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The U.S. Foundry Coke Industry

UNITED STATES DEPARTMENT OF THE INTERIOR

Information Circular 8759

The U.S. Foundry Coke Industry

By Franklin D. Cooper

March 3, 1849

UNITED STATES DEPARTMENT OF THE INTERIOR
Cecil D. Andrus, Secretary

U.S. BUREAU OF MINES

As the Nation's principal conservation agency, the Department of the Interior has responsibility for most of our nationally owned public lands and natural resources. This includes fostering the wisest use of our land and water resources, protecting our fish and wildlife, preserving the environmental and cultural values of our national parks and historical places, and providing for the enjoyment of life through outdoor recreation. The Department assesses our energy and mineral resources and works to assure that their development is in the best interests of all our people. The Department also has a major responsibility for American Indian reservation communities and for people who live in Island Territories under U.S. administration.

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THE U.S. FOUNDRY COKE INDUSTRY

by

Franklin D. Cooper [1]

ABSTRACT

This Bureau of Mines report reviews in detail the foundry coke situation in the United States in 1975. It discusses intrinsic production problems and identifies opportunities for modifying operating practices so that the quality and yield of foundry coke can be enhanced without unnecessary investment in new equipment.

Major topics include operating data and attendant practices and problems, the relationship of carbonization phenomena to coke quality and yield, environmental impacts of foundry coke plant operations, suggested research and development opportunities, and data on components of oven charges and on foundry coke production and shipments.

INTRODUCTION

The purpose of this Bureau of Mines report is threefold: (1) To synthesize relatively sparse and scattered factual data with observations made by industry experts and the author, thus bringing into sharper focus salient characteristics of the U.S. foundry-coke-producing industry, (2) to identify some of the more significant problems and constraints with which foundry coke producers are confronted, and (3) to offer suggestions and insights that may lead toward workable production improvements despite existing and prospective constraints over which the producers have little or no control.

Foundry coke is essential to the segment of the U.S. ferrous industry that produces cast and ductile iron products. Among the largest markets for such products are the transportation and heavy machinery industries, which in recent years have been operating in an uncertain investment-planning milieu. Difficulties in assessing the market outlook, combined with inflationary trends and impacts of health, safety, and environmental standards on foundry coke plants, have delayed outlays for new ovens and ancillary equipment.

Because of this situation, foundry coke producers continue to rely extensively on old ovens characterized by high labor inputs and low productivity. Another problem is that varying demands for foundry coke must be satisfied largely by putting more ovens into operation or, conversely, by banking ovens. Maintaining other than small stocks to conform to varying sales is impractical because of degradation of size, the cost of moving coke to and from stocks, and capital tieup.

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[1] Physical scientist, Division of Coal, Bureau of Mines, Washington, D.C.

Several measures are suggested for reducing production costs, increasing the yield, and improving the quality of foundry coke. Such measures cannot be applied uniformly because marked differences in yield and quality of foundry coke occur on a plant-to-plant basis owing to significant quality variations in coal charges, carbonization operating practices, and other factors.

Analyses of foundry coke operating practices contained in the report are based largely on data compiled by the Bureau of Mines on producing plants in 1975 and on calculations and estimated values derived therefrom. Additional supportive information and evaluations are interspersed throughout the report to help clarify selected operational problems, and means of resolving some of these problems in a practical manner are suggested. Since the supportive commentary and the estimated values derived from 1975 data are based on the author's research and development experience in foundry coke production and on opinions expressed by coke plant supervisors, such information is largely judgmental.

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INDUSTRY OPERATIONS

Although foundry coke producers easily satisfied market demands in 1975, the industry was faced with costly coke oven rehabilitation or replacement because of prospective demand growth. This situation was aggravated because larger cupola capacities required improved foundry coke quality, yield, and productivity.

What Is Foundry Coke?

Foundry coke is a complex, strong, versatile, finished product made to close specifications by the carbonization of selected metallurgical coals, anthrafines, and petrocoke. It is used in cold-, hot-, and divided-blast airblown cupolas to produce hot metal suitable for producing cast and ductile iron castings, pipe, and abrasion-resistant shapes.

In a cupola, foundry coke serves as a melting fuel and also helps maintain the necessary carbon content in the hot metal product. Breeze-free, smaller sized solids, produced simultaneously in the coking process, are screened from foundry coke sizes and are used to supplement blast furnace cokes; in minor quantities they are also used in elemental phosphorus furnaces, carburizing furnaces, inert- and protective-atmosphere generators, forges, tobacco drying, and residential heating. Coke breeze, a minus 1/2-inch product, is principally used for boiler fuel and inplant waste agglomeration.

Production and Shipments

Foundry coke production, requiring the use of high-grade coals, accounts for 5 to 6 wt-pct of the total metallurgical coal mixtures carbonized annually in the United States. Some producers use small amounts of petrocoke, anthrafines, and finely sized hard coke dust to replace a portion of the costly low-volatile coals and to increase the size of coke. In 1975, 13 companies, operating 16 plants in 10 Eastern and Midwestern States (appendix C), carbonized 5.0 million short tons of various mixtures to produce 3.9 million short tons (wet basis) of foundry coke and accompanying carbonized solids.

Some 93 pct (4,673,000 tons) of the components used in 1975 for foundry coke production were metallurgical coals, and most of the balance (6 pct) consisted of anthrafines (table 1). A small portion of petrocoke (0.7 pct) was consumed entirely by one plant in the Lake area. (See table 1 for definition of producing areas.) The estimated[2] weighted average moisture content (ASTM D271-70) of these mixtures was 6.8 wt-pct, while the calculated volatile matter (ASTM D271-70) of 4,673,000 tons of components (dry basis) averaged 24 wt-pct.

Low-volatile coal was present in the mixtures charged in all 16 plants; maximum use per plant was 569,000 tons in 1975 (table 2).

Components charged to ovens exceeded receipts by 100,000 tons in 1975 (table 3). Slightly more than one-half (2,573,000 tons) of the total components received and most (87 pct, or 1,612,000 tons) of the low-volatile coal originated in West Virginia.

Production of all carbonized solids totaled 3.9 million tons (commercial basis) in 1975 (table 4). The weighted average moisture content of these products was 9.7 wt-pct; thus the total output was equivalent to about 3.6 million tons (dry basis). The 2.6 million tons of foundry-size coke produced in 1975 contained 5.6 wt-pct moisture on a weighted average basis, substantially less than that contained in the breeze-free foundry rejects (17.1 wt-pct) and coke breeze (23.9 wt-pct).

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[2] Estimated in accordance with methods described by the American Society for Testing and Materials, as shown by specific designations in parentheses.

TABLE 1. - Components of foundry coke oven charges, 1975

	Geographic producing area[1]					
	Pennsylvania	Lake (New York, Ohio)	North-Central (Indiana, Michigan)	Midwest (Minnesota, Missouri, Wisconsin)	South (Alabama, Tennessee)	Total
Number of producing plants...........	3	3	3	3	4	16
Number of producing oven batteries....	5	3	7	5	9	29
Components of mixture charged:						
Coal, high-volatile..thousand tons..	239	187	359	169	505	1,459
Coal, medium-volatile thousand tons..	145	246	270	186	224	1,071
Coal, low-volatile.........do.......	269	334	425	355	760	2,143
Coal, anthrafines..........do.......	74	55	18	32	132	311
Petrocoke.................do.......	-	33	-	-	-	33
Total.................do.......	727	855	1,072	742	1,621	5,017
Moisture content[2]..........wt-pct..	7.6	8.5	3.6	6.8	7.8	6.8
Oven charges:						
Dry basis...........thousand tons..	672	782	1,034	692	1,494	4,674
Dry basis, volatile matter[2] wt-pct..	25.5	21.2	24.9	22.2	25.1	24.0

[1] Geographic areas in table 1 and other tables that follow are selectively delineated to maintain confidentiality of individual plant data.

[2] Weighted average.

NOTE.--Moisture content calculated by the author.

TABLE 2. - Coal mixtures charged at foundry coke plants

(Thousand short tons)

Coal mixtures charged	Total charged (all 16 plants)	Charge per plant	
		Minimum	Maximum
Coal:			
High-volatile........................	1,459	0	378
Medium-volatile......................	1,071	0	147
Low-volatile.........................	2,143	42	569
Anthrafines..........................	311	0	73
Petrocoke............................	33	0	33
Total............................	5,017	NAp	NAp

NAp--Not applicable.

TABLE 3. - Receipts of components by 16 plants producing foundry coke

(Thousand short tons)

State of origin	Coal[1]					
	High volatile[2]	Medium volatile[2]	Low volatile[2]	Anthrafines[3]	Petrocoke	All component
West Virginia	448	513	1,612	0	0	2,573
Virginia	602	468	246	0	0	1,316
Kentucky	89	0	0	0	0	89
Pennsylvania	89	22	2	152	0	265
Alabama	401	221	0	0	0	622
Utah	7	0	0	0	0	7
Oklahoma	0	12	0	0	0	12
Unknown	0	0	0	0	33	33
Total	1,636	1,236	1,860	152	33	4,917

[1] Volatile matter on moisture-free basis: High volatile--over 31 pct; medium volatile--22 to 31 pct; and low volatile--14 to 22 pct.

[2] Size determined by ASTM D410-38 method.

[3] Size determined by ASTM D310-69 method.

TABLE 4. - Production of carbonized solids, dry coke yields, and commercial shipments, 1975

	Geographic producing area					
	Pennsylvania	Lake (New York, Ohio)	North-Central (Indiana, Michigan)	Midwest (Minnesota, Missouri, Wisconsin)	South (Alabama, Tennessee)	Total
Coke production, commercial basis:[1] [2]						
Foundry sizes..........thousand tons	358 (5.0)	410 (4.4)	618 (5.8)	423 (6.2)	834 (6.0)	2,643 (5.6)
Rejects from foundry sizes..........do	129 (20.9)	203 (15.8)	158 (19.6)	118 (17.0)	367 (15.5)	975 (17.1)
Breeze..........do	74 (23.0)	70 (23.9)	101 (25.7)	58 (24.1)	28 (21.4)	331 (23.9)
Total..........do	561 (11.1)	683 (9.7)	877 (10.6)	599 (10.0)	1,229 (9.2)	3,949 (9.7)
Coke production, dry basis:[1]						
Foundry sizes..........do	340	392	582	397	784	2,495
Rejects from foundry sizes..........do	102	171	127	98	310	808
Breeze..........do	57	54	75	44	22	252
Total..........do	499	617	784	539	1,116	3,555
Yield of dry coke, dry-coal basis:[1]						
Foundry sizes..........wt-pct	50.6	50.0	56.3	57.4	52.5	53.4
Rejects from foundry sizes..........wt-pct	15.2	21.9	12.3	14.2	20.7	17.3
Breeze..........wt-pct	8.5	7.0	7.2	6.3	1.5	5.3
Total..........wt-pct	74.3	78.9	75.8	77.9	74.7	76.0
Foundry coke:						
Commercial shipments..........thousand tons	318	439	574	431	850	2,612
Shipments to stockpiles..........do	40	0	44	0	0	84
Shipments from stockpiles..........do	0	29	0	8	16	53

[1] Weighted average.

[2] Sizes determined by ASTM D293-69 test method; percentage of H_2O in parentheses.

NOTE.--Moisture content of various coke sizes calculated by the author.

At 25 million Btu equivalent per ton, the approximately 4.7 million tons (dry basis) of all oven charges (table 1) contained 116.9 trillion Btu. At 26 million Btu equivalent per ton, the approximately 3.6 million tons (dry basis) of all carbonized solids produced (table 4) contained 92.4 trillion Btu, or 79 pct of the Btu equivalent of the total oven charges.

Four plants in Alabama and Tennessee accounted for 32 pct (834,000 tons) of total foundry-size commercial coke production (2.6 million tons) in 1975, and three plants in Indiana and Michigan accounted for an additional 24 pct (618,000 tons). The remaining 44 pct of commercial foundry coke production was spread more evenly among the producers in the Midwest and Lake areas and in Pennsylvania. Production yields for total carbonized solids (dry basis) for the five geographic areas ranged between 74.3 and 78.9 wt-pct with a weighted average of 76.0 wt-pct.

Foundry coke producers shipped 2.4 million tons of commercial-grade coke to foundry cupolas in 46 States and 189,000 tons to foreign markets in 1975 (table 5). Approximately four-fifths (1.9 million tons) of domestic shipments were consumed by foundries in eight States: Michigan, Ohio, Alabama, Pennsylvania, Illinois, Indiana, Wisconsin, and New York. Due principally to transportation costs, markets were generally confined to the respective producing areas.

Although shipments of foundry coke declined 30 pct in the 1973-75 period, their total value, f.o.b. ovens, increased 37 pct, reaching $106.52 per ton in 1975 (table 6). The average value per ton increased to $114.43 in 1976.

Trends in Foundry Coke Operations

Because foundry coke production requires lower coking temperatures and longer coking time than blast furnace coke production, foundry coke oven life is usually longer and maintenance and replacement expenditures are usually smaller. Initial construction of the foundry coke ovens operating in 1975 occurred in 1902-67; the weighted average date of original construction was 1936.

Since their original construction, these ovens have required unknown numbers of jamb brick renewals, end patches, and complete wall relines and flue renewals. Undoubtedly, a few batteries were entirely rebuilt with the exception of the original foundation pad. It is estimated that the equivalent of a rebuild above the regenerators occurred on an average of once every 25 years.

