

High Carbon Ferrochrome Technology

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9.1 INTRODUCTION

9.1.1 High Carbon Ferrochrome and Its Production Base

High carbon ferrochrome represents a group of alloys with a chromium content typically between 60% and 70% and a carbon content typically between 4% and 6%. To meet this specification the alloy requires a chromite ore with a high Cr/Fe ratio (>2). Since the commercialization of the argon oxygen decarburization (AOD) process, it also became possible to produce ferrochrome from lower-grade chromite ores, which are available in countries such as South Africa, India, and Finland. These ores typically have Cr/Fe ratios of 1.5 to 1.6 and result in ferrochrome with a chromium content of 50% to 55% (and recently even below 50%) and carbon content typically between 6% and 8%. Ferrochrome produced from these ores is generally referred to as *charge chrome* and is often included in the broad category of high carbon ferrochrome.

The silicon content in conventional high carbon ferrochrome is normally below 2%, whereas the thermodynamic equilibrium allows charge chrome larger flexibility in terms of silicon content, which can vary between 2% and 5%. The silicon content in the alloy is dependent on the chosen production technology route and the selected slag operating regime.

High carbon ferrochrome is an intermediate product and is used as a feed material in the production of value-added materials such as stainless steel. Typical product types for high carbon ferrochrome are crushed lumpy product with a silvery metallic appearance (Fig. 9.1) and irregular, flaky granulated product with a greenish appearance.

High carbon ferrochrome does not have a single specification, as the ores in different regions differ, which impacts on certain components in the alloy (e.g., Cr, Fe, and C). Furthermore, the smelting process (slag metallurgy or technology route) employed also impacts on particular components in the alloy (e.g., Si, S). Finally, the type of reductant used will also impact on particular components (e.g., P). Therefore, rather than a universal standard specification, producers generally have their own specifications, which depend on their particular process and set of raw materials. Minor elements in the alloy are not normally specified, but could attract premiums from particular specialty steel producers (e.g., Ti).

Nevertheless, there are two broad categories of specifications, which follow the classical distinction between high carbon ferrochrome and charge chrome. These illustrative specifications are shown in Table 9.1.

Sizing specifications are typically in accordance with the client's requirements, which, in some cases, depend on the transport and product-charging infrastructure at their facilities. A lumpy product would typically have a bottom size limit of 6 or 10 mm and top size limit of 50 mm or larger. Material below 6 or 10 mm is classified as fines and normally attracts a discount. Weight adjustments are made for moisture content.



FIGURE 9.1 Lumpy high carbon ferrochrome. (Source: Outokumpu.)

Granulated material follows the same size pattern, but the size distribution is not determined by the crushing and screening process but rather by the granulation process. Unlike the cast product, granulated material is porous and could entrap some moisture, which could be viewed as being a process risk for the client. Granulated material generally also has a lower bulk density.

High carbon ferrochrome is historically primarily produced in submerged arc AC furnaces, utilizing a number of process routes as shown in the next section. For obvious cost reasons these production facilities are primarily in countries with sufficient resources of chromite ore, but other factors, such as relatively cheap electricity, may also facilitate production in other countries.

TABLE 9.1 Typical High Carbon Ferrochrome Specifications

Alloy Type	Elements				
	Cr	Si	C	P	S
High Carbon Ferrochrome	60–70	<2	<8	<0.015	<0.02
		2–3	<6	<0.03	<0.04
				<0.05	<0.06
Charge Chrome	50–55	2–3	<8	<0.015	<0.02
		3–4		<0.03	<0.04
		4–5		<0.05	<0.06

The worldwide production of high carbon ferrochrome production is shown in the [Table 9.2](#).

The raw materials for high carbon ferrochrome comprise a combination of suitable chromite ores, reductants, and fluxes.

Chromite ores were described in Chapter 8, which shows the distribution of chromite ore reserves and resources to be heavily weighted toward South Africa, having more than 70% of measured reserves. For high carbon ferrochrome production, lumpy or agglomerated ores are generally suitable for larger or closed alternating current (AC) furnaces, whereas finer ore fractions can either be agglomerated or be used in smaller or open furnaces and also in direct current (DC) furnaces. The application of ores in different processes is described in the following sections. Ore composition has a direct impact on the resultant slag composition and volume, whereas the physical quality of the ore impacts on the metallurgical efficiency in the smelting furnace. The typical distribution of chromite ore production is shown in [Table 9.3](#)

Fluxes are generally required to modify the slag-forming components in the chromite ore into a slag with the appropriate compositional characteristics for the targeted process metallurgy, melting temperature, and suitable tapping properties. A wide range of fluxes is used and often depends on availability of fluxes in close proximity to the particular smelter. Common fluxes are quartzite, dolomite, and limestone.

Reductants are used to reduce the reducible components in the chromite ore to the metallic or carbide states, which form the alloy. A variety of reductants is used in the production of high carbon ferrochrome, and the selected reductants for a particular smelter would depend on the technology process applied, the availability of reductants, and the perceived cost-effectiveness of a particular reductant. Physically competent reductants, such as coke, are deemed to contribute to the formation of a coke bed in the furnace, which is particularly relevant to and beneficial for larger furnaces. Volatiles in reductants can result in tar deposition in off-gas cleaning plants of closed furnaces, which is detrimental to the operation of these plants. Reductants can be classified in terms of their reactivity for a particular process. This classification is often used to select appropriate reductants. The sizing of reductants is specified in accordance with a particular furnace, as it impacts directly on the operating resistivity of the furnace. As each furnace and process has an optimal operating resistivity, the reductant size specification is important. Reductants for high carbon ferrochrome production are normally selected from one or a combination of the following: coke, gas coke, char, coal, anthracite, and even charcoal or petroleum coke in some instances.

The metallurgical efficiency (expressed as % Cr recovery to the alloy) and electrical efficiency (expressed as specific electrical energy consumption) vary in accordance with a number of factors. The mineralogy of the particular

TABLE 9.2 High Carbon Ferrochrome Production 2001–2010 (gross weight—metric tons)

Country	S	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Finland	p	236 710	248 180	250 490	264 492	234 881	243 350	241 760	233 550	123 310	238 195
Norway	p	82 600	61 100	—	—	—	—	—	—	—	—
Spain	p	—	—	—	—	—	—	—	—	—	—
Sweden	p	109 198	118 823	110 529	128 191	127 451	136 374	124 403	117 053	31 345	70 576
Turkey	p	41 480	—	24 603	24 956	15 500	55 900	58 846	66 492	36 263	50 878
Total W. Europe		469 988	428 103	385 622	417 639	377 832	435 624	425 009	417 095	190 918	359 649
Albania (e)	o	19 500	22 800	37 800	34 650	34 000	17 040	—	8 390	6 470	22 556
Croatia	p	—	—	—	—	—	—	—	—	—	—
Kazakhstan	p	526 985	629 907	755 146	819 511	907 670	928 177	1 070 000	955 202	938 675	1 073 237
Russia	p	38 099	26 393	76 230	147 164	295 000	304 312	345 092	261 808	135 770	241 080
Slovakia	p	5 371	4 869	1 901	1 712	867	19	—	—	—	—
Total E. Europe		589 955	683 969	871 077	1 003 037	1 237 537	1 249 548	1 415 092	1 225 400	1 080 915	1 336 873
S. Africa	p	1 939 584	2 288 652	2 721 630	2 960 258	2 505 611	2 818 400	3 535 871	3 238 985	2 316 754	3 663 275
Zimbabwe	p	276 963	289 998	261 095	218 065	257 271	213 512	200 833	151 729	73 600	156 118

(Continued)

TABLE 9.2 High Carbon Ferrochrome Production 2001–2010 (gross weight—metric tons)—cont'd

Country	S	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total Africa		2 216 547	2 578 650	2 982 725	3 178 323	2 762 882	3 031 912	3 736 704	3 390 714	2 390 354	3 819 393
Brazil	p	97 245	149 135	185 592	185 572	170 103	140 886	164 486	186 676	101 780	165 963
Total Americas		97 245	149 135	185 592	185 572	170 103	140 886	164 486	186 676	101 780	165 963
China	o	261 621	231 305	423 324	532 000	680 000	858 000	1 060 200	1 283 700	1 510 000	2 212 000
India	p	267 350	311 918	468 677	527 100	611 373	634 200	820 000	750 000	670 000	1 006 000
Iran (e)	o	8 430	15 000	17 000	17 000	17 000	17 000	17 000	10 000	9 000	3 389
Japan	o	104 300	87 700	6 600	5 700	1 900	3 500	300	—	—	—
Total Asia/M. East		641 701	645 923	915 601	1 081 800	1 310 273	1 512 700	1 897 500	2 043 700	2 189 000	3 221 389
Grand Total		4 015 436	4 485 780	5 340 617	5 866 371	5 858 627	6 370 670	7 638 791	7 263 585	5 952 967	8 903 267

S = sources; p = producers; o = industry organizations, others; — = no production; (e) = estimate.

Source: International Chromium Development Association (ICDA).

TABLE 9.3 Chromite Ore and Concentrate Production 2001–2010 (gross weight—metric tons)

Country	S	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Finland	p	575 126	566 090	549 040	579 780	571 103	548 713	556 100	613 543	246 817	583 120
Turkey	o	368 012	313 637	229 294	506 421	858 729	1 059 901	1 678 932	1 885 712	1 770 029	2 206 533
Total W. Europe		943 138	879 727	778 334	1 086 201	1 429 832	1 608 614	2 235 032	2 499 255	2 016 846	2 789 653
Albania (e)	p	129 700	72 600	98 000	158 392	119 964	201 120	323 570	203 850	256 000	455 505
Kazakhstan	p	2 056 648	2 349 640	2 781 725	3 290 000	3 581 202	3 366 078	3 687 211	3 614 188	3 544 197	3 702 612
Kosova	p	—	—	—	—	—	—	—	—	2 000	9 500
Russia	p	69 926	74 300	116 455	320 200	772 000	966 095	1 007 181	913 050	416 036	457 124
Total E. Europe		2 256 274	2 496 540	2 996 180	3 768 592	4 473 166	4 533 293	5 017 962	4 731 088	4 218 233	4 624 741
Madagascar	p	51 900	11 000	45 040	77 386	140 847	132 335	122 260	117 115	113 569	115 275
South Africa	p	5 616 949	6 372 739	7 136 666	7 309 575	7 244 112	6 950 279	8 720 330	9 267 848	6 394 815	8 749 875
Sudan (e)	p	20 500	14 000	37 000	26 000	21 654	28 772	15 476	31 890	19 000	65 447
Zimbabwe	p	727 670	734 011	666 357	621 269	819 903	712 908	663 593	484 482	279 366	542 561
Total Africa		6 417 019	7 131 750	7 885 063	8 034 230	8 226 516	7 824 294	9 521 659	9 901 335	6 806 750	9 473 158
Brazil	p	418 423	279 684	510 640	622 755	616 534	604 145	625 627	753 326	725 681	762 000
Cuba	p	26 000	21 150	27 600	42 487	14 729	5 047	—	—	—	—

(Continued)

TABLE 9.3 Chromite Ore and Concentrate Production 2001–2010 (gross weight—metric tons)—cont'd

Country	S	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Total Americas		444 423	300 834	538 240	665 242	631 263	609 192	625 627	753 326	725 681	762 000
Australia	p	11 800	132 665	138 826	265 987	241 865	260 112	253 400	224 809	131 941	186 917
China (e)	o	184 500	164 200	197 800	230 000	202 000	220 000	220 000	220 000	280 000	280 000
India	p	1 677 924	2 698 577	2 210 000	2 948 944	3 255 162	3 600 400	3 320 000	3 760 000	3 760 000	3 800 000
Pakistan	p	64 000	62 005	98 235	129 500	148 432	199 000	323 100	320 000	275 000	567 500
Philippines (e)	p	26 932	23 703	12 967	70 001	72 025	85 151	221 481	345 725	88 234	161 271
Vietnam (e)	o	105 026	113 957	143 518	194 909	78 915	73 037	103 828	55 885	37 105	58 675
Total Asia & Austral.		2 070 182	3 195 107	2 801 346	3 839 341	3 998 399	4 437 700	4 441 809	4 926 419	4 572 280	5 054 363
Iran (e)	o	104 905	80 000	120 000	183 171	223 623	244 603	185 758	188 032	255 129	350 537
Oman (e)	o	30 150	27 444	13 000	26 600	72 537	76 716	355 547	908 502	680 216	956 870
U.A.E. (e)	o	10 000	—	—	7 089	—	—	13 066	34 355	6 490	40 484

Total Mid. East	145 055	107 444	133 000	216 860	296 160	321 319	554 371	1 130 889	941 835	1 347 891
Grand Total	12 276 091	14 111 402	15 132 163	17 610 466	19 055 336	19 334 412	22 396 460	23 942 312	19 281 625	24 051 806
End Uses*	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010
Metallurgical	10 768 124	12 688 135	13 825 672	16 261 958	17 833 420	18 324 097	21 476 787	22 565 916	18 307 558	22 837 358
Refractory	162 472	127 861	118 143	101 012	206 992	198 423	142 729	178 869	198 863	139 314
Chemical	1 000 390	863 645	768 027	752 735	510 788	454 856	327 642	530 960	323 397	463 179
Foundry Sands	345 105	431 761	420 321	494 761	504 136	357 036	449 302	666 567	451 807	611 955
TOTAL	12 276 091	14 111 402	15 132 163	17 610 466	19 055 336	19 334 412	22 396 460	23 942 312	19 281 625	24 051 806

S = sources; p = producers; o = industry organizations, others; — = no production; (e) = estimate; (r) = revised. Excludes production of concentrate derived from SA UG2.

