2.

Coke Strength After Reaction (CSR)– percentage weight of the coke sample left in a drum after tumbling that is greater than 3/8" (9.525 mm).

CRI/CSR MEASUREMENT HISTORY

The initial research for evaluating the effect on coke reactivity as it relates to coke strength in the blast furnace was done by Nipon Steel in the 1970s. Early in the 1980s a procedure was agreed to per the ASTM procedure as outlined in the definition section. The heating cycle time soaking the coke in the presence of CO_2 at 2012F (1100C) for 120 minutes was established. [2]

Since typical cupola dwell time is approximately 60 minutes, the authors questioned if the ASTM procedure is relevant specifying 120 minutes. A research study was conducted in 1980 comparing different heat cycle times for different coke samples. Included at the end of this paper are two graphs (Figs. 18 & 19) from this study (Reference 4), for CRI and CSR. Both show a linear relationship which proves that the test soak time of 120 minutes is relevant to cupola melting. [3,4]

Of interest but not a claim in cupolas, based on coke testing in blast furnaces, there is a rule of thumb that for every 1 percent increase in CSR, a 3-pound reduction of carbon from the coke up to 55 CSR can be realized, thereafter, a 1 percent increase in CSR can result in a 1-pound reduction of carbon from the coke. [5]

LABORATORY TESTS

Table 1. Coke Chemistry Proximate Analysis, Dry Basis

	Foundry Coke	+4in. BF Coke	Normal BF Coke
Fixed Carbon Dry, wt.%	90.69	89.13	90.32
Ash, wt.%	8.62	9.28	9.22
Volatile, wt.%	0.69	1.59	0.46
Sulfur, wt.%	0.67	0.61	0.69
Moisture, % as received	3.39	5.42	
Source: Standard Laboratories Inc			

Comparing the analysis in Table 1, coke ash is higher for both +4in. BF coke and typical BF coke. It is important to note that the same coke producer made the foundry and BF coke. The higher volatile content of the +4in. BF coke was perplexing. Before proposing the possible reason for the higher volatile content, it is important to understand the method used to produce these cokes.

The traditional method for producing BF coke is in a byproduct slot oven battery. Normal BF coke produced in a slot oven has a top size of 2 inches (50 mm). The supplier of the +4in. BF coke produces coke in a beehive type oven. This method produces BF coke top size that is larger. Through extensive efforts the coke producer was able to scalp the coke larger than 4 in. (100 mm) for this cupola experiment.

One possible reason for the higher volatile in the +4in. BF coke is that the larger coke origin could be from the center of that oven. If so, perhaps the coal was not fully degasified hence the higher volatile content in the coke. The other possibility is error in the sampling of the coke. In any event it does not appear that higher volatile content negatively affected the performance of +4in. BF coke in the cupola.

Table 2. Coke Strength Analysis

	Foundry Coke	+4in. BF Coke	Normal BF Coke
CRI	43.24	31.43	24
CSR	6.98	52.31	63
Strength as Stability	31.48	58.12	61
Strength as Hardness	33.03	60.73	67
Porosity, %	52.44	48.77	
Source: Standard Laboratories Inc			

A coke strength analysis is provided in Table 2. The CRI for +4in. BF coke is lower than foundry coke but not as low as typical BF coke produced by the supplier. Measuring CSR, which is a measure of hot strength shows much higher for the +4in. BF e coke but not as high as normal BF coke.

Stability and Hardness indexes show the mechanical and abrasion strength of the cokes. The results show a remarkable improvement compared to foundry coke. The test results comparison of the +4in. BF coke were very close to the normal BF coke. The porosity of the cokes was also measured as it is a function of strength. The +4in. BF coke was slightly less than the foundry coke. Per discussion with experts in making BF coke, changing the CRI of the coke has no bearing on the porosity of the coke.

Table 3. Coke Ash Mineral Analysis

Weight %	Foundry Coke	+4in. BF Coke	Normal BF Coke
CaO	5.01	3.11	2.39
Fe_2O_3	12.96	11.81	14.29
MgO	1.40	1.17	1.14
TiO_2	1.39	1.45	1.34
Na_2O	0.61	0.63	0.59
K_2O	1.92	1.90	2.11
SiO_2	45.43	47.41	49.48
Al_2O_3	26.19	28.42	25.90
Catalytic Index	0.286	0.230	0.257
Catalytic Index = $(CaO + Na_2O + K_2O + Fe_2O_3) / (SiO_2 + Al_2O_3)$			Source: Standard Laboratories Inc

A coke ash mineral analysis is presented in Table 3.
The formula from the AFS "Cupola Handbook" 6th edition[6] (Chapter 8, page 17) was used to calculate the catalytic index based on the reported mineral content of the ash. Experts in the making of low CRI coke state that the coke ash mineral analysis will be less basic than higher CRI coke. [6] This test report concurs and shows that the BF coke ash mineral analysis is less basic than the foundry coke used in the cupola trial. It appears that during the substitution with BF coke in the cupola had the limestone in the charge been reduced along with the reduced BF coke charges it may have prevented an increase in cupola slag basicity that occurred during the testing.

COKE ASH FUSION

The relationship between the ash composition and the ash softening temperature (T_s) is shown in Table 4 with calculations.

Table 4. Calculated Coke Ash Softening Temperature (Ts) [7]

	Foundry Coke C/F	+4in. BF Coke C/F	Normal BF Coke C/F
Softening	1345/2454	1390/2535	1379/2514
$T_s = 19(\%Al_2O_3) + 15(\%SiO_2 + \%TiO_2) + 10(\%CaO + \%MgO) + 6(\%Fe_2O_3 + \%Na_2O)$			

The Cupola Handbook (Chapter 8)[7] states that the lower the ash softening temperature the better the carbon pick-up from the coke.
The +4in. BF coke T_s was 113°F (62.8°C) higher, but this cupola test showed a higher increase of carbon than foundry coke.

Another test in a hot blast cupola may or may not corroborate these results.

Table 5. Coke Ash Fusion Temperatures

		Foundry Coke (F)	+4in. BF Coke (F)	Temperature Difference °F/°C
Initial	**Oxidizing**	**2450**	**2636**	**+186°F / 103.3°C**
	Reducing	**2117**	**2267**	**+150°F / 83.3°C**
Softening	**Oxidizing**	**2530**	**2683**	**+153°F / 85°C**
	Reducing	**2383**	**2488**	**+105°F / 58.3°C**
Hemispherical	**Oxidizing**	**2568**	**2697**	**+129°F / 71.7°C**
	Reducing	**2473**	**2576**	**+103°F / 57.2°C**
Fluid	**Oxidizing**	**2645**	**+2700** *	**+55°F / 30.6°C**
	Reducing	**2544**	**2694**	**+150°F / 83.3°C**

Source: Standard Laboratories Inc
*** -** The maximum of the instrument scale is 2700F.

Coke ash fusion temperatures for initial, softening, hemispherical, and fluid states are shown in Table 5. Tests were run in a laboratory furnace, both in oxidizing and reducing atmospheres due to both conditions existing in the cupola.

The foundry coke ash softening temperature in an oxidizing atmosphere temperature is 108ºF (60°C) higher and 102ºF (56.7°C) lower in a reducing atmosphere as compared to the formula calculation (T_s).

The difference for the BF coke was 180ºF (100°C) higher in an oxidizing atmosphere and 79ºF (14.4°C) lower in a reducing atmosphere as compared to the formula calculation (T_s).

Also, it is interesting to note that all temperature results were higher in an oxidizing than in a reducing atmosphere. Furthermore, for every test state the +4in. BF coke ash fusion temperatures were higher than the foundry coke. This clearly supports the theory that lower CRI coke has higher ash fusion temperatures.

