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The Production of High-quality Silicon Metal at Simcoa

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Simcoa operates the world's only fully integrated silicon plant, which is situated at Kemerton, 160 km south of Perth, Western Australia. The production facilities consist of a sawmill, two charcoal retorts, two submerged-arc furnaces, and packaging and despatch facilities. Because of the total integration of the operation, Simcoa has long-term access to and control over the supply of the main raw materials required for high-quality silicon production.

Under Simcoa's control, quartzite is mined from a homogeneous orebody that is low in impurities. Charcoal, the main reductant, is produced at the smelter from a single wood species, Jarrah, which produces a highly reactive and high-strength charcoal with an ash content of less than 0,3 per cent.

Simcoa has capitalized on these features and maintains its competitive advantage by means of a comprehensive statistical process-control programme that monitors and controls all the raw-material supplies and the various stages of the production process.

Supported by these competitive strengths and a workforce that is strongly motivated and committed to the production of a quality product, Simcoa is actively pursuing recognition as a quality silicon producer by seeking accreditation to Australian Standards AS 3902 – 'Quality Management Systems for Production'.

Introduction

Simcoa started operations in December 1989 after many years of studies and smelting tests undertaken in Japan and Italy to establish the viability of Western Australian raw materials for the production of high-quality silicon metal suitable for the chemical and primary aluminium industries.

Since its inception, Simcoa has developed a philosophy of total customer satisfaction, and instils product-quality ethos in the minds of all its employees. This philosophy was embraced by management, and became a key element in the training programme of the workforce. Safety and quality go hand-in-hand as the most important aspects of the whole operation.

The quality of silicon metal has become more important as increased demands are made by the chemical, metallurgical, and electronics industries. Simcoa has three distinct advantages over other silicon producers in this regard. These are its total control over the supply of all the main raw materials, its advanced process-control systems, and its highly motivated workforce geared to the production of high-quality silicon metal. In the short period since production started, the workforce has achieved a high standard of control over the processes to produce high-quality silicon metal.

This paper briefly describes Simcoa's operation, achievements, and future aims to meet the challenge of becoming the world's foremost producer of high-quality silicon metal.

The Challenge

The challenge of becoming the world's foremost producer of high-quality silicon metal was addressed long before start-up of the operation. All the employees at the plant have full staff status, and this has aided in the breakdown of many of the traditional 'them and us' barriers that exist between Australian management and the workforce, which have been entrenched over the past 100 years through the organized trade-union movement. Most of the employees work twelve-hour shifts, which has resulted in a more stable operation. Good communications ensure that the workforce is fully aware of the requirements for specific goals. Regular training sessions in safety, quality, and process control are held throughout the year, and each shift holds monthly meetings to discuss and report on various safety, production, and quality issues.

Extensive training of supervisors and key furnace operators at an overseas silicon plant ensured a smooth start-up and assisted in the ongoing training of the furnace workforce. In addition, internal and external quality-awareness training before start-up reinforced the company's objectives to the whole workforce.

Simcoa's philosophy is to supply customers with their precise product requirements consistently and on a timely basis. All Simcoa employees from the Chief Executive to the process operators are dedicated to this doctrine.

The appointed Quality Control Manager on site is independent of the production departments, and reports direct to the Chief Executive. He has authority to reject all products and raw materials that fail to meet established standards. Simcoa has draft quality-control and quality-assurance manuals in place, and is actively seeking accreditation as a quality supplier of silicon metal to Australian Standards AS

