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A Review of Undergraduate Teaching and Postgraduate Research in Pyrometallurgy at the University of Stellenbosch

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Abstract – The pyrometallurgical activities at Stellenbosch University are reviewed in this paper. The history of the activities, both in teaching and research, is outlined, as well as some of the perceived research opportunities that the University of Stellenbosch is currently focusing on. The course content, as well as its relationship to other courses in the curriculum, is discussed and the interfaces between the courses are explained to present a holistic picture of the education an engineering graduate receives in process pyrometallurgy.

INTRODUCTION AND HISTORY

The Department of Process Engineering (previously known as the Department of Chemical and Metallurgical Engineering) at Stellenbosch University has been teaching pyrometallurgy as a core course since 1977, when extractive metallurgical engineering was offered as an area of specialisation within chemical engineering. Since the inception of the program in extractive metallurgical engineering, a number of lecturers, some well known for their research in pyrometallurgy (such as John Rankin, Cobus van der Colf, and Markus Reuter), have taught this course. However, there were a few years that pyrometallurgy was taught by lecturers for whom pyrometallurgy was not a core research area, even though they were actively involved in other aspects of extractive metallurgy, such as hydrometallurgy, electrometallurgy, and mineral processing. The lecturers involved in teaching pyrometallurgy specifically during the past 28 years are listed in Table I.

Table I: Lecturers in Pyrometallurgy (1977-2005) at the University of Stellenbosch

Lecturer	Lecturing Period
Prof. J. la Kock	1977-1978
Dr W.J Rankin	1978-1979
Prof. J.C.G.K. Van der Colf	1980-1982
Prof. J.S.J. Van Deventer	1983-1986
Prof. M.A. Reuter	1987-1989
Prof. L. Lorenzen	1990-1997
Dr S. Simukanga	1998
Dr J.J. Eksteen	1999-2005

While pyrometallurgy was taught at an undergraduate level, very little research occurred at the postgraduate level. Dr J.J. Eksteen has been the first person to pursue a sustained research program in pyrometallurgy from 1999. At the end of 1997, all of the existing infrastructure for pyrometallurgy was used for the practical component of undergraduate education. Since 1999, a major investment was made to gradually upgrade the facilities so that high quality research can be performed.

PYROMETALLURGICAL INFRASTRUCTURE DEVELOPMENT SINCE 1999

This infrastructural investment led to the purchase of three fully instrumented (temperature controlled by PID control) tube furnaces with an ability to operate at temperatures up to 1800°C, a bottom-loading furnace with a top temperature of 1800°C, a range of muffle furnaces, an induction furnace, and a custom-built DC plasma arc furnace. A gas-cleaning and control rig was built to handle five gases simultaneously, whereby traces of water vapour, CO_2, and O_2 can be removed from gas streams where they are not desired. The mass flows of gas are digitally controlled by computer. Additionally, differential thermal analysis (DTA) and thermogravimetric analysis (TGA) are used where applicable in kinetic and thermochemical research. For research in the application of particle image velocimetry (PIV) in pyrometallurgical applications, an ultra-high speed, high-resolution digital video camera with PIV software and associated frame-grabber was purchased. A range of simulation software and databases were purchased for the purpose of modelling pyrometallurgical processes. These include the most recent versions of:

- FactSage® (v 5.4 by CRCT) with additional databases from SGTE® for complex alloy melts. FactSage® is the most widely used thermochemical equilibrium software in industry and research institutions.
- HSC Chemistry for Windows® which is often used for a quick scan of possible equilibrium outcomes and for experimental planning.
- MATLAB® and associated toolboxes (such as Neural Networks, System Identification, Control, Statistics, Simulink, Optimisation, Signal Processing, and Symbolic Math) which is used as a powerful and versatile tool for modelling pyrometallurgical processes.
- FLUENT® which is used for computation fluid dynamics (CFD) and is the industry standard for CFD modelling of metallurgical operations. In addition, a magneto-hydrodynamics add-in is in use to model magnetically driven (caused through electro-magnetic induction) flow of melts in electrical furnaces.
- Pro II (by SimSci) process plant simulator.
- CSense® 3.3 for plant data-based modelling and control of processes.