TABLE 5. - Shipments of foundry coke in 1975, by geographic area of origin and destination

(Short tons)

Destination	Geographic producing area					
	Pennsylvania	Lake (New York, Ohio)	North-Central (Indiana, Michigan)	Midwest (Minnesota, Missouri, Wisconsin)	South (Alabama, Tennessee)	Total
Michigan...........	0	30,317	258,712	112,067	109,215	510,311
Ohio...............	67,107	163,916	79,858	1,860	69,041	381,782
Alabama............	0	0	0	0	327,599	327,599
Pennsylvania.......	142,424	21,281	4,375	0	2,178	170,258
Illinois...........	0	0	57,233	37,714	56,312	151,259
Indiana............	0	6,787	105,681	2,082	15,187	129,737
Wisconsin..........	0	0	12,872	115,459	483	128,814
New York...........	21,442	80,466	360	0	66	102,334
Virginia...........	4,630	23,689	4,388	0	39,429	72,136
Texas..............	0	0	1,228	10,103	59,778	71,109
Iowa...............	0	665	3,894	52,413	8,203	65,175
Tennessee..........	0	0	0	16,716	47,420	64,136
New Jersey.........	36,713	645	0	0	10,372	47,730
California.........	0	7,084	1,851	11,677	17,448	38,060
Kentucky...........	0	6,355	5,489	0	20,496	32,340
Missouri...........	4	0	753	23,719	1,023	25,499
Minnesota..........	0	0	0	14,164	0	14,164
Massachusetts......	10,417	1,001	1,282	0	0	12,700
Utah...............	0	5,403	3,166	804	2,157	11,530
Kansas.............	0	0	88	5,582	5,198	10,868
Georgia............	0	0	0	0	8,679	8,679
Connecticut........	5,919	468	0	0	0	6,387
North Carolina.....	0	0	0	0	7,205	7,205
Maryland...........	5,467	0	0	0	830	6,297
Washington.........	0	0	0	3,217	1,363	4,580
Nebraska...........	0	63	651	2,176	976	3,866
North Carolina.....	0	0	0	0	3,531	3,531
Rhode Island.......	2,473	0	0	0	0	2,473
Colorado...........	0	398	45	452	1,434	2,329
Arizona............	0	0	1,447	0	82	1,529
Oklahoma...........	0	0	0	757	740	1,497
Florida............	0	0	0	0	1,156	1,156
Arkansas...........	0	0	0	871	36	907
New Hampshire......	248	645	0	0	0	893
Louisiana..........	0	0	0	0	720	720
Oregon.............	0	155	0	539	0	694
North Dakota.......	0	0	0	627	0	627
Maine..............	456	0	0	0	0	456
Vermont............	0	453	0	0	0	453
Mississippi........	0	0	0	0	440	440
South Dakota.......	0	0	0	355	0	355
Wyoming............	0	0	0	0	352	352
Idaho..............	0	228	0	0	44	272
Montana............	0	234	0	0	0	234
West Virginia......	208	0	0	0	0	208
Nevada.............	0	56	0	0	0	56
Total.........	297,508	350,309	543,373	413,354	819,193	2,423,737
Exports.......	20,199	88,623	30,900	18,054	30,941	188,717
Grand total...	317,707	438,932	574,273	431,408	850,134	2,612,454

TABLE 6. - Value of foundry coke shipments, 1968-76

Year	Thousand tons	Value per short ton, f.o.b. ovens	Approximate cost per equivalent million Btu[1]	Increase in cost over prior year, pct
1968......	3,317	$32.43	$1.25	NAp
1969......	3,465	35.29	1.36	8.8
1970......	3,264	40.83	1.57	15.7
1971......	3,252	47.98	1.85	17.5
1972......	3,442	51.16	1.97	6.7
1973......	3,720	54.73	2.11	6.9
1974......	3,381	78.92	3.03	44.1
1975......	2,612	106.52	4.10	32.4
1976......	3,007	114.43	4.39	7.4

NAp--Not applicable.
[1] Basis: 26 million Btu per commercial short ton.

Production of foundry coke and undersized carbonized solids in 1975 took place in 29 batteries comprising 1,111 individual ovens. The number of ovens per battery averaged 39 in a range of 20 to 80. Table 7 shows the types of ovens used by the industry in 1975, the number of ovens in operation, and the weighted average date of their original construction.

TABLE 7. - Number of operating foundry coke ovens and weighted average year of construction

Type of oven	Number of ovens	Year of original construction, weighted average
Semet-Solvay horizontal flue..............	274	1913
Wilputte gas gun..........................	315	1952
Wilputte underjet.........................	102	1952
Koppers gas gun...........................	168	1927
Koppers-Becker gas gun....................	151	1937
Koppers-Becker underjet...................	61	1945
Simon-Carves..............................	40	1952
Total or average....................	1,111	1936

Source: Wilputte Corp.

Since 1960 the foundry coke industry has been closing production facilities, and not until recently have any improvements been made to existing facilities, or new facilities put on-stream. In 1965-73, over 500 foundry coke ovens were dismantled, resulting in a loss of about 5,150 tons per day of coke-producing capacity. In 1972-73, during a period of increased demand for foundry coke, two foundry coke sources on the East Coast went out of business and one producer in the South and another in the Midwest shut down one-half of their ovens (13).[3]

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[3] Underlined numbers in parentheses refer to items in the list of references preceding the appendixes at the end of this report.

The adverse effects of electric furnaces on foundry coke demand in recent years have been substantially offset by the increased requirements of larger cupola operations. Although additives having low sulfur contents were difficult to obtain in 1975, one major producer of petrocoke was able to supply 0.2- to 0.3-wt-pct and 0.6- to 0.9-wt-pct sulfur grades.

Since 1961, the value of hot blast operation for foundry cupolas has been verified by the use of cupola stack gas or other fuels to heat blast recuperative systems. Hot blast operation increases iron temperature, decreases coke consumption, increases melting rate with lower melt losses, assures less sulfur pickup, and increases ability to use lower carbon raw materials. Each 100° F increase in blast temperature decreases coke usage by 8 pounds per ton of iron tapped. The oxygen-enrichment process, employed with a divided blast cupola using two rows of tuyeres positioned at different heights, has reportedly reduced coke consumption by 15 to 20 wt-pct (6, p. 4).

Wiltse (20), citing an American Foundrymen's Society study, indicated that $10 billion of new investment capital will be needed over the next decade (1976-85), comprising $6 billion for new melting plant equipment and $4 billion for working capital and tooling. Expenditures for environmental controls are expected to drop from the 1975 level of 30 pct of total capital costs to about 20 pct in 1985. Wiltse urged coke producers to emphasize technological developments because there is no acceptable alternate fuel for the foundry industry. By 1985, the annual domestic demand for ferrous castings could reach 24 million tons--an increase of 20 pct over 1975 foundry capacity levels. The major portion of cast iron must come from cupolas requiring at least 4 million tons of foundry coke.

In the future, the foundry-coke-producing industry must obtain and operate less costly and consistently efficient oven-charging equipment. Development of completely new oven batteries is unlikely in the near future because of prohibitive costs. A logical alternative may involve the rehabilitation or replacement of individual ovens in existing batteries.

Impacts of EPA and OSHA Standards

Although coke oven operations have varying impacts on the environment, so far as is known, none of the batteries of the 16 plants producing foundry coke in 1975 has been cited as an offender by the Environmental Protection Agency (EPA). Generally, foundry coke producers have fewer problems with the control of emissions from wet coal charging, coke pushing, and coke quenching than producers of blast furnace coke. Pollution problems are reduced somewhat by the lower coking temperatures and longer coking cycles employed in foundry coke making, and by continuous attentiveness on the part of foundry coke battery operators. The benefits of pipeline charging of preheated coal were recognized in one instance, where it was in steady use on a portion of one retrofitted foundry oven battery and eliminated environmental pollution from oven charging.

Although the Occupational Safety and Health Administration (OSHA) standard on exposure to coke oven emissions did not become effective until

January 20, 1977, all coke oven batteries prior to that date had most of the controls required by the standard and according to the American Coke and Coal Chemicals Institute (ACCCI) all were generally following the required work practices. The ACCCI indicated, however, that the standards mandated more jobs to produce the same amount of coke. According to Ferguson (5) the standards probably will not materially affect coke oven production, but the cost of compliance will contribute to the spiral of inflation.

Air pollution standards have similarly affected foundry cupola operations. While several 42-inch-diameter cupolas were reportedly still operating in 1975, many small cupolas ceased operations between 1970 and 1975 as a result of the forthcoming pollution standards. Recently, much larger diameter cupolas using proven air pollution control equipment have come into use in the automotive and heavy machinery castings industries. A schematic flowsheet (fig. 1) and the following description of a 138-inch-diameter water-cooled cupola, operated by the Ford Motor Co. at its Michigan Casting Center, are presented through the courtesy of the ACCCI and the Ford Motor Co.:

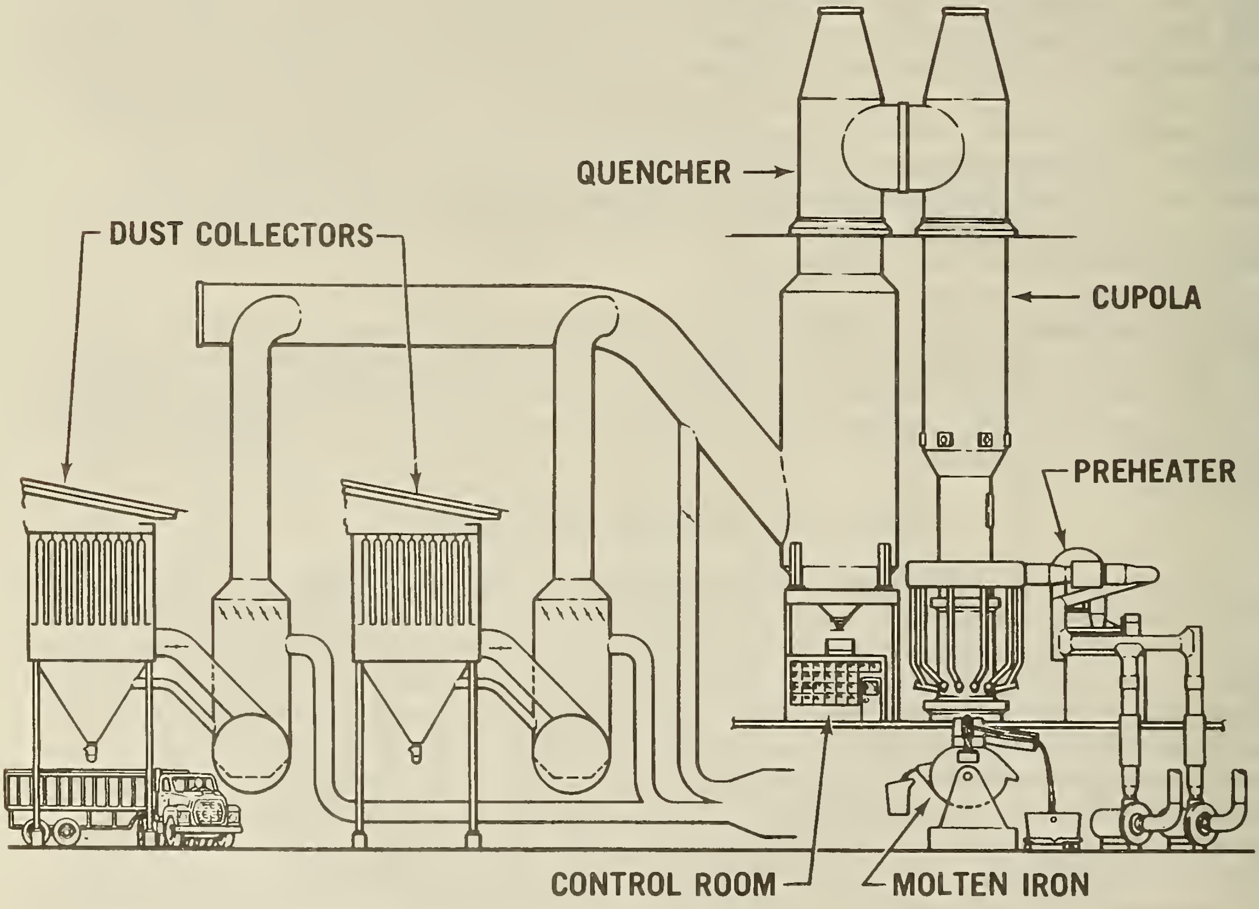

FIGURE 1. - Schematic flowsheet of water-cooled cupola. *(Courtesy, Ford Motor Co.)*

The coke-fired cupola frees the plant from exclusive reliance on electricity as a power source. At the same time, 15% less coal is needed to produce the coke for the cupola than would be required to produce an equivalent amount of electricity to melt one ton of iron in an arc furnace. The Ford cupola on an average in a 24-hour period produces 1,500 tons and under ideal conditions melts 1,900 tons. Preheated blast air is delivered to the melt zone through ten 8-inch diameter tuyeres located 5.25 ft above the bed plate. Cupola performance is well above the industry standard of 2.0 tons per hour for each 1,000 cfm of blast air. Iron-to-coke ratios at about 8:1 are also above the industry standards.

COKE QUALITY

All foundry coke made in the United States in 1975 came from slot ovens. Whereas beehive oven coke lacks size consistency and important physical and chemical properties, foundry coke is a complex product made to close specifications. It starts with the selection of different grades of coal. Customarily, 35 to 45 wt-pct or more of low-volatile, low-sulfur bituminous coals are used in an admixture with high-volatile-content bituminous coals and additives such as petrocoke and anthrafines to produce oven charges. The different types of coals are cleaned, pulverized, and blended before they are charged into the ovens.

While the careful selection and preparation of coals affects the cost of the finished product, the distinctive process for foundry coke making also contributes to unit costs that are higher than those incurred in blast furnace coke production. Coking time is considerably longer than for blast furnace coke. In addition, the release of a smaller weight of volatile matter because of the higher percentage of low-volatile coals in the coal mix generally results in a lower yield of salable byproducts.

Being a batch process, foundry coke production involves the use of coal mixtures lacking constancy and homogeneity in physical and chemical structure; in turn, conversion of coke from these mixtures is subjected to the vagaries of carbonization.

Despite the intrinsic limitations of coal charge quality control, foundry coke producers are expected to meet various specifications of their finished products. For example, foundry coke used in cupolas must be exceptionally strong and larger than cokes made for use in blast furnaces. Coke strength and other quality characteristics are based largely on individual usage practices however, and hence are not generally well defined.

What To Look for in Foundry Coke

Foundry coke from a producing plant that uses scrutinized operating practices, reasonably consistent-quality metallurgical coals, and fairly uniform quality additives such as anthrafines, fine coke dust, or petrocoke should have consistent shatter and hardness characteristics and low abradability and should be free of deep fissures other than those in the cauliflower ends. The coke should have consistent porosity (ASTM D167-24), pore wall thickness, and reactivity. The production of minus 3-inch-square-opening sizes should be less than 30 wt-pct of the carbonized solids pushed from any one oven.[4] These small sizes, obtained by screening, command less price per ton than the numerous sizes of plus 3-inch cokes usually specified by cupola operators.