TABLE I
PROCEDURES FOR THE CONTROL POINTS OF FIGURE 1

	Stream	Control	Procedure
	Quartz mine		
A	Exploration		Specification Grid drilling Deposit mapping Analysis Recovery planning
B	Mining	Visual appraisal	Specification
C	Crush, screen, and wash	Recovery (SPC) Grade (SPC) Sieve analysis	Plant operation Sampling Sieve analysis Chemical analysis Grade classification
D	Quartz stockpile		Stockpile control Maintenance and cleaning Grade tracking Transport equipment
E	**Wood supply**	Specification	Timber receipt and inspection
F	Woodchips	Visual inspection	
G	Sawmill	Grading Moisture analysis Wood recovery Block size control	
H	Wood block storage	Moisture control	
I	**Retort process**	Fixed carbon (SPC) Volatiles (SPC) Ash (SPC) Moisture (SPC) Size (SPC) Wood consumption (SPC)	Temperature-profile control Charcoal sampling
J	Screening	Size	
K	**Electrodes**	Supplier SPCs	
	Silicon process		
L	Batching system	Weight control system (SPC) Woodchip moisture (SPC) Charcoal size (SPC) Alarms	Feed control Feed-equipment calibration Sampling Analysis Specification
M	Furnace process	Tap weights (SPC) Temperatures (SPC) Tap analysis (SPC) Power consumption (SPC) Electrode consumption (SPC) Silicon yield (SPC) Minor element balances Tap time (SPC) Electrical parameters Carbon factor (SPC)	Furnace control Sampling Analysis Temperature measurement Taphole maintenance and cleaning Ladle maintenance Ladle preheating Ladle cleaning Tapping
N	Refining	Oxygen (SPC) Temperature (SPC) Refining time Cast analysis (SPC) Flux additions Refining parameters	Refining Temperature measurement Weighing
O	Casting	Inspection	Casting-table preparation and inspection Casting Sampling Analysis Weighing Grading Tap identification
P	**Storage**	Inspection	Storage of refined production
Q	**Crushing and packaging**	Particle size (SPC) Analysis (SPC) Packaging weights (SPC)	Processing of customer orders Plant setup Product sampling Packaging Housekeeping Container inspection

3902 – 'Quality Management Systems for Production', which are equivalent to ISO 9002-1987.

Statistical process-control (SPC) techniques are used extensively to confidently predict the outcome of the process. This is important since Simcoa supplies a world market that demands products varying as to both chemical and physical specifications.

Simcoa's other advantages include the production of low-ash charcoal; its total control over the mining, grading, and stockpiling of the crushed quartzite; and an advanced control system. The combination of the various quartzite grades, low-ash charcoal, low-ash woodchips, low- and high-ash electrodes, and local low-ash coal gives the operation the flexibility to meet customers' specifications, and results in close control over the composition of the tapped and cast metal.

Figure 1 is a schematic flowsheet of the entire operation that highlights the various control points. Table I lists the controls and procedures in place at these points. Wherever possible, SPC charts are required from suppliers of materials that have a direct effect on the quality of the silicon metal, for example suppliers of electrodes.

Raw Materials

Quartzite

The quartzite is mined at Moora, 345 km north of the plant. The deposit has proven reserves of more than 2 Mt of high-grade ore.

The Moora quartzite is economical to mine, thermally stable, and low in impurities, especially iron, titanium, aluminium, and calcium. Selective mining of the quartzite is achieved from the mine plan developed from the results of the annual exploration and grade-control drilling programme. Typical analyses of the quartzite are given in Table II. The small-scale quarry operation ensures close control over the quality of the ore milled.

TABLE II
ANALYSIS OF THE MAIN RAW MATERIALS

	Quartzite		Charcoal (ash)	Woodchips (ash)
	A Grade % (by mass)	B Grade % (by mass)	% (by mass)	% (by mass)
SiO_2	99,0	98,7	17,5	17,5
Fe_2O_3	0,09	0,10 – 0,15	24,0	24,0
CaO	0,1	0,35	18,4	18,4
Al_2O_3	0,2	0,40	10,0	10,0
TiO_2	0,02	0,03 – 0,05	1,3	1,3
Loss on ignition	0,1	0,10		
Carbon			93,0 – 94,0	22,0 – 25,0
Volatiles			4,0 – 5,0	73,0 – 76,0
Ash			0,3 – 0,4	0,05 – 0,1
Moisture			2,0 – 4,0	25,0 – 30,0

Mining is by contract under the control of the Simcoa Mine Manager. The ore is blasted and hauled to either waste or the crusher, depending on the analysis obtained from the exploration-drilling programme. The crushing is a two-stage operation to produce the size required by the furnaces. The crushed quartzite is screened, washed, sampled, and held in temporary stockpiles pending analysis by the Kemerton laboratory. These stockpiles are accepted or rejected by the Quality Control Manager. The crushed ore is either stockpiled according to selected grades at the rail siding adjacent to the mine, or transferred to the waste stockpile.