Analyses of samples are carried out by the University of Stellenbosch Central Analytical Facility, which includes a scanning electron microscope with an energy dispersive analyser (SEM-EDS), X-Ray diffractometer, an X-Ray Fluorescence analyser, an inductively coupled plasma mass spectroscopy analyser, a LECO analyser for the analyses of C, S, N, and O down to trace levels, a laser-diffraction particle size analyser, a BET surface analyser to characterise macro-, meso- and micro pores of materials such as coal, a rheometer to characterise the rheological properties of materials, and a range of optical geological and metallurgical microscopes. Furthermore, the research group is well equipped with sample preparation (milling and pulverizing), sample splitting, cutting, mounting, and polishing equipment. The pyrometallurgical laboratory is equipped with cooling water, vacuum, nearly 1 MW of power (3-phase AC to single phase DC), ventilation, steam, and pressurized air. The research group has also pursued partnerships with other research institutions where either expertise or equipment is lacking for a specific part of a research project.

THE UNDERGRADUATE CURRICULUM

Course structures are dynamic and have to comply with a range of requirements as set by statutory bodies such as the Engineering Council of South Africa (ECSA), as well as external international bodies such as the Institution of Chemical Engineers (IChemE). The curriculum has changed from 2006, to allow for a one-year course in language (Afrikaans or English) in the first year to equip students with the necessary language skills. This was done to broaden the intake of students in engineering, without language being an impediment to studying. All courses presented in the first year are presented in parallel in both English and Afrikaans. Subsequently (i.e. from the second year), it is expected of the students to be sufficiently bilingual to be taught in either language. A dual-medium rather than a parallel medium approach is therefore followed from the 2nd year of study, as this was found to be the only pragmatic approach for the particular social and regional context within which the department has to function. The first two years of the engineering curriculum covers the basic engineering and science skills and knowledge areas which are required in the 3rd and 4th years, and include the foundation courses in engineering mathematics, chemistry, physics, materials science, professional communication, mass and energy balances, fluid mechanics, and classical thermodynamics, statistics, and an introduction to pilot plant laboratory experiments with associated report writing, presentation, and data processing. From the 3rd year onwards a focused program in process engineering is presented. The courses specifically of relevance to an engineer working on a smelter are as follows (3rd and 4th years):

- **Chemical Thermodynamics** (which covers chemical reaction equilibria and phase equilibria, non-ideal solutions, and non-ideal gases)
- **Particle technology** (characterisation of particles and their distributions, solid-liquid separation, flow of fluids through packed beds, comminution and agglomeration, fluidisation, settling, particle segregation, and sampling of particulate systems)
- **Transport phenomena** (energy and mass transfer)
- **Mineral processing and hydrometallurgy** (process mineralogy, mineral beneficiation through physical processes and flotation, leaching,

precipitation, and ion exchange), also including the mathematical modelling of these operations

- **Pyrometallurgy and electrometallurgy** (discussed in more detail below)
- **Extractive metallurgical and mineral processing pilot plant** (discussed in more detail below)
- **Mass transfer operations** (distillation, gas absorption, solvent extraction, adsorption)
- **Homogeneous and heterogeneous reactor engineering** (two semester courses covering reaction kinetics, catalysis, mixing in reactors, non-isothermal and multiple reactions, equilibrium limitations, gas-solid, gas-liquid, liquid-liquid, and liquid-solid reactions)
- **Modelling and optimisation** (dynamic modelling of process systems, empirical modelling methods, linear and non-linear constrained optimisation)
- **Process instrumentation and control** (basic feedback control, feed-forward-, cascade-, and optimal control, multivariable and expert control, digital control, filtering, control strategies for plant control)
- **Process plant design** (preliminary hazard analysis, HAZOP studies, process flow diagrams (PFDs), piping and instrumentation diagrams (P&IDs), process plant layout, methods used in the conceptual design of processes, scanning of processing options)
- **Environmental engineering** (environmental impact assessment, life cycle analysis, engineering methods for abatement of soil-, water-, and air-pollution, immobilisation and disposal of hazardous wastes, socio-economic impacts, recycling of resources and water, renewable energy, impact of processes on the environment through ozone layer depletion, greenhouse gas emissions, etc.)