*Production figures assumed 100% metallurgical when breakdown not available.

Source: International Chromium Development Association (ICDA).

chromite ore plays an important role, and the selected technology route is also a strong determinant. Furthermore, the selection of reductants and slag metallurgy will also impact on the process efficiencies. Illustratively the example of a mass and heat balance for high carbon ferrochrome (HCF_{Cr}) production in a large closed furnace with preheated feed with typical process results is shown in [Table 9.4](#).

This mass and energy balance requires information on the ratios and analyses of feed materials, the furnace power input, the preheater outlet temperature, and the assumed silicon content in the alloy and calculates the distribution of elements to the slag and alloy phases, the electrical energy requirement, and the expected product masses (alloy, slag, and dust). Mass and heat balance models can be used to calculate the ratio of feed materials, the electrical heat requirements, and the efficiencies of a particular process, when actual results are used.

9.1.2 Uses and Applications of High Carbon Ferrochrome

Chromium is an essential alloying element for the production of all types of stainless steels and special alloy steels, on account of the special properties chromium imparts to these materials. The use of low carbon ferrochrome and ferrosilicochrome for chromium addition was common practice until the 1960s, the vacuum argon decarburization (VOD) process being commercialized in 1964 and the AOD process in 1968. In 1972, the Creusot-Loire Uddeholm (CLU) refining process was developed. These three processes, in particular the former two, introduced a revolution in the alloy steel production technologies. Quite a few other similar and modified processes have been developed subsequently.

With the advent of AOD and VOD technologies, the use of high carbon ferrochrome, for introducing chromium into steel with much improved process economics, was established. However, with the worldwide standardization of these technologies, not only the use of high carbon ferrochrome was established; it was also established that lower grades, with even less than 50% chromium content, can be efficiently used in the production of stainless steels and other special alloy steels. This resulted in the arrival of charge chrome as the most economical and established route of chromium addition to steels. Because the charge chrome production technology permits the use of lower-grade chromite ore, charge chrome was accepted as a suitable alloy for stainless steel production, in response to the depleting resources of high Cr /Fe ratio lumpy chromite ore.

High carbon ferrochrome is primarily used in the production of stainless steel. More than 90% of high carbon ferrochrome is used in the production of stainless steel ([International Chromium Development Association \[ICDA\], 2011](#)). The majority of the balance is used in the manufacturing of special steels (including high chromium steels).

TABLE 9.4 Typical Mass and Energy Balance for a HCFcCr Furnace

Mass and Energy Balance for Large Closed Furnace with Preheating											
Furnace power				56 MW							
Preheated feed temperature				492°C							
	Cr	Fe	C	Si	SiO ₂	MgO	Al ₂ O ₃	CaO	Cr/Fe	T°C	Flow, t/h
Feed											
Pellets	30.43	19.13	0.00		3.97	10.60	13.03	0.47	1.59	492	26.86
Lump ore	24.41	13.73	0.77		11.17	16.10	11.60	1.20	1.78	492	15.11
Coke		0.65	87.30		6.27	0.10	3.07	0.33		492	8.64
Quartzite					95.33	0.37	0.83	0.33		492	5.54
Products											
Alloy	53.61	34.86	7.10	3.91					1.54	1580	18.40
Slag	8.81	3.83	0.72		31.33	23.66	24.92	1.58	2.30	1680	22.20
Dust	7.98	6.55	17.24		26.95	17.87	6.24	0.80	1.22	900	0.22
Gas phase				CO	CO ₂	H ₂	H ₂ O	N ₂	O ₂	T°C	Flow, Nm ³ /h
Furnace gas				84.82	6.01	5.96	0.40	2.81	0.00	900	12 654
Burner				83.45	5.91	5.87	2.00	2.77	0.00	45	3 215
Balance				83.45	5.91	5.87	2.00	2.77	0.00	45	9 646
Total furnace feed			469 700 tpa			Slag/alloy			1.21		
Total slag production			187 800 tpa			Total dust production			1 900 tpa		
Total alloy production			155 400 tpa			Paste consumption			1 173 tpa		
Cr recovery to alloy			84%			Specific energy consumption			3 070 kWh/t		

9.2 TECHNOLOGY ROUTES FOR THE PRODUCTION OF HIGH CARBON FERROCHROME

9.2.1 Introduction

When a particular technology route is selected, a number of considerations should be taken into account. However, previous practice or the known status quo in a particular organization often plays a determining role in the selection of a process route. The substantially different outcomes of different technology routes are therefore not always fully acknowledged in the decision-making process. The financial return on a particular capital investment primarily depends on the operating cost of the selected technology route and is normally less dependent on the initial capital investment cost.

Various technology routes are available for the production of high carbon ferrochrome. Some of these routes are established, whereas others are relatively recently commercialized. Intellectual property constraints and even patents make some of the technology options less accessible than others for outsiders. Although there are a large variety of technology routes, with a multitude of varying operating features, there are probably four groupings that cover almost all commercial processes for the production of high carbon ferrochrome. These groupings are as follows:

1. Open/semiclosed submerged arc AC furnaces
2. Closed submerged arc AC furnaces
3. Prereduction followed by closed submerged arc AC smelting
4. Open arc DC furnaces.

The considerations for technology selection are often determined by factors such as access to a particular technology, availability of raw materials, cost of electricity, and environmental and occupational health legislation. History has shown that companies most often continue with known, tested technology routes that fit into their existing portfolio. The industry seems to be risk averse and investments are seldom made in technologies that are perceived to be unproven. Few companies are prepared to assume the risk of investing in breakthrough technologies. Eventually most expansion decisions are strongly influenced by the cost of the investments, and not necessarily by the operating cost benefits associated with the selected technology.

A number of outcomes for a chosen technology route decision are hereafter briefly discussed to demonstrate what the expected results could be for different decisions. When efficiencies are quoted, typical results with South African chromite ores are used illustratively. Ores with different reducibility characteristics could result in different quantitative results. However, relative efficiencies remain valid.

9.2.1.1 Metallurgical Efficiency

On open furnaces with low-quality raw materials (e.g., unscreened lumpy ores), Cr recoveries to the alloy are generally below 80%. With screened lumpy ore,

together with briquetted fines, the chrome recovery should increase to about 80%. When lumpy and fine ore are replaced by pellets, the Cr recovery responds favorably and increases to about 85%. When the smelting process is preceded by prereduction, this efficiency parameter improves further to about 90%. A similar high level of Cr recovery is achieved when fine ore is smelted in the open bath of a DC arc furnace. Given the fact that the return on any investment is primarily determined by the operating cost, it is clear from these numbers how investment decisions could potentially benefit from higher-efficiency processes.

From the preceding discussion it becomes obvious that metallurgical efficiencies are directly related to the quality of the feed material directed to the furnace. In general, the better the physical strength of the ore are, the more favorable the furnace smelting conditions and resultant metallurgical efficiencies would be. Chromite ore is often friable and the mined product contains varying percentages of fine ore. To prevent the adverse effect of these fines in the furnace, the fine ore requires some form of agglomeration. The most common agglomeration processes are briquetting and pelletizing. Briquetting normally takes place at low temperatures and utilizes a binding agent such as lime and molasses, starch, or cement. Normally the binding process is not followed by a form of induration. The general shortcoming of using briquettes in a furnace is that the briquettes lose their strength at elevated temperatures, resulting in decrepitation and fines generation in the furnace. On the other hand, good-quality sintered pellets generally have good physical properties even at elevated temperatures and are internally porous, which results in metallurgical reduction performance even better than lumpy ore. Ores are sometimes classified in terms of a refractory index (RI), which indicates the ore's durability at the high temperatures in the reaction zone of the furnace, and therefore also its ability to take part in refining reactions within the molten slag bath.

The chosen slag metallurgy will also impact on the metallurgical efficiency. It is well documented that processes operating under highly basic slag conditions result in improved reduction of Cr_2O_3 , and therefore improved chromium recoveries. However, highly basic conditions reduce the electrical resistivity in the furnace burden, which may impact adversely on furnace operating conditions and power input. Highly basic conditions also favor desulfurization of the alloy and favor the production of a low Si alloy. On the other hand, processes operating under highly acidic slag conditions also result in improved reduction of Cr_2O_3 and therefore improved chromium recoveries. However, operating outcomes that are generally adversely affected by highly acidic conditions are slag/alloy separation, slag viscosity, and refractory lining wear. From these observations it is therefore clear that process metallurgy selection will also impact on equipment and process design.

9.2.1.2 Electrical Energy Efficiency

On smaller, open furnaces operating with unscreened raw materials, specific energy consumption is suboptimal for reasons explained later and could be as high as 4500 kWh/t. This number will improve substantially when screened

lumpy ore is used and when the furnace size is increased. When preheating is introduced to the pelletized feed to a large, closed submerged arc AC furnace, this efficiency will improve to about 3100 to 3200 kWh/t, depending on the level of preheating. When the smelting process is further preceded by prereduction, the efficiency improves further to below 2500 kWh/t—which could be reduced further to below 2000 kWh/t when the level of prereduction is maximized. It should be clear what the implications of these different levels of electrical energy efficiencies are in an environment of rapidly increasing energy costs.

It is therefore apparent that electrical energy efficiencies depend on a number of factors, of which the size of the furnace, the quality (including chemical composition) of the raw materials (especially the type of agglomeration), and the utilization of preheating or prereduction are the most important. It must also be understood that the total energy requirement for the high carbon ferrochrome production process is driven by the process thermodynamics and remains fundamentally the same, regardless of the selected process route. What could change is the source of energy, which can either be electrical energy or some form of chemical energy (e.g., heat from the combustion of a type of fuel). This should be taken into account when prereduction processes are considered.

9.2.1.3 *Economy of Scale*

If the large variation in furnace sizes (and capacities) from 5 to 135 MVA is taken into account, it will become clear that economy of scale benefits in terms of investment cost will apply, but normally the metallurgical and electrical efficiencies also improve as the furnace size increases. The general trend is still toward larger furnaces, and older, small furnaces are gradually being replaced with larger ones. A 135 MVA submerged arc AC furnace, such as the furnace commissioned by Outokumpu in Finland in 2012, can produce close to 250 000 tons of high carbon ferrochrome annually—more than the total plant output of many of the smaller plants. Larger furnaces require skilled operating personnel and strict raw material quality control compared to smaller furnaces. The choice therefore becomes a risk/return decision.

9.2.1.4 *Capital Investment*

There is a marked contrast in capital investment cost when the simple layout of a conventional open furnace is compared to a vertically integrated complex with facilities for ore preparation, induration, prereduction, and smelting. Understandably, the contrast in investment cost has to be weighed against the benefits in operating efficiencies and economies of scale. In countries or areas where the chromite ore is predominantly fine, the ferrochrome producer has little choice but to consider technology routes that can

handle fine ore, such as DC arc smelting and routes based on ore agglomeration, or even prereduction. These technologies invariably require larger capital investment. However, as will be shown later, the appropriate parameter to consider is not the capital investment cost but the investment cost per ton of product.

9.2.1.5 Occupational Health

It is generally understood that open and semi-closed furnaces produce an order of magnitude more hexavalent chromium in the off-gas than closed furnaces due to the oxidizing conditions favoring hexavalent chromium generation. The occupational health effects of hexavalent chromium are described in more detail later. Regulatory constraints and occupational health risks could become a determining factor in terms of approval for new projects (as is the case in South Africa).

Summarized, some of the outcomes for the different process selections are shown in [Table 9.5](#). Note that numbers used in the table are based on the use of similar, comparable raw materials. The relative values are relevant, although the quantitative numbers may vary among countries and types of raw materials.

Furnace design principles and parameters apply to all ferroalloy furnaces, but the specific design parameters differ in accordance with the particular alloy. These parameters include dimensional and operating specifications such as the following:

1. Furnace diameter and height
2. Electrode spacing (pitch circle diameter [PCD])
3. Electrode diameter
4. Furnace operating power, resistivity, and electrode current.