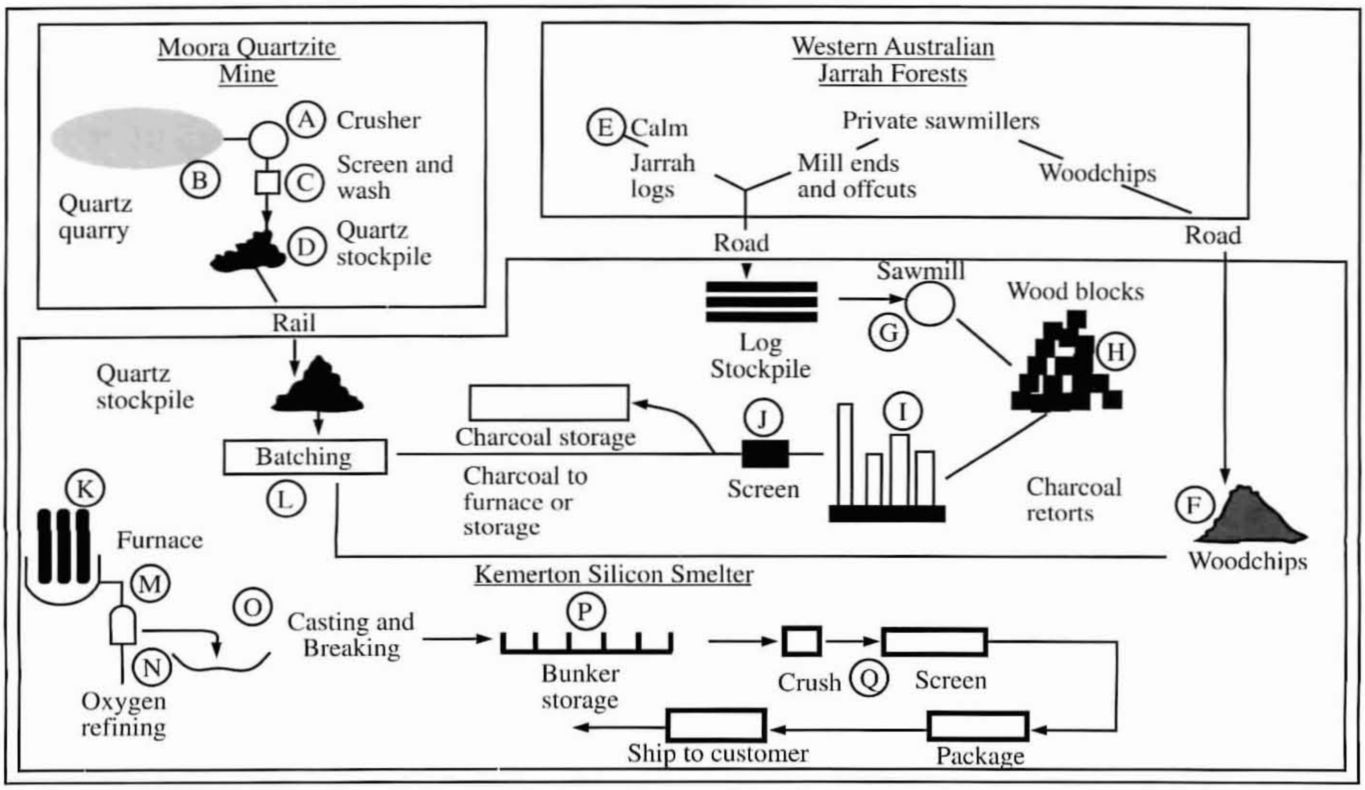

FIGURE 1. Schematic flowsheet of Simcoa's operation

Mining is carried out from May to October, with about 60 kt of ore stockpiled at Moora at the end of the mining season. The quartzite is railed to Brunswick Junction, 20 km east of Kemerton, and trucked to the plant, which has a stockpile capacity of about 9 kt.

The Quality Control Manager controls the quantity and quality of the quartzite stockpiled at the smelter.

Wood

The Jarrah wood *(Eucalyptus marginata)* was selected for the production of charcoal owing to its very low ash levels, high structural strength, and high reductant reactivity in the form of charcoal. Jarrah woodchips are used in the silicon process for the same reasons. Table II gives typical analyses of Jarrah wood.

The wood is supplied from locally obtained waste Jarrah timber from several sources within a 70 km radius of the plant, including dieback-affected forests, mill ends from local sawmill operations, private mining or clearing works, and falldown from conventional logging operations.

The quality of the logs, blocks, and woodchips is controlled against tight specifications at the suppliers' locations and at the Kemerton site during delivery. All the types of wood are sized; are free of bark, dirt, and sawdust; and, most importantly, are only of the Jarrah wood species. The Sawmill/Retort Superintendent controls the wood quality by visual inspection and by monitoring the analyses provided by the suppliers.