Foundry coke should have uniform minimum volatile matter, ash, sulfur, and water content within narrow ranges (ASTM D121-62). This ideal situation is difficult to attain over long time periods because of variances in qualities of metallurgical coals and additives, inattention to pulverizing and mixing operations, segregation during the handling of the coal mixtures to and from oven bins, variances in bulk density of the coal mixtures after charging into the coke ovens because of the differences in surface moisture content and oil additions, and inattention to, oven heating operations.

Important characteristics of foundry coke are--

1. Chemistry--Less than 0.8 pct sulfur, 8.0 pct ash, and 1.0 pct volatile matter, and more than 90 pct total carbon (ASTM D121-62) are required. Ash is necessary for coke strength.

2. Uniformity of size--Uniformity affects the blast permeability of the coke bed, gas distribution, and combustion efficiency. Coke is sized to many dimensions. For example, coke sized as 4 by 6 inches can be shorter or longer than 6 inches. There is no practical method for sizing coke to three dimensions without a resulting excessive selling cost.

3. Tumbler stability and strength (ASTM D294-64)--Sufficient resistance to abrasion and size degradation and adequate strength to support the cupola charge weight even when the coke is incandescent are important.

4. Consistent bulk density--Weight-volume ratio affects combustibility or reaction rate. It is determined by the weight of coke placed in an 8-ft^3 container using a consistent filling procedure.

5. Color--Coke should have a consistent dark gray to black metallic color except for a grayish surface where exposure to oven wall heat is greatest. Discoloration does not mean inferior quality; for example, brown spots indicate the presence of iron oxide and not inferior quality.

Standard testing procedures for determining these and other characteristics, specified by ASTM (appendix B), are regularly conducted by coke producers. Special equipment and experienced personnel are necessary.

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[4] All weight-percentages of coke products and coal charges are designated as being retained on or passing through a square-opening screen cloth designated, for example, as plus 3 inches or minus 1/8 inch. The size of anthrafines is described according to the percent retained or passing a round-hole perforated plate.

According to an ACCCI brochure (1), foundry coke currently produced in the United States is superior to foundry cokes produced elsewhere in the world. U.S. foundry coke has improved in quality in the past 20 years because of continuing research in coking practices, coal blending, and control of volatile matter and ash content. Fixed-carbon content and strength of the coke have been increased. These improved quality cokes are suitable for gray iron production where carbon pickup is required. The extent of improvements in quality over the past three decades is evident in table 8.

TABLE 8. - Typical composite analyses of coke, 1946-50 and 1970-76, wt-pct

Dry basis	1946-50	1970-76
Volatile matter.................	0.90	0.50- 0.60
Ash.............................	7.50- 8.50	6.50- 7.50
Fixed carbon....................	90.75-91.75	91.00-93.00
Sulfur..........................	.58- .63	.50- .60
Shatter test: 2-inch screen....	88.00-90.00	90.00-98.00

Source: Foundry Facts (6, p. 16).

An estimate of the volatile matter content of carbonized solids produced in 1975 is shown in table 9.

TABLE 9. - Estimated volatile matter content of carbonized solids produced in 1975,[1] wt-pct

Size	Weighted average	Geographic producing area					
		Pennsylvania	Lake (New York, Ohio)	North-Central (Indiana, Michigan)	Midwest (Minnesota, Missouri, Wisconsin)	South (Alabama, Tennessee)	Total
Plus 6 inches..	2.0	1.33	1.38	1.24	1.21	1.27	1.27
6 by 5 inches..	1.8						
5 by 4 inches..	1.5						
4 by 3 inches..	1.1						
3 inches by 1/2 inch......	1.3	2.26	1.96	2.29	2.13	1.48	1.94
Minus 1/2 inch.	4.0						
Total carbonized solids.....	-	1.60	1.59	1.51	1.45	1.33	1.47

[1] Based on operating experience of author.

Stability and Hardness

Most U.S. foundry cokes have an ASTM stability in the 57 to 65 range and an ASTM hardness in the 61 to 67 range. The ranges are influenced by the composition of the coal mixture carbonized, coking time, maximum oven-wall temperatures, and the ASTM Gieseler fluidities (D2639-67T) of the coal mixture components. It is generally conceded that the low-volatile coals used should have a maximum Gieseler fluidity of 17 to 40 dial divisions per minute (DDPM), the medium-volatile coal should be in the 800- to 5,000-DDPM range, and the high-volatile coals preferably should not exceed 20,000 DDPM, when high ASTM coke stability and hardness are to be maintained.

Increasing instances show that some satisfactory coking coals can be further improved by selective coal cleaning so as to increase the content of dull (durain) coal in the high-volatile coal product. However, the ash in the modified coal must be held low to hold the ash content of the total coal mixture to a desired level to compensate for the use of high-ash anthrafines. Only small gas pressures develop during the critical stages of coke formation from durain because of the release of the evolved gas. Some of the excellent-grade low-volatile coals (Pocohontas No. 3 in particular) release most of their volatile matter in the temperature interval between the attainment of maximum Gieseler fluidity and the final Gieseler solidification temperature. Perhaps because of this behavior, the past use of approximately 50 wt-pct low-volatile coals in foundry coal mixtures was detrimental rather than beneficial.

No known studies have been made of the unsatisfactory wettability of small coal particle surfaces by the presence of adherent clay. Certainly, clay degrades the qualities of foundry cokes made from otherwise excellent quality metallurgical coals.

Size and Shatter[5]

The production of closely sized foundry coke in different size ranges is essential because it enables the user to select the proper size of coke for his particular operation. Having this choice available permits the foundryman to exercise greater control over cupola performance and metal composition than otherwise would be attainable.

Some typical sizes of foundry coke produced follow: "A," 9 by 6 inches and 6 by 5 inches; No. 2, 6 by 4 inches, 5 by 4 inches, 4 by 3 inches, and 3-1/2 by 3 or 2-3/4 inches. To meet the foundry coke sizes specified by the coke purchasers, producers maintain many sizes of screen cloth for use on vibrating screens, which have generally replaced grizzly rolls whereby coke was subjected to a combination of sizing and mild impact to remove loosely bound ends from the larger butts. Even for the larger sizes of coke, sizing is generally performed using vibrating screens, whose operation and performance are better than those of grizzly rolls. Table 10 lists the estimated approximate weighted average size distribution and particle size of the carbonized solids produced.

The screening of foundry coke into several narrow dimensioned sizes contributes to less breakage in subsequent handling and shipping in open-top and container railroad cars and trucks. Proper coke-handling practices at the foundry also can eliminate fines from the coke charged into the cupola and result in improved overall cupola performance with reduced melting costs. For example, definite changes in spout metal analysis and in overall cupola operation are observed with small changes in coke size. Where small-sized coke is used to reduce the spout total carbon content, the lowering of the carbon level is secured without operating the cupola under excessive oxidation conditions. The removal of minus 3-inch sizes, which often comprise 3 to 4 wt-pct of the coke received at the foundry, is claimed to permit a reduction of more than 20 pct in coke in the cupola charge while improving cupola performance.

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[5] Size determined by ASTM D293-69 method, and shatter determined by ASTM D2640-67 method.

TABLE 10. - Approximate size distribution (dry basis), particle size, and volatile matter content of carbonized solids produced in 1975,[1] wt-pct

Size	Geographic producing area					
	Pennsylvania	Lake (New York, Ohio)	North-Central (Indiana, Michigan)	Midwest (Minnesota, Missouri, Wisconsin)	South (Alabama, Tennessee)	Total
Plus 6 inches....	9.0	10.0	3.0	2.0	2.0	4.6
6 by 5 inches....	6.0	5.0	6.0	5.0	3.0	4.7
5 by 4 inches....	9.0	12.0	9.0	8.0	15.0	11.3
4 by 3 inches....	44.0	36.0	56.0	59.0	50.0	44.4
3 inches by 1/2 inch........	20.6	28.0	16.5	18.0	28.0	22.9
Minus 1/2 inch...	11.4	9.0	9.5	8.0	2.0	7.1
Total.......	100.0	100.0	100.0	100.0	100.0	100.0
Total plus 3-inch particles..	4.27	4.50	3.93	3.83	3.90	4.09
Total carbonized solids..........	2.90	3.00	2.00	2.50	3.00	2.82

[1] Estimated weighted average.

Demonstrations by the British Coke Research Association and the British Cast Iron Research Association (BCIRA) showed that cupola performance improved as the mean size of foundry coke increased from about 2 inches to 3.5 inches. In a more recent investigation BCIRA found no further benefit when the mean size was increased above 3.5 inches. Although increasing the mean coke size over the range of 3.4 to 5.9 inches improved combustion efficiency and reduced the heat loss in the cupola stack gas, this gain was offset by an increase in stack gas temperature and an increase in the sensible heat loss. For this study, a supply of 5- by 9-inch U.S. coke, shipped in containers, was compared with large (unspecified size) British cokes made using prolonged coking times. Cold airblast cupolas having 30-, 60-, 72-, and 87-inch diameters were used for the tests (10).

Foundrymen specify coke with higher strength and less undersize. The size of the coke and its uniformity of size are equally important. A smaller coke of good strength may perform better than a large coke that is weak.[6] When using small, strong coke, cupola conditions can be established to obtain optimum results.

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[6] The terms "weak" and "strong" are not definitive. One foundry coke user having developed the best operating practices for a cupola claims that the coke is strong, although another operator would dispute this classification.

Because weak cokes are subject to shatter breakage, proper operating conditions in a cupola are difficult to set up. A properly designed screening station at the coke-producing plant acts as a consistent equalizer of coke quality because it is practically impossible to obtain uniformity of the coke as it is pushed from the ovens. Although intentional rough handling of coke before screening breaks the weak pieces, this procedure reduces the yield of the larger coke because most of the size degradation occurs at the producer's plant.

Coke size, but not necessarily resistance to shatter, is improved by the addition to the oven charge of as much as 10 to 17 wt-pct anthrafines, finely pulverized hard coke dust, and petrocoke (uncalcined carbon residue from petroleum-cracking operations). Chars made by low-temperature carbonization of high-volatile coals are not useful as an additive to the coking coal mixture, although some believe that such chars containing 10 to 17 wt-pct volatile matter can replace some of the low-volatile metallurgical coal in the oven charge. It is known that low-temperature chars made from coal are not wetted by the oils and tars released from metallurgical-grade coals, even though such coking coals have an H:O weight ratio greater than 0.8. Coals having an H:O weight ratio less than 0.8 produce oils and tars with a substantial oxygen content that decreases their wettability capability. Low-temperature chars from coal usually exhibit a maximum Gieseler fluidity of less than 5.0 DDPM.

Coke strength is also influenced by factors such as the heating rate, the thermal soaking of coke following normal coking time, and the bulk density of the carbonization charge. In this regard, the size-shatter strength correlation of foundry coke is quite important. For example, foundry cokes produced at maximum temperatures between 1,300° and 1,470° F are the largest in size and have the highest shatter resistance. As the temperature of carbonization is increased to 1,650° F and then to 1,830° F, both the percentages of plus 4-inch coke and the 1-1/2-inch shatter index diminish. Cokes produced from low- and medium-volatile coals having less than 30 wt-pct volatile matter have a higher 1.5-inch shatter index than cokes produced from low- and high-volatile coals having more than 30 wt-pct volatile matter.

Mott and Wheeler (14) reported that there is an optimum rate of heating for each coal mixture to obtain maximum resistance to shatter and that very slow heating has a more adverse effect on coke strength than very rapid heating.

Foundry cokes usually have an ASTM shatter value of 60 to 70 wt-pct retained on a 3-inch-square-opening screen and 90 to 95 wt-pct on a 2-inch-square-opening screen. A few plants operating with 16-inch ovens and 22- to 28-hour coking times reportedly produce cokes possessing shatter values of 60 to 65 wt-pct retained on a 4-inch-square-opening screen and 80 to 81 wt-pct retained on a 3-inch-square-opening screen.

Reportedly, some improvement in foundry coke strength and shatter values resulted from the use of 40 wt-pct cleaned high-volatile coal, containing a higher weight ratio of durain to clarain plus vitrain than existed in the total unmodified cleaned coal. The modified cleaned high-volatile coal was produced using sand having a larger than normal range of size in a heavy-medium cone provided with numerous drawoff conduits at different elevations. The best ratio of the two coal portions used in the modified remixed high-volatile coal was determined by tests in commercial ovens. The presence of large contents of durain in the coal charge must be limited when large weight-percentages of high-ash anthrafines are used in the oven charges.

Hesp (9), in correlating the 2-inch shatter index of 1,650° F cokes and the volatile content of the parent coals, indicates that a reduction of 1 wt-pct in the volatile content corresponds to an increase of 1.2 units in the 2-inch shatter index of the resulting coke. Hesp also found a decrease in coke size with an increase in the volatile content of the parent coal, particularly for plus 4-inch coke, the proportion of which diminished from 75 to 30 wt-pct with an increase in the volatile content of the coal from 20 to 42-wt-pct. Coal mixtures best suited to the production of large foundry coke are those having an ASTM volatile content of 20 to 25 wt-pct (dry basis).

Surface abrasion hardness values are influenced considerably by the chemical and physical changes that occur during the transition from semicoke to hard coke. The determining factor could be the swelling pressure, which is responsible for fusing the coal particles together. The higher the swelling pressure, the more nearly achieved is the uniform bonding of the nonfused coal particles in the plastic mass, and stronger coke results.

Crushing Strength

Tests to evaluate the compressive crushing strength only furnish empirical data that vary widely even when made on full-length representative pieces of coke. Crushing-strength tests are unsatisfactory because it is difficult to produce 1-inch cubic samples free of minute knife-edge-thick shrinkage fractures.

Fissuring and Shrinkage

Shrinkage of the coke mass, resulting from continued devolatilization as the temperature increases, leads to fissuring and to the breaking up of a large piece of coke into closely spaced, smaller pieces. Although fissures are usually prevalent in the portion of the hard coke that is near the oven heating wall, fissuring also occurs in coke made at a greater distance from the oven wall, although it is less pronounced in the incompletely coked butts.