In general, substantial benefits are to be gained when furnace size is increased to optimal. These benefits include economy of scale benefits, thermal and metallurgical efficiency benefits, and capital investment cost benefits. On the other hand, operating large furnaces requires increased levels of sophistication and quality control. Examples of these constraints are stringent raw material quality control and challenging electrode design and management. A typical schematic view of a submerged arc furnace is shown in [Figure 9.2](#).

The four representative groupings of technology routes are separately discussed in more detail in the following sections.

9.2.2 Open/Semiclosed Submerged Arc AC Furnaces

Open or semiclosed furnaces represent the most common, original type of submerged arc furnaces for the production of ferroalloys. These furnaces are generally smaller (typically <30 MVA) than closed furnaces. A large number of these furnaces have been in operation for a long time and originate from the early days of ferroalloy production. China and India are countries with

TABLE 9.5 Comparative Results for Different HCFeCr Process Routes

Type of Furnace	Metallurgical Efficiency (%Cr Recovery)	Specific Energy Consumption (kWh/t)	Economy of Scale (maximum size of single furnace/output from single furnace)	Occupational Health Indicator (indexed Cr ⁶⁺ generation)
Open AC furnace (without raw material screening)	70–75	4300	30 MVA/50 ktpa	10
Closed AC furnace (with pelletized feed and preheating)	83–88	3200	135 MVA/240 ktpa	1
Prereduction followed by closed AC furnace	88–92	2400*	66 MVA/160 ktpa	1
Closed DC arc furnace	88–92	4200	60 MW/110 ktpa	1

*Only electrical energy in the furnace; excludes fuel energy associated with prereduction kiln.

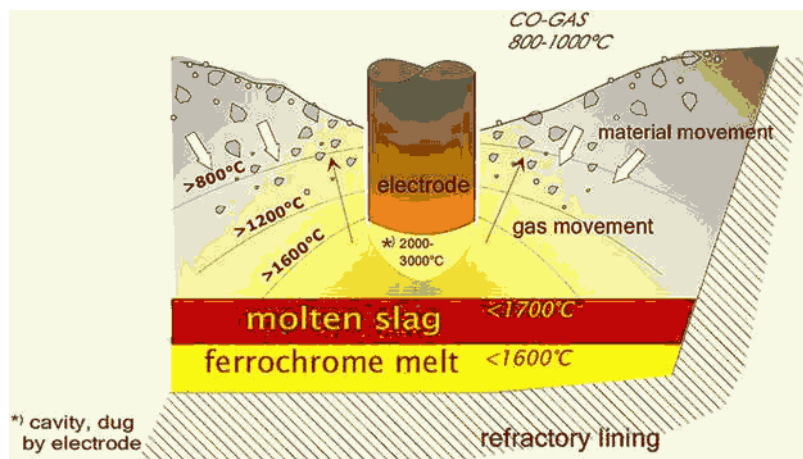


FIGURE 9.2 Schematic view of an AC submerged arc furnace. (Source: Outotec.)

a significant number of small, open furnaces. Other common characteristics of these furnaces are simple raw material feed systems, lack of gas cleaning equipment, and manual labor practices.

One of the most relevant characteristics of these furnaces is that they have less stringent requirements in terms of raw material quality and can successfully operate with high fines content in the feed materials. As a result of the lower-quality raw materials, open furnaces generally require frequent rabbling of the furnace bed to improve bed porosity and to break crust and bank formation. Eruptions due to the furnace bed condition are common on these furnaces. Rabbling of the furnace bed is done by means of a variety of methods, ranging from manual rabbling to mobile rabbling machines.

Generally, open furnaces have lower thermal and metallurgical efficiencies. Thermal inefficiencies result from suboptimal heat transfer in the furnace (due to erratic gas flow patterns) and higher heat losses through the furnace bed and sidewalls. Metallurgical inefficiencies also result from suboptimal gas flow and heat transfer in the furnace. Furthermore, a portion of the finer-sized raw materials (notably fine ore) is tapped with the slag, resulting in a substantial amount of unreduced material lost in the tapping process. This causes increased metallurgical chromium losses and could result in difficult tapping conditions.

Benefits of the operation of open furnaces are generally the simplicity of the operation (which could exclude screening of raw materials), easy access to the furnace bed and electrode equipment (which assists with maintenance), and visibility of the furnace bed (which provides a visual indication of the condition of the process). A further benefit is the low capital investment cost due to the simplicity of the layout and lack of sophisticated control systems. A typical flow diagram for this production process is shown in [Figure 9.3](#).

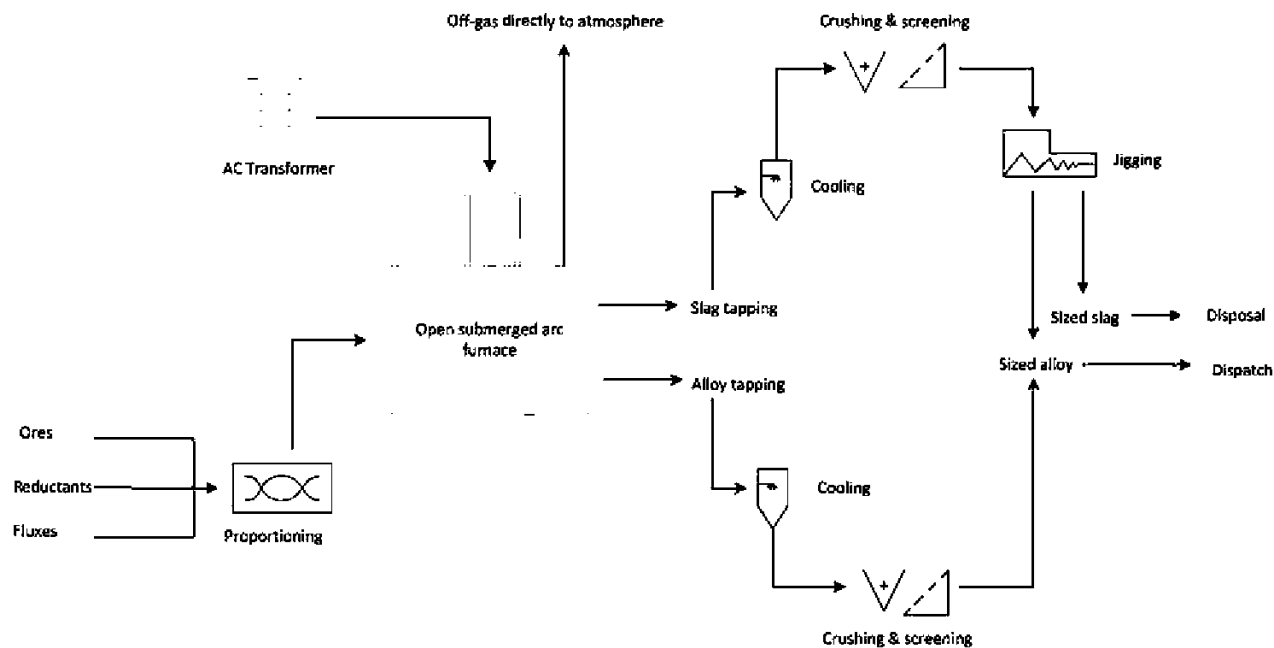


FIGURE 9.3 Typical flow diagram of an open furnace process route.

9.2.3 Closed Submerged Arc AC Furnaces

This technology route generally consists of submerged arc furnaces that are closed and generally larger (>30 MVA). A closed furnace has an airtight roof that prevents air ingress and combustion of the process gases. The gas scrubbing equipment is therefore sized for lower gas volumes than for open furnaces, and the process gas, consisting of primarily carbon monoxide (CO), can be utilized for its calorific value. Furnaces of up to 135 MVA are in operation, although few furnaces in operation presently actually exceed 78 MVA.

The size of these furnaces places constraints on the design and operating parameters. When Söderberg (self-baking) electrodes reach diameters approaching or exceeding 2000 mm, it becomes difficult to design operating conditions for effective baking of the electrodes. Also, due to the physical size of the furnace, it becomes critical to establish a porous furnace bed for effective process gas flow, which can only be achieved by stringent raw material quality requirements. Pelletized ore feed and coke form important success factors for large, closed furnace operation. The quality of the ore is essential for good process efficiencies and for the stable operation of the furnace. The raw material to the closed AC smelting furnace must therefore be in agglomerated or screened, lumpy form. The benefits of large, closed furnaces, when overcoming the mentioned obstacles, are economy of scale benefits (low unit capital investment cost) as well as improved metallurgical and electrical efficiencies.

An appropriate example of successful integrated large closed AC furnace operations can be found in the Outotec ferrochrome process (Fig. 9.4), as it covers all the principles for ore agglomeration, waste heat utilization, and maximization of furnace size. The most representative plant utilizing this technology is Outokumpu's ferrochrome plant in Tornio, Finland. The core of the following process description was provided by Outotec in November 2011.

Outotec's ferrochrome process consists of the smelting of high carbon ferrochrome in a closed and sealed submerged arc furnace, using mainly sintered pellets as raw material, preheating the furnace feed in a shaft kiln located above the furnace, cleaning the furnace gas in two venturi scrubbers and further in a CO filter (optional), and utilizing a portion of the produced CO gas for preheating and sintering of the pellets.

Raw materials to the smelter are chromite pellets and lumpy ore, coke as reductant, and quartzite for fluxing. Other fluxing agents may also be used depending on the ratio of slag forming components in the ore.

First, the pelletizing and sinter process for the chromite ore is briefly described (Fig. 9.5). Feed material is fed to the grinding mill to homogenize the raw material mixture. Coke is preferred as carbonaceous material, although char and gas coke are also successfully used as the main external energy source in the sintering process. Fine coke (<4 mm) is added to the ore concentrate before milling. In the milling circuit the concentrate mixture is wet milled in an

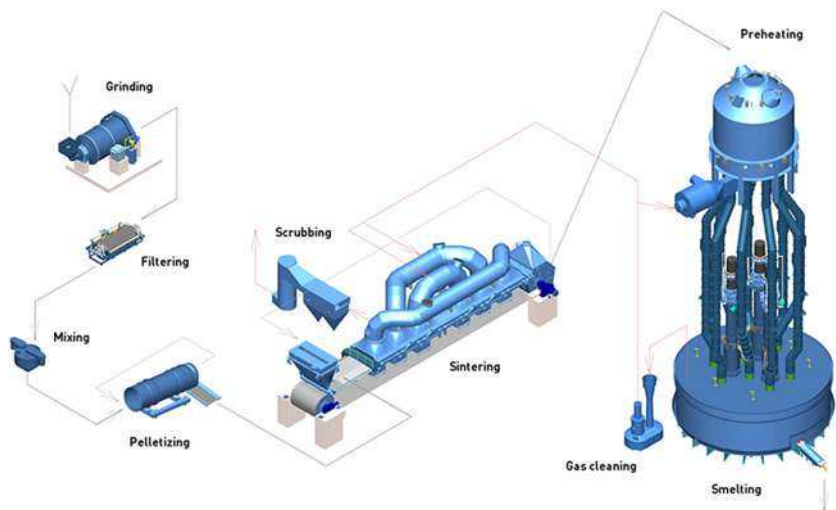


FIGURE 9.4 Flow diagram of the Outotec ferrochrome process. (Source: Outotec.)

open circuit ball mill (without recycling). The purpose of milling is to mill the mixture to a particular grain size distribution, which is suitable especially for pelletizing, but also for sintering. The grain size distribution required is $>80\%$ of the fraction less than $74\ \mu\text{m}$. Ceramic filters (i.e., capillary disc filters) are used to dewater the slurry from the mill into a filter cake. The moisture content of the filter cake is normally about 8.5% to 9%.

The filter cake is collected in a number of filter cake bins, which are equipped with disc feeders to measure and control the feed of material to the pelletizing circuit. Bentonite is used as a binding agent in the pelletizing process and is added in a very fine powder form to blend homogeneously with the filter cake. Dust from the pelletizing plant dust scrubber can be recycled and blended with the milled material. This dust is already in an oxidized form and its addition to the mill has an adverse effect on sintering. The total feed of already sintered recycling material must therefore be limited to a maximum range of 3% to 4% of the concentrate to ensure the production of good quality pellets. The proportioned materials are then well mixed in a mixer before pelletizing in a pelletizing drum, resulting in pellets with an average diameter of 12 mm.

The sintering furnace is a multicompartiment unit through which the green pellets are carried on a perforated steel conveyor belt. The counter-current flow of cooling gases carries waste heat from sintered pellets to those entering the front-end compartments. Sintered pellets are used as a bottom layer on the steel belt to protect it from excessive temperatures. The temperature of the bed is gradually increased to the sintering temperature, which, depending on the mineralogy of the ore, is about 1400° to 1500°C .