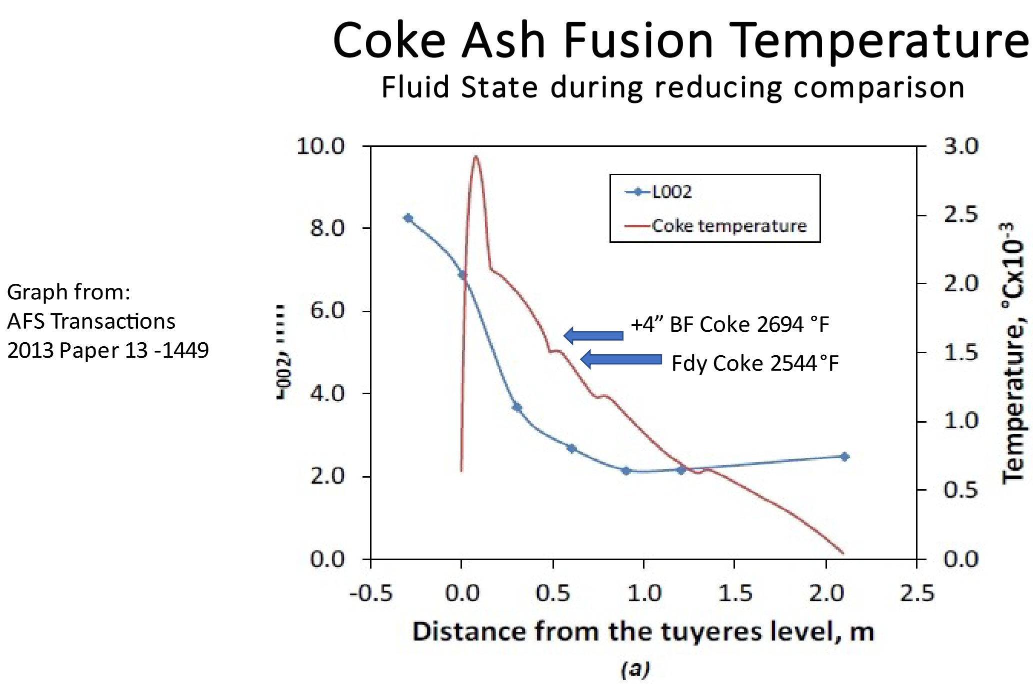

Figure 1. Plot of coke ash fusion temperature as a function of distance from tuyeres level.[8]

A graph from the "Studies of a Quenched Cupola Part IV: Coke Behavior" paper[8] is shown in Figure 1. This graph shows the coke temperature from a cupola computer simulation program. In addition, it shows L_{002} (average carbon stacking height) or the degree of graphitization. Coke enters the cupola as amorphous carbon. As the coke descends, it increases in temperature and starts graphitizing at the coke/liquid metal interface above the tuyeres. The authors added to this graph test results of coke ash fusion liquid temperatures in a reducing atmosphere depicted with heavy arrows. Comparing the two, BF coke was 150°F (83.3ºC) higher than foundry coke. The ash fusion temperature in an oxidizing atmosphere was not plotted because the laboratory furnace was only capable of measuring a maximum of 2700F (1482C).

The authors believe the ash fusion liquid temperature is an important consideration. The theory is that perhaps the ash may insulate the carbon inside the coke until the ash is released when it becomes liquid thus exposing the carbon at a higher temperature. Furthermore, the higher coke temperature transforms more carbon from amorphous to graphitic carbon.

EXPERIMENTAL TRIALS

COKE SAMPLING PROCEDURE:

Five-gallon bucket samples of coke were collected randomly for the duration of the tests for both the foundry and +4in. BF coke. The buckets were then emptied into three 55-gallon (208 liter) drums each for foundry and BF coke. The total weight of each coke sample was approximately 600 lb (272 Kg).

The original test sequence was to obtain base line data on the first day with foundry coke only. The second day was to start blending 30% +4in. BF coke working towards 50%. The third day was to start at 50% BF coke and work towards 100% barring problems producing the required molten iron.

It became apparent on the second test day that the next truckload of BF coke was not going to arrive in time to start testing on the third day. Based on the promising performance of the BF coke a decision was made to accelerate to 100% BF coke.

In the afternoon, we that the cupola slag changed color suggesting the slag was more basic. In addition, spout carbon increased dramatically while silicon began decreasing. This further suggested that perhaps the cupola slag was becoming more basic which could be detrimental to the refractory.

Accordingly, further testing of the second truckload of BF coke was delayed until a complete chemical composition of the cupola slag and coke could be obtained. In addition, a review of the cupola performance including all charge materials and overall conditions of the cupola needed to be performed.

The foundry practice where this testing was performed was to vary the blast rate of the cupola to match the molten metal demand at the molding line. Sometimes, low melt demand dictates a lower blast rate such that an under-blowing condition (stack gas ≤ 11% CO) is created. When this occurs, the slag dwell time in the well of the cupola increases which normally would inhibit carbon gain, but if limestone is not reduced to compensate for lower basicity ash of the BF coke, the slag basicity and volume can increase enough to create an environment where carbon increases and silicon decreases.

When the second truckload of BF coke was run, the foundry agreed to change the cupola operation practice during times of lower melt demand. The cupola blast rate was held constant and when less molten metal was needed the blast rate was turned off until the molding line consumed enough metal. Then the blast rate was restored. Since the blast off-time was less than fifteen minutes, it resulted in more consistent carbon and silicon concentrations at the cupola spout.

Data collection/test days were:

- Baseline data foundry coke: 8/16/22
- 1st day with BF coke: 8/17/22 (Fig. 2)
- 2nd day with BF coke: 11/10/22 (Fig. 3)

Table 6. Characteristics of the Test Production Cupola

- Cold blast
- Partially lined (pre-heat zone (PHZ) and unlined melt-zone (MZ)
- 58in. ID PHZ, MZ and Well
- Oxygen injection
- (4) WRIB tuyeres, 5in. ID and 8.375in. OD, 13in. protrusion
- 8.3ft. unlined water cooled height
- 8.3ft lined PHZ height
- Effective stock height 13.9ft.
- Full cupola is seven charges
- 24in. bottom thickness
- 9in. iron dam and 11in. slag notch
- Taphole 3in. high x 2in. wide rectangular
- Approx. well depth 24in. (center tuyeres to center cupola bottom)

Tracking the melting operation during the baseline and testing periods consisted of monitoring each charge and charge components, cupola blast variables, cupola variables and molten iron/slag results (Tables 6-9, Figs. 4-6).

Table 7. Typical Charge Makeup

Charge Material	**Wt-lb (%)**
Steel P & S Heavy	900 lb (34.8%)
Pig Iron	300 lb (11.6%)
Returns	1,300 lb (50.3%)
50% Ferrosilicon Brx	77 lb (3.0%)
63% Ferro Mn Brx	10 lb (0.39%)
Total Load	2,587 lb
Coke	380 lb (14.69%)
Stone	80 lb (21% of coke)

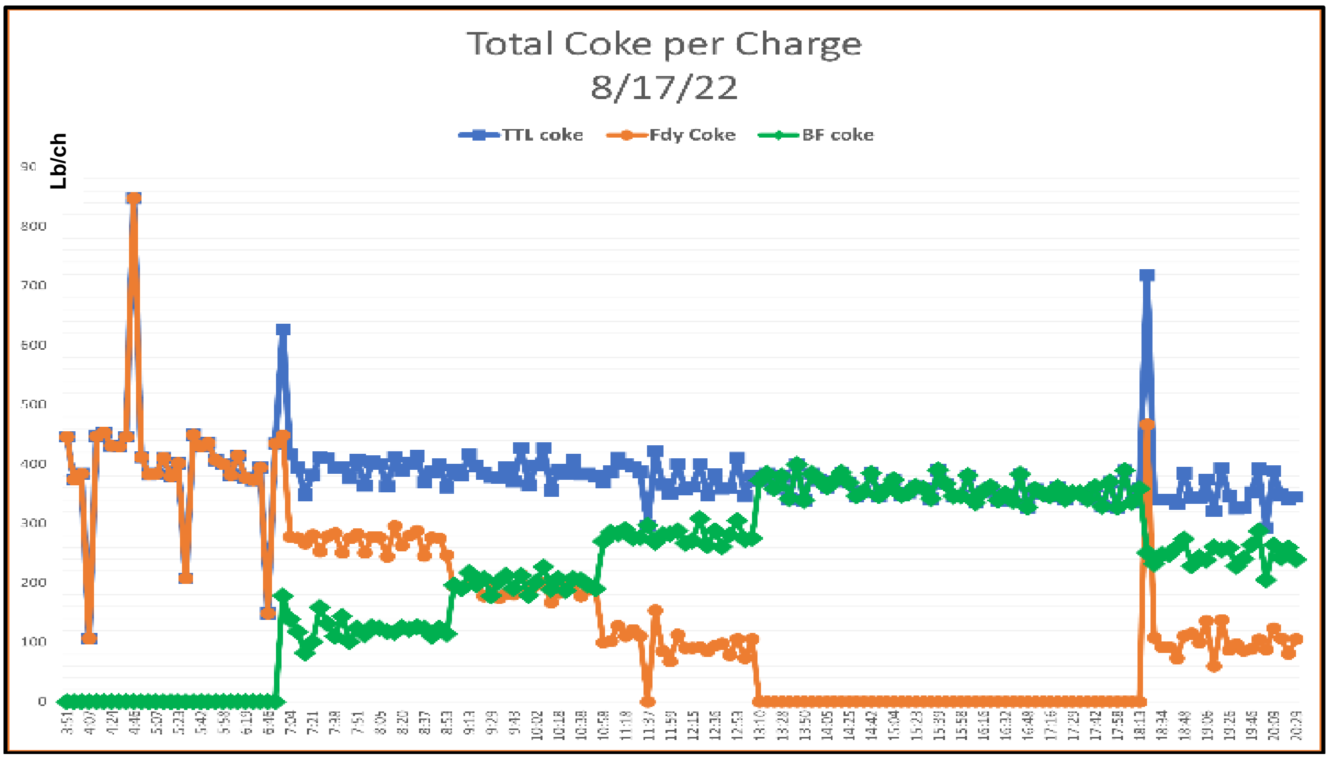

Figure 2. Foundry and BF coke addition profile during Day 1 testing.

