THE AlloyStream^{TM} PROCESS FOR HCFeMn PRODUCTION

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ABSTRACT

The AlloyStream^{TM} process is a new technology that can be applied to convert manganese ore fines and coal fines into high-carbon ferromanganese. The process was developed from bench scale experiments into pilot plant trails, and then to the current demonstration furnace. In 2012 and 2014 two campaigns were completed on the demonstration furnace, the latter running for a period of 11 months. The fully enclosed demonstration furnace has a diameter of 5.3 m and is rated at producing 8000 tons per year.

The furnace is powered by a dual energy source consisting of a coreless inductor and an oxygen enriched combustion zone. The inductor supplies electrical energy to the process via the liquid metal bath. A material mixture of ore, coal and fluxes is fed onto the bath through the furnace roof. The enclosed space above the heaps forms a combustion zone into which enriched air and natural gas are introduced via lances and burners. The oxygen enriched blast air burns the natural gas, coal volatiles and reaction gases emanating from the heaps to generate radiation heat, which drives the reactions in the material heaps. Consequently the bulk of the process energy requirement is provided from the combustion zone.

The AlloyStream^{TM} process configuration allows for process flexibility in terms of feed material type and quality. The process operates utilizing 10mm materials size fraction, and metal fines can be added as part of the main feed. Ore quality variations are better tolerated than in submerged arc furnaces because energy input is not directly influenced by slag chemistry, the reductant feed stream can be coal only, and feed ore type restrictions due to gas evolution can be negated. The paper describes the results from the recent demonstration furnace campaign, as well as process development experiences to date.

INTRODUCTION

The submerged arc furnace (SAF) is most widely used for the industrial production of high-carbon ferromanganese (HCFeMn). SAFs require feed in the form of lumpyore, sinter and reductant feed materials to ensure sufficient gas permeability for even gas distribution through the burden [1].The close packing of fines fed to a SAF increases the risks of calcined bridge formation and gas eruptions, which ultimately decreases the furnace efficiency and productivity [1]. Electrical energy is supplied to SAFs with electrodes submerged in the burden, with the energy input and electrode penetration a function of the burden conductivity and slag chemistry, managed through the feed mixture [2]. SAFs have to be fully closed at the top to allow for the production of CO-rich off-gas that can be used for energy generation. In fully closed SAFs the air ingress rates are limited and specific electrical energy consumption decreases with increasing off-gas CO_2 percentages, as opposed to open SAFs where the off-gas combusts with ingress air without benefit to the furnace efficiency [2].

The AlloyStream^{TM} process was developed as a single step production unit of steel and ferroalloys, which includes HCFeMn, from ore fines and thermal coal as described in U.S. patent 6146437 [3]. The furnace raw material feed mixture consists of a blend of fine ores, carbonaceous reductants and fluxes. The process schematic is depicted in Figure 2. In the AlloyStream^{TM} process the raw material blend is fed onto a liquid metal bath, forming heaps of reacted material. The heap material surface is heated from above by heat radiated from the burning of combustibles with enriched air. The combustibles consist of natural gas, coal volatiles, coal carbon and gaseous reaction products emanating from the heaps. Final reaction and smelting of the reduced heap material is achieved by energy transferred from the induction-heated metal bath. The material mixture is reacted at temperatures in excess of 1400°C. The process operates in a narrower temperature range as compared to a SAF where temperatures are expected to range from room temperature to more than 1600°C below the electrode tips.