The logs are inspected by the supplier in the forest for diameter, bark, and rot content, and are then sized to length and transported to the Kemerton sawmill stockpile. The Superintendent, at the time of delivery, accepts or rejects the logs, and any rejected logs are disposed of by the supplier. The size and rot content of the logs are important for the optimum conversion of the logs to retort blocks. Bark, dirt, and moisture contents are controlled for both the retort process and the charcoal production.

The wood blocks produced at the Kemerton sawmill and supplied by the local sawmills must be correctly sized for both moisture and retort process control. The moisture content of the blocks is reduced to less than 25 per cent by the stockpiling of blocks in the open air for several months before they are fed to the retorts. Samples from the various stockpiles are taken for moisture analyses to determine the wood-block drying rates and availability as feedstock to the retorts.

The woodchips are inspected visually by the Superintendent during delivery, and are accepted or rejected before being unloaded. The specification for woodchips is the same as for the other forms of wood.

Production of Charcoal

Charcoal is produced in two vertical gas-rinsing retorts with associated gas-handling, combustion, cooling, and cleaning systems. The charcoal plant has an annual capacity of 27 kt of charcoal.

Dry wood blocks are elevated by skip hoist and charged to the top of the retorts via an air-lock hopper. As the wood descends through the retorts, it is progressively dried, preheated, carbonized, and cooled before charcoal is discharged via an air lock chamber at the bottom of the retorts. Heat for the carbonization process is supplied from the combustion of the pyroligneous wood gases in an incinerator connected to both retorts. Typical operating parameters for the two retorts are given in Table III.

TABLE III
DETAILS OF THE CHARCOAL RETORTS

Dimensions	Height 27 m Diameter 3 m
Rinse-gas volume	6 000 Nm^3/h
Rinse-gas temperature	600 °C
Wood species	*Eucalyptus marginata* (Jarrah)
Woodfeed size	150 mm x 150 mm x 250 mm
Woodfeed rate	6,2 t/h
Woodfeed moisture	15 – 30%
Charcoal production	39 t/d
Charcoal size	d_{50} = 24 mm
Charcoal analysis	
Fixed carbon	93,5%
Volatile content	4,5%
Ash content	0,3%
Moisture content	3,0%

Close control over charcoal quality is essential because it is the main reductant used for the high-quality silicon metal produced at Simcoa. The charcoal quality is controlled for

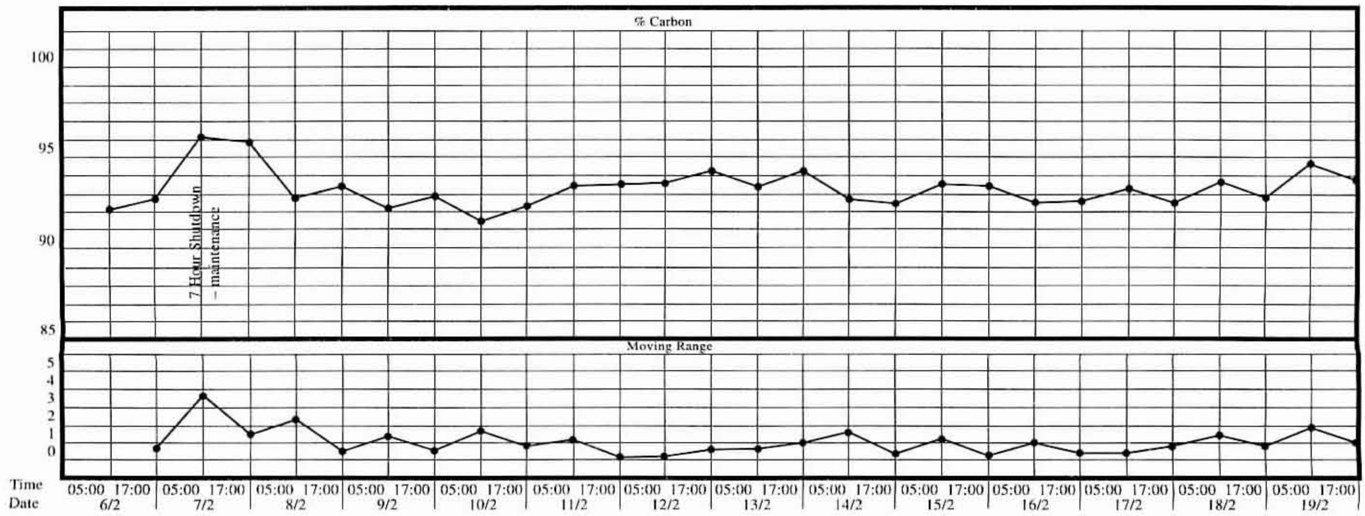

FIGURE 2. Retort operator's chart for control of the carbon content in the charcoal

its carbon, volatile-matter, ash, and moisture contents by strict control of the retorting operations. The retort DCS continuously manages the retorts, while the operator adjusts the process based on the charcoal analyses and procedures currently in place. Statistical process-control charts are used as a tool to control the quality of the charcoal and the process actions taken by the operators. Figure 2 is an example of the operator's control chart for carbon content.