Table 8. Schedule of Coke Additions 8/17/22

Time	Fdy Coke Target, lb.	BF Coke Target, lb.	Total Coke, lb.	BF Coke %	Comments
3:51	390	0	390	0.0	
4:46	428	0	428	0.0	Split/booster
7:02	270	120	390	30.8	
9:06	190	200	390	51.3	
11:03	110	280	390	71.8	
11:35	90	280	370	75.7	
13:17	0	370	370	100.0	
14:36	0	360	360	100.0	
16:14	0	350	350	100.0	
18:32	100	250	350	71.4	Continued to end of melt 20:40

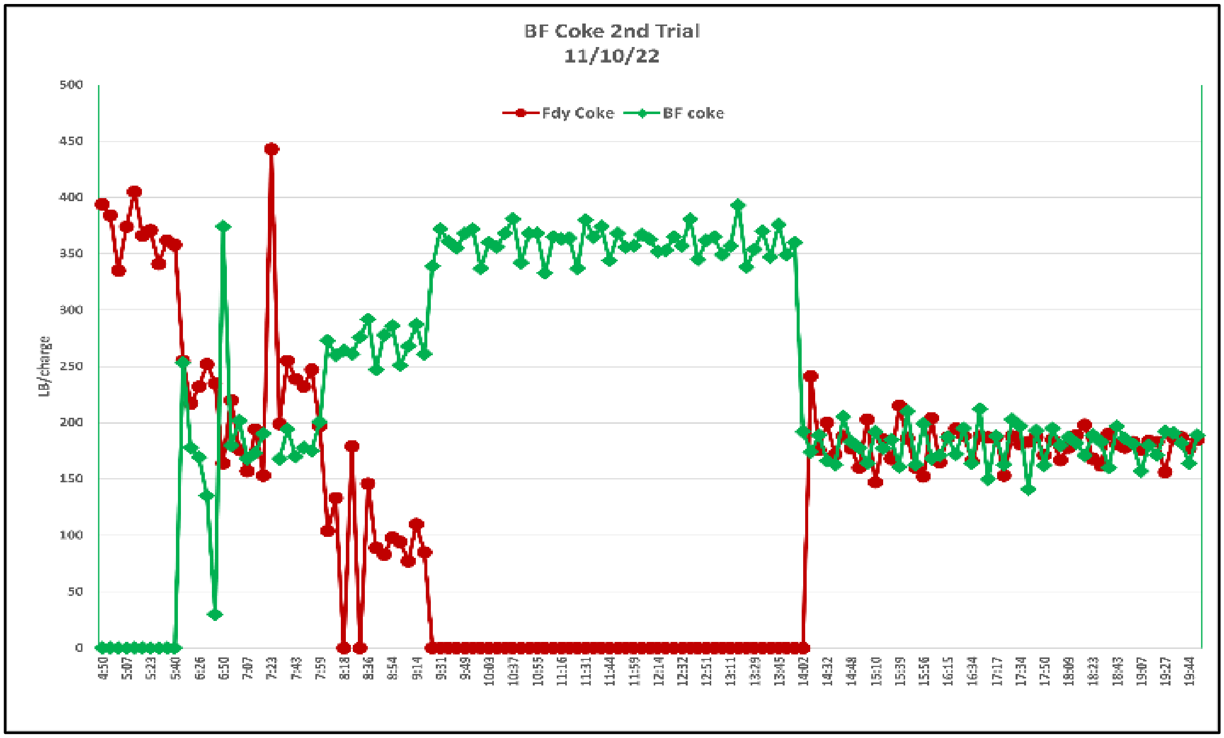

Figure 3. Foundry and BF coke addition profile during Day 2 testing.

Table 9. Schedule of Coke Additions 11/10/22

Time	Fdy Coke Target, lb.	BF Coke Target, lb.	Total Coke, lb.	BF Coke %	Comments
4:50	360	0	360	0.0	
6:14	240	180	420	42.9	Communication error
6:50	180	180	360	50.0	
7:23	400	0	400	0.0	Split/booster
7:38	240	180	420	42.9	
8:06	90	270	350	75.0	
9:26	0	360	360	100.0	
14:07	180	180	360	50.0	Continued to end of melt 20:00

Figure 4. Foundry coke.

Figure 5. Blast furnace coke, 4+ in.

Upper stack gases were collected continuously and analyzed for CO and CO_2 concentration

Stack Gas Sample Collection

Figure 6. Photos of stack gas sample collection equipment.

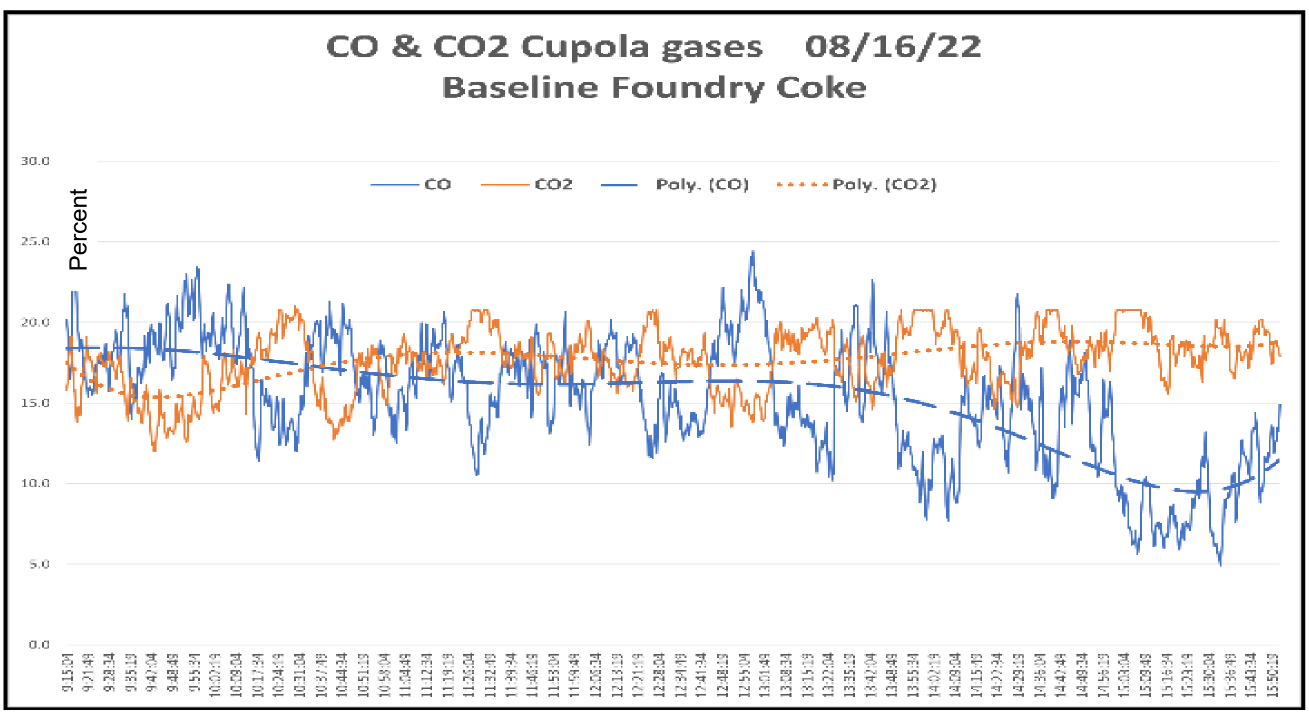

Figure 7. CO & CO_2 top gas concentrations during baseline foundry coke the day before testing with BF coke. Note that gas concentrations are mostly consistent until late in the day when the CO concentration dropped suggesting a lower cupola blast rate.