Fissuring increases when the percentage of volatile matter in the initial semicoke stage is greater. If the volatile matter retained by the semicoke at the end of the coal plastic state could be reduced during normal carbonization, a less fissured hard coke would be obtained (11, pp. 4-5).

Because the percentage of volatile matter is of value only as a reference, the coefficient of shrinkage on solidification, and not the percentage of volatile matter, is the main characteristic. The swelling of bright coal decreases with decreasing carbon content and is more prevalent at a right angle to the bedding plane of the coal than in the direction parallel to it.

The fissuring of coke can be reduced appreciably by a rational heating program. This is achieved by slow heating up to about 1,100° F, followed by an increased rate of heating above 1,300° F. Similarly, for rapid coking, the rate of heating should be reduced at the beginning and increased toward the end of the coking process.

Between the final temperature of solidification of the plastic coal blend resulting in the formation of semicoke and the final temperature reached by hard coke (1,650° to 1,830° F), the solid phase shrinks 10 to 12 vol-pct. Semicoke, batchwise produced between 930° F and 1,020° F, when heated to 1,650° F or 1,830° F with attendant conversion to hard coke, shrinks to an extent little different from that of the semicoke transition stage inside a commercial coke oven. This comparison shows that the internal stresses at the contact surface of the particles are small, and explains why shrinkage is not much affected by the size of the semicoke particles. However, considerable internal stresses that produce small fissures are produced in the semicoke mass; this effect is more pronounced in the case of larger particles, with a corresponding reduction in the cohesion.

Other properties of coke are influenced simultaneously during the heating process. Reactivity, which increases to a maximum and then decreases as the carbonization temperature is increased, is affected by the rate of heating. Fissuring not only determines the size of the pieces of coke but also influences its hardness; it causes undesirable abradability due to the angularity of the fractured pieces of coke. Distorted pores on coke surfaces indicate that appreciable gas pressures are associated with apparent liquefaction (12, p. 277).

In cokes prepared from durain, either only small gas pressures developed during the critical phases of coke formation or the gas pressures developed were readily released.

Wu and Frederic (22) noted the effect of mineral matter by stating:

> The effect of ash content upon the strength of the resulting cokes reflects the mineral matter content of the coals. The former effect differs with the three coke-strength indices. The 1/4-inch tumbler index decreases with increasing ash content of the parent coal, but the 1 1/4-inch shatter index increases. The 1-inch tumbler index either increases or decreases depending on the second or third composition parameter used in the correlation. Considering the cost of coal preparation and the increase in the 1 1/2-inch shatter index of the resulting coke, it is preferable to retain a beneficial amount of mineral matter in the parent coal. An optimum amount of the mineral matter may give the resulting coke the highest tumbler and shatter indices possible, as a result of a compromise between the positive and negative effect of the ash content upon the indices; or, it may give a desired value of one index at the expense of the others. This optimum amount may vary with the composition of the parent coal. The 1/4-inch tumbler index most likely represents the abradability of coke; the 1 1/2-inch shatter index, the reciprocal fissuration; and the 1 inch tumbler index, the result of competition between these two strengths.

Moisture Content

Moisture content is related to coke size and water-quenching time. Coke containing a large percentage of size "A" material (9- by 6-inch) usually has a final moisture content less than 0.75 wt-pct, and size No. 2 coke (6- by 4-inch) contains less than 2.00 wt-pct moisture. These lower moisture contents result because the heat retained inside the larger sizes evaporates much of the moisture present on the surfaces of the pieces after termination of quenching. Sizes in the 3- by 4-inch range and smaller retain much more moisture.

Because the moisture content of coke is removed by the flow of hot gases in the top section of a cupola, it has no effect on carbon control in the liquid iron, in contrast to moisture in the blast air. However, moisture in coke receipts adds to freight cost without furnishing any heat value.

Reactivity With CO_2 and Ignition Temperature

Carbon dioxide in the cupola gas will partially decrease the carbon content of the hot metal product unless the ratio of $CO:CO_2$ is maintained above that of the gaseous equilibrium constant in the cupola. The effects of the quality and uniformity of coke on cupola performance have been vigorously debated by coke oven and cupola operators.

At 2,200° F the reaction $C + CO_2 = 2\,CO$ occurs rapidly. The reactivity of coke is an additive property and is essentially a proportionate average of the individual cokes made from the several coals blended to produce the foundry oven's coal charge. The expected coke reactivities of coals and coal mixes can be reasonably estimated from microscopic analyses of the coals used in the mixture charged without having to produce coke.

There is an approximately linear relation between the reactivity of foundry cokes and the maximum temperatures attained during the carbonization cycle (12, p. 912). Reactivity is also closely correlated with the hydrogen content of the coke, which is dependent on the temperature of carbonization but is independent of the hydrogen content of the original coal. The hydrogen content of cokes for various carbonizing temperatures according to Lowry (12, p. 913) follow:

Temp, ° C	Hydrogen, wt-pct
800	0.92
900	.74
1,000	.50
1,050	42
1,100	.33

The hydrogen content of the coke on a dry, ash-free basis closely follows the equation

$$\mathrm{Log}_{10}H + 1.42 - 0.00173T,$$

where H is the weight-percent hydrogen content and T (in ° C) is the maximum carbonization temperature.

Unrelated to Lowry's findings, it was determined by the author that when finely ground coke samples were tested for volatile matter content by heating a 1-gram sample in a covered crucible at 1,740° F for 7 minutes, a portion of the hydrogen and some oxygen and nitrogen were released in the following approximate weight ratios: Hydrogen, 40; oxygen, 40; and nitrogen, 20. No sulfur was released during this volatile matter determination.

Reportedly, the average reactivity of five U.S. cokes made separately from high- and low-volatile coals indicated weight losses of 11.4 units for cokes produced at 1,830° F and 9.2 units for 2,010° F cokes (12, p. 913).

Most methods for coke reactivity pass 5 ml/min of CO_2 through a 7-cm-diameter column of coke sized through 10- and on 20-mesh sieves in a 1.4-cm-diameter tube maintained at 1,740^6 F. However, the low gas velocity in this test does not provide effective scrubbing of the reaction surfaces.

The measurement of the initial ignition temperature is the oldest method developed for characterizing the reactivity of cokes. A sample is gradually heated in contact with a controlled input of air, and the ignition temperature is considered as the point at which the coke temperature begins to rise above the furnace temperature, or when a detectable small amount of CO_2 is produced per unit of time. The ignition temperature is as much a function of the test apparatus as it is of the coke, and the results, while significant for comparative purposes, do not supply data from which the reaction rate can be calculated.

In either the CO_2 or the initial ignition temperature method for measuring reactivity, it is impossible to secure representative samples of the coke to be tested because it is necessary to work with granular samples comminuted to a small size range. The results of reactivity measurements give little more information than the order in which different cokes should be placed with respect to increasing reactivity.

Coke reactivity follows a fair relationship with the petrographic or microscopic composition of the coals used in the carbonization mixture. The reactivity is related to the effective organic inert constituents of coals that do not melt during the coking process. The reactivity of foundry cokes produced using a mixture of high- and low-volatile coals is a proportionate average of the reactivities of the individual cokes (18).

The sensitivity of coke reactivity measurement has use in monitoring the maximum temperature reached during the coking operation. Operating factors influencing the maximum temperature of the coke are--coke pushing time schedule, coal charge bulk density, oven heating flue temperature, and heat transfer character of the coal mix.

The reactivities of coke increments vary in respect to their distance from the oven wall during carbonization.

Analyses made by the author of full-length pieces of foundry coke first cut into 1-inch-thick full-length slabs and then cut transversely into 1-inch cross sections showed that the volatile matter of the several sections increased with distance from the oven wall as follows:

Distance from oven wall, inches	Volatile matter, wt-pct
0 to 1	0.5
1 to 2	.7
2 to 3	.9
3 to 4	1.2
4 to 5	1.6
5 to 6	2.0
6 to 7	3.4
7 to 8	5.0
8 to 10	7.0

Although reactivity measurements were not made on these individual samples, it is reasonable to conclude that cokes produced at greater distances from the oven wall are more reactive. This explains why some operators of small-diameter cupolas specify that their foundry coke be larger than 6 by 6 inches. Other cupola operators specify that their coke receipts be closely sized, for example, in the 3- by 3-1/2-inch range.

Declining Emphasis on Reactivity

In the 1930's many operators contended that the cupola required coke having a low reactivity with carbon dioxide because the unregulated production of carbon monoxide consumed coke pointlessly. In the early 1970's interest in recuperative hot blast systems increased because of the prospective efficiencies and economics and the need to comply with forthcoming clean air standards requiring the elimination of carbon monoxide by combustion. The hot blast recuperative system was designed to burn cupola stack gas to preheat the cupola tuyere air to 800° F and cool the stack gases below 1,000° F. One system was designed for a maximum blast rate of 25,000 ft^3/min and a melt rate of 60 tons/hr of ductile iron.

At present, less attention is given to coke reactivity. Carbon monoxide in regulated concentrations must be maintained in the cupola's atmosphere to prevent partial decarburization of the molten iron. Increasing the reactivity of coke increases its production costs correspondingly because of the required extended coking time and lower coking temperature. The decreased productivity from high-capital-cost carbonization equipment would increase the amortization and labor costs, although maintenance costs would be lower. The inevitable result is a rather high-cost coke. For example, at $135 per net ton delivered and 8,000 available Btu per pound at 15 vol-pct carbon monoxide and 12 vol-pct carbon dioxide in the cupola gas, the fuel cost is approximately $8.50 per million useful Btu.

The current trend is to use less costly, less reactive coke. The cost of coke could be steady for some time as oven cycle times are decreased to make less reactive coke. The consumption of coke per ton of iron in the cupola will increase, as will the carbon monoxide content of top gases. Somewhere, there is a minimum cost for the foundry that will be the controlling factor in view of the wide range of reactivities and costs in foundry coke production.

Porosity

In a recent study conducted in England (3, pp. 33-36), no systematic influence of coal particle size distribution on coke structure was observed, although the porosity of the coke decreased with increasing charge density. The effect was associated with variations in the mean pore size, although the mean pore-wall thickness showed negligible change with charge density. Restriction of the expansion of the plastic layer either vertically or horizontally caused the released volatile matter, trapped within the plastic layer, to exist at higher pressure within smaller pores. Pore coalescence occurred during the postfusion swelling, and pore nucleation continued at higher temperatures.

Tensile Strength

Little apparent interest in tensile strength is given to the blocky coke used in cupola operation because of the downward mass flow of cold charge and the charge undergoing combustion, melting, and fluxing in the lower portions of the cupola stack.

Tests (4, p. 11) indicate that tensile strength is not related to the rank of coal carbonized to produce foundry coke. Rectangular specimens and blends of semicokes prepared from four coals of different rank were tested for variance of tensile strength at various temperatures up to 1,650° F. For all four coals the tensile strength of the cokes increased with carbonization temperature, values of 20 to 30 kg/cm^2 being attained at 1,650° F; the tensile strength did not change uniformly with coal rank. The strength appeared to decrease linearly with increasing porosity of the coke over a limited range. By changing the bulk density of the coal charge and preheating the coal charge, the tensile strength of the coke product was increased.

Thermal Diffusivity and Thermal Conductivity

In a theoretical analysis of heat transfer through fissured coke, it was shown (4, pp. 11-12) that thermal diffusivity and thermal conductivity increase linearly at temperatures up to 1,650° F, with lower values for a direction parallel to heat flow in the coke oven and higher values for the perpendicular direction, although the difference decreased with increasing temperature. The difference is ascribed to the presence of transverse fissures in the coke parallel to the oven wall.

OVEN HEATING

Oven-heating data are evaluated to show that fuel gas and excess combustion air can be reduced by giving greater attention to heating practices. In addition to reducing fuel consumption, improved oven heating should result in a more uniform quality coke product.

Oven-heating operations constitute the backbone of the foundry coke-making process and, at the same time, are the most difficult operations to control. Even recognizing the fact that the oven design requirements imposed on heating processes vary substantially from one coke oven to another, even within the same battery of ovens, there continues to be a wide range of efficiency levels within the industry.

Coke production is a batch process involving materials handling, comminution, mixing, materials of construction, combustion, and heat transfer for the conversions of nonhomogeneous coal charges having varying physical and chemical characteristics. These feed solids are carbonized in oven batteries comprising individual ovens each of which has its own behavior pattern and operation problems. Table 11 indicates the dissimilarity of oven design and characteristics of resulting heating operations for the foundry-coke-producing industry in 1975.

TABLE 11. - Coking operation data for 16 foundry coke plants

Coking operation data	Weighted average or total[1]	Per plant	
		Minimum	Maximum
Coal mixtures charged:			
Tons per oven	15.60	8.75	27.55
Bulk density[2] ... lb/ft^3	47.3	42.1	53.2
Tons per day	[1] 13,745	317	2,831
Thousand tons per year	[1] 5,017	116	1,073
Ovens pushed per day	[1] 880	18	146
Coking time ... hours	30.3	23.0	38.0
Coking rate ... in/hr	0.594	0.421	0.800

[1] Total for 16 plants.

[2] Weight of charge to coal line divided by volume of charge.

Source: Wilputte Corp.

Since foundry coke production continues to be a complex art (table 12), the successful operation of a battery of ovens demands the steady attention and cooperation of the heating crew. Oven problems relating to flue irregularities, fuel gas and excess air inputs, and oven widths can be partially corrected by the constant attention of flue tenders under the direction of performance-conscious battery supervisors.

TABLE 12. - Yield of carbonized solids produced in 16 foundry coke plants (dry basis), wt-pct

Carbonized solids produced	Weighted average	Per plant	
		Minimum	Maximum
Foundry sizes	70.2	40.3	86.8
Breeze-free foundry rejects	22.7	6.5	56.9
Breeze	7.1	.8	11.8
Total	100.0	NAp	NAp

NAp--Not applicable.

Derived oven-heating performances of 16 foundry-coke-producing plants are reviewed below.

Heating System Designs

The 7 types of heating systems used by the 16-plant foundry-coke-producing industry in 1975 comprised 3 different basic designs: horizontal flue, vertical underjet, and gas gun ovens. Figure 2 shows schematic views of typical byproduct ovens.