In addition to the above, courses on engineering economics and profitability, management of technological innovation, project management, and biotechnology are presented as part of the core curriculum (each as a semester course). While various electives were offered in the past, it was not economically feasible and all the courses presented above form part of the obligatory core curriculum. Finally the course is completed with a final year plant design and a research project related to extractive metallurgy, in the case where the student is a mining house / metallurgy company bursar.

The two semester courses that require a more detailed discussion, with regard to the context of this Southern African Pyrometallurgy 2006 conference, is the Extraction Processes course on Pyrometallurgy and electrometallurgy (presented in the second semester of the 3rd year in 2005, but shifting to the final year from 2006) and the Extractive Metallurgical and Mineral Processing Pilot Plant (module: Mineral Processing D344).

THE SEMESTER COURSE IN PYROMETALLURGY AND ELECTROMETALLURGY

As the courses in Chemical Thermodynamics cover multiphase-multicomponent reaction and phase equilibria, these aspects (common to many pyrometallurgy courses elsewhere) are not repeated in this course, neither are the reaction kinetics aspects covered in detail as they are treated in sufficient depth in the courses in homogeneous and heterogeneous Reactor Design. The course has seven sections, being:

- The thermodynamics of melts and ionic solutions found in metallurgy.
- Thermodynamic stability of compounds and their representation on diagrams (Ellingham, Kellogg, Pourbaix diagrams) and the use of these diagrams as sources of information for process selection and first order process evaluation.
- The interpretation of binary and ternary phase diagrams to predict phase equilibria, crystallisation processes, and equilibrium crystallisation pathways. This also covers the relationships between microstructure and phase equilibria, and phase equilibrium reactions. Experimental ways of determining phase and reaction equilibria are also studied.
- The simulation of pyrometallurgical reactions and phase equilibria using FactSage®.
- The physico-chemical nature of melts (slags, mattes, molten salts, and molten alloys) in pyrometallurgy. This covers the activity models, the viscosities and viscosity models, the thermal and electrical conductivities and their models, and interfacial tension properties of melts. Moreover, it evaluates a range of fundamental models of the polymerisation behaviour of slags, and the chemical factors that influence the capacity of slags to absorb tramp elements such as sulphur and phosphorus.
- Furnace technology, energy, fuels, reductants, and refractories. This section introduces the student to the interrelationships between a reductant and its simultaneous influence on both the energy balance and the chemical partitioning of components within a furnace. Moreover, the nature of reductant with regard to particle size, electrical conductivity, porosity, reactivity, rank, ash content and chemistry, and petrology are presented and how reductant types are matched to furnace types (e.g. to compare the reductants or their blends used in a blast furnace compared to a submerged arc furnace or a DC plasma arc furnace, or a rotary DR-kiln, based on the characteristics given above). The link between electrical heating and combustion heating is explored, as well as heating through electromagnetic induction. The effect of reductant characteristics and furnace characteristics on the power factor and electrical interaction is explained, where applicable. The students are introduced to the main criteria for refractory selection and the use of phase diagrams to help explain refractory behaviour in contact with slags.
- Finally, electrometallurgy is covered for melts and aqueous solutions. Both the thermodynamics (based on the Nernst equation) and the kinetics (based on the Butler-Volmer equation are discussed). Mass

transfer effects are covered in relation to their effect on slowing the overall kinetics, as well as the effects of over-potential and electrode surface characteristics. The various components contributing to potential drop are presented, and the qualitative requirements of electrochemical cells are covered for melts, as well as for aqueous solutions.

It is clear that the course is quite full and that knowledge of chemical thermodynamics, kinetics, and reactor design, particle technology, electro-technology, energy and mass transfer, and chemistry are all required before the students can properly appreciate the complexities of pyrometallurgical process analysis and design.