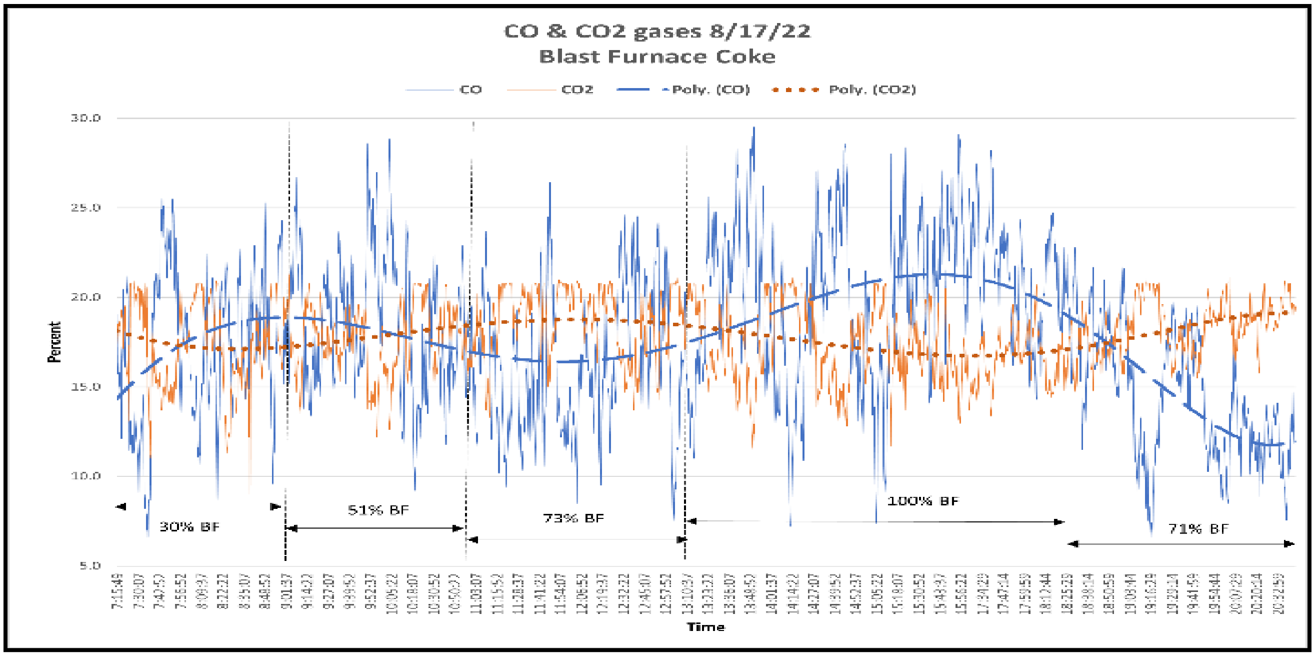

Figure 8. CO & CO_2 top gas concentrations during the first day of testing BF coke. Gas concentrations display a normal variation until after approximately 40 minutes into 100% BF coke when the CO concentration began increasing. Our interpretation of this was the cupola was over-fueled. Lower CO concentration later was due to a lower cupola blast rate.

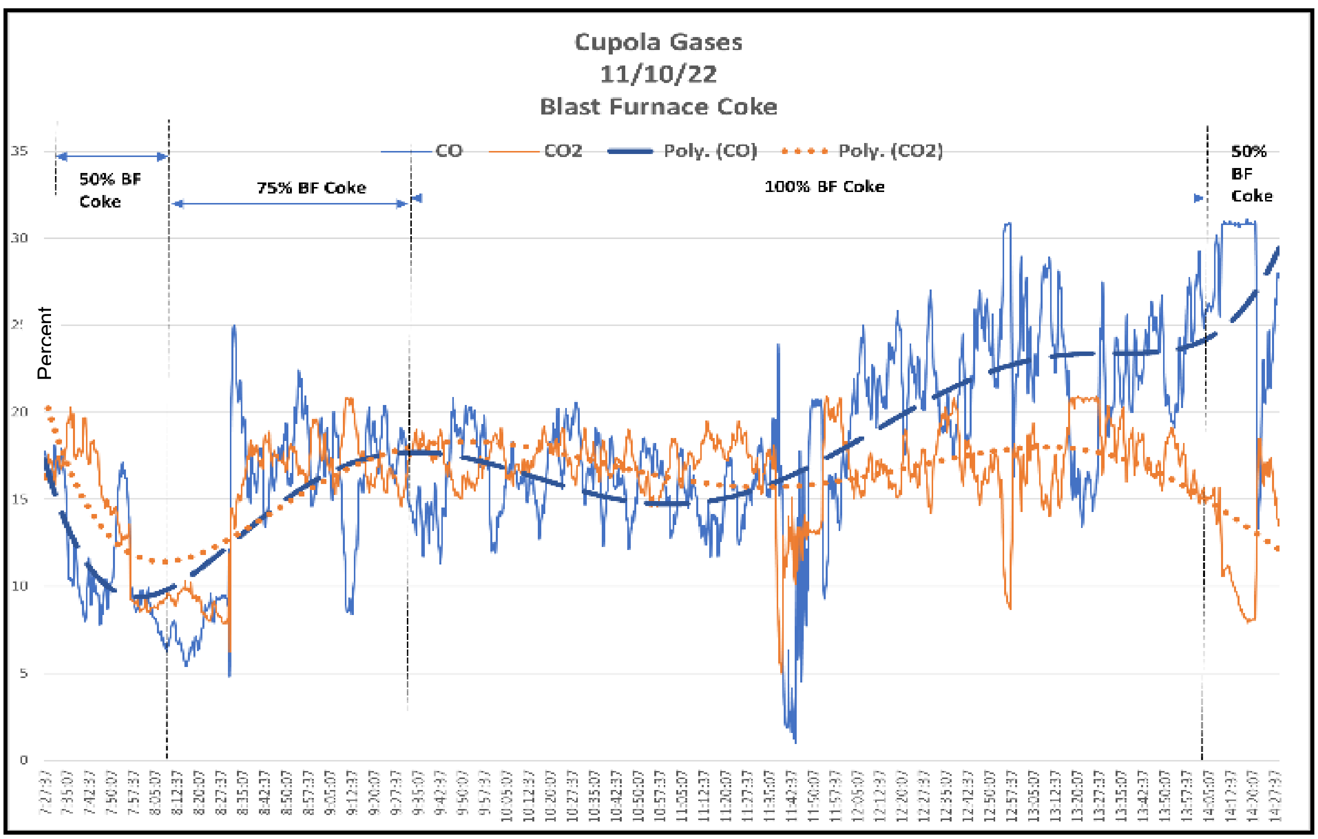

Figure 9. CO & CO_2 top gas concentrations during the second day of testing BF coke. Gas concentrations display a normal variation until approximately two hours into 100% BF coke when the CO concentration began increasing. Our interpretation of this was that the cupola was over-fueled.

Data collected from the cupola output included iron and slag data. Molten iron samples were obtained from the cupola trough at twenty-minute intervals and analyzed for chemical composition by thermal analysis and spectrochemical analysis. Molten iron temperature was also obtained at twenty-minute intervals. Slag samples were obtained on a less frequent interval and submitted to an external lab for analysis.

EXPERIMENTAL RESULTS

Figures 7-15 and Tables 10-14 show selected operational variables comparing the baseline day using foundry coke with the two days of BF coke testing.

Table 10. Observed Charge Differences by Day

Day	Coke	% Total Coke	% BF Coke	Sprue % of Charge	Steel % of Charge	Pig % of Charge	Average TPH
8/16/22	Baseline	15.4	0.0	52.2	41.9	6.0	10.5
8/17/22	BF Coke Test	15.2	8.8	52.0	42.0	6.0	11.0
11/10/22	BF Coke Test	15.0	10.6	53.8	40.2	6.0	10.4
% Total Coke = Operating coke + boosters			***Metallics (Returns+steel +pig) as denominator**				

Table 11. Observed Charge Differences by Coke

Day	Coke	Elapsed Time, hours	% Coke	Sprue % of Charge	Steel % of Charge	Pig % of Charge
8/16/22	Baseline 100% Fdy Coke	17.30	15.4	52.2	41.9	6.0
8/17/22	100% BF Coke	5.03	14.3	51.6	42.5	6.0
11/10/22	100% BF Coke	4.31	14.4	54.0	39.8	6.1