Each of the three designs was, at best, imperfect. Horizontal flue ovens offered the best control of fuel gas input by the use of orifices at the ends of the flues, but control of combustion air was influenced by the void volume in the regenerators and the stack' pull.

Underjet ovens use a system of fuel gas headers, choke cocks, and gas pressure regulators located in the basement of the oven battery. Input air to each vertical heating flue is roughly controlled by the positioning of a horizontal slidebrick located at the top of each duct.

Gas gun heating systems have a fixed-diameter ceramic nozzle in the fuel gas input duct of each vertical flue; the input of preheated air is individually regulated by the positioning of a horizontal slidebrick at the top of each duct. Obviously, fuel gas input could only be partially regulated by changing the pressure of the input fuel gas.

As in the horizontal flue ovens, operations of the underjet and gas gun systems are largely influenced by the void volume in the regenerators and stack pull.

Oven Linings and Heating

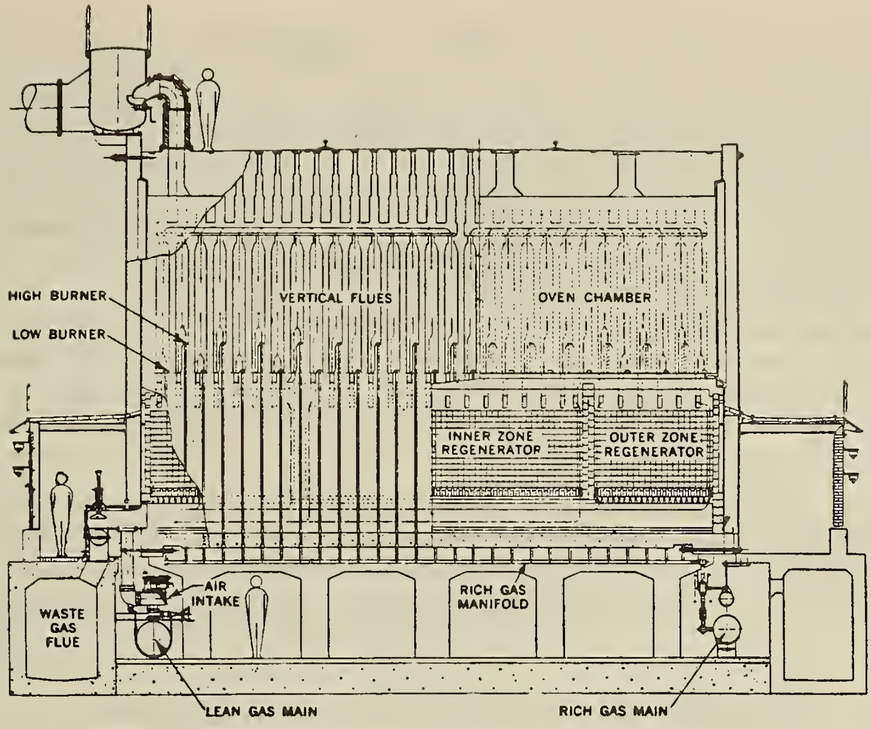
With few exceptions, the three oven designs described above use low-density silica brick, weighing 106 lb/ft^3, for the wall liners of operating ovens having dimensions as shown in table 13.

TABLE 13. - Oven dimensions and wall area of 1,111 ovens operating in 16 foundry coke plants

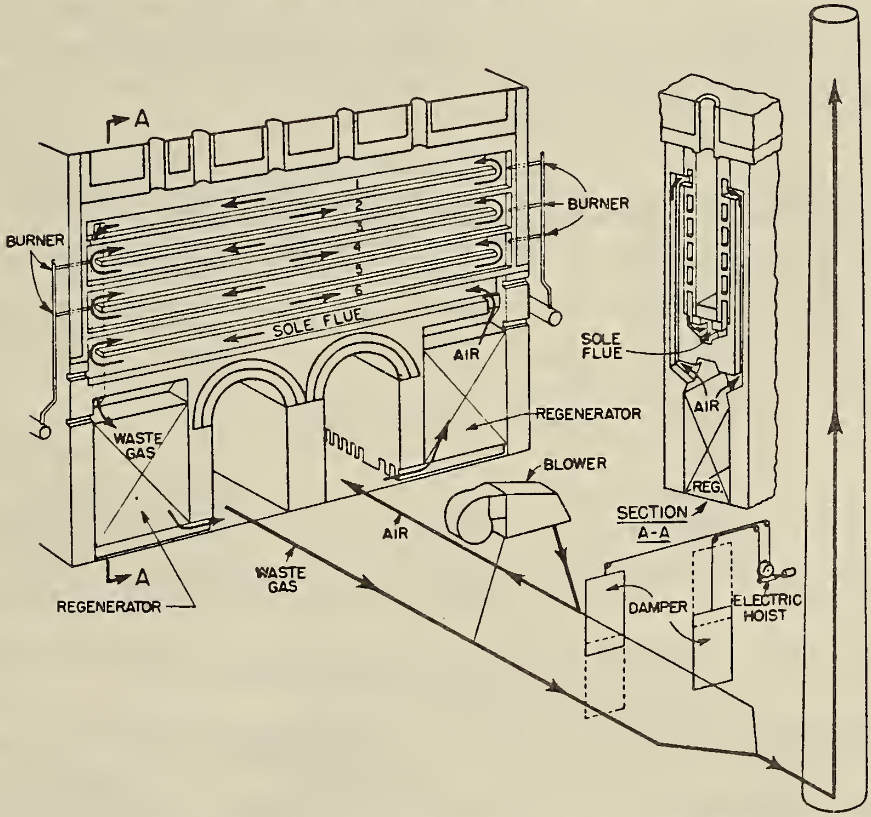
Oven dimensions and wall area	Weighted average or total	Per plant	
		Minimum	Maximum
Width..............................inches..	18.0	15.5	21.0
Height to coal line................feet..	10.7	8.5	15.4
Length..............................do...	41.2	37.0	48.7
Coal volume.........................ft^3..	659	406	1,127
Area of walls to coal line..........ft^2..	[1]991,656	35,112	193,550

[1] Total area of walls for 16 plants.

Source: Wilputte Corp.


HIGH BURNER
LOW BURNER
VERTICAL FLUES
OVEN CHAMBER
INNER ZONE REGENERATOR
OUTER ZONE REGENERATOR
AIR INTAKE
WASTE GAS FLUE
RICH GAS MANIFOLD
LEAN GAS MAIN
RICH GAS MAIN

Longitudinal section through a Wilputte oven.


A
A
BURNER
BURNER
1
2
3
4
5
6
SOLE FLUE
AIR
REGENERATOR
WASTE GAS
REGENERATOR
AIR
WASTE GAS
BLOWER
SOLE FLUE
AIR
REG.
SECTION A-A
DAMPER
ELECTRIC HOIST

Cross section of Semet-Solvay oven showing flow of air and gases during the updraft.

FIGURE 2. - Schematic views of typical byproduct ovens. *(Courtesy, Wilputte Corp.)*

The thermal conductivity of 4-inch-thick low-density silica oven liners is approximately 3.75 Btu/hr/ft^2 per degree Fahrenheit of temperature difference. Considering the range of fuel gas input to the heating flues for all 16 foundry-coke-producing plants in 1975 (958 minimum and 2,058 maximum Btu/hr per square foot of oven wall area) and using a generally established value of heat transmittal through the oven walls of approximately 60 pct of the Btu in the fuel gas input (575 minimum and 1,235 maximum Btu/hr per square foot of oven wall area), the temperature differential between the heating flues and the coal side of the heating walls ranged from 153° to 330° F.

Also, on the basis of an average 4-inch oven wall lining, the indicated flue temperature for one plant on 38.0-hour coking time, by difference, would give a 1,632° F average temperature at the coal side of the oven lining. For another plant on 22.1-hour coking time, a coal side temperature of 1,840° F is indicated.

So long as wet coal mixtures are carbonized, cracks in the oven liners and mortar joints will persist. However, the consistent use of superficially dried or preheated coal charges will prevent some gas leakage from oven chamber to heating flues. The resulting increased yield of coke oven gas and other byproducts and less smoky battery stacks are in some situations worthy of attainment.

Flue Temperature, Oven Width, and Coking Time

Table 14 summarizes varied empirical experiences in different plants coking wet coal charges, as expressed in the relation of coking times to flue temperature and average oven width. Derived equations developed are included to permit the calculation of coking times for average flue temperatures other than those shown in 90° F intervals.

TABLE 14. - Relation of flue temperature and oven width to coking time

Flue temp, ° F	$\log_{10}$ flue temp	Coking time, hours		
		15.75-inch oven	17.75-inch oven	19.70-inch oven
2,640	3.421604	11.7	12.1	14.5
2,550	3.406540	12.2	14.0	16.8
2,460	3.390935	13.9	15.9	19.2
2,370	3.374748	15.6	18.0	21.6
2,280	3.357935	17.4	20.1	24.1
2,190	3.340444	19.2	22.3	26.8
2,100	3.322219	21.2	24.7	29.5
2,010	3.303196	23.2	27.0	32.4
1,920	3.283301	25.2	29.6	35.4
1,830	3.262451	27.5	32.3	38.6

Equations relating flue temperatures in ° F and coking times in hours:

For 15.75-inch-wide oven: $10^{0.009445\,CT} = \dfrac{3{,}328}{\text{Flue temp}} = 3.522206 - \log_{10}$ flue temp.

For 17.75-inch-wide oven: $10^{0.007860\,CT} = \dfrac{3{,}282}{\text{Flue temp}} = 3.516112 - \log_{10}$ flue temp.

For 19.70-inch-wide oven: $10^{0.006619\,CT} = \dfrac{3{,}295}{\text{Flue temp}} = 3.517836 - \log_{10}$ flue temp.

Source: Author's derivation.

Excess Air in Heating Flues

The easiest way to insure complete combustion and required flame length is to use input air in excess of that required to support the theoretical combustion of the fuel gas supplied to the oven flues. However, coke oven gas is no longer a taken-for-granted carbonization byproduct because it now has a calorific content valued at $1.00 to $1.80 per million Btu. As shown elsewhere in this publication, fuel gas input can usually be decreased by reducing the excess air to the heating system. For example, one foundry coke battery in 1975 was operated successfully using a 1,052-Btu input per pound of coal carbonized and 117 pct excess air.

Vertical flue ovens regulate combustion air input by--

1. General control over entire battery by adjustment of draft in the waste-gas main.

2. Control at individual waste-gas regenerators by adjustment of dampers.

3. Control at individual flues by damper bricks.

4. Control of air by size adjustment of finger-plate gaps.

Cost savings on fuel gas could support other improvements, such as the training and upgrading of the oven-heating crew and fixed and portable excess air indicating and recording instruments.

The 16 foundry-coke-producing plants were heated using coke oven gas as fuel, as shown in table 15, with an excess of air preheated to approximately 1,000° to 1,200° F. Flue temperatures and excess-air data for these plants are shown in table 16.

TABLE 15. - Coke oven gas data and heating inputs for 16 foundry coke plants

Data for 16 plants	Weighted average	Per plant	
		Minimum	Maximum
Per-ton oven charge basis:			
Gas yield[1] ....scf..	9,642	7,659	12,752
To flues[1] ....scf..	4,368	3,825	5,218
To flues...................million Btu, gross..	2.402	2.104	2.870
Btu input to flues:			
Per hr/ft^2 oven wall area.......................	1,388	975	2,080
Per lb charge carbonized......................	1,201	1,052	1,435

[1] 550-Btu/ft^3 basis.

NOTE.--Btu input to flues derived by author.

TABLE 16. - Flue temperature and excess combustion air data for 16 foundry coke plants

	Flue temperature, ° F	Excess air in flues, vol-pct
Weighted average	1,920	203
Range...........	1,650-2,170	117-307

Because 9 of the 16 plants were heated with benzolized coke oven gas and 7 plants used debenzolized coke oven gas, the following gas analysis was used as the basis for theoretical flame temperature and excess air calculations:

CO_2	vol-pct	1.8
Illuminants	vol-pct	3.3
O_2	vol-pct	0.3
CO	vol-pct	5.8
H_2	vol-pct	51.8
CH_4	vol-pct	31.1
N_2	vol-pct	5.9
Btu/ft^3 (gross)		556
Btu/ft^3 (net)		496

Theoretical flame temperature was calculated as 3,400° F using zero excess air preheated to 1,000° F for combustion, with consideration given to gaseous dissociation phenomena above 3,400° F. For coke oven gas having the analysis shown, calculations were made based on fuel gas at 60° F and preheated combustion air at 1,000° F.

The effect of excess air on flue temperature is shown by the following empirical equation:

$$FT = \frac{2,580}{10^{0.000632p}},$$

where FT = ° F,

and p = volume-percent excess air in the products of combustion (POC) leaving the heating flues.

Closer control of oven heating with an attendant reduction in excess air used for combustion could reduce the fuel Btu (gross) input for oven heating without a reduction in flue temperature. Calculations indicate the following relation:

Excess air in POC, vol-pct	Gross Btu input per lb charge carbonized
203	1,201
183	1,162
163	1,123
143	1,084

A reduction of excess air from 203 pct to 143 pct could reduce Btu input to the heating flues by 9.8 pct.

The relation of percentage of excess air introduced for combustion of fuel to gas input per pound of charge carbonized indicates that the five plants with the lowest excess air input, averaging 1,080 Btu/lb in a 1,051- to 1,100-Btu/lb range, had a median excess of air equaling 191 pct in a 117- to 203-pct range. The five plants having the highest excess air input, averaging 1,231 Btu/lb in a 1,099- to 1,375-Btu/lb range, had a median excess of air equaling 261 pct in a 247- to 307-pct range. This relates to a reduction of 151 Btu per pound of charge when the excess air decreased 70 pct, or 21.6 Btu per pound of coal carbonized for each 10-pct incremental decrease in excess air. Stated otherwise, a 12.3-pct reduction of input Btu to the flues resulted from a reduction of excess air from 261 pct to 191 pct. A lower velocity of the POC in the heating flues lengthens the time for efficient heat transfer to the oven wall.

Some foundry coke producers contend that it is necessary to maintain a high input of excess air when burning benzolized gas. However, nine plants heated ovens with benzolized gas using 219 pct excess air in a range of 143 to 307 pct. It is concluded that some of those plants using plus-219 pct excess air did not attain the beneficial results available by utilizing the maximum flame radiation possible from the combustion of the carbon contained in the crude light oil constituents, which principally comprise benzene, toluene, xylenes, and solvent naphtha.