The charcoal is screened to remove fines before it is transferred to the furnaces. Fine charcoal hinders the stability of the furnaces by affecting the carbon–silica balance. Size analyses are obtained, together with the carbon analyses of routine charcoal samples. The production of fine charcoal is minimized by monitoring of the wood quality, screening-equipment integrity, and charcoal-handling systems.

All the charcoal quality data and control charts are available to the silicon-furnace operators for process control.

Woodchips and Other Reductants

Jarrah woodchips are used in the furnaces and supply between 15 and 20 per cent of the carbon requirement of the process.

Local low-ash (2,5 to 3,5 per cent) sub-bituminous coal from Collie can be used to replace up to 15 per cent of the carbon requirements of the furnaces. The coal is used to adjust the metal chemistry, especially the aluminium content.

Smelting Process

The aim of the smelter is to produce silicon metal, consistently and at a competitive cost, that meets every customer's specification. Since commissioning, great emphasis has been placed on continuous review of the critical areas of the process, and the setting up of control points to monitor how well the process is performing to meet Simcoa's high quality standards. A number of areas use control charts to give operators visual feedback on how well the process is performing under their control. Specific procedures are in place to correct any 'out-of-control processes', which ensures minimum disturbance of the total process. To date, this has resulted in significant improvements in recovery, lower operating costs, and higher yields, and has also given the operators more confidence and awareness of the process under their control.

The following sections briefly describe the various controls used in the furnace area including the batching system, furnace operation, refining, and casting.

Batching System

Quartz is delivered to the site from the various stockpiles at the mine. A composite sample is taken each day for minor metal balances across the furnaces.

Woodchips from the daybin are sampled daily for moisture, which is charted in the furnace control room.

Charcoal is sampled every 8 hours as it is discharged from the retorts, and the carbon content is recorded on charts in the furnace control room. This chart has specific operating areas with strict procedures for their interpretation and for the actions to be taken. This system has been in place for only a short period, and has resulted in a more stable process than obtained with the previous moisture and fixed-carbon analyses of daybin material. Previously, the batching-system recipe was updated on the 8-hourly data, which often led to both furnaces becoming unstable owing to incorrect carbon balances.

Daybin charcoal samples are taken for screen analyses every 8 hours. The content of minus 10 mm material is recorded on a chart, and trends towards higher percentages of fines are compensated for by adjustment of the proportions of material from the two daybins, or by use of a higher proportion of woodchips until the problem of finer charcoal has been alleviated.

The batching system was designed to minimize the breakage of charcoal by quartz. The burden kibble is divided into two concentric compartments, with charcoal in the outer compartment, and quartzite and woodchips in the inner. The furnace bins call for new feed when the bin level has fallen enough to receive a full-burden kibble, which ensures minimum breakage of the charcoal and reduces segregation of the feed in the furnace bins.

The batching system is DCS controlled, with the batch size of quartzite and woodchips and the furnace carbon factor keyed into the system by the furnace controller. The DCS calculates the batch size of the charcoal from the latest analysis for reductant carbon in the recipe. The operator can instruct the system to take different ratios of feed from either the quartzite or the charcoal daybins. The system is flexible and, if required, can deliver feed of different carbon factors to any of the six furnace bins.

Extensive electronic monitoring of the batching system ensures that the operator receives early warning of impending problems, enabling him to take timely corrective action to minimize disturbances to the process.

The batching system was recently changed from the previous batch-correction system, which corrected any batch carbon factor in subsequent batches to that furnace-bin number. The present system corrects each batch before it is transferred to the furnace bins. The current system weighs out the quartz, woodchips, coal, and about 70 per cent of the target charcoal. The system then checks all the weights, recalculates the required charcoal for the batch carbon factor, and tops up the remaining charcoal. This has resulted in an accuracy of about 0,5 per cent in the batch carbon factor, as shown in Figure 3.