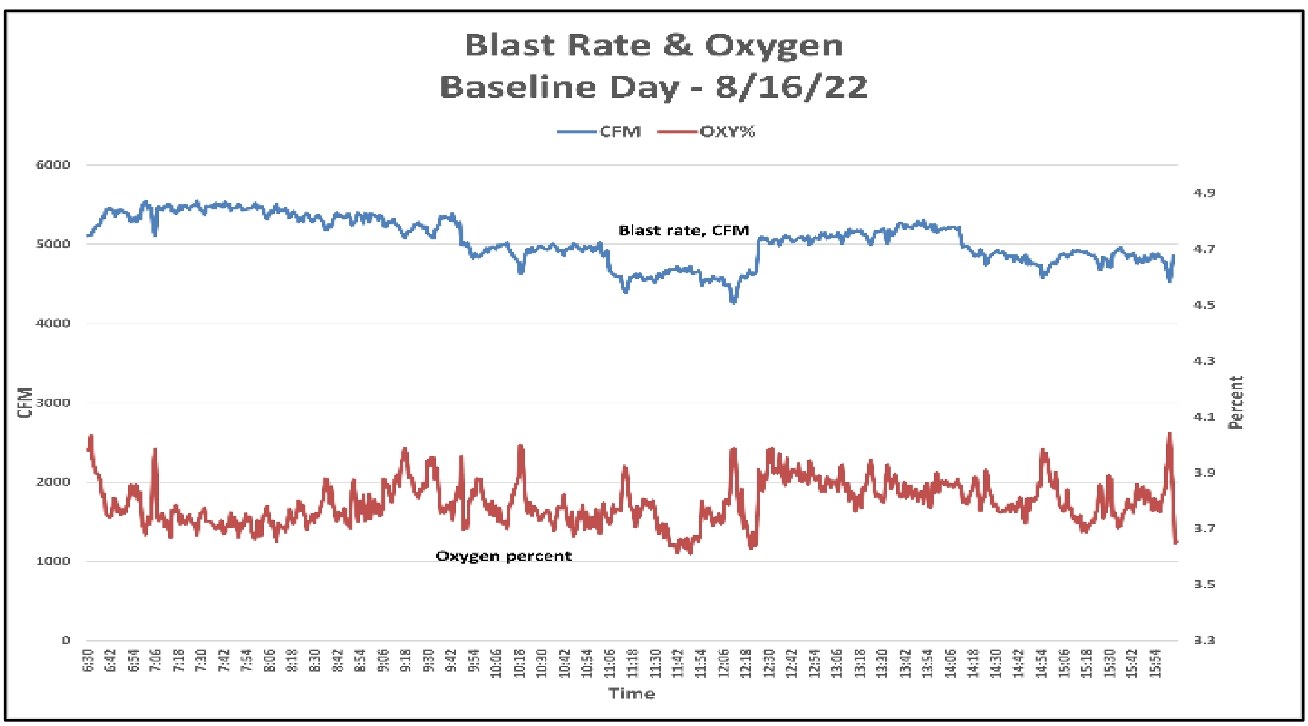

Figure 10. Blast and oxygen rate – Baseline Day melting with foundry coke. (CFM = Cubic Feet Per Minute)

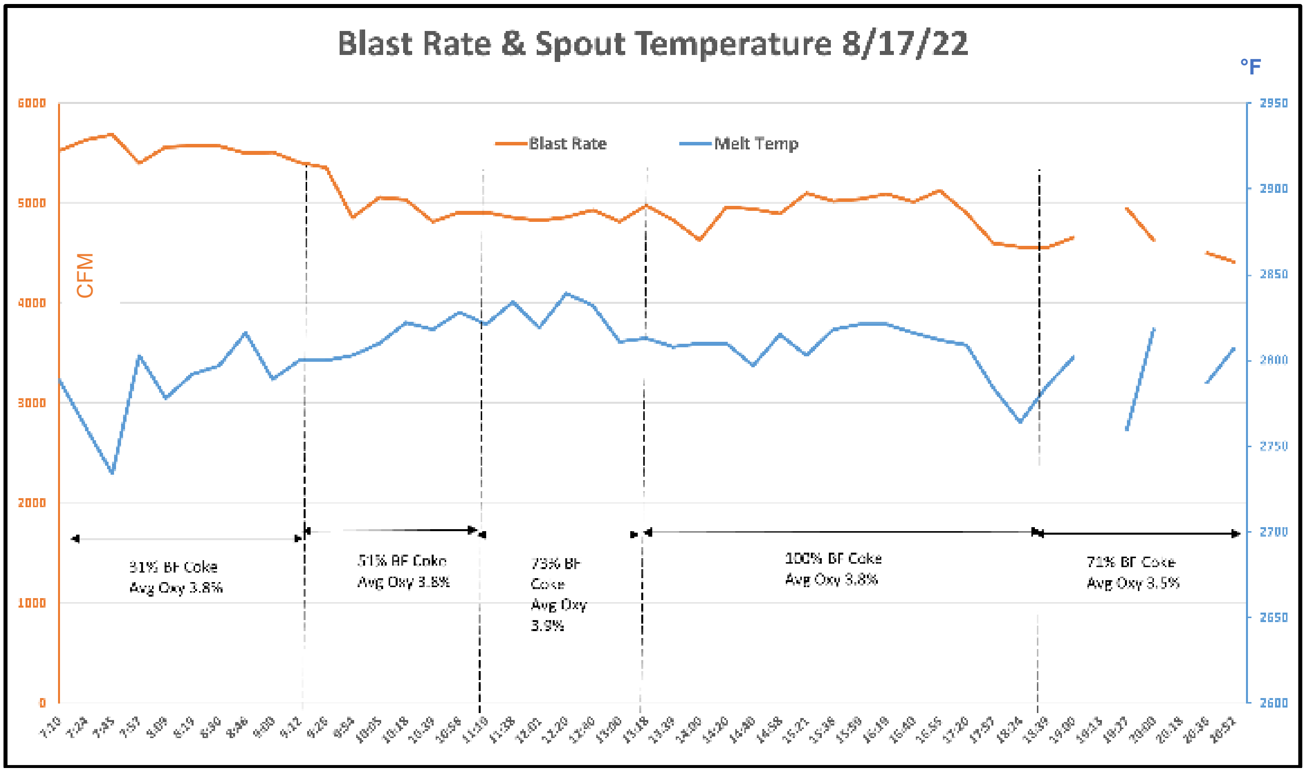

Figure 11. Blast, melt temperature and oxygen rate – First day melting with BF coke.

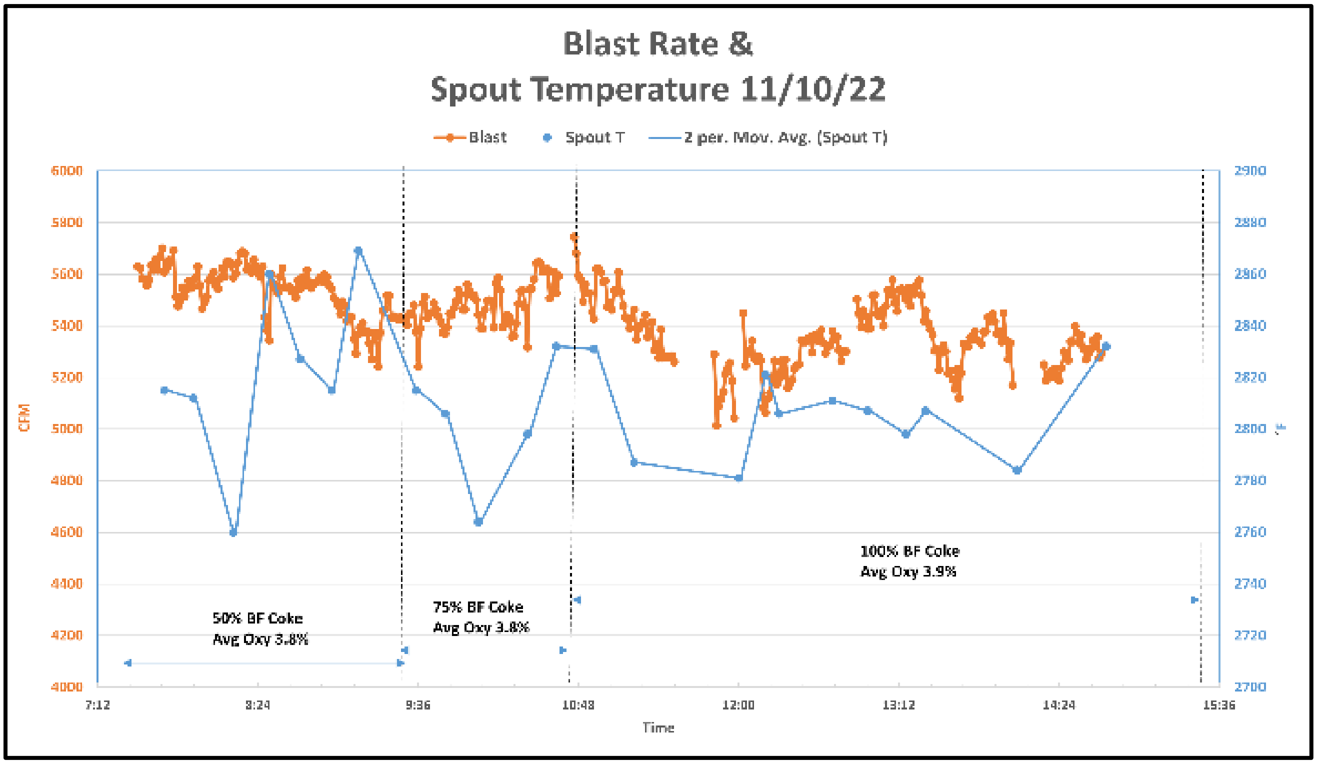

Figure 12. Blast, melt temperature and oxygen rate – Second day melting with BF coke.