Average flue temperature and average percentage of excess air are not to be construed as being attained consistently. Fuel gas and preheated excess airflows to the flues fluctuate in volume and temperature and produce patterns of the burning gas varying from stubby blowtorch-type flames to long, lazily burning, smoky flames. Short flames release most of their energy in a small distance, thereby producing localized overheating.

Because most coke oven batteries use 150- to 225-foot-high stacks to handle the POC from the heating flues, operators depend on stack pull to maintain the inflow of preheated combustion air to the flues. Waste gases leaving the regenerators at 550° to 650° F enter the base of the stack, averaging 37- to 44-mm-kerosene gage suction. (This average suction varies with wind velocity and ambient air temperature.) Suction on the POC leaving the flues is always regulated to obtain a required controlled draft, which seldom exceeds 23-mm-kerosene gage. Variations of 2.5-mm-kerosene gage are quite common during high winds. However, there is no possibility of increasing stack pull during windless days and as a result the top of the stack may emit a light to medium smoke density. No situations are known where an induced draft fan has been installed to insure a steady stack pull.

It should be noted that average flue temperature is a concept depending on factors such as the residence time of the POC in heating flues and the elapsed time since the last damper reversals. Flue temperature usually decreases 110° F during the 30-minute damper-reversal period. Immediately after the reversal of dampers, the temperature of the preheated combustion air leaving the regenerators will exceed 1,000° F, thereafter diminishing to approximately 875° to 925° F. During normal operating conditions the greatest regenerator top temperature variation is 150° F.

Most operators of 13-foot-high ovens maintain a 5- to 6-mm-kerosene pressure in the hydraulic collector main and a 3-mm-kerosene pressure in the oven standpipes. However, this pressure is greater in a standpipe handling an above-average flow of gas from a freshly charged oven. Carbon buildup in standpipes is due to the amount of free space and temperature in the top of the oven.

Temperature Variations

Silica brick in the 1,800° to 2,600° F range has a total expansion of 0.9 pct. The crushing strengths at three temperatures approximate the following (8):

Temperature, ° F	Crushing strength, psi
1,800	1,620
2,000	1,700
2,300	1,820

The sensible heat content of the average U.S. coke ranges from 580 Btu/lb for a 1,700° F coke to 715 Btu/lb for a 2,000° F coke (8).

Although no data were found on temperature variances in the contents of a typical foundry coke oven shortly before pushing the oven, the following test data at a higher flue temperature and shorter coking time in a 17-inch test oven illustrate that a temperature differential exists even after an 11-hour extension of normal coking time. Temperature variances in a foundry coke oven prior to pushing are undoubtedly greater than shown in the following data.

Using 105-lb/ft^3 silica liners at a constant 2,180° F flue temperature in a 17-inch movable-wall test oven, the coking was considered to be complete when the center of the coke mass reached 1,700° F at the end of a 17-hour coking cycle of the 4.2-pct-moisture, 49.5-lb/ft^3-bulk-density coal being carbonized. The coal mixture comprised 53 pct Pittsburgh seam, 27 pct Freeport seam, and 20 pct Pocahontas No. 4 seam coals. After 28 hours, while still using a 2,180° F steady flue temperature, the temperature drop from the flue side of the chamber wall to the center of the coke was 350° F; that is, coke at center of the oven was 1,830° F, or a 130° F temperature rise resulted at the center of the oven contents following the extra 11-hour soaking time (extension of the coking cycle). At 1,975° F constant flue temperature, the ASTM coke stability was 61.0. A further decrease in average flue temperature appeared to have little effect on stability. With 117-lb/ft^3-density silica brick liners, the test oven production capacity was increased 20 pct (15).

According to Van Ackeren (19),

> Plus 96% of the heat transmitted from flame to flue is transmitted by radiation from the up-flowing burning gases when using coke oven gas as fuel. Length-wise adjustment has been accomplished satisfactorily. However, the vertical distribution of heat is not difficult, providing that the basic calculations and designs are correct. The first correction was to raise the location of the horizontal flue and sometimes to decrease the thickness of the oven wall liners in the upper portion of the oven. Both expedients helped to some extent. Lower liners are slowly gouged by the action of the pusher shoe grinding coke against the wall, but can be corrected by proper maintenance. Sometimes pieces of metal, etc., become wedged between the shoe and the oven lining and floor,

thereby causing gouging. Similarly, non-horizontal elevation of the pusher machinery track, or a warped pusher ram and appended pusher head and shoe, result in damage to the silica lining and floor brick. Three principal ways to attain the maximum possible flame temperature are: (1) by liberating the heat of combustion as fast as possible (i.e., by surface catalysis) to minimize conduction losses from the flame; (2) by using only a small amount of excess air; and (3) by increasing the sensible heat in the gas-air mixture. In practice, the easiest way to lower the flame temperature is to use air inputs in excess of the amount required for theoretical combustion. Reducing the flame temperature by this means results in an increase of sensible heat leaving the stack because of the greater mass of outgoing gases and less efficient absorption of heat within the flues. Perfect heating means that the temperature of the resultant coke should be constant within a 50° F range in a vertical line from top to bottom, excluding the top foot and bottom foot and excluding the area covered by the horizontal flue. Perfect heating will not correct temperature inequalities caused by coal packing during oven charging, segregation due to size of coal, and other practices.

Preheating the air for combustion of the fuel gases in the oven-heating flues offers one means for attaining and controlling the desired flue temperature. It is accomplished by regenerators that add to the entering air a part of the sensible heat earlier recovered from the POC. Regeneration is a discontinuous process whereby the heat from the hot flue gases is transmitted to the cold air entering a mass of checkerbrick that serves, alternately, as a reservoir to absorb heat from the POC from the oven-heating flues, and then to heat the entering air for combustion. Mechanical dampers are required for periodically reversing the flows of input air and POC. The temperature of the preheated air varies because the regenerative process is discontinuous.

The regenerators use high-heat-capacity firebrick positioned to form a number of vertical passages. The arrangement and size of checkerbrick vary. The temperature of the air leaving the checkerwork decreases during the customary 30-minute reversal period during which, with constant air and fuel gas inputs to the oven heating flues, less sensible heat enters the flues in the combustion air and consequently the flue temperature decreases.

The efficiency of heat transmission from and to the checkerbrick is influenced by its cleanliness. This is a minor factor when using coke oven gas only as fuel, but ovens heated with blast furnace gas must use dust-free gas.

Increased Coking Rate

The trend toward larger ovens and faster coking rates to reduce coke production costs developed from efforts to match higher capital and operating costs. Coking rates have been increased by using higher density silica liners for oven walls and higher flue temperatures. These practices permit the coking rate to be increased in many new 18-inch-wide ovens.

Faster coking rates require higher wall temperatures or narrower oven widths to drive the heat into the center of the coal charge in a shorter time. Higher average coke and foul gas temperatures result. Faster coking rates also are attained by increasing the area or efficiency of the regenerator checkerbrick system. Radiation and convection losses increase but not in proportion to the increased coke production.

Coke is pushed hotter in some coke plants now, not only because of faster coking rates, but also to minimize pushing emissions as required by air pollution regulations. This is even true for foundry batteries operated at less than a 0.8-in/hr coking rate.

Coal charged in coke plants since 1945 has had an increased average moisture content because most coals have had to be washed because of mechanical mining; also, stored coal now is generally small in size and increases in moisture content more readily. Coal moisture is rarely less than 6 wt-pct of the wet coal charge and is often 8 to 10 wt-pct. Fuel input for heating increases about 19 Btu per pound of oven charge for each 1-pct increase in moisture content.

When substantial excess combustion air is used in underfiring, less operating labor and supervision are required and operations are easier. This excess air is heated and leaves the battery heating flues in the POC. A 10-pct increase in excess air increases gross fuel input by about 19.5 Btu per pound of wet coal carbonized.

Although waste gas temperatures are unavoidably higher at fast coking rates, the waste gas temperature can be maintained near the minimum required to provide adequate stack draft by increasing the quantity or efficiency of the regenerator's checkerbrick. Reportedly, doubling the quantity of checkers can save 108 Btu per pound of wet coal carbonized. The only substantial factor over which the battery designer has any real control is the regenerator design and its effect on the heat content of the waste gas.

Efficiency

Heat input, neglecting sensible heat of the coal charge on a 60° F basis, equals the Btu of the fuel gases to the heating flues. Efficiency is measured by the fuel gas Btu input (A), plus the exothermic heat released (B) during the carbonization of low-oxygen-content coking coals, less the stack and radiation losses (C) from the coke oven, divided by the total of the fuel value of the flue gas (D) plus the exothermic heat from the carbonization process (E), or

$$\frac{A+B-C}{D+E} = \text{efficiency.}$$

This efficiency, when using coke oven gas as fuel for oven heating, generally averages 60 pct of the Btu value of the heating gas. When using blast furnace gas as fuel, the efficiency is about 64 pct because of the smaller latent heat loss resulting from the combustion of the low-hydrogen-content blast furnace gas.

Up to 24 pct of the Btu value of the fuel gas is recovered in the regenerators from the sensible heat in the POC leaving the heating flues. By difference, radiation losses from the oven equal about 4 pct of the fuel gas heating value, and approximately 12 pct of the fuel gas Btu value is considered as stack loss.

Firebrick in the regenerators is customarily in contact with the POC from the heating flues for a period not exceeding 30 minutes between damper reversals. In the 30-minute heat recovery period the checkerwork absorbs approximately 5.2 to 7.5 Btu per square foot of surface (8). This range of heat absorption varies with differences in the temperatures of the POC, the particular pattern used in positioning the checkerbrick, and the void volume of the checkerwork.

As stated earlier, calculations of the percent of excess air used in the heating flues were based on air from the regenerators averaging 1,000° F. This is close to reality because just prior to the damper's reversals the preheated air leaving the regenerators is usually in the 875° to 925° F range. In other isolated sections of the regenerator the first flow of preheated air leaving the regenerators is probably in the 1,200° to 1,500° F range. Depending on the variable effects of other operating factors, the recovery of the sensible heat in the heating flue POC entering the regenerators ranges up to 60 pct.

The fuel input per pound of charge carbonized is usually 1,050 to 1,200 gross Btu, and varies principally owing to bulk density and moisture, operating practices, heating system, and to a certain extent the nature of the blended charge.

For many years oven design was based on a gross fuel input of 1,100 Btu per pound of wet coal carbonized when underfiring with coke oven gas at a coking rate not exceeding 1 in/hr. Actual underfiring is generally close to this design figure.

Another variable is the net exothermic heat of reaction during carbonization of the coal charged. This characteristic can vary from nearly zero to over 200 Btu per pound of coal (dry basis). Some of the poorer coals used for coke production have a lower net exothermic heat of carbonization and therefore require higher fuel inputs.

CARBONIZATION BEHAVIOR

Despite intensive investigations concerning carbonization behavior since the advent of coke ovens in the United States in the late 19th century, many unanswered questions remain as to what actually occurs during the carbonization process. The following discussion covers several significant aspects of carbonization behavior and how some may be altered by industrial practices prior to phase transformations of the initial coal mixtures into the final coke product. Generally, the causal events discussed have been substantiated by both standardized tests and empirical observations.

Effect of Plus 1/8-Inch Particles in Coal Charges

The effects of the presence or absence of plus 1/8-inch-square-opening particles equaling 3.5 wt-pct of a carbonization mixture containing equal weights of coals with 17.0 wt-pct volatile matter and coals with 30.0 wt-pct volatile matter were evident when the mixtures were coked for 36 hours in commercial 22-inch-wide horizontal flue ovens. Full-length pieces of coke produced in 10 ovens from each lot of coal were sawed into 2- by 3-inch sections. Specimens produced from the coal mixture containing 3.5 wt-pct plus 1/8-inch particles had a 1.5-inch ASTM shatter value of 92 and an ASTM stability index of 55. The other coke, made from the same coal mixture freed of plus 1/8-inch particles, had a 1.5-inch ASTM shatter value of 94.5 and an ASTM stability index of 71. These mean values represented five shatter and stability tests made on each lot of coke.

Effect of Additives

French investigators (11, pp. 15-16) found that the addition of special chars made from coal containing 40-wt-pct volatile matter by the fluidization method at 930° F or in a rotary furnace produced some increase in the size and hardness of the coke and increased abradability. The benefit of the char was always less marked than that of fine hard coke dust. It was therefore possible to add larger quantities of char without seriously altering the cohesion of the coke matrix. However, the antifissurant action of the char was not as strong as that of hard coke dust. The size distribution of the char was of less importance than that of fine hard coke dust. The addition of hard coke dust to strongly expanding coals, while increasing the size and hardness of the coke from some coals, was not as satisfactory as the addition of durain (dull) coal to reduce expansion pressure.

Coal containing 1 wt-pct boric acid produced a 3.5-wt-pct tar yield instead of 5.0 wt-pct tar. The yield of gases under the same conditions decreased about a third, but the total coke yield increased about 2 wt-pct. The evolved tar and gases were free of boric acid. The coke retained 95 pct of the original boric acid, and 5 pct was assumed to have volatilized with the water of decomposition (12, pp. 253-254).

Small particles of anthracite and semianthracite contract in proportion to their volatile-matter content. Tests made using Upper Kittanning low-volatile bituminous coal indicate that the purer the coal, the greater the resulting expansion for a coal of a given volatile-matter content. When enough fusain was added to a coal already containing 3.9 wt-pct fusain to bring the fusain content to 12.7 wt-pct, expansion was lowered from 5.5 pct to 1.2 pct and shrinkage from 3 pct to 1 pct (12, p. 265).