From 2006, all chemical engineering students will follow this course. To broaden the context, examples related to coal combustion and gasification, cement manufacturing, glass manufacturing, and nuclear processing will be covered as well. However, this does not add to, or alter, the content, as the engineering fundamentals are the same irrespective of the context.

EXTRACTIVE METALLURGICAL AND MINERAL PROCESSING PILOT PLANT

The pyrometallurgical pilot plant laboratory is a 3rd year 2nd semester practical course where students are given a fairly open-ended metal theme. The practical sessions are performed as a team effort, with students from the University of Cape Town (UCT) and Stellenbosch University (SU) working together in mixed teams. The practicals are managed under the auspices of the Western Cape Mineral Processing Facility (WCMPF), an initiative partly funded by the Mineral Education Trust Fund (METF). The objectives of this collaborative WCMPF effort are threefold[1]:

- To continuously improve academic programmes for the education of students in mineral processing and extractive metallurgy primarily through the development of practical programmes and facilities.
- To ensure the co-operation, mutual interaction, and development between tertiary educational institutions teaching mineral and metal processing in the Western Cape.
- To rationalize and make optimum use of the equipment and manpower for education in mineral and metallurgical processing in the Western Cape.

It has always been an important goal of the institutions to give the students an exposure to mineral processing pilot plants that is different from the traditional practicals that are very much focused on laboratory work (bench-scale practicals or research-type practicals). The emphasis of this course is not to perform research-type investigations (which is covered in the final year research project), but rather to work with imperfect systems, where statistical uncertainty plays an important role, where mass balances do not close unless they are reconciled, and where safety and operational aspects are very important. The emphasis of the pilot plant laboratory is the development of practical hands-on engineering skills, where engineering intuition plays an important role and where it is required of the students to observe not only measurements, but also many operational and qualitative aspects of the practicals. The interaction between skills acquired, the practical programme, and the theoretical courses are diagrammatically outlined in Figure 1 below.