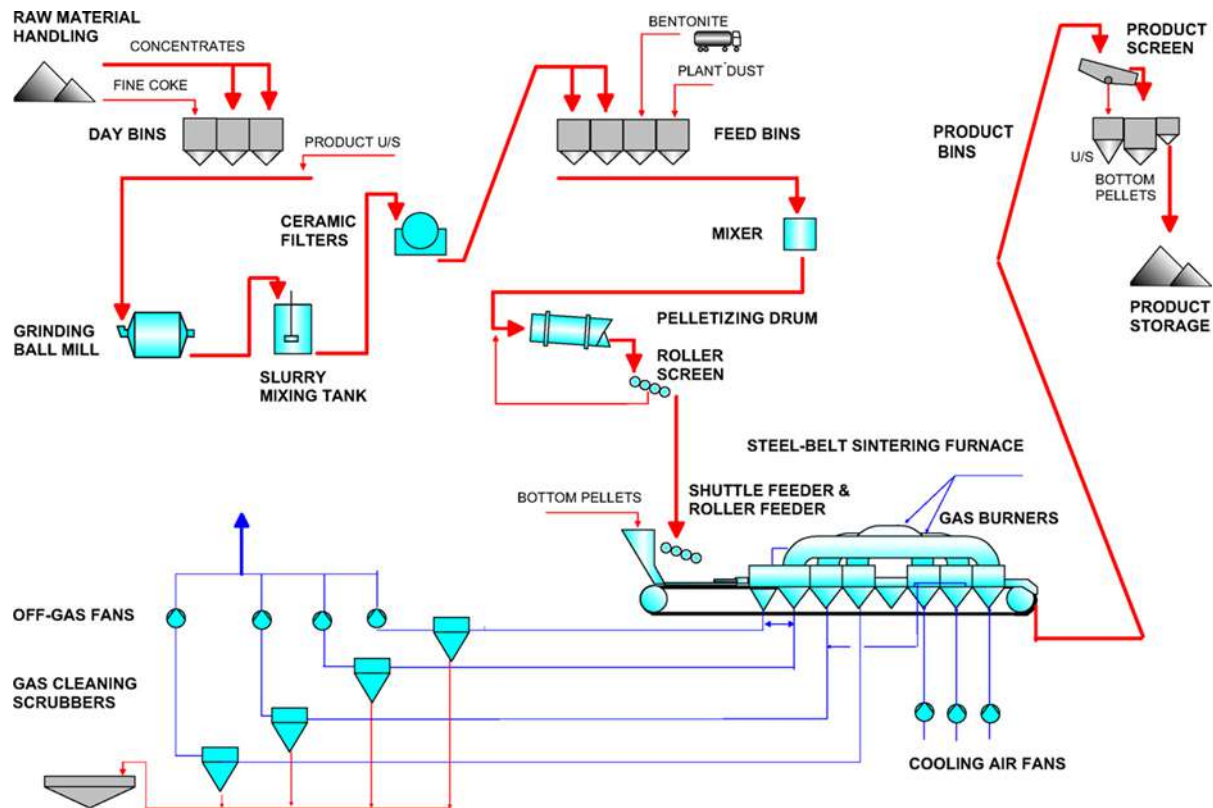


FIGURE 9.5 Flow diagram of the Outotec pelletizing and sinter process. (Source: Outotec.)

Sintered pellets are cooled in three cooling compartments by blowing air through the bed from below. Fresh sintered pellets are, together with bottom layer pellets, discharged onto a belt conveyor transporting them to pellet bins via a screening plant. During typical operation the produced pellets are screened at +6 mm and fed to fill the bottom layer feed bin at the front end of the sintering machine. The final product pellets are conveyed to the smelting furnaces.

Secondly, the ferrochrome smelting process is briefly described (Fig. 9.6). The ferrochrome smelting is based on using sintered chromite pellets as the main chromite source, blended with lumpy ore, although a 100% pellet feed can also be used. Pellets are typically produced from concentrate, which results in a high chromite content in raw material, lowering the slag-to-metal ratio. The chemistry of the chromite ore is also altered by preoxidation in the sintering process, which enhances the smelting step. The chromium recovery is improved and specific energy consumption lowered during the smelting of pellets compared to conventional smelting of lumpy or fine ores.

Good-quality metallurgical coke with a high fixed carbon is preferred, although char and gas coke are also successfully used in some operations. The use of coal and anthracite is not recommended because of the formation of tar in the preheating kiln and in the closed smelting furnace, which also adversely affects the furnace gas production and quality. The strength of the coke is

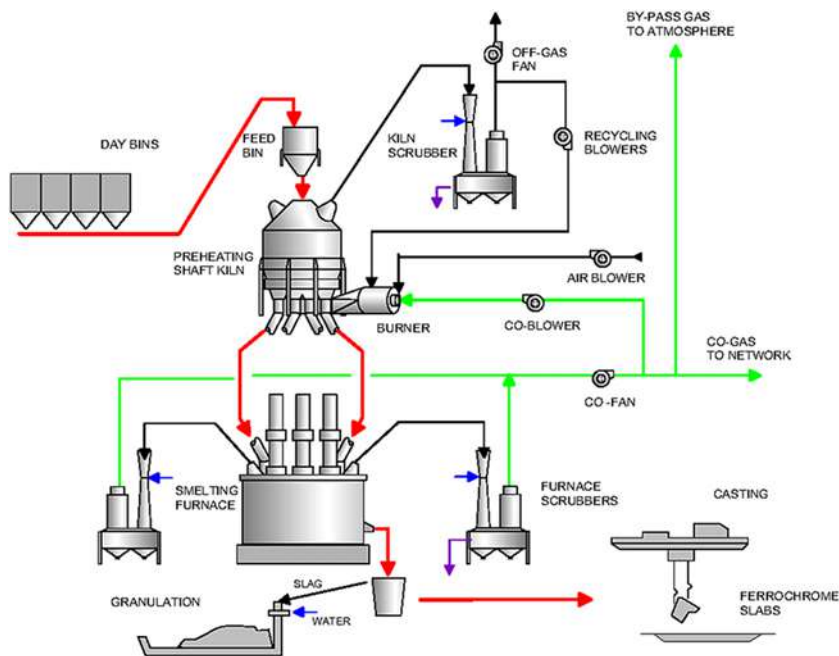


FIGURE 9.6 View of an HCFeCr furnace with a preheater. (Source: Outotec.)

important so that it can move through the preheating kiln and feeding systems without decrepitation. The silica content of the quartzite must preferably be high to minimize other slag-forming components. The physical quality must be such that it can be heated without decrepitation. The smelting process is based on an acidic slag composition. Some limestone or dolomite may have to be added for fine-tuning of the slag chemistry.

The batching system is critical for controlling the feed mixture to smelting; it has to be accurate and reliable. All raw material corrections for smelting are made in the batching station before preheating. The process after batching is a closed system.

The purpose of preheating is to eliminate the moisture from the feed charge mixture and to calcine and preheat it to as high a temperature as possible without igniting or oxidizing the coke. The Boudouard reaction ($C(s) + CO_2(g) \leftrightarrow 2CO(g)$), is the limiting factor. The preheating temperature in the shaft kiln is limited to 650° to 700°C depending on the reactivity of the coke, but the average temperature of the hot outlet material is typically about 450° to 550°C. The thermal power in preheating during normal operation is about 8 to 11 MW for a large furnace.

The Outotec preheating shaft kiln is a steel silo located above the smelting furnace (see Fig. 9.6). The material flows freely through the charging tubes to the smelting furnace. The material in the tubes and in the silo forms a gas seal between the gas spaces in the furnace and in the kiln. The charge material is preheated counter-currently by hot gas that is produced by combusting CO (carbon monoxide) gas in a separate combustion chamber. Preheating generally decreases the electrical energy consumption in the smelting furnace, but it also increases the CO content of the furnace gas and stabilizes the resistivity of the burden. Preheating improves the operation, production, and safety of the smelting process.

Smelting is carried out in a closed submerged arc furnace. The smelting furnace is closed with a flat roof. The furnace is sealed so that there is no combustion of gas and no gas leakage to the surroundings. The CO fan is used to control the pressure in the furnace under the roof to atmospheric level to avoid leakages. The electrode system comprises self-baking Söderberg electrodes, which are not moved extensively.

The specific energy consumption in the smelting furnace depends on the raw material quality. Good, sintered pellets represent high-quality feed that gives stabilized smelting conditions, high chromium recovery, and low specific energy consumption. The lumpy ore, which accompanies the pellets, must also be of high quality. With an increasing amount of fines and dust, the operation becomes unbalanced, which results in decreased power input and thus decreased production. High-quality pellets and lumpy ore allow high operational efficiency and facilitate the successful use of large furnaces.

The furnace is lined with highly heat conductive carbon-based freeze lining. The furnace shell is water-cooled and the furnace bottom is air-

cooled. The freeze lining forms a protective slag skull inside the surface of the lining. Because of skull, the life of the heat conductive linings is typically considerably higher than that of traditional linings. The thickness and profile of the furnace linings are monitored with a sophisticated lining monitoring system.

CO gas is formed in the furnace during reduction. The gas is extracted to two high-pressure venturi scrubbers. The CO gas is further cleaned with CO gas filters, and can then be widely used for heating purposes in the plant or be sent to a CO holding vessel. A CO holder in the network stabilizes the pressure in the line so that all the CO gas can be utilized effectively. The CO-rich off-gas can be used in electricity generation.

The produced ferrochrome and slag are tapped intermittently every 2 to 2½ hours into a ladle or double-ladle system. The alloy settles in the ladles while the slag overflowing the ladle flows via the slag launder to a water granulation installation. The granulated slag is then transported to a stockpile. The slag does not contain significant amounts of alloy or any harmful components. It is directly usable for secondary application purposes.

The alloy ladle is skimmed and the alloy is cast on an alloy fines bed. A fork truck lifts the solidified alloy as big ingots for cooling and for further sizing. The product is crushed in a jaw crusher to a sized product. The ladles are preheated with CO gas to minimize the skull formation.

The skimmed material, spillages, and skulls from the launders and ladles contain alloy. These are treated in a recovery plant, and the recovered alloy fines are returned to the cast beds.

The scrubber slurries contain some cyanides originating from the closed furnace reducing gas atmosphere. The overflow from the thickener is recycled to slag granulation for evaporation and decomposition of the cyanides. Virtually no hexavalent chromium is formed due to the reducing gas atmosphere in the furnace. Water from the granulation goes to settling ponds for recycling. Sand filters are used for cleaning of the recycled water.

9.2.4 Prereduction and Submerged Arc AC Smelting

The history of ferrochrome production includes a substantial number of initiatives to develop a successful prereduction process. These efforts range from laboratory scale testing to piloting and full-scale production. It is, however, accurate to state that most of these initiatives did not result in viable commercial processes. To develop a totally new process requires a strong commitment by an organization to fund the development work, as well as the patience for and financial commitment to the commercial optimization, which could take a long time—often more than a decade.

A number of development projects involved shaft furnaces. Professor Gasik (Sr.) performed extensive test work in Ukraine on blast furnaces in the 1970s, whereas Outokumpu performed selective iron reduction in shaft kilns as far

back as the 1960s. Other projects involved converters and fluidized bed reactors. Kawasaki performed prereduction of chromite ore successfully in a fluidized bed reactor, using methane and hot reaction gases. Outokumpu successfully demonstrated agglomeration and prereduction in a rotary kiln the 1970s.

In the 1980s, Krupp Industrietechnik performed successful prereduction of nonagglomerated chromite in a rotary kiln. This chrome direct reduction (CDR) process was subsequently commercialized by Middelburg Steel & Alloys in the late 1980s and this huge 120 000 tpa (throughput) plant was operated with mixed success during the 1990s. The cyclicity of the ferrochrome market and a lack of long-term commitment to resolve the remaining operational challenges resulted in this operation being discontinued.

The most successful chromite prereduction process proved to be the solid state reduction with carbon (SRC) process, developed by Showa Denko and successfully operated by their JV company with Nisshin Steel, Shunan Denko, in Japan for a long period in the 1970s and 1980s. The technology was successfully replicated by CMI on its plant at Lydenburg, South Africa, in the mid-1970s. This plant is still operational under its present owner (Xstrata), albeit in a slightly modified fashion (referred to as the Premus process). Xstrata has subsequently built another plant (Lion Ferrochrome) in Steelpoort, South Africa, based on this technology, which has been in operation since 2007. A duplicate plant of Lion Ferrochrome was under construction in 2012. It should be mentioned that the original SRC plant in Japan operated at high levels of Cr metallization (approximately 70%), whereas the plants built in South Africa are operating at lower levels of Cr metallization (approximately 50%).

The Xstrata Premus process is used as the reference technology in this section. This technology is a slightly modified version of the SRC technology, originally owned and patented by Showa Denko. The core of the following process description was provided by Xstrata Alloys in November 2011.

