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Silicon-metal Production on a Trial Basis from River Pebbles Originating in Australia

D.P. O'SHAUGHNESSY*, A.E. FIREK†, and J.E. TRUNZO‡

**Hatch Associates Limited, Hull, UK*
†Pancontinental Mining Limited, Sydney, Australia
‡Silicon Metaltech Inc., Wenatchee, USA

Pancontinental Mining Limited purchased a high-quality deposit of river pebbles in central New South Wales with the intention of examining the feasibility of becoming a silicon-metal producer. In order to verify theoretical and laboratory-scale investigations, a two-week trial was run on these pebbles in a 9 MW furnace at the plant of Silicon Metaltech Inc. in Wenatchee, Washington. The results confirmed the quality issues, and premium-grade silicon metal was produced on a continuous basis. The size of the pebbles and their resistance to decrepitation were found to be satisfactory; in fact, furnace efficiency factors were found to have improved over those when standard raw materials were used.

Introduction

In May 1988, Pancontinental Mining Ltd (PML) entered into an agreement to purchase a high-quality silica-pebble deposit at Glenella, which is 25 km southeast of Cowra in central New South Wales (Figure 1). In early 1989, some laboratory-scale decrepitation tests on samples of these pebbles confirmed their suitability as a source of raw material for a commercial silicon-metal operation. However, for scale-up purposes, PML determined that the next essential milestone was to complete a commercial-scale test since riverbed materials have been known to behave quite differently outside a laboratory environment.

In October 1989, PML requested the assistance of Hatch Associates Limited to locate a suitable test site. After some preliminary enquiries, Silicon Metaltech Inc. (SMI), a silicon-metal producer with a smelter at Wenatchee, Washington, USA, indicated its willingness to participate in the test programme. Having agreed on the terms and conditions for the test, PML made arrangements to recover and screen out 800 t of the Glenella pebbles in the size range shown in Table I. The pebbles, of a size somewhat smaller than that usually specified by silicon-metal producers, were delivered to the Wenatchee smelter site in 2 t bags during April 1990, and the test programme commenced shortly afterwards. Since the purpose of the test was primarily to evaluate the quartz performance, it was agreed that SMI would substitute the Glenella pebbles for its own quartz, and continue to charge its own reductants using standard operating procedures. In this way, the relative merits of the Glenella pebbles could be readily determined on a commercial scale.

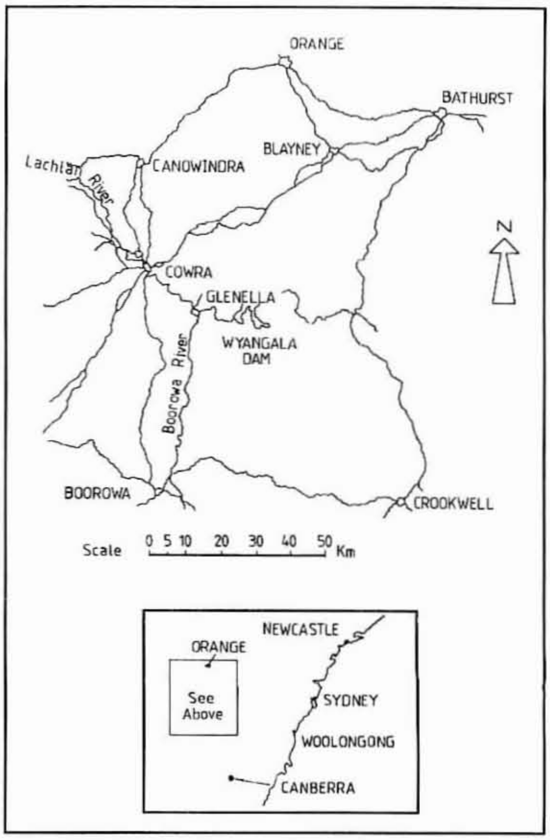

FIGURE 1. Map showing the location of Glenella deposit

TABLE I
THE GLENELLA PEBBLES AS RECEIVED AT SMI

Analysis, %	Constituent
99,100	SiO_2
0,009	Fe_2O_3
0,091	Al_2O_3
0,004	CaO
0,005	TiO_2
0,50	Moisture
Size fraction	Analysis, %
-5 mm	4
-25 mm + 5 mm	25
- 50 mm + 25 mm	50
-75 mm + 50 mm	20
+75 mm	1