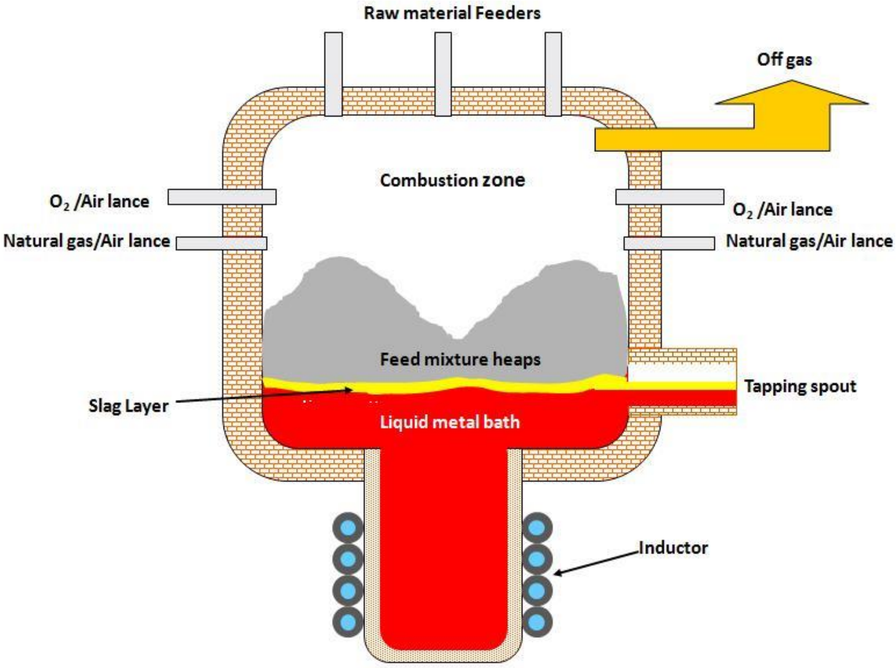

Figure 2: AlloyStream^{TM} process schematic

The furnace is lined with a basic material lining consisting of brick, castable and rammable refractory materials, which were developed with key suppliers over 15 years. The slag line is equipped with copper coolers, and consequently slag chemistry management is done to protect the slag line MgO refractory. In the demonstration unit alloy and slag was tapped from the same tap hole by tilting the furnace. Metal bath temperatures are in the order of 1550°C and combustion zone temperatures are 1600°C.

In addition to the furnace, the plant system includes the raw material weighing and mixing plant, dry off-gas system, water cooling plant, and product handling equipment. The selection of equipment for the furnace was driven by space restrictions. In the operation of the plant high standards for safety, health, environment, and quality are maintained. AlloyStream^{TM} was awarded with OHSAS 18001:2007, ISO 9001:2008, and ISO 14001:2004 certification, the latter for which the highest score among companies from 27 countries was received during the 2009 audit[4].

In development of the AlloyStream^{TM} process, several campaigns were completed on pilot plant and demonstration plant scales.Process principals determined from initial bench scale tests were confirmed in pilot plant campaigns in a 2.5 m diameter pilot plant furnace. Four ferromanganese campaigns, as well as a ferronickel and steel campaign were completed in the pilot plant during the period of 2003 to 2009. To test scale-up of the process a 5.3 m diameter demonstration furnace was constructed (Figure 3) and used to complete two HCFeMn campaigns during the period of 2012 to 2014, operated on a semi-commercial basis. Results from the more recently completed campaign are discussed further.

Figure 3: AlloyStream^{TM} demonstration furnace

CAMPAIGN OVERVIEW

Hot commissioning of the recent HCFeMn campaign on the 5.3 m diameter demonstration furnace commenced on 15 July 2013, and feeding of raw material for production started on 4 August 2013. During this campaign 5014 tons of HCFeMn was tapped from the demonstration furnace. During the campaign spanning 11 months, the furnace was used to test variances in the types and ratios of ores and reductants, as well as in other operational parameters, of which some are discussed below. Raw materials fed to the furnace consisted of a blend of mostly two South African ores, one classified as a carbonate type ore (containing mostly $MnCO_3$), and the other as a semi-oxidized type ore (containing mostly Mn_2O_3)[5]. The reductants tested included thermal coals, semi-coke (char), and coke breeze, with the primary reductant used being supplied by mines from Exxaro Resources (Leeuwpan, and Grootegeluk).

Specific periods were selected for discussion of the process performance during which the most important input parameters remained constant. The results obtained in the campaign are presented for these specific periods, and as trends of the following parameters over time to illustrate the extent of the campaign run. The tapped metal analyses are shown in Figure 4, the tapped slag analyses are shown in Figure 5, and the hourly production rate and metal bath temperature is shown in Figure 6. The furnace was in idle mode for extended planned maintenance for April and May 2014, thus data for this period is not shown.

These result trends should be evaluated considering the major changes in the feed mixture. From the middle of October 2013 to early January 2014 a feed mixture was tested containing 43% of a South African carbonate type ore, and the balance of semi-oxidized type ore. Prior to, and after this period higher percentages of the carbonate ore were fed that typically ranged between 70 and 80%. Up to the end of February 2014 mostly Leeuwpan coal was utilized as the primary reductant, after which it was replaced with Grootegeluk coal, and from the middle of April a 67:33 blend of Leeuwpan and Grootegeluk was fed. From the middle of February 2014 HCFeMn metal fines were fed mixed with raw material feed.