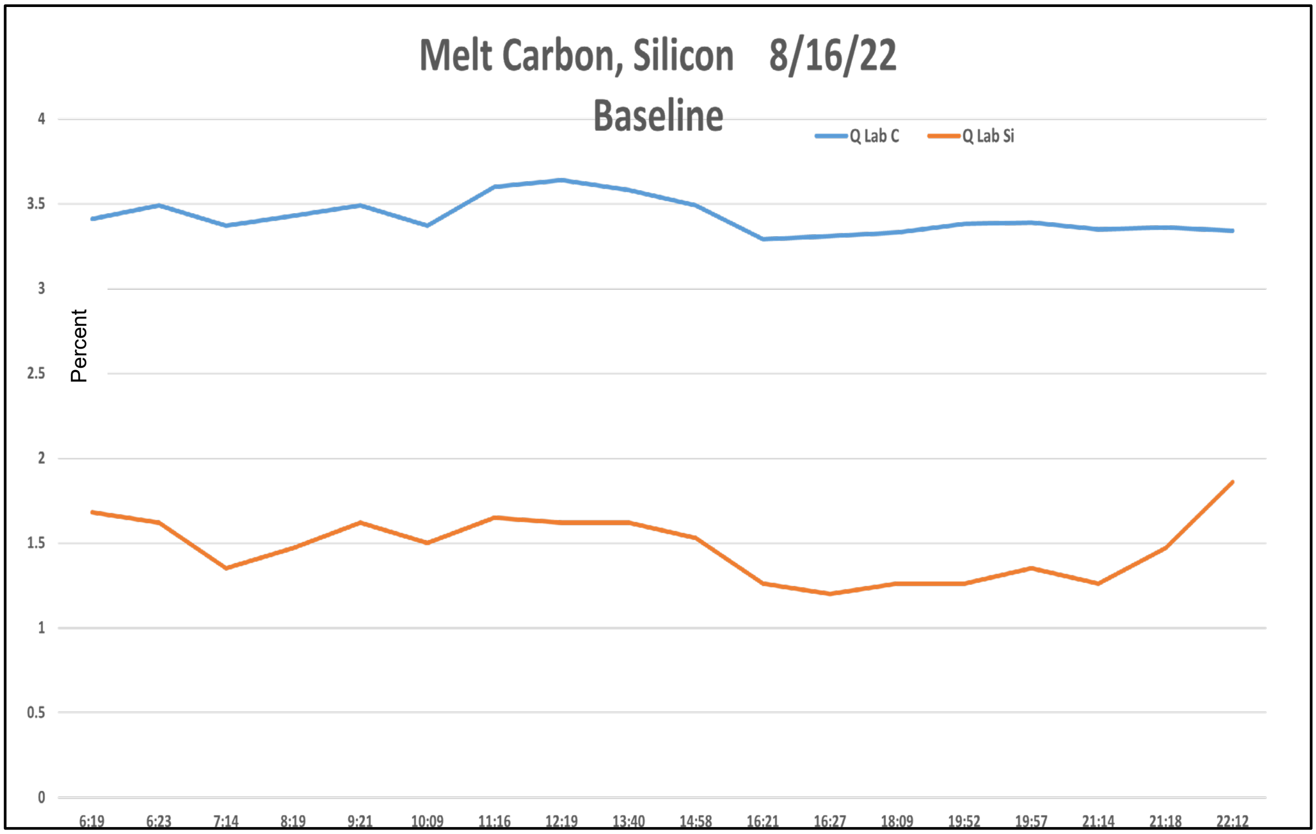

Figure 13. Lower percentages of carbon and silicon at the cupola spout imply under-blowing the cupola.

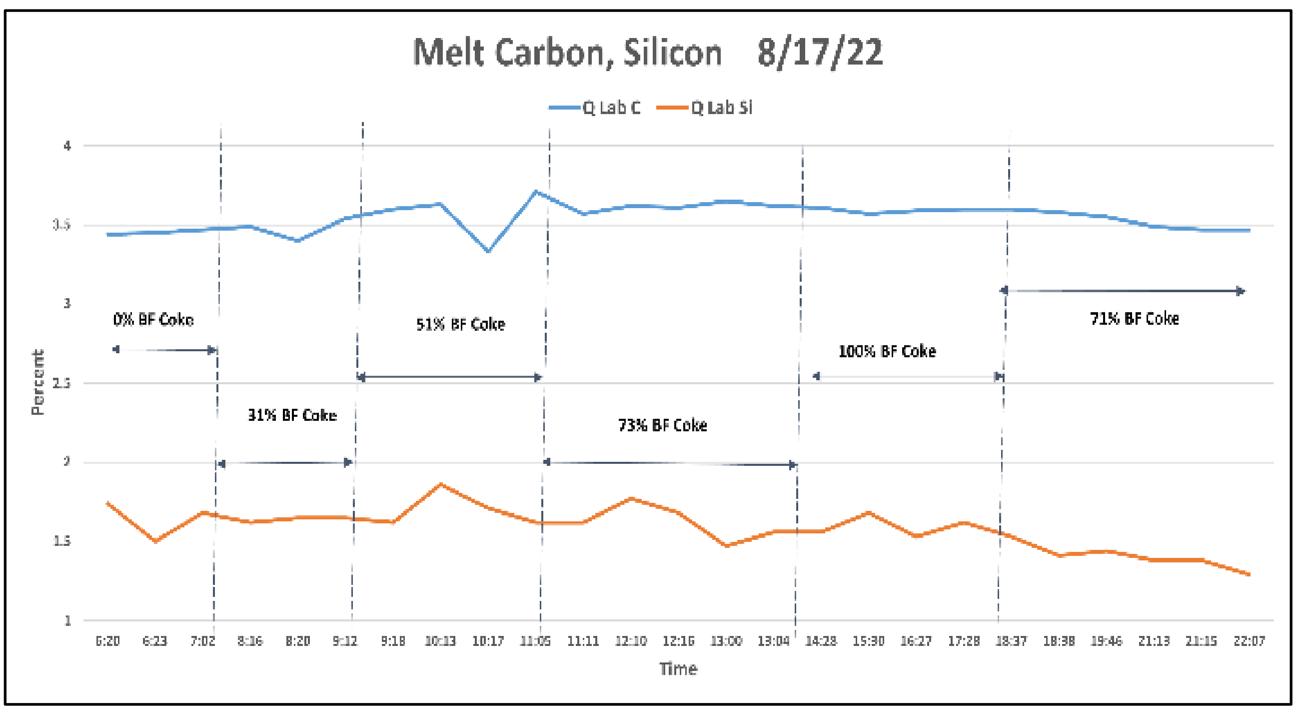

Figure 14. First test day with BF coke. Lower percentages of silicon toward the end of the heat may be partially due to under-blowing the cupola.

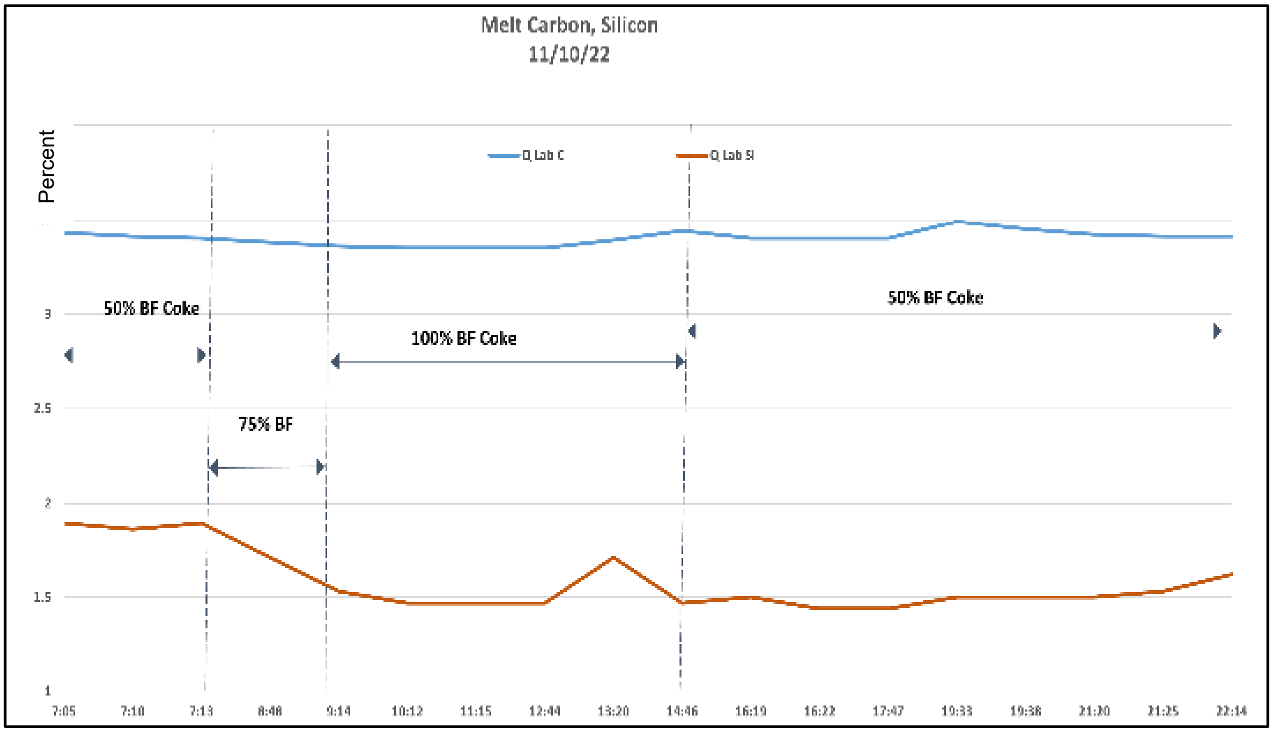

Figure 15. Second test day with BF coke.