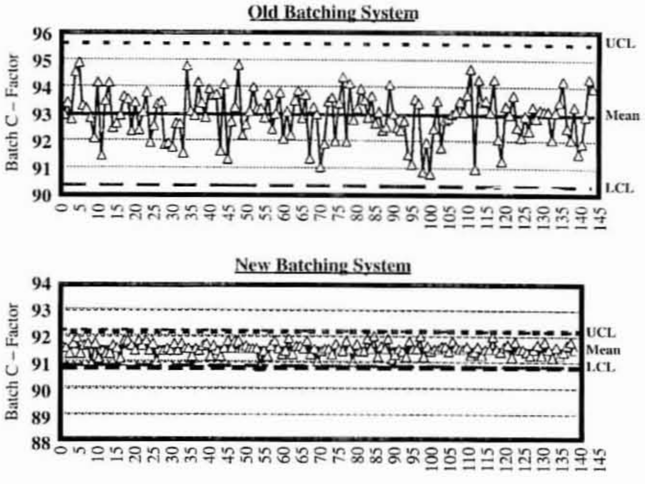

FIGURE 3. The variation in carbon factor in the old and new batching systems

The carbon factor for each batch is recorded and displayed on the DCS for the last 150 batches for each furnace. This trend gives the operators a visual indication of the variation in each batch, and whether or not the batch is within the required control limits. The trend also has visual alarms for batches that fall outside the specified limits, which require investigation by the operator.

Process Control

The furnace-control system is modern, and gives the operator access to a variety of data and operating trends that show how stable the furnaces are operating. The system generates 12-hour reports, which are used by the furnace controller to generate production and process-efficiency data. Logsheets are used for the logging of the critical operating parameters and conditions.

All the downtime in the furnace and ancillary equipment, and reduced furnace power, are extensively logged by the operator. The data are reviewed critically for their effect on quality and productivity, and hence initiate actions to improve critical equipment availability and process stability.

Detailed procedures are in place to ensure that all the operators are consistent in their roles. This has been the major advantage of the 12-hour shift, especially the stoking, tapping, and refining operations. Set guidelines are given with respect to furnace operating and refining parameters.

Details of the furnaces are given in Table IV, and typical iron contents in the silicon metal are shown in Table V.

TABLE IV
FURNACE DETAILS

Number of furnaces		2
Type		Demag 27 MVA submerged arc
Capacity		15 kt/a
Operating load		18 to 21 MW
Voltage supply		132 kV
Transformer capacity		3 x 9 MVA single phase
Electrodes		3 x 1145 mm amorphous pre-baked carbon
Shell		Steel rotating, 4 °/h
Crucible	Diameter	8,0 m
	Depth	2,9 m
	Refractories	Carbon with high-alumina backing
	Tapholes	4 x 150 mm
Tapping method		Electric stinger/kiln gun
Refining method		Bottom refining

TABLE V
TYPICAL SILICON ANALYSES (IN PERCENTAGES BY MASS)

Impurity	S-1	S-2	Special range
Fe	< 0,20	< 0,35	0,10 – 0,4
Al	< 0,30	< 0,30	0,08 – 0,40
Ca	< 0,02	< 0,07	0,002 – 0,20
Ti	< 0,04	< 0,04	0,02 – 0,04
Si	> 99,20	> 99,20	99,20 – 98,95

Tapping, Refining, and Casting

The furnaces are tapped every 2 hours, the tapholes being open for 60 minutes. The tapping and refining area has had significant input to reduce costs and to increase efficiencies and recoveries. This area is under the direct supervision of the tapping controller.

As Simcoa is a high-quality silicon producer, great emphasis is placed on ensuring that there is no contamination of the metal by iron or other contaminants. The ladles are insulated, preheated, and covered to reduce metal losses to crusts and skulls. They are equipped with moulds or drip trays. The spouts are cleaned into the drip trays before tapping and, under the current continuous rotation mode, new tapholes are opened into the drip moulds until the taphole is running before tapping into the ladle to reduce the quantity of off-specification metal.

The tappers use a variety of tools for taphole opening and maintaining the metal flow, including a stinger, a kiln gun, steel and graphite lances, wooden poles, and graphite bott tools. The tapholes are usually closed with a paste that was developed in-house.