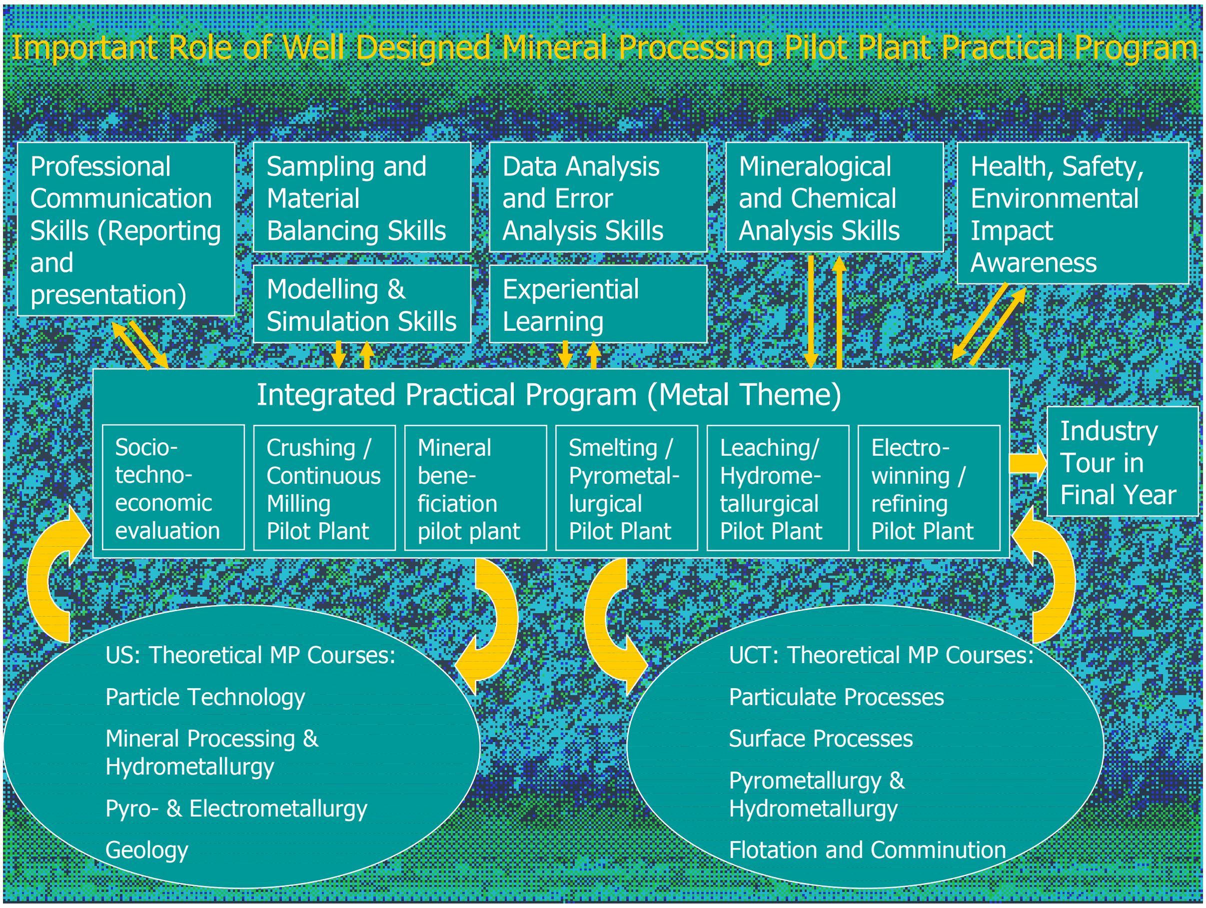

Figure 1: The pilot plant experimental program in relation to skills acquired and course content

The aspects that we (within the WCMPF) view as unique to this practical program are:

- The practicals are not idealized systems, but the students get to work with the actual mineral- and metal-containing process streams.
- Safety and environmental issues are taken seriously due to the 'real life' aspects of the practical program.
- In no other course (practical or theoretical) do the students get such an exposure to measuring actual process streams, processing the data, taking into account the nature of the measurements and the associated errors.
- These are only made possible due to the efforts of trained individuals with actual industrial experience (i.e. not a post-graduate demonstrator for whom it is the last of their priorities).
- The practical programme provides context and support to the theoretical courses taught in the 3rd and 4th years.

- The integrated nature (all related to a given metal theme) gives the students the opportunity to understand the interrelationships between the various stages of mineral and metal extraction.
- The students are taught practical mineralogical, chemical, and physical characterization techniques for materials, normally not taught in any other course (at the two institutions).

In 2005, the students had chromium as a metal 'theme', and the pilot plant practicals that were performed are shown in Table II:

Table II: Pilot plant practicals performed in 2005

Practical	**Objectives and variables**
Crushing of waste ferrochrome slag containing entrained alloy	Determination of the specific energy associated with breakage, particle size distribution.
Gravity-based recovery on high carbon ferrochrome from slag in an In-line pressure jig	Hutch water, pulse frequency, and pulse amplitude are varied. The separation efficiency of the unit was investigated by performing a sensitivity analysis on the operating parameters by determining the density of the tailings and the concentrate streams.
Continuous closed-circuit milling and classification (using a screen) of ferrochrome-based slag	The effect of mill charge, pulp density, and mill speed were varied, and the effect on mill power, particle size distribution, and alloy liberation were studied.
Hot acid leaching of chromite, hot filtration, and chromium alum crystallisation	The effect of pH, stirring rate is studied on leaching kinetics. The effect of seed crystals is studied on crystal yield during the crystallisation of the alum.
Electrowinning of chromium from chromium alum solutions	pH, cell operating temperature, current density were varied. The current efficiency and recovery vs time is determined.
Production of high carbon ferrochrome from chromite fines, limestone, quartz, and anthracite in a DC Plasma Arc Furnace	Fine chromite, fluxes, and reductants are fed using a vibratory feeder into a plasma arc furnace. The off-gas is cooled and ventilated, and the dust is captured. Arc-length, current, slag basicity and the reductant to chromite ratio is varied and their impacts on metal and slag yields and chemistries are determined. The students are required to reconcile the material balance on the furnace. An infrared pyrometer is used to estimate temperatures of the slag in a graphite crucible.
Mineralogical characterisation of the materials used in the practicals, using SEM-EDS for slags, XRF for total elements, and LECO (for carbon)	The aim of the mineralogical characterisation is to expose the students to characterisation methods and the metallurgical information they can provide.
Simulation of the high-carbon ferrochrome practical conditions using FactSage	The effect of changes in basicity, temperature, and reductant-to-chromite ratio in the production of high-carbon ferrochrome in a plasma arc furnace are simulated using FactSage®, to evaluate the effect on the amounts and types of phases formed, and the composition of the phases (such as slag-liquid, spinel minerals, liquid alloy, and $(Fe,Cr)_7C_3$ carbides and gas.