The Glenella Pebbles

The Glenella pebbles were sampled on each eight-hour shift throughout the test programme, and composite samples were submitted daily for chemical and size analyses. The consignment included many deep-red and dull-black pebbles, which individually contained more than 1 per cent iron and 0,5 per cent aluminium. However, the average analysis of the total delivery, as shown in Table I, clearly indicates that these coloured pebbles had little adverse effect on the overall purity of the consignment.

Testwork Programme

The No. 2 furnace at the SMI smelter, which is a 9 MW open submerged-arc furnace, was used for the testwork. The furnace had been producing silicon metal from quartz rock brought in from the SMI quarry at Golden, British Columbia. For the first 24 hours of the test, a blend of rock and pebbles was fed to the furnace and no operating problems were encountered. The silica source was therefore changed to 100 per cent pebbles and then maintained continuously for the next 16 days, after which a blend was re-introduced until all the pebbles had been consumed. During the 16-day test, 660 t of pebbles were consumed in the furnace. The remaining 140 t of pebbles were smelted during the blend periods.

The reductants utilized during the test programme were a low-ash coal from Kentucky and petroleum coke from Minnesota. The amount of carbon consumed was maintained at between 92 and 95 per cent of theoretical requirements, based upon the overall reaction

$$SiO_2 + 2\,C = Si + 2\,CO.$$

The wood chips obtained locally are generally softwoods. SMI typically operates with a ratio of 2:1 for quartz to wood chips. This same ratio was maintained throughout the test programme.

Products

The three outputs from a silicon operation are the metal itself, dross, and gases including fume. At SMI, the metal is weighed after being discharged from the casting pans, and a 98 per cent factor is applied to determine the quantity of saleable metal; this is the key production number at the plant. The dross is the accumulation of crusts that form during ladle refining, the ladle and runner scrapings, and sundry spillages and cleanings. The dross is weighed on a daily basis. Fume is the recondensed silica that is collected in the fabric-filter baghouse. The fume from the No. 2 furnace is blended and bagged with fume from the other two furnaces on the plant; it cannot be weighed or sampled separately. At the time of the test programme, the tapping and refining fume was vented to the atmosphere.

The tapped metal is sampled in the runner. The metal collected in the ladle is then treated with oxygen for the removal of the calcium and aluminium impurities; the refined metal is sampled during casting. The quantities of the different grades of silicon metal that were produced during the 16-day test are shown in Table II, and most was primary aluminium grade material. The high-calcium silicon metal was produced specifically for the secondary aluminium industry using an alternative reductant blend, and was not produced as a result of the Glenella pebbles being smelted in the furnace.

TABLE II
QUANTITY OF EACH GRADE OF SILICON PRODUCED DURING THE TEST

Grade	Specifications, %		Taps	
	Fe	Ca	No.	Mass, t
Premium primary aluminium	0,21–0,25	<0,07	36	59,2
Standard primary aluminium (A)	0,26–0,30	<0,07	71	112,1
Standard primary aluminium (B)	0,31–0,35	<0,07	27	43,4
Secondary aluminium	0,36–0,50	<0,20	17	28,1
Totals			151	242,8

Test Results

Throughout the test, the reductant blend was 85 per cent coal and 15 per cent petroleum coke on a carbon basis. The results of the Glenella pebble-smelting test were very promising from a viewpoint of the efficiency of the operation. As shown in Table III, the results reflected a 10 per cent reduction in electrode consumption, a 5 per cent reduction in electric-power consumption, and an increase in silicon recovery of about 4 percentage points over standard operations. While these improvements may have been attributable in part to the increased attention to furnace operations during the test programme, the use of the Glenella pebbles most certainly improved the plant performance.