Table 12. Silicon Loss During 100% Times

	Period	Elapsed time, hours	Silicon loss %
8/16/22	Baseline 100% Foundry Coke	17:30	29.1
8/17/22	100% BF Coke	5:03	22.8
11/10/22	100% BF Coke	4:31	18.7

Table 13. Spout %Carbon and %Silicon

	Baseline Foundry Coke		BF Coke Day 1		BF Coke Day 2	
	%C	%Si	%C	%Si	%C	%Si
Avg	3.42	1.48	3.52	1.56	3.40	1.58
Std D	0.103	0.188	0.083	0.129	0.036	0.153
Obs	18	18	19	19	18	18

Table 14. Spout %Sulfur and Iron Temperature

	Baseline Foundry Coke		BF Coke Day 1		BF Coke Day 2	
Avg	%S 0.09		%S 0.08	2804(F)	%S 0.10	2810(F)
Std D	0.017		0.011	21	0.006	26
Obs	18		19	43	18	23

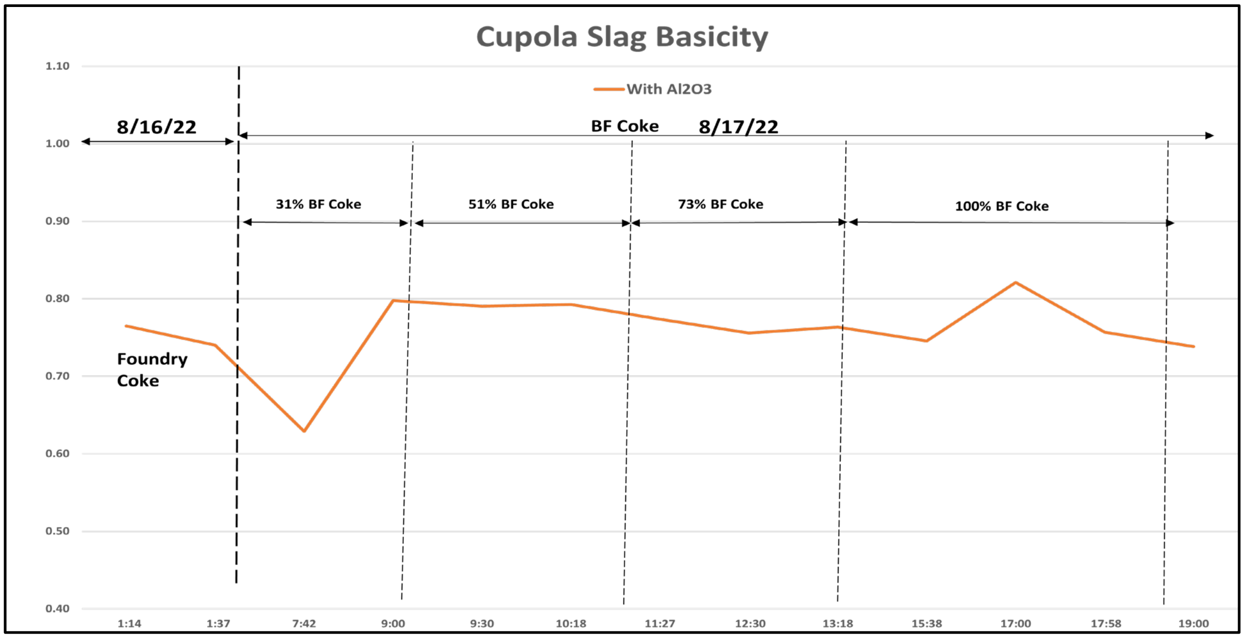

Figure 16. Comparison of cupola slag basicity between a baseline foundry coke day and the first day of foundry coke.

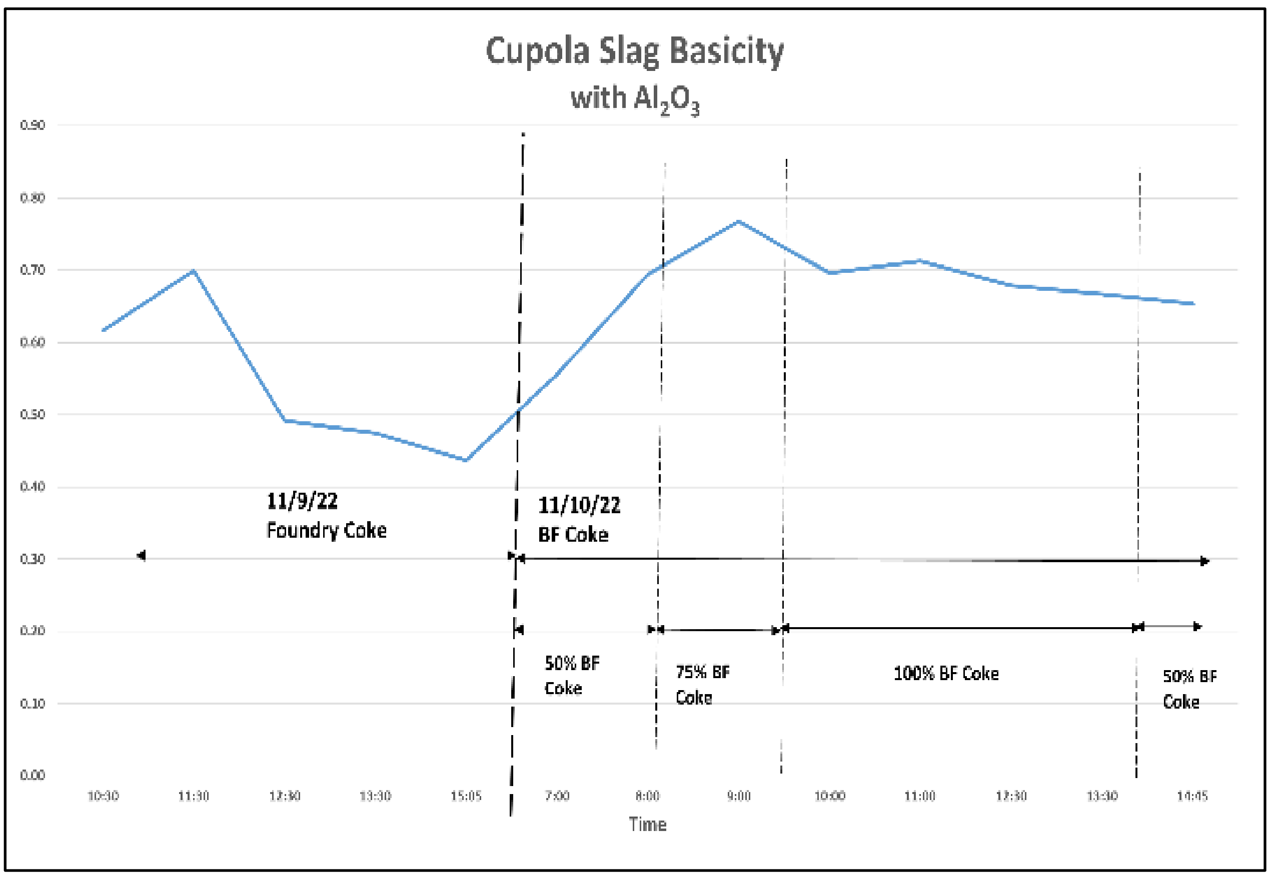

Figure 17. Comparison of cupola slag basicity between baseline foundry coke day and the second day of BF coke trials. Slag Basicity during the times BF coke was used as a fuel was notably higher than with foundry coke.

CONCLUSIONS

The low CRI/high CSR coke (BF coke) performed better than low CSR/high CRI coke (Foundry Coke) as evidenced by:

- improved carbon recovery resulting in less coke needed.
- improved silicon recovery.
- no difference in spout temperature.

As stated in the abstract, the authors believe the higher strength of BF coke versus foundry coke provided better performance due to larger coke pieces reaching the melt zone.

If it is desired to reproduce this test the following items will be necessary:

- BF coke must conform to cupola size needs (i.e., 4 x 6 or 4 x 9 sizing).
- Proximate and ash analysis of the BF coke should be similar to BF coke used in this testing.
- Amount of limestone may need to be adjusted if less BF coke is required to prevent expected higher slag basicity.
- Coke breeze generated from handling should be tracked and measured.

FUTURE CONSIDERATIONS

The authors suggest further testing in a hot blast cupola to confirm whether similar or better results with BF coke can be obtained. Also, the authors extend a challenge to the coke producer industry to produce a suitable foundry coke with lower CRI and higher CSR. Based on the results of this test it appears that cupola foundries could realize lower coke usage with this type of coke which would be a potential cost savings, emissions reduction, and an increase in melt rate.