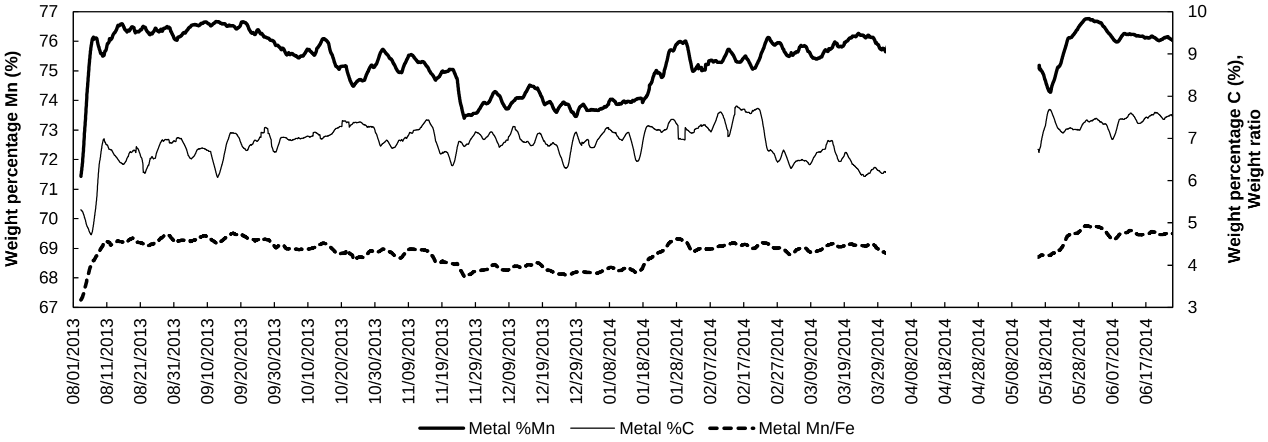

Figure 4: Tapped metal analyses

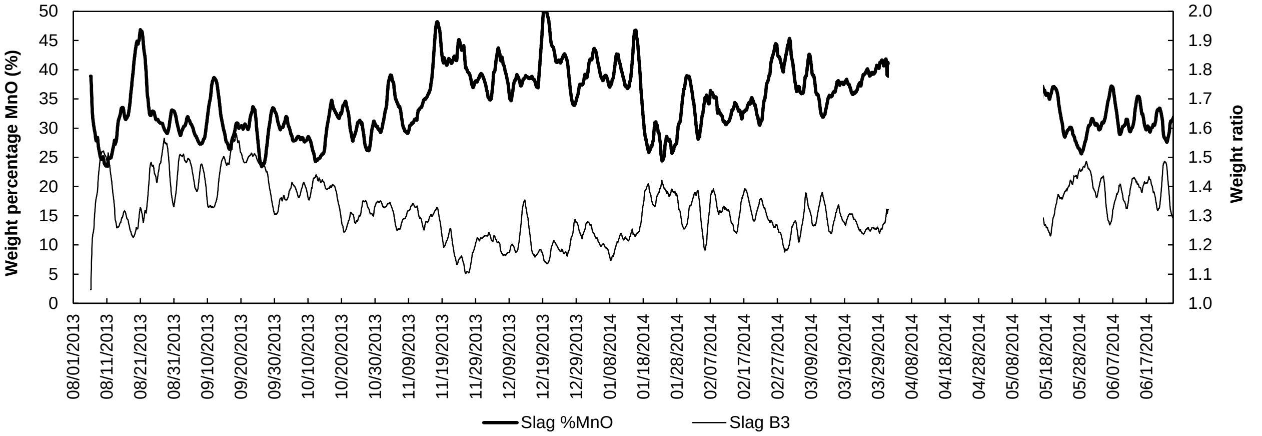

Figure 5: Tapped slag analyses: %MnO and Basicity

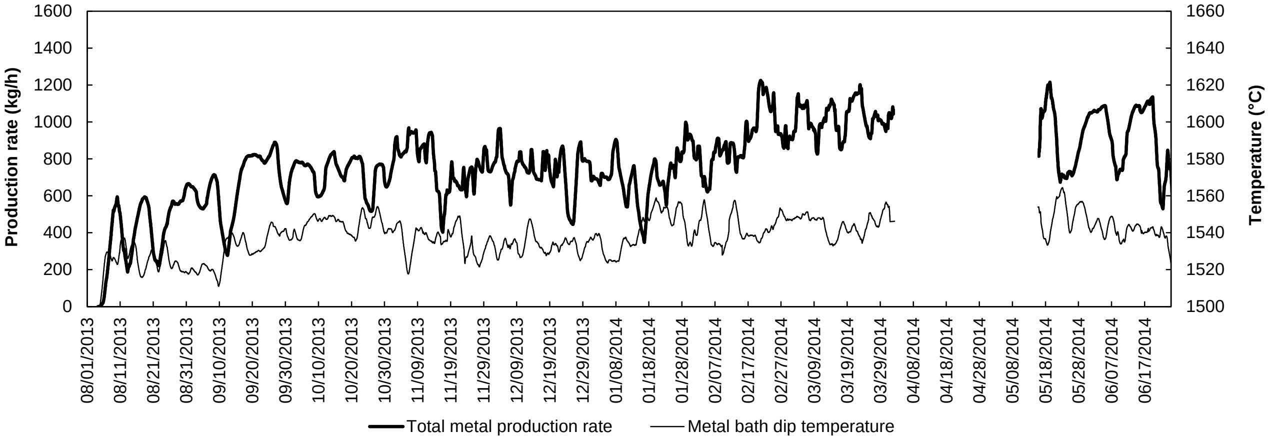

Figure 6: Hourly feed rate and alloy production rate

PROCESS PERFORMANCE

Process Control Tools

During the development of the technology a vast volume of time-dependent data is generated and captured from which the process performance is derived, and analysed to gain understanding of the deviations caused by equipment failures, human interventions, and process changes. A set of process tools has been developed to assist with analysis and control of the AlloyStream^{TM} process. These tools are based on the current process understanding and include:

- discrete and continuous databases, with automated data capturing and reporting functionalities,
- slag evaluation software utilizing thermochemical calculations for the illustration of slag analyses on ternary phase diagrams and the online estimation of slag phase compositions, effective viscosity, and level of satura-

tion in refractory constituents to indicate slag chemistry trends over time and allow for timeous invention to adjust feed composition and chemistry, and