The Xstrata plants at Lydenburg and Steelpoort (Lion) in South Africa are the only commercial, large-scale high carbon ferrochrome plants worldwide utilizing a prereduction step. Chromite ore concentrate, reductant (typically coke, but also char or anthracite), and binder (typically bentonite) are proportioned and dried prior to milling. The milling operation is closely monitored in order to ensure that the discharge is appropriately finely ground with a typical sizing of well over 90% less than the 74 μm required to achieve the requisite green pellet strength and subsequent sintering and prereduction performance.

Despite the relative differences in the work index of ore and reductant, the relatively large proportion of reductant added at lower density yields ultimately a similar size distribution of major constituents in the mill discharge, thus enabling sound pelletizing characteristics and appropriate prereduction kinetics.

Following dry milling, the fine milled material is moistened and pelletized on large diameter pan pelletizing units, yielding consistent, compact pellets

typically controlled between 12 and 18 mm in diameter. Close control of the pelletizing operation is important to ensure appropriate characteristics of both the moist green pellets together with their subsequent performance through the drying and preheating stages of the process, thus ensuring that the pellets entering the kiln have sound integrity and suffer minimal degradation during subsequent exposure to the high temperature prereduction environment of the kiln.

The prereduction process remains the core element of the Premus process. Conducted in 80 m long kilns, 5 m inside diameter, at temperatures exceeding 1300°C, the carbon-rich pellets progressively increase in temperature to a point where reduction of initially Fe species and subsequently Cr species can take place. The design of the kiln and integration of kiln and furnace units is such that operational conditions can be varied to optimally suit prevailing electricity availability and pricing conditions to ensure the maintenance of the most cost-effective operation possible. In this regard, kiln energy input is maintained at an optimally high level, with pellet ore and reductant proportion tailored to suit conditions of either higher degrees of metallization in the kiln, with corresponding minimum electrical energy requirement in the final smelting stage (a strategy suited to constrained supply of high-priced electrical energy), or more typically maximized kiln throughput at moderate levels of metallization to optimally complement the smelting capacity of the large 63 MVA downstream submerged arc furnaces, with corresponding high-alloy output rates.

At all times, the process is typically operated around a strategy that enables maximum energy input to the kilns to be maintained, with up- and downstream adjustments in operation to minimize overall alloy production costs.

Following prereduction, the hot prereduced pellets are discharged into refractory lined conveyor bins, where the residual components required for smelting (fluxes and carefully controlled carbon makeup requirements) are added and the hot charge is transferred into refractory lined furnace feed bins, located a relatively short distance above the furnace roof.

The hot charge containing prereduced pellets descends through refractory lined feed chutes into the closed furnace.

The raw material mixture makeup and hot transfer arrangement including furnace bins and transfer chutes are so arranged to ensure that the maximum practical retention of heat in the feed entering the furnace is achieved.

Although the furnace configuration is essentially that of a typical high-powered submerged arc smelter unit, specific allowance has been included in the design to cater to the different characteristics of a fully pelletized and prereduced charge under typical operating conditions, but with sufficient flexibility to accept cold charged prereduced pellets and even lump ore if required. The process is shown schematically in [Figure 9.7](#).

Even though the Premus process capital cost is higher than the capital cost for a conventional process, it is claimed to have the lowest capital cost per

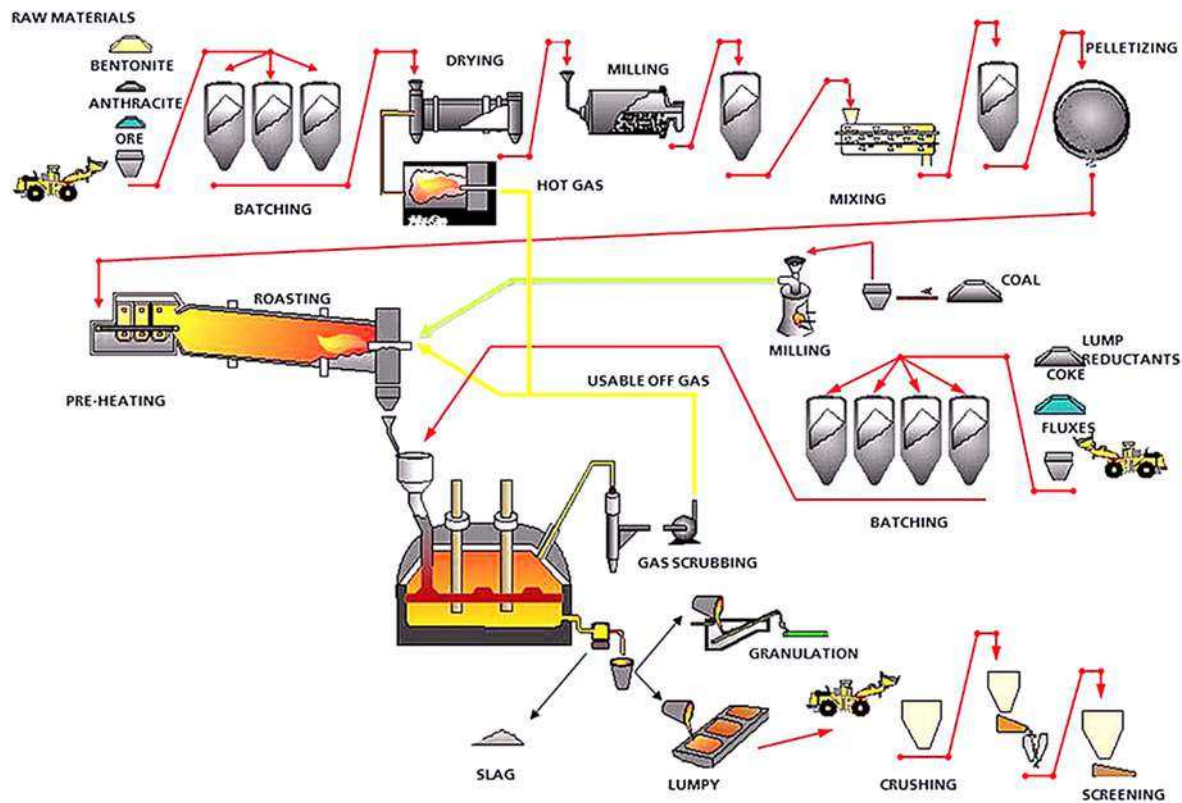


FIGURE 9.7 Flow diagram for the Premus ferrochrome process. (Source: Xstrata.)



FIGURE 9.8 View of the Premus plant. (Source: Xstrata.)

annualized ton of alloy compared to other alternative environmentally acceptable processes available. It is expected to also result in cost of production at the bottom of the cost curve for the foreseeable future. Not only does it result in superior efficiencies (typically 90% chromium recovery and 2.4 MWh/t specific electricity consumption in the smelting furnace), but it also provides important benefits such as low coke consumption and 100% chromite ore agglomeration, and it produces a low silicon product and good environmental results. A view of the Premus plant is shown in [Figure 9.8](#).

9.2.5 Open Arc DC Furnaces

The history of commercial DC arc furnaces for high carbon ferrochrome production is strongly linked to the committed research program by the Council for Mineral Technology (MINTEK) in Randburg, South Africa, over a number of decades. Although numerous major organizations were involved in research work and even pilot scale testing, it was the MINTEK-based work that led to the commercialization of the technology. Selected facts from T. R. Curr's presentation have been used in the following two paragraphs ([Curr, 2009](#)).

MINTEK and Middelburg Steel & Alloys (now part of Samancor Chrome) conducted smelting trials on Tetronics's pilot transferred-arc plasma furnaces as far back as 1979–1980. Although these trials were metallurgically

successful, constraints with scale-up were experienced. At the time plasma torches could not be scaled up to larger than 5 MW due to excessive electrode wear.

In the 1970s, ASEA in Sweden developed high-power thyristor rectifiers and investigated the conversion of AC open arc furnaces to DC mode, principally for steelmaking. They identified a graphite cathode electrode arcing onto a slag/metal bath as the anode and devised an electrically conductive hearth and a hollow graphite electrode for finely sized iron ore smelting.

The process was metallurgically proven at Tetronics, and together with the scale-up potential of ASEA's DC arc furnace, it provided the synergies for a workable large-sized unit. This resulted in Middelburg Steel & Alloys converting an existing AC furnace at its Palmiet works (now Mogale Alloys) to a 12 MW DC arc furnace of ASEA design in 1984. It also resulted in MINTEK building a 1.2 MW pilot DC arc furnace in 1983, to support this development and extend it to other applications. The 12 MW furnace at Palmiet was upgraded to a 32 MW furnace in 1988. A 42 MW DC arc furnace (which was later upgraded to 60 MW) was built at Middelburg Ferrochrome in 1996 and was followed by another 60 MW DC arc furnace on the same site in 2009.

Swedechrome produced high carbon ferrochrome on a transferred plasma furnace with three 6-MW nontransferred torches between 1987 and 1990 in Malmö, Sweden (the Plasmachrome process). The operation only reached about 70% of design capacity and was shut down for economic reasons.

In 2012 a number of DC arc furnaces were in the planning and design phases in South Africa, awaiting electricity allocation from the capacity-constrained national electricity supplier, while at ENRC's Aktobe Ferrochrome Plant in Kazakhstan, four SMS Siemag designed 72-MW DC furnaces were commissioned during 2013. A substantial increase in new generation DC arc furnaces is expected to be commissioned in the second decade of the 21st century.

Due to the open bath nature of DC arc furnaces, the process operates on a thermal knife-edge and power/feed control is critical. When graphite electrode sections are joined off-line, the furnace availability is affected adversely. The high free board temperatures and direct contact of the molten materials with the refractory lining require special measures for the cooling of the roof and refractory lining. Copper cooling elements are typically installed in the bottom part of the lining and tap hole areas. Furnaces are operated with hollow electrode feed, side roof feed, or combinations thereof.

Fundamentally the benefits of DC arc furnaces (Fig. 9.9) for the production of high carbon ferrochrome are as follows:

1. Utilization of fine, nonagglomerated (lower-grade) ore
2. Utilization of fine, lower-value reductants (e.g., coal or anthracite)
3. High metallurgical efficiencies (chromium recovery)
4. Simplified furnace control (as it excludes burden characteristics).

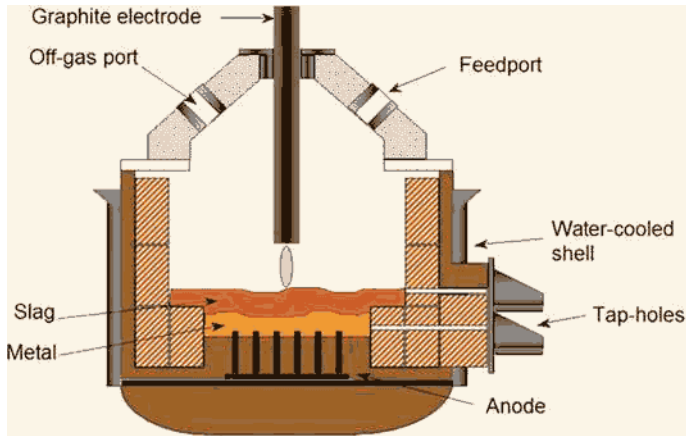


FIGURE 9.9 Schematic diagram of a DC smelting furnace. (Source: MINTEK.)

The DC arc technology route as practiced by Samancor Chrome is presented as the reference technology here. The specific process route selected is the application at the company's Middelburg Ferrochrome plant in Middelburg, Mpumalanga, South Africa, where two furnaces (both 60 MW) are in operation. Samancor Chrome provided the core of the following process description in November 2011.

At this plant the DC process is utilized for the efficient processing of chemically high-grade fine ores, as well as chemically low grade fine ores such as UG2 (Upper Grade 2) tailings from the platinum group metals (PGM) operations. In DC furnaces the input of power is not limited by the electrical conductivity of the materials being processed. This type of furnace can respond to process changes in a relatively short period. Very high temperatures can be attained; however, it should be pointed out that, at the same throughput and power flux, the thermal efficiency of the DC furnace is lower than that of the submerged arc furnace. Two factors are responsible for this effect: More energy is lost to the walls and roof of the furnace by radiation from the open arc and molten bath, and some vaporized material is lost to the off-gas stream from the arc-attachment zone.

The open bath system provides opportunities for excellent process and product control, as the use of an open bath permits greater control of the process metallurgy than in a choke-fed system.

In the case of Middelburg Ferrochrome, the DC furnace is fitted with a solid graphite electrode (contrasting with the hollow graphite electrode used by Mogale Alloys) supported by a hydraulically operated mechanical arm, which can be raised and lowered as and when required. These arms also serve as current conductors to the electrode.