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6. AFS “Cupola Handbook,” 6th Edition, Chapter 8, page 17, American Foundry Society (1999).
7. AFS “Cupola Handbook,” 6th Edition, Chapter 8, page 5, American Foundry Society (1999).
8. Ricardo E Aristizabal, Paula A. Perez, Harold D. Machado, Ana M. Perez, S. Katz “Studies Of A Quenched Cupola Part IV: Coke Behavior,” Paper #13-1449, American Foundry Society (2013).

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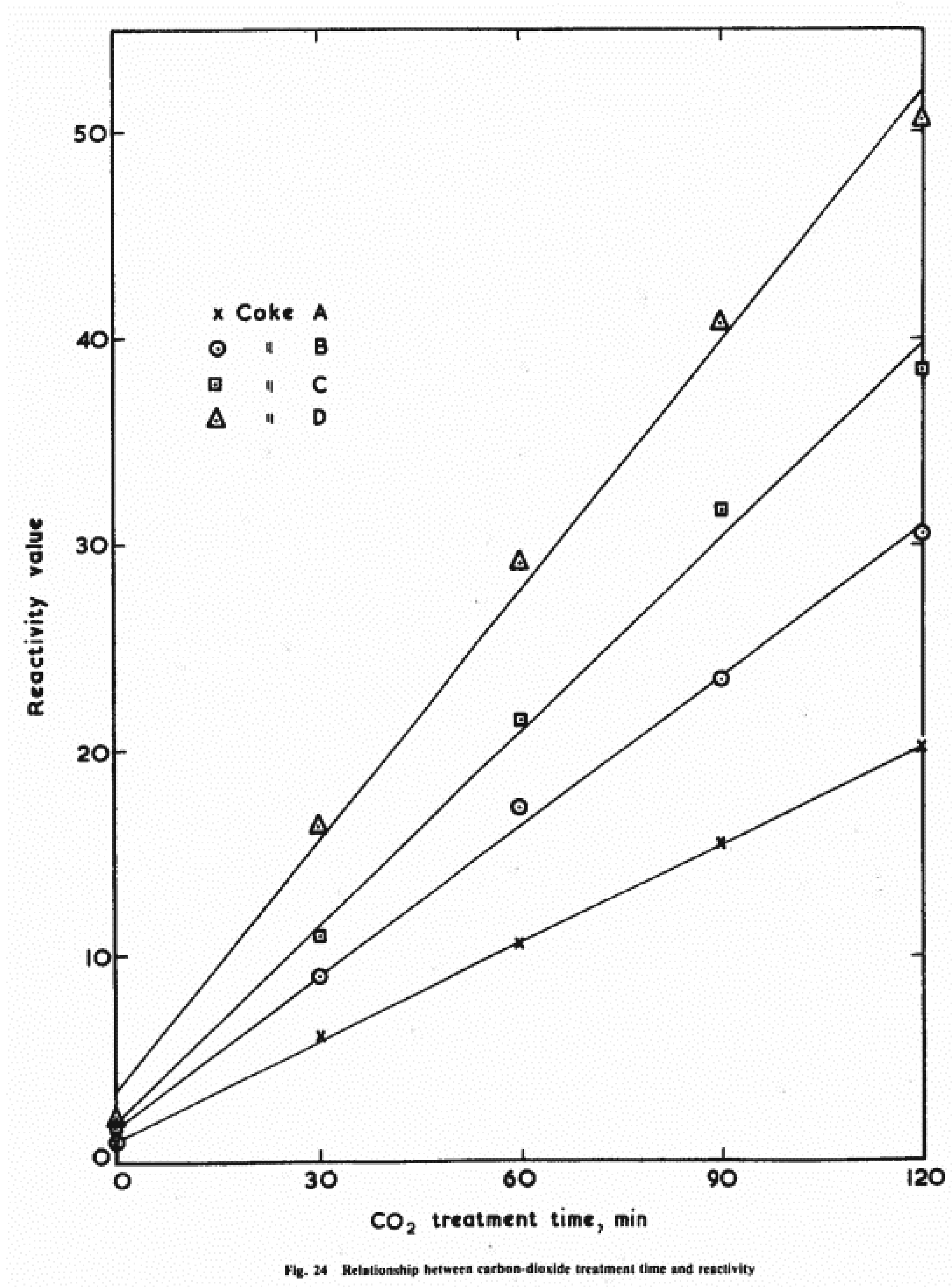

Figure 18. Relationship between carbon dioxide treatment time and reactivity. (Artwork from: "Carbonization Research Report 91, The Evaluation of the Nippon Steel Corporation Reactivity and Post-Reaction Test for Coke," The British Carbonization Research Association, Figure 24 (December 1980).[4]

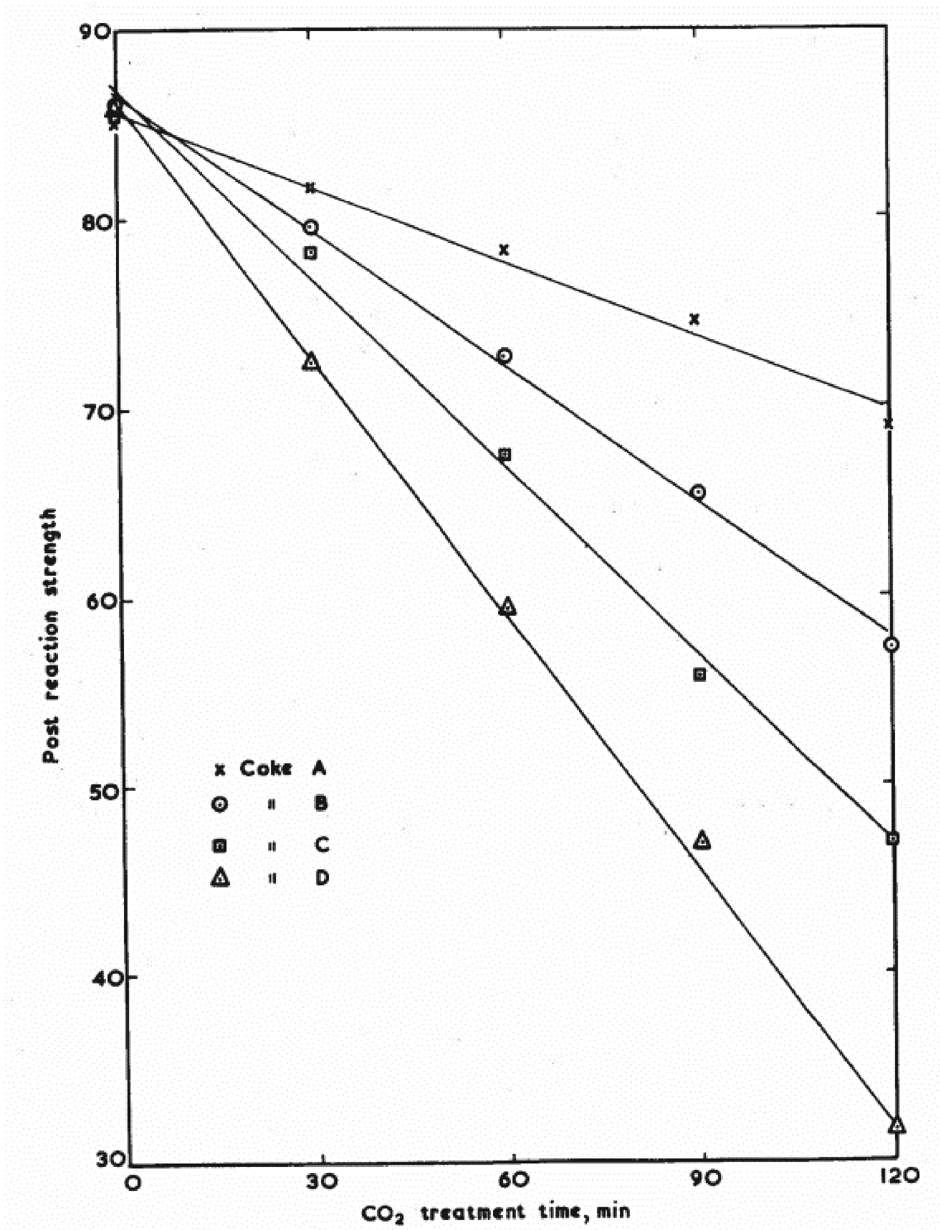

Fig. 25 Relationship between carbon-dioxide treatment time and post-reaction strength

Figure 19. Relationship between carbon dioxide treatment time and post-reaction strength. (Artwork from: "Carbonization Research Report 91, The Evaluation of the Nippon Steel Corporation Reactivity and Post-Reaction Test for Coke," The British Carbonization Research Association, Figure 24 (December 1980).[4]