- a detailed mass and energy balance configured for steady state calculations, as well as for being calculated on a continuous basis for accounting and reporting purposes using process measurement data as input.

Raw Materials

Analyses and coefficients of variance of the ore utilized are shown in Table 1, and analyses of the reductants are shown in Table 2. For both ores and reductants, the analyses presented are of 24h composite samples taken at the weigh off points in the raw materials handling plant. The objective was to exclude any fluxes from the feed, however, ore characteristics occasionally demanded the addition of dolomite or limestone.

Results in Table 1 indicate the semi-oxidized type ore to have been more variable in composition as compared to the carbonate type ore. Also to note is the higher volatile content of Grootegeluk coal as compared to Leeuwpan coal, as indicated in Table 2.

Table 1: Ore analyses

		Semi-oxidized type ore		Carbonate type ore	
Specie	**Units**	**Percentage**	**Coefficient of variance**	**Percentage**	**Coefficient of variance**
SiO_2	[wt. %]	7.26	11.1	5.89	6.1
Al_2O_3	[wt. %]	0.29	13.4	0.21	14.5
CaO	[wt. %]	4.70	16.0	12.48	5.8
MgO	[wt. %]	0.74	23.2	3.77	8.8
FeO	[wt. %]	12.14	8.5	6.99	9.3
MnO	[wt. %]	63.67	2.4	49.12	2.9
BaO	[wt. %]	0.37	41.9	0.098	45.4
C	[wt. %]	0.66	38.6	4.33	8.3
LOI	[wt. %]	3.77	29.2	15.54	5.7
Mn/Fe		5.26	9.5	7.05	8.5
$B3 = CaO+MgO/SiO_2$		0.76	31.2	2.77	6.7