The graphite electrode is centralized and an anode is embedded on a copper dish in the furnace hearth. The molten alloy in the furnace is in electrical contact with the anode. Energy is supplied to the furnace by means of an open plasma arc that impinges on the upper surface of the molten material. The arc is a sustained high velocity high temperature jet, driven by electromagnetic acceleration in the constricted region near the arc's root on the electrode surface. The arc is generated by interaction between the fluid flow, the thermal field, and the electromagnetic fields.

Important characteristics of a typical DC furnace power supply are (1) balanced three-phase load; (2) high-power utilization—constant power input into furnace; (3) ability to operate at reduced load; and (4) constant, stable arc.

Electrical operating parameters vary depending on the design capacity of the furnace. A typical DC power configuration consists of a medium voltage circuit breaker, rectifier transformer, DC isolator and earth switch, and DC reactor.

A transformer and rectifier supply a continuous direct current. The central graphite electrode forms the cathode and the hearth forms the anode. The anode and the metal bath are kept at earth potential, while the arc is struck between the cathode and the slag bath. Convection between the arc, a high-velocity jet of plasma (ionized gases and electrons) and the bath results in most of the energy transfer to the bath.

The balance of the energy transfer is achieved by resistive heating from the current flowing through the bath. The control of this open bath process is extremely critical, because of the ease with which unwanted reactions can become significant if a suitable temperature and feed distribution are not maintained.

The DC smelting process is an open-bath carbothermic reduction of metal oxides in the presence of slag. The following reaction sequence is observed. First, dissolution of metal oxides into the slag phase at the surfaces and within the bath, followed by the reaction of dissolved metal oxide with solid carbon at the slag interface. Formed metal droplets start to descend through the bulk slag phase to the bulk alloy phase, simultaneously reacting with the slag. Finally, the process approaches the equilibrium at the interface between the bulk slag and the alloy.

As the feed increases, the most probable rate-limiting step would be (1) dissolution of metal oxides in the slag or (2) reduction of the dissolved oxide by carbon, as both occur at the surface of the liquid slag bath.

It is a requirement with the DC arc furnace operation to balance the raw material feed rate with furnace power input. The feed into the furnace is therefore controlled from the raw material hoppers on a loss-of-weight basis, in order to continuously monitor and adjust the furnace feed rate to the required levels. The control system is such that the hoppers are never completely emptied, so that each feeder and partially filled hopper may serve as seal against the hot gases from the furnace. Typical feed characteristics are: the ore is fed dry at <1% moisture and

particle size –6 mm; limestone and quartzite are used for fluxing purposes. A mixture of lower-grade reductant blends of anthracite, coal, and char is used.

The high-temperature open bath operation enables separation of slag and metal, consistently giving a reasonably clean tapped alloy into the ingot molds. The furnace consists of two tap holes, positioned on opposite sides of the furnace. One tap hole is for alloy tapping, and the other is for slag tapping, with the slag tap hole at a higher level than the metal tap hole. Each tap hole is provided with an efficient tapping drill and clay gun combination, as the tap holes are normally closed against the flow.

Alloy is tapped at intervals equivalent to 70 to 90 t of alloy production. Alloy is tapped until the slag appears from the alloy tap hole. The furnace alloy level is managed by adhering to a regular tapping schedule (2 taps per shift) and the procedure of tapping alloy continues until the appearance of the slag. Visual monitoring of furnace levels and bath conditions is usually done on a daily basis through the inspection port situated on the furnace roof. This inspection is done during all electrode additions.

The tapped alloy is cast into ingots and the cooled ingots are transported to stockpiles by means of road tractors. The material is later crushed through a tertiary jaw crushing system. The fines generated through crushing are reused as molds for the ingot casting operation.

The resulting CO gas from the ferrochrome smelting process is collected through the off-gas duct. The furnace off-gas duct transfers the hot and dusty CO gas from the furnace off take (at approximately 1780°C) to an off-gas cleaning plant, where it is cooled, scrubbed, and washed to remove entrained dust.

Two options for cleaning of the off-gas are employed for the DC furnaces: a wet venturi scrubbing system and a disintegrator scrubber system. The cleaned gas is flared and the entrapped dust is settled in a clarifier; the resulting slurry is processed through a filter press. The solids are responsibly discarded and the clean water is pumped back to the plant water system. The process flow diagram for a DC high carbon ferrochrome smelting plant is shown in [Figure 9.10](#).

9.2.6 Other Technology Routes

In the early days of ferroalloy production, a number of other process routes were tested. These included various versions of shaft furnaces, rotary kilns, and converters. These process routes were typically part of an integrated stainless steel production line where “direct reduction” process routes were developed and where ferroalloys were not produced as intermediate products. In the late 1980s, an oxygen converter process was extensively studied and tested on a 30-tons-per-day scale by the Research Institute for New Smelting Technologies in Japan. Chromite ore fines were preheated in a rotary kiln and smelted in a top and bottom blown oxygen converter ([Izawa et al., 1992](#)). The Tecnored process was extensively researched and incorporated the production of cold bonded chromite and carbon pellets, which were indurated and prereduced in a shaft kiln by using gas from the

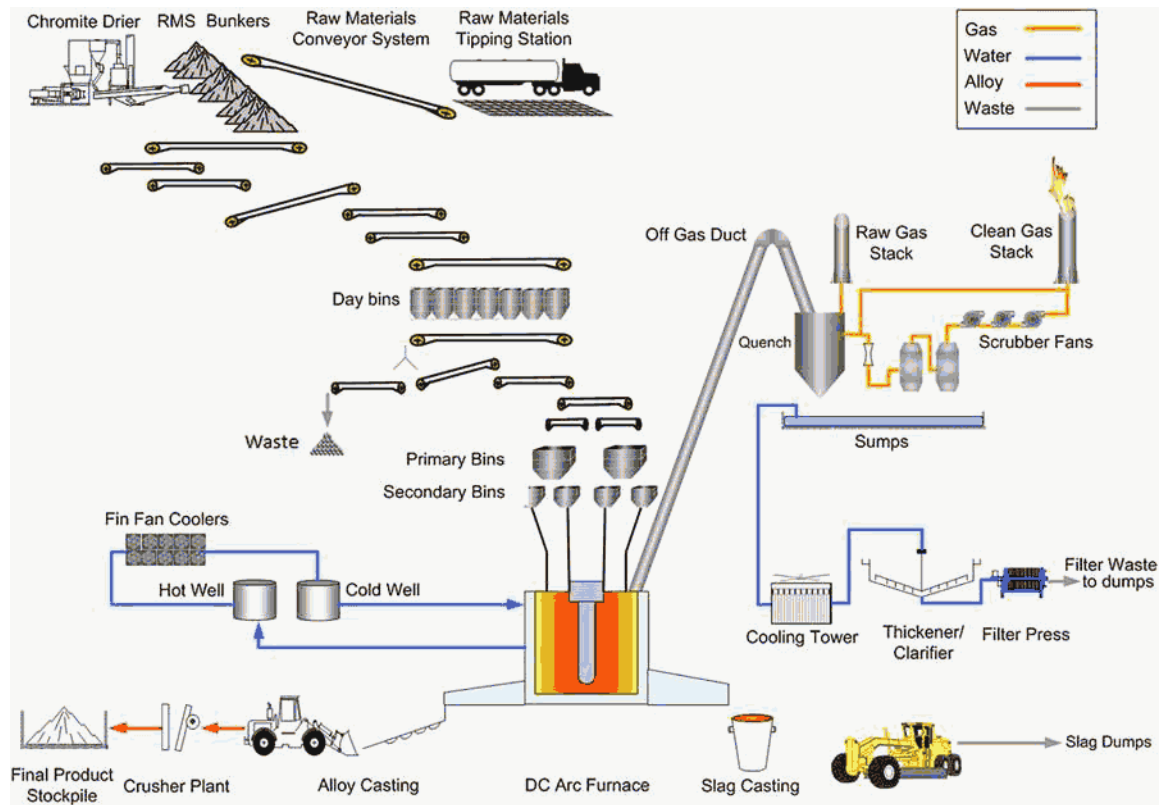


FIGURE 9.10 Process flow diagram for a DC smelting plant. (Source: Samancor Chrome.)

lower smelting zone, followed by the introduction of solid fuel and hot oxygen-enriched gas. The process was tested at pilot scale level and produced promising results (Contrucci et al., 1994). The SKF-developed Plasmachrome utilized nontransferred arc gas torches to supply superheated gas to a coke-filled shaft kiln, together with fine chromite and fluxes (Srinivasan et al., 1987). This process was commercialized and is briefly discussed in Section 9.2.5.

There are presently very few (if any) high carbon ferrochrome plants that do not utilize one of the four main technology routes described in the preceding sections or variations thereof.

9.3 POST TAP HOLE PRACTICES AND PRODUCT TYPES

9.3.1 Alloy and Slag Tapping

As limited superheating of either alloy or slag takes place inside a choke-fed submerged arc furnace, the selection of slag composition (and therefore liquidus temperature) is important for the slag to tap at a temperature that allows marginal superheating of the alloy. As mentioned earlier, the entrenchment of raw materials (especially fines) into the molten slag can also impact on the viscosity of the slag and the effective separation of molten alloy and slag in the furnace. This would impact on the tapping process.

The opening of the tap holes can take place manually, by using an oxygen lance, or mechanically, by using a tap hole drilling machine. The latter method contributes to the reduction of damage to the tap hole and surrounding refractories, whereas oxygen lancing can cause physical and oxidation damage. Tapping of a high carbon ferrochrome furnace takes place either through a single tap hole, where both alloy and slag are tapped simultaneously or via separate slag and alloy tap holes. In the case of tapping via separate tap holes, the furnace has to be sufficiently large to allow slag/metal separation to take place inside the furnace and to create a height differential for separate tapping. When separate tap holes are used, the alloy tap hole is normally closed when the first slag becomes visible. Under normal conditions the alloy level does not reach the height of the slag tap hole. Therefore, slag and alloy from this configuration are typically clean and minimal separation steps outside the furnace are required.

Tap holes are either closed manually, by ramming a clay or carbon-based plug into the tap hole, or mechanically, by using a mud gun to force a clay or carbon-based plug under high pressure into the tap hole. The process of mechanically opening and closing tap holes with high-quality tap hole material ensures that the tap hole is continuously refurbished and kept in good condition.

When a common tap hole is used for both slag and alloy tapping, a post-tap hole cleaning step is required to obtain slag-free alloy and also alloy-free slag. The most common practice is to tap into cascading ladles, which results in the alloy collecting in the first ladle and the slag overflowing into a slag ladle or into a slag pit. Alloy ladles are typically steel ladles with a refractory lining,



FIGURE 9.11 View of furnace tapping. (Source: Xstrata.)

whereas slag ladles are typically cast steel ladles without refractory linings. The layer of slag in the alloy ladle is separated from the alloy by a decanting and slag skimming operation. The alternative tapping arrangement is to tap the alloy directly into ingots or molds, in which case slag/metal separation can take place by utilizing a liquid skimming process situated between the tap hole and the molds, enabling the slag and alloy streams to be separated and handled separately. Slag and alloy can also be tapped directly into molds without skimming, but this technique results in slag-containing alloy ingots that have to be cleaned mechanically afterward. When alloy is tapped into ladles, this provides the opportunity for the alloy to be granulated (Fig. 9.11).

Where high carbon ferrochrome production facilities are adjacent to stainless steel plants, the option to transfer the alloy in liquid form to the end user is also available. The alloy is tapped in suitably designed ladles and, after taking measures to minimize heat loss from the ladles, the alloy is transported in liquid form to the stainless steel plant where it is fed directly into a converter, or other suitable vessel, and processing thereof commences immediately. Utilization of liquid high carbon ferrochrome provides substantial benefits in terms of energy savings, reduction of post-tap hole alloy losses, improved space utilization, and logistical simplification. Examples of liquid transfer being applied are at Outokumpu's Tornio works in Finland and between Samancor Chrome's Middelburg works and Columbus Stainless plant in South Africa.

9.3.2 Product Types

The most common product type for high carbon ferrochrome is a sized, lumpy product. This product type typically originates from the crushing and screening

of cast ingots into different size fractions. This product type can be offered to customers either in bags or in bulk.

An alternative product type is a granulated product. Granulation of high carbon ferrochrome generally takes place by pouring liquid high carbon ferrochrome into water. Solidification takes place immediately, and the resultant product comprises typically green-tinged, irregular particles. The benefits of this product route are the relatively low cost of granulation, reduced fines generation, and the speed of the operation. The relatively low popularity of this product type can be attributed to its lower bulk density, higher porosity, and the client's perception of the product being oxidized, based on the greenish surface color. The two most common granulation technologies used for high carbon ferrochrome granulation are Showa Denko (SDK) granulation and Granshot granulation.