Tap weights and ladle temperatures have been recorded by the tappers on trend charts for an extended period, which has resulted in a better understanding of the process by the operators. The tappers make comments on these charts as to the reasons for tap weights or temperatures that have fallen outside the guidelines, or for unfavourable trends in tap weight, temperature, or metal analysis. This has been so successful in providing an understanding of the process and cross-shift communication, that the charting of other process variables was started recently. Figure 4 is a facsimile of the charts used on the tapping floor.

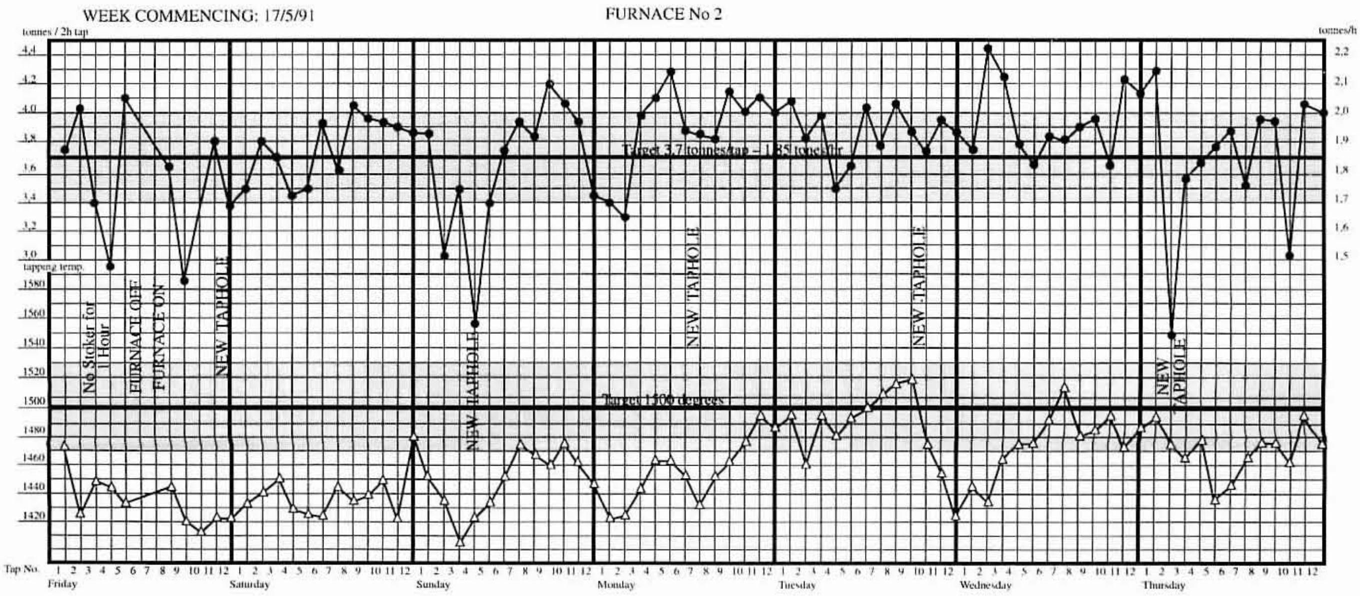

FIGURE 4. Furnace tappers' chart for recording tap weights and temperatures

Refining procedures are displayed in the tapping area, and depend on the specification of the metal being produced. Wherever possible, a range of parameters is provided to give the operators a degree of control over the process.

The refining technique changed recently from top refining using graphite tubes to bottom refining using Radex purge plugs. This has had a significant affect on ladle temperatures, metal losses, metal quality, slag–metal separation, and refining costs.

The silicon metal is cast into iron moulds. Samples are taken as every mould is filled, and are composited as cast analyses for product grading by the laboratory.

The samples taken during tapping and casting are immediately prepared and submitted to the laboratory for analysis. The sample preparation and analysis are controlled by the laboratory, which is also responsible for grading and storing the metal.

Product Handling

Product handling includes the final quality-control operation prior to the shipping of the product to the customer. This operation is under the direct control of the Quality Control Manager, who ensures that the product is the precise size and chemical grade of silicon metal required by the various customers, including packaging.

The Quality Control Manager co-ordinates with the marketing department as to the availability of the various grades, and with the product-handling operators as to the required size, grade, and packaging type for each order. The product is sized, sampled, and packaged. Once the analysis, size, and packaging specifications are verified, the Quality Control Manager releases the shipment for despatch. If any of the specifications are not met, the material is rejected and another shipment is prepared.

Analytical, process, and shipment data are stored on a computer-network database for efficient access by all personnel. This system contains the complete history of every tap since start-up, and is used to monitor the various process efficiencies and to supply the customers with information in accordance with their quality procedures. The total workforce at Simcoa is responsible for the product quality.