Table 2: Reductant analyses

		Reductant			
Specie	**Units**	**Leeuwpan coal**	**Grootegeluk coal**	**Grootegeluk semi-coke**	**Coke breeze**
Moisture	[wt. %]	4.66	3.54	16.30	8.70
C	[wt. %]	66.80	72.84	72.41	79.24
H	[wt. %]	2.91	4.68	0.002	0.029
O	[wt. %]	9.26	9.45	3.67	1.32
N	[wt. %]	1.64	1.52	1.19	0.90
S	[wt. %]	0.57	1.03	0.97	0.93
Ash	[wt. %]	17.90	10.36	22.08	17.57
Volatiles	[wt. %]	22.34	36.61	6.24	2.04

Performance Periods

Performance periods are discussed to illustrate process performance for different feed materials and feed mixture recipes. Table 3 shows the feed material recipes for each performance period. To be noted is that in periods 3 to 5HCFeMn metal fines were added to the material feed. The metal fines are generated when primary HCFeMn product is crushed and sized in preparation for sale.

Ore proportions of the two ores varied between 43 and 80% of the carbonate-type ore in order to test process effects whilst still attaining 75% manganese in the alloy at the typical manganese recovery levels, as well as slag line magnesia refractory protection. The AlloyStream^{TM} process design circumvents the dangers related to bed permeability and gas evolution in SAFs operating with high percentages of carbonate ores in the feed mixture. SAF operators usually limit carbonate ore quantities in order to reduce the risk of gas excursions. The AlloyStream^{TM} process can safely operate even at 80% carbonate ore feed, but with productivity negatively affected due to the lower total metallic contents in typical carbonate ores and the higher process energy requirement for calcination of the carbonates.

In the AlloyStream^{TM} process energy input is also not directly dependent on bed conductivity or slag chemistry, as is the case with SAFs [2]. Feed mixture selection is therefore not constrained in terms of the quantity of basic ore or carbon, which is necessary in SAFs to enable electrical energy input via the electrodes through highly resistive slag [6].

Table 3: Feed mixture changes

Material	Units	Period				
		1	2	3	4	5
Carbonate type ore	[kg/100 kg ore]	43.8	58.8	68.7	69.0	80.4
Semi-oxidized type ore	[kg/100 kg ore]	56.2	41.2	31.3	31.0	19.6
HCFeMn metal fines	[kg/100 kg ore]			13.3	15.3	14.8
Leeuwpan coal	[kg/100 kg ore]	51.8	53.0		45.9	43.1
Grootegeluk coal	[kg/100 kg ore]			52.8		21.6
Coke breeze	[kg/100 kg ore]	0.1		1.9		
Grootegeluk semi-coke	[kg/100 kg ore]			5.1	12.8	
Limestone	[kg/100 kg ore]		0.9			
Dolomite	[kg/100 kg ore]	6.7	0.8			

In Table 4 and Table 5 the tapped metal and slag accountabilities are shown for the selected performance periods. The metal mass tapped is the actual metal mass weighed off at the product handling plant after manual separation of slag and metal. The produced metal mass is calculated from the mass balance based on actual feed mixture masses, actual chemical analyses of the feed and product streams, and percentages of feed lost to dust. From a mass balance over the campaign it was estimated that 1.2% of the carbonate type ore, and 0.5% of the semi-oxidized type ore fed were lost to the off-gas as dust.

Table 4: Metal accounting results

Parameter	Units	Period				
		1	2	3	4	5
Metal produced	[ton]	292	278	238	236	184
Metal tapped	[ton]	262	245	204	216	182
Unaccounted produced	[ton]	29.4	33.2	34.1	19.6	1.9
Unaccounted produced	[%]	10.1%	11.9%	14.3%	8.3%	1.0%

Table 5: Slag accounting results

Parameter	Units	Period				
		1	2	3	4	5
Slag produced	[ton]	286	300	205	204	158
Slag tapped	[ton]	320	338	232	222	168
Unaccounted produced	[ton]	-34.3	-38.2	-26.5	-17.9	-9.7
Unaccounted produced	[%]	-12.0%	-12.7%	-12.9%	-8.8%	-6.1%

From the performance results in Table 6, several process aspects can be deduced. Although the carbonate-type ore requires more energy per ton of alloy produced than the semi-oxidized type ore, better manganese recovery rates were achieved when the carbonate type ore proportion has been increased (periods 2 to 5). This effect relates to the differences in ore chemistry of the individual ores and how the ore phase chemistry develops upon metallization [7].