The SDK technology was introduced by Showa Denko in Japan and comprises the controlled pouring of liquid high carbon ferrochrome into a strongly flowing stream of water. The energy of the water stream solidifies and breaks the high carbon ferrochrome into small particles, followed by further cooling and dewatering of the particles, resulting in granules. The size distribution of the particles can be controlled by regulating the casting rate, the water jet characteristics, and the profile of the pouring launder. CMI (now Xstrata) improved and modified this technology.

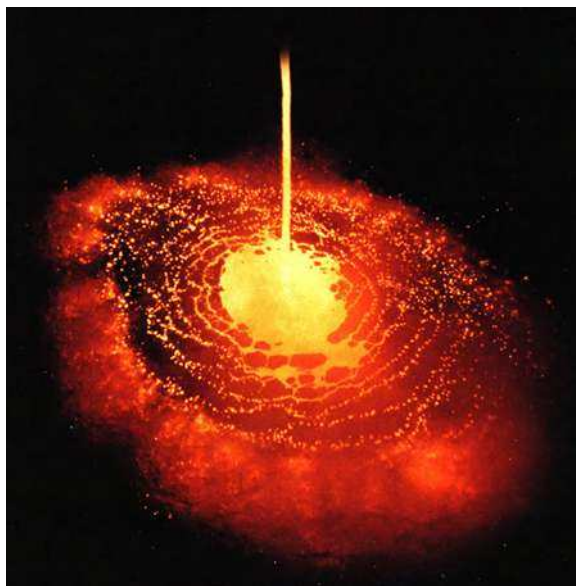


FIGURE 9.12 View of Granshot granulation process. (Source: *Uvân Hagfors Teknologi [UHT]*.)

The Granshot granulation technology is owned by Uvån Hagfors Teknologi (UHT) (originally Uddeholm) and comprises the pouring of liquid high carbon ferrochrome through a nozzle in a tundish onto a refractory splash plate and the partly solidified droplets then drop into a cooling water tank (Fig. 9.12), from where they are pumped across a dewatering screen. Again, the size distribution of the particles depends on the size of the tundish hole and therefore the flow rate. Product from this process is generally more round and solid than product resulting from the SDK process.

9.3.3 Slag Handling and Utilization

The most common handling method for slag is to tap the slag directly into a slag pit filled with water. The slag solidifies, cools down, and is removed from the pit to a dump or stockpile area. Another method is to granulate the slag by allowing the slag to flow through a set of water jets. In the first method the slag solidifies in large lumps and requires crushing if further processing is required. In the second method the slag solidifies into small, stringy particles, which can readily be pumped and dewatered.

Depending on the slag and alloy properties, as well as the selected tapping configuration, the final slag still contains alloy particles entrapped in the slag. The alloy content in the slag is substantial and comprises typically 1% to 4% of the total alloy tapped. It is therefore normally viable to attempt recovery of this alloy from the slag. The most common recovery process is to crush the slag (in the case of the first slag-handling method) and recover the alloy particles in a wet jigging process. In particular cases where the high carbon ferrochrome is sufficiently magnetic, magnetic separation techniques can also be applied. The quality of the product from the recovery process depends on the process settings, as a balance has to be found between alloy recovery and alloy product quality.

High carbon ferrochrome slag generally has favorable properties that could be utilized in various economically beneficial applications. It must, however, be emphasized that the permissibility of these applications may be differently regulated in different countries, which may impact on the permissibility of certain applications. In European conditions high carbon ferrochrome slag is certified to be chemically stable and compliant with regulations SFS 5904 and EN 13285. According to Outotec, successful applications for high carbon ferrochrome slag include the following:

1. Heat recovery
2. Road construction, both for the support layers (granulated slag) and the tarmac (crushed slag)
3. Refractory applications
4. Sandblasting
5. Mineral wool production.

9.4 ENVIRONMENTAL CONTROL AND OCCUPATIONAL HEALTH

9.4.1 Environmental Impact of High Carbon Ferrochrome Production

In terms of high carbon ferrochrome production, the main environmental focus is to reduce emissions of dust from stacks and tapping processes to prevent contamination of groundwater with hazardous components and to reduce/limit the release of carbon dioxide emissions to the atmosphere.

In terms of carbon dioxide emissions to the atmosphere, a number of sections in this chapter have shown that various technology-related options are available to reduce unit electrical energy consumption, and thereby unit carbon dioxide generation. This is commonly referred to as the carbon footprint of the operation. These options include the following:

1. Selection of more energy-efficient production routes (e.g., large, closed furnaces).
2. Utilization of CO process off-gas for preheating of the furnace feed, ore sintering (both of which improve the overall energy efficiency), and other heating applications, as well as electricity cogeneration. The latter particularly applies to countries where primary electricity is generated from fossil fuels.

In the following sections, various systems are described for the cleaning of furnace off-gas.

9.4.1.1 Gas Cleaning Systems

The gas cleaning systems may comprise different processes and methods depending on the specific plant requirements. The most common technologies utilized are venturi-type scrubbers, disintegrators, bag filters, and electrostatic precipitators.

Venturi-Type Scrubbers

A venturi scrubber is designed to effectively use the energy from the inlet gas stream to atomize the liquid being used to scrub the gas stream. This type of technology is a part of the group of air pollution controls collectively referred to as wet scrubbers. Venturi scrubbers are the most common gas cleaning systems on closed furnaces due to gas volumes being low in their noncombusted state. However, as emission requirements become more stringent, venturi scrubbers reach their efficiency limits and need to be improved technically to remain viable.

A venturi scrubber consists of three sections (Fig. 9.13): a converging section, a throat section, and a diverging section. The inlet gas stream enters the converging section and, as the area decreases, gas velocity increases in accordance with the Bernoulli equation. Water is introduced either at the throat or at the entrance to the converging section. The inlet gas, forced to move at

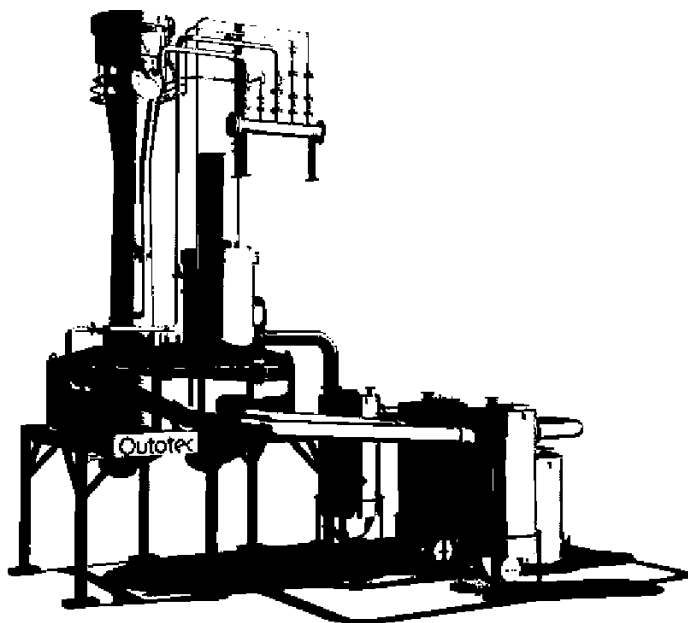


FIGURE 9.13 Schematic diagram of a venturi scrubber. (Source: Outotec.)

extremely high velocities in the small throat section, shears the liquid from its walls, producing a large number of very tiny droplets.

Particle and gas removal occur in the throat section as the inlet gas stream mixes with the fog of tiny liquid droplets. The inlet stream then exits through the diverging section, where it is forced to slow down. Venturis can be used to collect both particulate and gaseous pollutants, but they are more effective in removing particles.

Equipped with a water seal, the venturi scrubber is especially designed for handling explosive gases in the safest possible manner. This applies directly to closed submerged arc furnaces that produce CO gas. The efficient and secure operating principle is to both cool and clean the gas and to quench sparks from the furnace. The venturi scrubber is simple to operate, as it has no moving mechanical parts. Venturi-type scrubbers are primarily used on closed furnaces where the off-gas volume is low, which makes the venturi scrubber installation relatively small. The cleaning efficiency of venturi scrubbers typically complies with environmental requirements that stipulate that the outlet gas should contain less than 50 mg/Nm³ particulate content.

Disintegrators

As an alternative to venturi scrubbers, a disintegrator gas washing system (as patented and supplied by Theisen) has been installed on a number of ferroalloy

plants, including some high carbon ferrochrome furnaces. The Theisen disintegrator (Theisen, 2009) is a self-conductive wet separator with a particularly high efficiency separating rate, for solid particles and harmful gaseous pollutants. The volumetric performance ranges from 10 Nm³/h up to 150 000 Nm³/h, which is indicative of the flexibility of this high-performance wet separating machine.

The dirty furnace gas enters through two inlets, axially into the disintegrator housing, where a set of rotor and stators are arranged (Fig. 9.14). Spraying cylinders and the carrier disc are mounted on to the rotor shaft, which is supported by external bearings. Also attached to the carrier disc are the rotating impingement-bar cages. These incorporate the central stators, likewise fitted with impingement-bar cages that are rigidly bolted to the housing walls. The scrubbing fluid is conveyed through pipes to the spraying cylinder where it is atomized and then distributed over the entire rotor width. As a result of the centrifugal force of the rotor bars, the gas–fluid mixture is thrown against the stationary impingement bars of the stators, producing a fine scrubbing mist that covers all solids in the dust-laden gas. This process is repeated within each rotor and stator cage, thus achieving very high separating efficiency rates, even with the finest dust particles, by using a corresponding number of rotor and stator impingement-bar cages. Each Theisen disintegrator is always succeeded by a scrubbing fluid separator in which the scrubbing fluid droplets are separated from the cleaned gas.

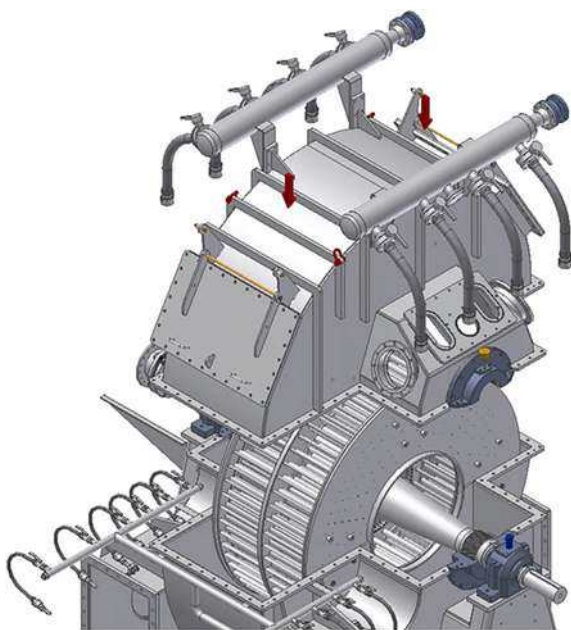


FIGURE 9.14 Schematic diagram of a disintegrator section. (Source: Theisen.)

Theisen scrubbers are generally more efficient in lowering the particulate content in furnace off-gas and levels of 10 to 20 mg/Nm³ are achieved. The installation is generally much larger than for an equivalent venturi system and therefore more expensive.

Bag Filter Plants

The use of bag filter plants is common for capturing the fume generated by open ferroalloy furnaces. Gas volumes are higher for these applications, as the CO gas is combusted on the furnace bed, resulting in increased volume. Whereas pressure-type bag filters have been the norm historically, the modern trend is toward suction-type bag filters (Actom, 2001).

Reverse air collectors are effective for various applications involving very fine dust and where low emissions are required. Bags are cleaned by reversing the airflow and blowing air back through the fabric. Of necessity the bag filter needs to be of multicompartment design in order to isolate individual compartments for reverse air cleaning. The simple cleaning design involves few moving parts, resulting in low maintenance cost, low operating costs, and extended bag life.

Figure 9.15 illustrates a pressure type baghouse. The principle is the same as for a suction type, except that the fan is on the clean air side and the casing is of sealed construction, unlike pressure baghouses where the casing is typically an corrugated iron clad structure.

The generation and collection of dry dust from bag filter plants provides different challenges and opportunities than would be the case with slurry or sludge from wet venturi scrubbers. The dust contains hazardous components, such as hexavalent chromium, which causes occupational risk conditions when in contact with humans. Efficient collection, transport, and disposal processes have to be in place to prevent dust from disseminating into the atmosphere. In most countries with appropriate environmental pollution legislation, these handling and disposal processes have to be strictly controlled.



FIGURE 9.15 Bag filter plant. (Source: Actom.)

Bag filter dust has beneficial properties (including binder-enhancing characteristics) that allow the dust to be utilized in various industrial applications. Dust can be used as a cement extender in concrete applications and can also be included as a contributory binding agent in briquetting and pelletizing processes. Generally bag filters are more efficient than venturi scrubbers in terms of reduction of particulate content in the gas stream. Levels of $< 20 \text{ mg/Nm}^3$ are achievable.