In 1949, Phillip Savage (16) of Donner-Hanna Coke Corp. stated the following views on coke formation, which have had extensive industrial verification since that time:

> Our practical experience with strip coals, low and high, and with anthracite fines and fine coke dust, has brought me to the conclusion

> that the coking qualities of low-volatile coal have very little to do with the quality of coke produced. I believe that the physical quality of the coke produced, providing sufficient total agglutinating material is present in the mix, is due to the viscosity of the plastic zone. If, to the coal mix, we can add carbon material, which is fine enough and of such a character that it can be wetted by and become part of the plastic mass when coal is coked, I believe such inert carbon will have all the beneficial effects we now get from low-volatile coal additions, provided, of course, that the agglutinating material in the mixture carbonized is sufficient. Coal in my opinion has the characteristics of a thermal-setting plastic, and the inert material in low-volatile coal acts as a filler just as wood flour and other inerts do in forming moulded products from phenolic resins. I am inclined to think that we in the coke-oven industry have not done it as well as the housewife, but have taken the easy way by blending in the high-quality low-volatile coals that, until the last few years, have been readily available.

Expansion

Even though a coal exhibits a high initial expansion pressure, as indicated by a sole heated oven test apparatus, there is no danger to the oven walls if the expansion pressure abates early in the coking process. When the coal mixture contains 0.3 to 0.5 wt-pct boric acid and is heated progressively within the softening stage, the coal will no longer show expansion. The expansion pressure of a coal producing a total coke yield of 75 to 80 wt-pct was completely eliminated after heating in admixture with 0.5 wt-pct boric acid (12, p. 253).

Coal mixtures rich in durain are especially suitable for reducing expansion pressure. Quite often, coking coals exhibiting high expansion pressures can be made safe for carbonization by the addition of only 10 to 20 wt-pct durain (dull) coal prepared under surveillance using modern petrographic analytical techniques. According to Lowry (12, pp. 251, 276),

> Durain has no harmful expansion behavior when coked at 46.8-lb-per-ft^3 bulk-density although at 56.2-lb-per-ft^3 bulk-density it closely approached the dangerous expansion zone. Vitrain when coked at 46.8-, 49.9- and 56.2-lb-per ft^3 bulk-density showed high expansion pressures and unsatisfactory shrinkages. Clarain when carbonized at 46.8 and 49.9-lb-per-ft^3 bulk-density was judged harmless while at 56.2 lb-per-ft^3 bulk-density it developed very dangerous expansion properties and gave but little shrinkage.

The ASTM free-swelling index (FSI) (D720-67) of a blend of two individual coals may be considerably below the mathematical average of the indexes of the two individual coals.

Coke oven walls currently are designed and guaranteed to withstand an expansion pressure of 1.9 psig.

Considerable expansion occurs during the time when two plastic layers are coalescing midway between the oven walls. This confirms the fact that the increased rate of coking in the coalescing zone increases the expansion pressure. The FSI is an approximate indicator of the pressure developed during coking. Medium- to high-swelling coals in a 5- to 8-FSI range yield the hardest cokes, while coals with plus 8 FSI do not always produce coke having an improved abrasion index.

The residue resulting from the carbonization of fusain shows no indication of fusion or shrinkage.

Fluidity

The carbonization of coal in coke ovens is an exceedingly complex process. Brewer (2) provides an excellent description:

> Briefly stated, the formation of coke from bituminous coking coals is characterized by a softening of the coal particles, which accompanied and followed depolymerization and decomposition of the coal substance to produce gaseous, liquid, and solid products. With continued progressive heating some of these products escape; and others, by physiochemical and chemical changes, unite the individual particles of the charge into a more or less homogeneous mass. The void spaces between the particles of crushed coal and the pores inside the particles become filled with products of depolymerization and decomposition, and on further heating there is formed a vesicular structure, which allows the escape of gas from the resultant coke. In commercial coke-oven practice the charge of crushed coal particles, no matter how close the packing resulting from choice of grain size of coal, from pressure due to the falling of coal from a height (top-charging), or from stamping or leveling of the charge, always contains no less than 25 vol-pct of free void space. The individual particles of coal must therefore be capable of swelling at least 25 vol-pct if the charge is to be agglomerated thoroughly when it is coked.
>
> Ability to swell, then, is a primary requisite of coking coal. The successive stages in the formation of coke during heating of a charge of coking coal are (1) pre-softening, (2) decomposition and softening, (3) swelling, (4) agglomeration, (5) solidification, and (6) hardening. The property of plasticity is exhibited to a greater or less degree in all of these stages.

During coke formation from crushed coal particles, wetting phenomena appear to have great importance. Coals that do not produce much or suitable wetting liquids do not make strong cokes.

The fusion of coal particles results from softening and swelling preceding the formation of a mass that is hard and cohesive and that has an open structure. The behavior during fusion (17) governs the abradability of the coke and to some extent its hardness.

Fluidity is increased with increased rate of heating. The fluidity of a coking coal in the plastic range can be reduced and its fusion temperature raised by prolonged heating in the preplastic range. The lowering of the fluidity can be considerable, because of the preponderance of large molecules formed in rendering the coal compounds less sensitive to temperature by preheating.

Some coals produce even better cokes after preheating in air at 300° F than those obtained directly from the fresh coal itself.

Removal of slate from some high-volatile coals lowers their melting point range approximately 90° F (12, p. 209).

The softening behavior of coking coals comprises three overlapping phases: froth fluidity present during the softening-bitumens phase; the gaseous phase comprising the distillation of gas and vapors; and the solid nonplastic residual semicoke phase. Oxidation shortens the range of plastic temperature and lowers the fluidity of coal (12, p. 223).

Increasing evidence indicates that the maximum Gieseler fluidity of a foundry coal mixture is in the 800- to 20,000-DDPM range. However, the author has had considerable experience in producing foundry cokes using coal mixtures in the 300- to 700-DDPM maximum Gieseler fluidity range. Coals were blended to attain this DDPM range; as much as 60 wt-pct of 16.5-wt-pct volatile-matter coal was used in a mixture with high-volatile coals intentionally containing half their weight of high-splint-content, moderately coking coals. In several other tests 16.5-wt-pct volatile-matter coal, when carbonized alone, produced good-quality foundry coke without pushing problems or damage to oven walls.

To produce good-quality coke, it is recommended that a coal blend should contain two coals that enter the plastic stage at different temperatures. The coal of lower softening temperature should not attain the solidification stage before the other coal produces a plastic phase. Such a choice permits the higher temperature plastic phase to flow around the solid particles of the earlier formed plastic mass, thereby improving wetting and adherence. Conversely, if two thick, semiliquid masses are present at the same time, intermingling will occur more slowly because of mutual viscosity and resistance characteristics.

Plasticity

Using polarized light, it is possible to distinguish cokes produced from coals of different rank, because anisotropy increases with the rank of the coal and the particles of coal retain some individuality during fusion.

The porosity of coke may be reduced by adding fine, hard coke dust to the coal mixture charged into the coke oven. This material, by acting as an adsorbent, reduces the plasticity of the softened mass and allows the gases to escape freely without producing a bloated coke. The texture of the final hard coke is slightly firmer, and the coke density is increased by this treatment.

Coal particles in sizes ranging from 0.1 to 1.0 mm have the same plastic temperature ranges but higher maximum resistance to gas evolution with increase of particle size. As the plastic layer increases in thickness, the volume-percent of gas yield on the cold side of the plastic zone decreases.

By increasing the rate of heating, the temperature of coal softening is little affected; however, the temperature zone of softening and the resolidification temperature and degree of plasticity are increased. With more rapid heating the proportion of plastic material is increased. Low-volatile coals retain plasticity to a higher temperature but retain more volatile matter to be evolved from the porous semicoke after termination of plasticity. Certain coals are sensitive, with respect to their ability to yield a good coke, to changes in the average rate of heating; to produce the best coke, an appropriate rate of heating for each individual coal mixture must be determined by commercial oven tests.

During the coking process the temperature of the charge is gradually increased with the result that the coal softens and then starts to decompose. The release of vapors and gases from the plastic portion of the charge during carbonization produces pores before the plastic phase solidifies to form a porous semicoke. After this main formative stage the relative porosity of the semicoke is little influenced by the further loss of volatile matter during the transition from semicoke to the hard-coke product.

The release of the volatile matter during carbonization produces fissures that weaken resistance to breakage of the coke. The amount of volatile matter retained in the final coke is the major factor determining the shatter strength, although this quality is influenced also by other factors such as the rate at which the volatile matter is released, the temperature dependence of volatile-matter evolution, the resistance of the plastic layer to volatile-matter evolution, and the nature of the chemical reactions involved.

The general trend toward a decrease in coke size accompanies an increase in the volatile-matter content of the parent coal. Generally, coal charges best suited to the production of large foundry coke contain 20 to 25 wt-pct volatile matter (dry basis). Volatile products increase as the coal particle size and resistance to diffusion increase; at the same time fluidity increases, and initial softening temperature decreases.

Surface abrasion hardness is affected by the release of volatile matter from the plastic stage and by the chemical and physical changes in the transition from semicoke to hard coke. The determining factor is the swelling pressure, the factor responsible for fusing the coal particles together. At higher swelling pressures, more uniform distribution of the nonfused coal particles in the plastic mass is achieved and the semicoke so formed is stronger. The solidification of the plastic material provides a cementing agent between the nonfused coal particles.

A decrease in the initial softening temperature of a coal mixture results in an increase in the shrinkage during resolidification.

The initial softening temperature of preheated coal often is higher than that of nonpreheated coal. A coking coal having a high active-hydrogen content when carbonized produces a greater plastic layer thickness.

Petrographic Evaluations of Coking Coals

Disruption of normal supplies of coking coals may necessitate the blending of inferior coking coals with those of better quality. Because small changes in either the amount or quality of the coals blended will cause significant differences in coke strength, close control of the blending operation and knowledge of the coals' coking characteristics are essential. Such control and knowledge can be attained by conducting petrographic reflectance (ASTM D2799-69T) evaluations--a practical method that enables a coke plant operator, in 2 hours, to monitor the efficiency of his blending system and predict the ASTM coke stability of a single coking coal or blends. This method also permits the operator to evaluate the rank and quality of coal and to estimate the effects of oxidation of coals in a rapid and cost-efficient manner (7).

SELECTED OPERATING PRACTICES

Foundry-coke-producing operations can be enhanced by modifying several practices prior to and during the charging of the coal mixtures into the ovens. Four key elements of such practices are discussed below.

Bedding Storage

Foundry coke producers can benefit by using stockpile bedding to produce relatively uniform coal feeds to their pulverizing equipment from the numerous and generally small tonnages of coals received from different sources. Coals retrieved from bedding storage, even after 4 to 6 weeks of retention, will have reasonably uniform coking characteristics.

In the past, bedding was considered costly. Now, however, large material handling and mobile compacting equipment, combined with careful dumping of coal onto the stockpiles, can reduce the cost of bedded storage. Proper compaction prevents hot spots or minor fires in the bedding storage and permits full-height retrieval of coal. The latter capability reduces the age variation between the earliest coal stored in the lower layers of the pile and the latest coal placed in the top layers.

The total cost of coal bedding, estimated at $1.25 per ton, need not represent a large capital investment because most foundry coke plants maintain relatively small tonnages in storage.

Preparation of Coal Charges

Mixing of coals and additives to prepare charges is usually performed by simultaneously feeding the desired volumetric portions (not weights) of the components into a hammer or ring mill. However, because of the wear and erosion of hammers, rings, and cage bars, the desired degree of pulverization cannot be maintained beyond a comparatively short duration of equipment operation. The final mixture increases in content of oversized, low-Hardgrove-grindability-index (ASTM D409-71), high-volatile coals, slate, and bony coal. In subsequent transfer to and from the larry-car bunkers, segregation persists; coke quality suffers because of variances in oven-charge bulk density in the ovens, and oven door sealing is hampered by tar leaking around sealing strips or through luting clay.

Better mixing and elimination of most of either the plus 1/8-inch or preferably the plus 8-mesh particles (ASTM D311-30) from a pulverized coal mixture can be attained by passing the product from the hammer or ring mills through an inclined, slowly rotating, 40- to 50-ton-capacity, cylindrical shell provided with lifting flights. If desired, the wall of the last section of the rotary mixer can have 1/8-inch holes to permit discharge of all but the oversize coaly particles, blasting wire, straw, and wood splinters from the rotary-mixed coal charge. These undesirable items can be separately discharged by the use of inclined cutter blades prior to discarding.

Preheated Coal Charging

Three batteries equipped to produce foundry coke from preheated coal in 1975 were located in Ironton, Ohio, Tarrant, Ala., and Detroit, Mich. Only a portion of the retrofitted Michigan battery used preheated coal charging in 1975; however, this portion attained a 40-pct increase in foundry coke production per operating oven. The Ohio battery produced blast furnace coke in 1975. The Alabama battery, completed in 1975, had some mechanical and startup problems that held the use of preheated coal to an insignificant tonnage.

The three batteries used the Coaltek system for pipeline charging of preheated coal. The advantages of the Coaltek system reportedly are the elimination of smoke and particle emissions during coal charging, up to a 50-pct increase in coke production per unit of time, usability of lower grade coals to attain better coke quality, and reduced overall maintenance. The essential features of the Coaltek system follow:

1. The coal carrier is superheated steam, which minimizes all fire and explosion hazards.

2. The efficiency of the system, stated in pounds of solids transported, is 10 times that of conventional systems for a given pipe size.

Carbonization tests conducted by the Bureau of Mines showed that, compared with coal carbonized on an as-received basis, preheated coal gave similar yields of coke, light oil, and ammonia, a higher yield of tar, and lower yields of gas and liquor. The heating value per cubic foot of the gas was slightly higher for the preheated coals (21).

Reduction of Solids Carryover During Oven Charging

Recent tests by British investigators indicated that, during the gravity charging of preheated coal, the main factor influencing solids carryover appeared to be ingress of air into the oven, aggravated by high suction at the base of the ascension pipe. High air leakage into the oven, caused by the combined action of high suction, leaking doors, and gaps between the bases of the charging-car hoods and the oven surface, considerably increased the amount of carryover. With no air ingress into the oven, an increase in the suction at the base of the ascension pipe during charging had no effect on the amount of solids carryover. The amount of solids carryover appeared to be little affected by a change in flue temperature in the 2,190° to 2,340° F range, or by a change in the volatile matter of the coal from 25 to 37 wt-pct; the solids carryover was also little affected by changing the charging technique from simultaneous to consecutive or by increasing the percentage of less than 0.10-inch coal in the charge.