The viability of feeding HCFeMn metal fines with the material mixture into the furnace was proven. From the results it is clear that high recovery rates of the metal fines resulted in an additive effect on alloy production rate with the overall manganese recovery levels remaining of the same order compared to performance periods without metal fines feed.

Reactions in the combustion zone are more sensitive to the reductant type than the reactions in the heaps, influenced largely by the quantity of reductant volatiles available for combustion. When feeding Grootegeluk coal with a high volatile content as the main reductant it was observed that the natural gas addition to the combustion zone could be reduced, in some instances to zero, since the coal volatiles substituted for the natural gas in the combustion process. This effect is seen from Table 6 by comparing natural gas feed for period 3 to that of period 4.

The rates of oxygen and natural gas required are functions of the furnace freeboard area heat losses, and were controlled to maintain target freeboard temperatures and fully combusted off-gas. The off-gas from the furnace typically contained less than 1% of CO and H_2, with no negative effect on the process observed even when operating with excess oxygen in the off-gas. A furnace larger in size is expected to have lower specific heat loss rates to enable operation without natural gas addition.

Table 6: Performance period results

		Periods				
		1	**2**	**3**	**4**	**5**
Parameter	**Units**	Low carbonate ore feed ratio (no metal fines) - 14 days	High carbonate ore feed ratio (no metal fines) - 14 days	Grootegeluk, coke breeze/semi-coke, metal fines - 10 days	Leeuwpan, semi-coke, metal fines - 10 days	Leeuwpan/ Grootegeluk blend, metal fines - 7 days
Average availability	[%]	98.24	96.50	79.83	93.96	97.52
Metal product:						
Mn	[%]	75.3	75.4	75.8	75.6	76.1
C	[%]	7.1	7.2	6.5	6.7	7.5
S	[%]	0.005	0.007	0.004	0.007	0.003
P	[%]	0.051	0.067	0.091	N.A.	0.058
Si	[%]	0.036	0.066	0.068	0.043	0.029
Slag MnO	[%]	33.8	34.4	40.5	37.2	32.0
Slag basicity B3[1]		1.30	1.32	1.25	1.31	1.40
Metal productivity[2] (during on-time)	[kg/h]	959	933	1138	1105	1104
Mn recovery	[%]	74.9	72.4	73.5	75.7	77.9
Metal entrainment in tapped slag	[%]	2.6	1.9	4.7	3.5	3.4
Electricity consumption[3]	[kWh/t alloy]	2295	2837	2187	2393	2455
Total process energy requirement	[kWh/t alloy]	3512	3864	3144	3033	3237
Electrical process energy consumption	[kWh/t alloy]	1196	1403	1151	1245	1409
%Process energy from electricity	[%]	34	36	37	41	44
Reductant consumption	[t/t alloy]	1.18	1.32	1.21	1.15	1.28
Raw material rate	[kg/h]	3466	3602	4018	3760	3919
Air rate	[Nm^3/h]	2136	2197	2172	2174	1863
Oxygen rate	[Nm^3/h]	1144	1303	1266	1310	1399
Fuel rate	[Nm^3/h]	268	378	62	286	199

1: B3=(mass% CaO+mass%MgO)/(mass%SiO_2); 2: Metal produced as calculated in the mass balance; 3: Inductor electrical energy input divided by metal produced as calculated in the mass balance.

CONCLUSIONS

- The AlloyStream™ process enables HCFeMn production from ore fines and thermal coal raw materials.
- Fully combusted furnace off-gas is generated from which waste heat can potentially be recovered.
- Thermal coal with either low or high volatiles content can be used as feed material.
- HCFeMn metal fines generated in alloy crushing can be processed in the AlloyStream™ process with ore and coal feed without negatively affecting throughput.
- Energy input into the raw materials is relatively unaffected by ore feed chemistry allowing some flexibility in setting aim slag basicity levels.
- The AlloyStream™ process design circumvents the effect of dangerous gas excursion, which is often experienced in the SAF process.
- The AlloyStream™ process operates with more energy supplied chemically from the combustion zone than electrically from inductor,
- Process and engineering scale-up parameters were confirmed in scaling from the 2.5 m diameter pilot to 5.3 m demonstration furnace.

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