Electrostatic Precipitators

Electrostatic precipitators function by electrostatically charging the dust particles in the gas stream. The charged particles are then attracted to and deposited on plates or other collection devices. When sufficient dust has accumulated, the collectors are shaken to dislodge the dust, causing it to fall with the force of gravity to hoppers below. The dust is then removed by a conveyor system for disposal or recycling. Depending on dust characteristics and the gas volume to be treated, there are many different sizes, types, and designs of electrostatic precipitators.

Electrostatic precipitation removes particles from the exhaust gas stream of a variety of industrial processes. Often the process involves combustion, but it can be any industrial process that would otherwise emit particles to the atmosphere. Six activity steps typically take place (Neundorfer, 2011):

1. Ionization: Charging of particles.
2. Migration: Transporting the charged particles to the collecting surfaces.
3. Collection: Precipitation of the charged particles onto the collecting surfaces.
4. Charge dissipation: Neutralizing the charged particles on the collecting surfaces.
5. Particle dislodging: Removing the particles from the collecting surface to the hopper.
6. Particle removal: Conveying the particles from the hopper to a disposal point.

For high carbon ferrochrome furnaces, electrostatic precipitators are not, however, commonly used, mainly for the following reasons: (1) fineness and high resistivity of the dust from an electric arc furnace can limit the dust removal efficiency, (2) risk of explosion because of high voltage sparking if there is CO in the gas during startup, and (3) relatively high investment cost because gas volume is small compared to typical electrostatic precipitator applications.

9.4.1.2 CO Gas Reticulation and Utilization

Closed furnaces invariably produce a noncombusted off-gas with high levels of CO content. This brings challenges in terms of safety and occupational health, but also opportunities in terms of potential utilization of the energy potential of the gas.

CO gas is potentially explosive when brought into contact with air and therefore requires a carefully designed and operated reticulation system. The

objective is to operate the closed furnace under slightly positive pressure to prevent ingress of air on the furnace roof and around the electrodes. Extreme care must also be taken during shutdown and startup processes on the furnace to prevent the development of explosive conditions. CO gas is furthermore extremely dangerous to inhale and has caused many deaths over the history of the industry. This risk is further exacerbated by the fact that CO gas is both invisible and odorless. Proactive measures must always be in place to prevent human exposure, such as the effective utilization of CO monitors in enclosed and high-risk areas.

CO gas has a high calorific value of approximately 3 kWh/Nm^3 and provides heat during combustion. This property makes CO gas amenable to applications such as ladle preheating, other gas burner applications, preheating of feed materials, sintering of chromite ore, and cogeneration of electricity.

Once upgraded and refined, CO gas can also be used in a number of applications such as the production of methanol, formic acid, dimethyl ether, synthetic natural gas (methane), and Fisher Tropsch wax. Of these options, the production of formic acid and Fisher Tropsch wax probably have the most potential for commercial viability, as indicated by Outotec in November 2011.

Electricity can be generated from furnace off-gas in internal combustion engines or steam turbines, both of which are well-proven, commercially viable processes. The particulate content in furnace off-gas from venturi scrubbers, and mostly from disintegrator plants as well, is not low enough to make the feed gas suitable for cogeneration engines. A further gas-cleaning step is therefore required. Although a number of potential technologies exist for this post-cleaning step, the most common filter process applied is the CO filter supplied and developed by Outotec (Fig. 9.16). The filtering element is a sintered HDPE

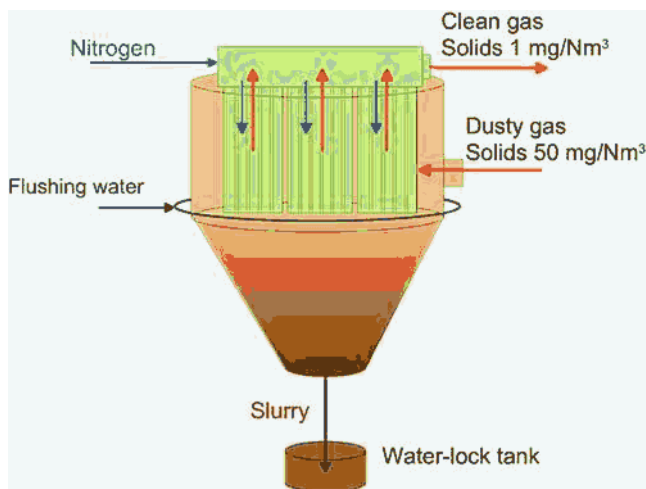


FIGURE 9.16 Schematic diagram of a CO filter. (Source: Outotec.)

material with minutely small pores. This filter reduces the particulate content in the gas to well below 5 mg/Nm³.

Electric power generation can take place via the illustrative configuration (provided by Outotec in November 2011) shown in [Figure 9.17](#). Depending on the quality of the CO gas stream, additional electricity amounting to almost 20% of the combined furnace power can be generated.

Finally, sludge from wet scrubbing systems is normally pumped to water treatment, storage, and reticulation systems. The nature of the chemical treatment of the water is determined by the accumulation of hazardous or valuable components that collect in the furnace off-gas and are washed out by water in the scrubbing systems.

9.4.2 Occupational Health Hazards

9.4.2.1 Hexavalent Chromium

Chromium is encountered mainly in the following three oxidation states: metallic (Cr⁰), trivalent (Cr³⁺), and hexavalent (Cr⁶⁺). Hexavalent chromium, Cr⁶⁺, is formed in small quantities as a by-product during high carbon ferrochrome production. Certain Cr⁶⁺ species are regarded as carcinogenic, with specifically airborne exposure to these Cr⁶⁺ species being associated with cancer of the respiratory system ([Beukes et al., 2012](#)). Cr⁶⁺ formation in properly closed furnaces is very low, in some cases almost undetectable, whereas the prevalence is an order of magnitude higher in open, oxidizing furnaces.

As indicated by [Beukes et al. \(2012\)](#), Cr⁶⁺ can be generated during various ferrochrome production processes. With regard to Cr⁶⁺ content, fine particulate matter originating from the off-gas of high temperature processes can be regarded as the most significant Cr⁶⁺-containing waste material generated by the high carbon ferrochrome industry. Exposure to airborne Cr⁶⁺ by inhalation is also much more hazardous than other exposure routes, which further emphasizes the importance of these fine, potentially airborne materials. Studies have consistently shown that elevated chromium levels persist in the lungs for many years after the cessation of exposure. Cr⁶⁺ is able to penetrate the membrane of red blood cells, where it is reduced ([Huvinen, 2002](#)).

Measures to prevent or minimize the exposure of employees to risks associated with Cr⁶⁺ would therefore focus on design aspects to contain bag filter dust in closed collection and transport systems and to equip employees with appropriate protective equipment to prevent inhalation and exposure of the skin.

[Ma and Garbers-Craig \(2006\)](#) have reported on the formation, treatment, and stabilization of certain South African hexavalent chromium containing metallurgical wastes and pointed out that there are a number of different methods to deal with these wastes:

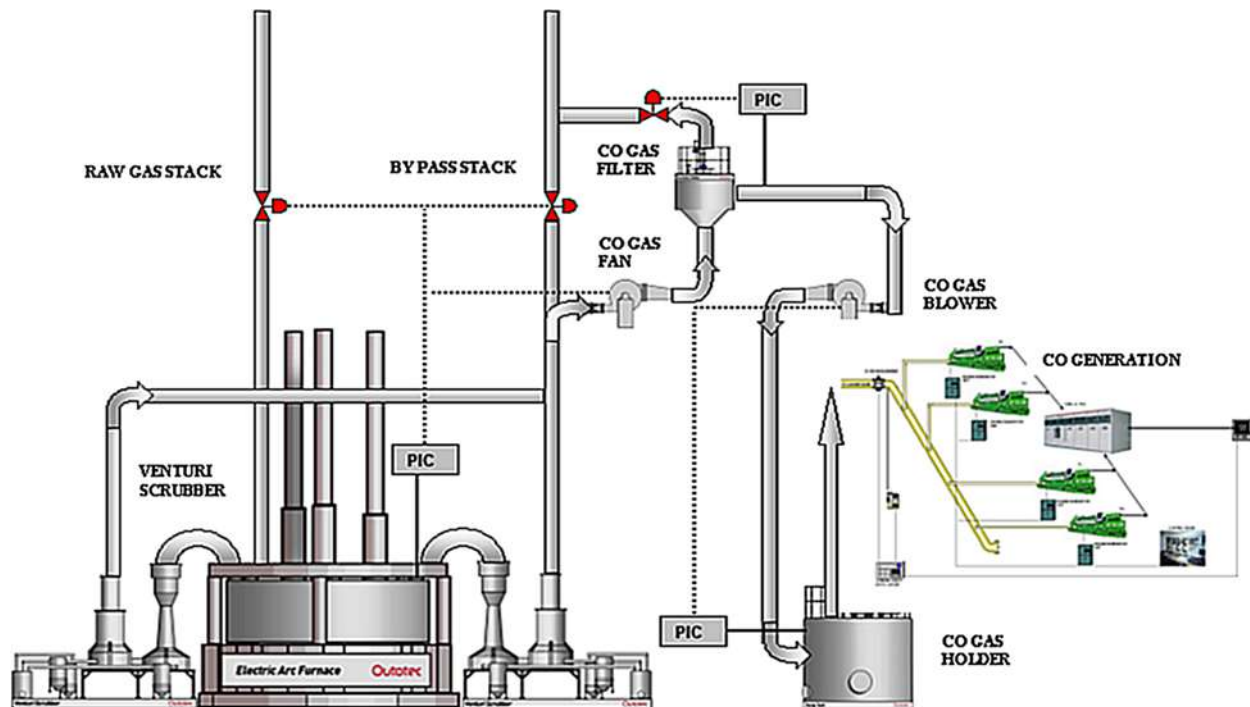


FIGURE 9.17 Schematic diagram of a cogeneration plant. (Source: Outotec.)

1. Minimization of the wastes at the source by optimizing the operational parameters
2. Direct recycling of certain materials to the furnace
3. Recovery processes, which include hydrometallurgical and pyrometallurgical methods
4. Solidification/stabilization methods—for instance, cementation and vitrification (formation of glassy state) processes
5. Use as a raw material in an appropriate product, such as fertilizer
6. Treatment and land filling.

Although these findings relate to South African plants, the trends are similar in all high carbon ferrochrome plants.

According to [Ma and Garbers-Craig \(2006\)](#), most of the above-mentioned treatment options are used at least to some degree within the South African high carbon ferrochrome industry on possible Cr^{6+} containing wastes. Minimization of the wastes at the source by optimized operational parameters is a prime objective of all SA high carbon ferrochrome producers, as minimized waste implies higher profitability. Direct recycling is also applied. However, direct recycling of furnace off-gas wastes (e.g., bag filter dust and scrubber sludge) to a high carbon ferrochrome smelting furnace could lead to the buildup of more volatile species, such as sodium and zinc, resulting in lower production capacity and even possibly the risk of explosions.

By far the most common process for dealing with possible Cr^{6+} containing waste in the SA high carbon ferrochrome industry is aqueous chemical Cr^{6+} reduction with suitable reducing agents (e.g., ferrous sulfate), with subsequent precipitation of the Cr^{3+} hydroxides and land filling in specially designed waste facilities.

In general, it can be stated that wet venturi scrubbers should be regarded as a better control mechanism for removing Cr^{6+} -containing particulate matter from off-gas than bag filter systems ([Actom, 2011](#)). This belief stems from the fact that wet scrubbers immediately contact the particulate matter possibly containing Cr^{6+} with water during the capturing mechanism. This is in contrast to bag filter systems, which capture the particulates as dry matter. As mentioned previously, airborne Cr^{6+} is more hazardous than aqueous Cr^{6+} .

9.4.2.2 Dust and Fumes

Besides the risk of Cr^{6+} -containing dust explained previously, dust generation is a more general problem in high carbon ferrochrome production. Several processes contribute to dust generation, of which the following are the most prolific:

1. Raw material handling, including off-loading, crushing and screening, transportation, feeding to furnace bunkers
2. Leakages from furnace roof area, charging chutes

3. Furnace rabbling
4. Furnace tapping and casting
5. Final product (slag and alloy) removal
6. Wind-blown dust from stockpiles and roads.

Systems therefore have to be in place to limit dust generation (e.g., dust suppression systems) and to protect employees against dust exposure (e.g., dust masks, safety glasses). These measures are required to prevent unhealthy respiratory conditions and to improve working conditions for equipment and workers.

The most common processes producing hazardous fumes are paste loading and tapping. Both these processes have the potential to generate coal tar pitch volatiles (CTPVs), from the electrode paste and mud gun plugging mixture, respectively. Employees working in these areas should be equipped with appropriate protective masks to prevent inhalation of toxic fumes present in the CTPVs.

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