TABLE III
TEST RESULTS

No. of days	16
Operating time (%)	94
Average load while operating (MW)	9,0
Production of saleable metal (net t/day)	16,5
Silicon recovery (%)	77
Power consumption (kWh/pound* silicon)	6,1
Unit electrode consumption (pounds†/net t silicon)	240
Average iron content of product (%)	0,276

* 13,4 kWh/kg silicon
† 464 kg/net t silicon

All 28,1 t of the high-calcium material produced during the 16-day test (Table II) actually contained 0,30 per cent iron or less. The material was therefore designated a secondary-grade product only because of the lower refining requirements. As a result, 198,5 t or 82 per cent of the total production contained 0,30 per cent iron or less. This result was achieved with a coal-to-coke blend that is normally used when a maximum of 0,35 per cent iron in silicon metal is produced from standard SMI rock. In fact, the overall average iron content during the test was 0,276 per cent. While some variability in the iron content of the pebbles was suspected (and, as noted before, the red pebbles contained more that 1 per cent iron), the iron content of the silicon metal only varied over a 10-point spread between 0,22 and 0,32 per cent.

Mass Balance

The chemical analyses of the raw materials in the as-received condition were used as the basis for the mass balance. While the analyses of the Glenella pebbles, coal, petroleum coke, wood chips, silicon metal, and fume are considered to be representative for the test period, there was less certainty about the electrode and dross analyses. However, electrode ash was confirmed at about 7 per cent of the total electrode material. Dross is typically variable, particularly in carbon which usually originates from the tapping and refining equipment.

The mass balances for silicon and iron are given in Table IV. The silicon balance was closed on the assumption that all the silicon not reporting to the metal and dross would be collected in the fume. The silicon recovery to saleable metal was therefore calculated to be 77 per cent (or 78,5 per cent at the taphole). Based on the same mass inputs for the iron balance, 1,14 t of Fe_2O_3 entered the furnace during the 16-day test. Of this total, only 5 per cent of the iron came from the Glenella pebbles, while close to 83 per cent of the total input of iron reported to the saleable silicon metal. The fact that 75 per cent of the iron originated from the coal, which is a high-quality reductant, highlights the importance of reductant selection in the production of silicon metal. The iron analysis of the electrode ash was estimated, but is considered to be reasonably correct; again, the availability of low-ash electrode material must be seen as a product quality issue. The difference or error in the iron balance was 0,31 t of Fe_2O_3 of 0,22 t of iron. This would be equivalent to an average of 1,5 kg of iron per tap entering the silicon metal after the taphole if all the material analyses are truly representative.

The carbon balance is shown separately in Table V, because carbon is consumed in the reduction reactions and leaves the furnace in the off-gases as carbon monoxide. The error factor indicates that the balance closed to within 6 per cent of the total input over the 16-day test. However, it is likely that most of the carbon in the dross comes from insulating material added during tapping that is dumped in the dross bins after casting. Therefore, after the carbon used in the reduction reactions and that which leaves the fume had been subtracted, only 19,1 t or 7 per cent of the total carbon might not have been accurately accounted for in the 16-day test. If is is assumed that all the electrode carbon is consumed in some way in the reduction reactions, the balance indicates that approximately 50 per cent of the wood-chip carbon is burnt off at the surface of the furnace. Evidently, an increase in the proportion of wood chips charged to the furnace would only raise the temperature of the furnace off-gas without improving smelter efficiencies.

TABLE IV
SILICON AND IRON MASS BALANCES FOR THE 16-DAY TEST

	Total	SiO_2		Si		Fe_2O_3		Fe	
	t	%	t	%	t	%	t	%	t
Inputs									
Glenella pebbles	661,3	99,1	655,35	–	–	0,009	0,06	–	–
Low-ash coal	314,3	0,18	0,57	–	–	0,27	0,85	–	–
Petroleum coke	37,0	0,17	0,06	–	–	0,038	0,01	–	–
Wood chips	371,8	0,15	0,56	–	–	0,005	0,02	–	–
Electrodes	28,7	3,0	0,86	–	–	1,5	0,20	–	–
Totals			657,40				1,14		
Outputs									
Saleable silicon metal	238,9	–	–	98,91	236,30	–	–	0,275	0,66
Silicon-metal fines losses	4,9	–	–	98,91	4,85	–	–	0,275	0,01
Dross	28,6	12,5	3,58	70,7	20,22	0,1	0,03	0,6	0,17
Fume	108,1	87,5	95,49	–	–	0,2	0,22	–	–
Error factor					–		(0,31)(3)	–	–
Totals					261,37(1)		1,14		0,84 (2)