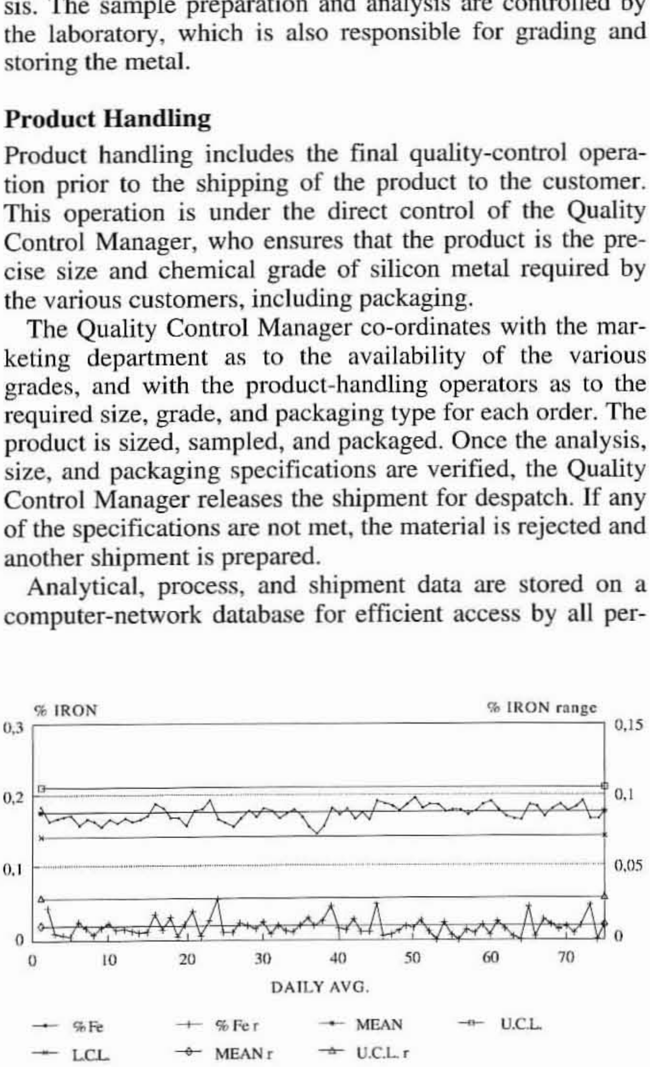

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FIGURE 5. SPC graphs for iron

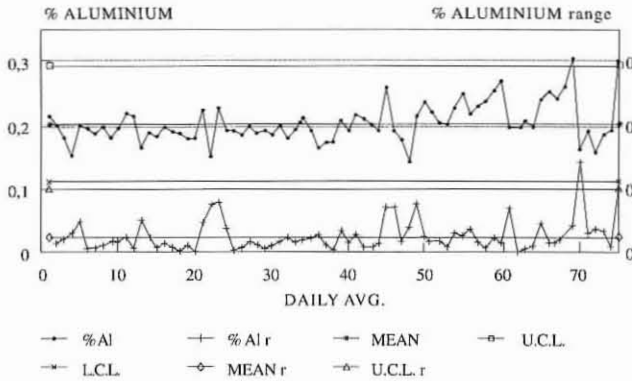

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FIGURE 6. SPC graphs for aluminium

Marketing

The Quality Control Manager provides support to the marketing department by supplying up-to-date information on product quality and availability. Quarterly, the quality-control department publishes a summary of statistical quality information. Figures 5 and 6 are examples of the SPC graphs for iron and aluminium for review by any of the silicon customers. These graphs also display the capability index for the particular specification, and are used to measure Simcoa's ability to produce silicon that meets or exceeds the customer's expectations. These indexes also show how Simcoa's process continues to improve.

The Future

Simcoa has already made substantial progress towards its goal of having the entire operation under Total Quality Management (TQM) as specified by AS3902 'Quality Management System for Production'. The current programme calls for Simcoa to obtain accreditation with the appropriate authorities early in 1992.

The use of SPC in certain key areas of the smelter has succeeded in improving the efficiency of these operations. SPC is therefore being extended to all the other key areas within the operation.

Acknowledgments

The authors express their appreciation to the entire Simcoa management and staff for their permission and encouragement to present this paper. Without their efforts and dedication to the Simcoa quality philosophy, this would not have been possible.