With poor oven operation (high suction at the base of ascension pipe, air ingress into the oven during charging), the amount of solids carryover (tar-free) from preheated charges could be very high; values for four tests ranged from 0.45 to 0.92 wt-pct of the charge. With good oven operating conditions (low suction at the base of ascension pipe, no air ingress into the oven during charging), the amount of solids carryover (tar-free) for 42 10-ton oven tests ranged from 0.10 to 0.43 wt-pct of the charge; the average value was about 0.2 wt-pct. For wet charges the amount of solids carryover was lower and also less variable than for preheated charges; for conditions of high suction at the base of the ascension pipe and leveling of the wet charge, the amount of solids carryover (tar-free) ranged from 0.07 to 0.20 wt-pct of the charge, and the average value for seven 10-ton oven tests was 0.12 wt-pct. With low suction and leveling of the wet charge, the amount of solids carryover might be reduced to 0.01 wt-pct of the charge. The carryover obtained from preheated charges contained a smaller proportion of tar and was of much finer size than that obtained from wet coal charges.

The analyses of the dry tar-free solids carried over from both wet and preheated charges indicated that they were fine, heat-affected coals; they were noncaking, low in volatile matter, and in general slightly higher in ash than the corresponding coke. Although almost all the material was less than 0.04 inch, the size distribution was the main difference between the solids carried over from wet and from preheated charges. In general, for preheated charges the solids carried over were very fine, being about 50 wt-pct less than 0.002 inch, 90 wt-pct less than 0.01 inch, and 97 wt-pct less than 0.02 inch. In comparison, the solids carried over from wet charges were much coarser, being 20 wt-pct less than 0.002 inch, 50 wt-pct less than 0.01 inch, and 85 wt-pct less than 0.02 inch (3, pp. 29-31).

SUGGESTED RESEARCH AND DEVELOPMENT

Increased yields of foundry coke from existing oven batteries appear feasible through further research on coal preparation and treatment techniques. Since the undeveloped methods described below are applicable to both foundry and blast furnace coke making practices, they merit consideration for commercial oven testing. A summary of these methods follows:

1. Coal cleaning deserves further attention for the substantial reduction of clay in the cleaned product from the coarse- and small-sized coal

circuits, for the modification of cleaned high-volatile coal to increase its durain content, and for varying coal-cleaning practices to assure recovery of more fusain from the currently discarded preparation-plant refuse.

2. Carbonization practices consider the removal of plus 1/4-inch particles from coal mixtures prior to charging into the ovens and the benefits and disadvantages of the pipeline charging of preheated coal.

3. Bedding storage of coal receipts is advocated. Considerable attention is given to carbonization phenomena and how they singly or in combination affect the quality and yields of foundry coke.

Coal Cleaning for Elimination of Clay Content

Cleaned metallurgical coals contain variable amounts of clay. The use of anthrafines in foundry coal mixtures also introduces clay, whether the fines are produced from recently mined anthracite or recovered from weathered culm banks.

Some coal-cleaning-plant operators intentionally maintain a high clay content in the circulating dense-medium circuit, thereby lowering the input of new fine sand or magnetite to the dense-medium circuit. As a result, the coarser sizes of cleaned coal have cleavage and bedding interstices coated with clay.

When clayey raw coals are wet-cleaned, clay is present in all flowsheet circuits. Fine coals produced in the centrifugal and flotation circuits have a larger surface to weight ratio than does plus 1-inch clean coal produced in dense-medium equipment. Varying amounts of clay accompany the fine clean coal, either by adherence or by mechanical entanglement.

Because of the undesirable effects of clay in coal mixtures and inadequate processes for its reduction, development work in this area seems essentail. For example, while sodium silicate or causticized starch are useful in clarifying the supernatant liquid in thickeners, they have no effect as repellents to reduce the adherence of clay on surfaces of coal in classifiers and flotation cells. Adherent clay prevents the wettability of the fine coal particles during the plastic stages developed during the carbonization process. On the other hand, the complete absence of clay coatings would tend to counteract part of the poor wettability of less costly higher-oxygen-content coking coals.

Clay on coal surfaces hinders the removal of surface water from clean coal particles in filter and centrifugal equipment. Moreover, the addition of oil to increase the bulk density of the coal mixtures charged into the ovens must often be doubled because of the oil-repellent behavior of clay on the coal surface.

In a similar vein, research efforts could be directed toward assessments of the relative wettability characteristics of vitrain, clarain, durain, and fusain by the bitumens present in the plastic stage during coal carbonization.

It appears that this information may be better determined by use of the agglutinating index than by the Gieseler fluidity characteristics. The relative volumes of the four coal constituents are determined by ASTM method D2797-67T.

Modified Durain Content of Cleaned, Coarse, High-Volatile Coal

The use of multiple-level drawoff conduits from the vertical cylinder appended to the conical section of a dense-medium washer permits a substantial separation of a durain-rich product from the vitrain- and clarain-rich components of the total cleaned coal.

Although durain undergoes no substantial plastic stage during carbonization, it does serve as the principal carbon-contributing constituent of coking coals. Because of its relatively low Hardgrove grindability index, it does not report in large percentage to the finer particles of the pulverized foundry coal mixtures as normally pulverized. When not coated by a clay film, it exhibits good wettability by the plastic stages associated with vitrain and clarain carbonization.

Obtaining more of the coke-carbon supply from an increased-durain-content modified high-volatile coal instead of from more costly low-volatile coals should permit the foundry coke producer to reduce the cost of his foundry coal mixture and to assure the consistent production of high-quality coke.

Fusain Use in Coking-Coal Mixtures

The recovery of fusain during the wet cleaning of raw coal deserves more attention because a small consistent content in foundry coal mixtures can definitely improve foundry coke quality. Modifications to the fine-coal-cleaning flowsheet and the judicious use of selective flotation agents may substantially increase the recovery of fusain from the fine refuse now sent to dumps.

In the 1930's one foundry coke producer, operating captive mines using conventional mining methods, used unwashed coal fines to produce foundry coke. The unwashed mixture charged to the ovens comprised equal weights of Pocahontas No. 3 low-volatile coal containing 6.3 wt-pct ash and Eagle seam high-volatile coal containing 5.5 wt-pct ash. The coal mixture contained 0.65 wt-pct sulfur and 4.0 wt-pct fusain. Foundry coke made in 21-inch-wide ovens, containing 7.3 wt-pct ash and 0.57 wt-pct sulfur, had excellent size, strength, and abradability characteristics. In the 1940's, still using conventional mining methods, the raw low-volatile Pocahontas coal from the same mine was wet-cleaned without significant recovery of the minus 200-mesh fines. Equal weights of the cleaned low-volatile coal and raw Eagle seam coal, when coked in 21-inch-wide ovens, produced a coke with less remarkable qualities because the 50-50 wt-pct coal mixture contained less than 1.2 wt-pct fusain. Later, wet cleaning facilities were also used on the raw Eagle seam high-volatile coal. The 50-50 wt-pct mixture of the two cleaned coals contained less than 0.8 wt-pct fusain. Coke characteristics and yield were acceptable but definitely inferior to those of the 1930's product. Coal mixtures charged using all raw coals or all washed coals were pulverized to 94 pct minus 1/8 inch. Coking time in all situations was 36 hours.

CONCLUSIONS

The facts and opinions assembled on foundry coke operations characterize an industry requiring major adjustments in the near future. Since consumers of foundry coke will continue to insist on uniform high-quality coke, producers cannot delay indefinitely decisive actions ranging from the implementation of minor revisions of operating practices to costly rehabilitation or replacement of coke ovens. Continued reliance on relatively old batteries of ovens merely aggravates poor operating conditions and low productivity.

Some operational problems, of course, appear immutable. Foundry coke production is a batch process using cleaned coal and additives, none of which have consistent chemical and physical characteristics. Some of the answers to such problems may lie in more simple and practical approaches, as suggested in this report. Optimum results in foundry coke operations, however, will continue to be maintained primarily by quality workmanship and proficient oven battery supervision.

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APPENDIX A.--GLOSSARY

Agglutinating value.--the adherence caused by viscous substances formed by heating coal out of contact with air.

Anisotropic.--having unequal responses to external stimuli.

Anthrafines.--the product from anthracite coal-preparation plants, usually smaller than one-eighth inch.

Bulk density.--the average weight per unit volume of an oven charge after completion of its introduction into the carbonization equipment.

Butt.--the less fissured end of a piece of coke. Also refers to a piece of foundry coke not appended to the fissured end produced in closer proximity to the oven wall.

Byproduct coke.--coke manufactured with attendant recovery of byproducts in ovens that are heated externally.

Carbonization.--the process of decomposing a nonvolatile carbonaceous substance, usually coal, into solid, liquid, and gaseous products, by heating in a reducing atmosphere.

Char.--denotes the weak solid produced from 40 wt-pct volatile-content coal by the fluidization method at 930° F or in a rotary furnace (11).

Clarain.--the macroscopically recognizable bright lustrous constituent of coal, which is striated by dull intercalations.

Coal.--a solid, brittle, more or less distinctly stratified, combustible carbonaceous rock.

Coal charge.--the carbonaceous mixture introduced in an oven before the start of the carbonization cycle.

Coal line.--the top surface of the mechanically leveled coal charge in an oven, usually 18 to 24 inches below the oven roof.

Coke.--the residue remaining after volatile constituents are removed from bituminous coal by heat, comprising carbon and the ash bonded together. Also defined as an amorphous form of carbon without definite crystal structure.

Coke breeze.--the fine screenings from crushed coke or from coke as taken from the ovens of a size varied in local practice but usually passing a 1/2-inch-square screen opening.

Coke end of oven.--the end of an oven from which coke is discharged by a pusher ram.

Culm bank.--the waste of anthracite mines consisting of fine coal, more or less pure, and coal dust and dirt.

Dissociation.--the process by which a chemical combination breaks up into simpler constituents, especially by the action of heat or other forms of energy on gases.

Durain.--the macroscopically recognizable dull bands in coal characterized by their gray to brownish-black color and rough surface, having a dull or faintly greasy luster.

Endothermic.--characterized by the absorption of heat.

Equilibrium.--a balanced condition in which two reactions occur simultaneously at such rates that each utilizes immediately the products of the other.

Exothermic.--characterized by the evolution of heat.

Flame.--a body of hot vapor or gas usually made luminous by the combustion of carbon in the fuel.

Fusain.--recognized macroscopically by its black or gray-black color, its silky luster, its fibrous structure, and its extreme friability. It is the only constituent in coal that marks or blackens an object with which it comes in contact.

Hard coke.--the final solid product obtained by bituminous coal carbonization. Hard coke results from the action of increasing temperature on semicoke whereby additional volatile matter is released. Hard coke consists primarily of amorphous carbon having a range of strength, cell structure, and impurities content.

Miscible.--refers to the ability of liquids to mix.

Oven width.--the median of the door frame internal widths at the pusher and coke ends of an oven.

Oxidation.--the union of oxygen with other substances.

Petrocoke.--the residue from petroleum distillation containing 5 to 10 wt-pct volatile matter, 90 to 95 wt-pct fixed carbon, from a trace to 0.3 wt-pct ash, and from 0.5 to 1.0 wt-pct sulfur.

Plasticity.--a complex phenomenon resulting from the pressure of gases and vapors when, under the action of heat, the molecules at the surface attain a degree of freedom comparable with that obtained in a liquid.

Proximate analysis.--the analysis of coal based on the percentages of moisture, volatile matter, fixed carbon, and ash.

Pusher end of oven.--the end of an oven through which the pusher ram is inserted.

Regenerative heating.--the use of hot waste gases to heat refractory checkerwork through which air is cyclically passed to support combustion of fuels.

Semicoke.--a low-strength solid containing substantial volatile matter resulting from the carbonization of bituminous coal out of contact with air, and existing at the termination of the plastic stage in the temperature range of 800° to 980° F.

Swelling.--the increase of volume of coal during carbonization. In some instances, only a linear change occurs, usually in a vertical direction. In other cases, an increase of pressure within the coal charge is denoted.

Ultimate analysis.--the analysis of coal based on the percentages of its chemical elements.

Vitrain.--the macroscopically recognizable, very bright bands of coal, usually 3 to 5 millimeters in width.

Volatile matter.--those gases and vapors, exclusive of moisture, given off by a material when heated, as prescribed in ASTM method D271-70.

APPENDIX B.--ASTM STANDARD TESTS FOR COAL AND COKE

ASTM designation	Title
D167-24	Volume of Cell Space of Lump Coke.
D311-30	Sieve Analysis of Crushed Bituminous Coal.
D410-38	Sieve Analysis of Coal.
D121-62	Terms Relating to Coal and Coke.
D294-64	Tumbler Test for Coke.
D141-66	Drop Shatter Test for Coke.
D720-67	Free Swelling Index of Coal.
D2639-67T	Plastic Properties of Coal by the Automatic Gieseler Plastometer.
D2640-67	Drop Shatter Test for Large Coke.
D2797-67T	Microscopical Determination of Volume Percent of Physical Components of Coal.
D310-69	Sieve Analysis of Anthracite.
D2799-69T	Preparing Coal Samples for Microscopical Analysis by Reflected Light.
D293-69	Sieve Analysis of Coke.
D271-70	Laboratory Sampling and Analysis of Coal and Coke.
D409-71	Hardgrove-Grindability Index.

APPENDIX C.--U.S. FOUNDRY COKE PRODUCERS

State	Producer	Plant
Alabama	Alabama Byproduct Corp	Tarrant.
Do	Empire Coke Co	Holt.
Do	U.S. Pipe and Foundry Co	Birmingham.
Indiana	Citizens Gas and Coke Utility	Indianapolis.
Do	Indiana Gas and Chemical Corp	Terre Haute.
Michigan	Allied Chemical Corp	Detroit.
Minnesota	Koppers Co., Inc	St. Paul.
Missouri	Great Lakes Carbon Corp	St. Louis.
New York	Allied Chemical Corp	Harriet.
Ohio	.....do	Ironton.
Do	Diamond Shamrock Co	Painesville.
Pennsylvania	Eastern Gas and Fuel Associates	Philadelphia.
Do	Koppers Co., Inc	Erie.
Do	Shenango, Inc	Neville Island.
Tennessee	Chattanooga Coke and Chemical Co., Inc.	Alton Park.
Wisconsin	Milwaukee Solvay, Coke Division Pickands Mather.	Milwaukee.

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