(1) Equivalent to 559,23 t of SiO_2
(2) Equivalent to 1,20 t of Fe_2O_3
(3) 27 %

TABLE V
CARBON MASS BALANCE FOR THE 16-DAY TEST

	Carbon, %	Carbon, t
Inputs		
Glenella pebbles	–	–
Low-ash coal	55,95	175,85
Petroleum coke	83,91	31,05
Wood chips	10,5	39,04
Electrodes	88,7	25,46
		271,40
Outputs		
Silicon metal	–	–
Dross	9,0	2,57
Fume	7,78	8,29
SiO_2->Si consumption	–	223,39
SiO_2->SiO consumption	–	18,80
Fe_2O_3->Fe consumption	–	0,27
Al_2O_3->Al consumption	–	0,81
CaO->Ca consumption	–	0,15
Error factor	–	16,52
		271,40

Energy Balance

The energy balance for the 16-day test is summarized in Table VI. Sensible and calorific heat in the off-gas and fume amounts to 59 per cent of the total output, and the metallurgical reactions account for a further 24,9 per cent. The only other significant energy output is losses to the cooling water. There is a 3 per cent discrepancy between input and output energy, which is considered to be an acceptably low value for the measurement techniques available. While it would be advantageous to minimize further off-gas losses of energy, the practical requirements of a silicon-metal smelting operation on a commercial scale (such as the need for frequent charge stoking) has to date prevented significant advances from being made in this regard.

Conclusions

The conclusions to be drawn from the 16-day smelting test on Glenella pebbles are as follows.

(1) While the use of river pebbles in the production of silicon metal is not novel, sizing preferences can be quite different between plants. The as-received pebbles were in a size range of plus 6 mm and minus 75 mm, and were smelted in a standard 9 MW submerged-arc furnace as the sole source of silica without any raw-material or furnace-operational problems. The successful use of pebbles in this size range therefore further advances the optimization of burden sizing for silicon-smelting operations.

TABLE VI
ENERGY BALANCE FOR THE 16-DAY TEST

Inputs	MBTU*	%
Petroleum coke	1 223,22	4,3
Blue Gem coal	10 044,40	35,5
Wood chips	5 162,52	18,2
Electrodes	948,82	3,3
Electric power	11 046,16	38,9
	28 425,12	100,0
Outputs		
Tapped metal and dross	427,94	1,5
Metallurgical reactions	7 146,85	24,9
Off-gas and fume	16 911,82	59,0
Transformer losses	383,08	1,3
Cooling-water losses	3 824,64	13,3
	28 694,33	100,0
Error	(269,21)	(0,9)

* 1000 BTU = 1055 kJ

(2) The coal-to-coke ratio used during the test was that typically employed by SMI to obtain a product with 0,35 per cent maximum iron; 82 per cent of the silicon metal produced from the Glenella pebbles was 0,30 per cent maximum iron, indicating a 0,05 per cent iron advantage. Therefore, lower-iron silicon metal was produced without the usual operational penalty when a change is made to a lower coal-to-coke ratio.

(3) The efficiency of the furnace operation improved noticeably during the test period, and the use of sized pebbles was a contributing factor. With an increase in the daily production of 4 per cent and the silicon recovery raised to 77 per cent, the unit power and electrode consumption decreased by 5 and 10 per cent respectively.

Trial shipments of silicon metal produced exclusively from the Glenella pebbles were sent to two of SMI's primary aluminium customers. Since the chemistry of this material was almost identical to the standard SMI product, a positive response was received. Therefore, based on the results of the commercial-scale test, it was concluded that the Glenella pebbles may be used as the sole source of silica for a smelter producing saleable high-grade silicon-metal products for the aluminium and chemical industries.

The availability of reductants for a silicon smelter in New South Wales, Australia, has yet to be assessed. No comments can be made on the prospects of this project reaching maturity. The paper deals solely with the comparative performance of pebbles and SMI quartz.

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