Before the students commence with the practical programme, they have to understand the context within which the practical is performed. Topics to be studied were the geology and mineralogy, raw materials and resources, routes to ferrochrome production, routes to chromium metal production, properties-applications-markets and environmental impact, toxicology, safety and health aspects. Figures 2 and 3 are photographs of students operating the DC plasma arc furnace (Figure 2) and the In-line pressure jig (Figure 3).

Figure 2: A student running the 60 kW DC plasma arc furnace for the smelting of chromite fines

Figure 3: Students operating the in-line pressure jig pilot plant

Part of the practical programme includes one-day field trips to mineral or metal processing industries in the region, such as Mittal Steel in Saldanha. This allows the students to see their work in the industrial context.

RESEARCH AND POSTGRADUATE STUDIES IN PYROMETALLURGY

The research programme in pyrometallurgy, since its inception in 1999, has had three major components:

i. Melt thermochemistry and behaviour (1 PhD, 5 MSc)
ii. Measurement, modelling, and control of pyrometallurgical processes (2 PhD, 4MSc)
iii. Metallurgical accounting and reconciliation of smelter operations (1 PhD, 3 MSc)

It is felt that these main lines of research in pyrometallurgy are sustainable within the Southern African context. The context of process engineering will naturally influence the angle of approach of the research, compared for example, to a mineralogist's, physical metallurgist's, or materials scientist's approach. In the long run, it is the aim of the research group to accurately characterise, predict, model, and control process phenomena at high temperatures. Items (i) and (iii) therefore support the main research thrust, which is captured in item (ii). However, it is believed without a good foundation in either (i) or (iii), wrong research conclusions and strategies will evolve.

The first graduation (MSc) took place in 2001; 2 PhD's and 7 MSc's graduation with pyrometallurgically related projects since then. The research is coordinated by Jacques Eksteen and Chris Cutler. Co-supervisors contribute where their expertise complements that of the research coordinators. Collaboration occurred with Prof. Markus Reuter (University of Melbourne), Prof. Yongxiang Yang (Technical University of Delft), Dr Sharif Jahanshahi, and Dr Shoui Sun (CSIRO), Prof. Candy Lang (UCT), and Prof. Chris Aldrich (US).

Within these categories the projects recently completed and currently in progress at the Department of Process Engineering are (with the researcher included in brackets):

i. For Melt thermochemistry and behaviour:
   a. An experimental study of slag foaming behaviour (Stadler, MSc)
   b. Pyrometallurgical recovery of cobalt from waste reverberatory furnace slag by DC plasma arc furnace technology (Banda, MSc)
   c. The effect of temperature, slag chemistry, and oxygen partial pressure on the behaviour of chromium oxide in melter slags (Bartie, MSc)
   d. The computational thermodynamic modelling of the phase equilibria pertaining to the TiO_2-Ti_2O_3-FeO slag system (Fourie, MSc)

e. Chromium partitioning, solubility, and mineralisation between Fe_xO-MgO-SiO_2-Al_2O_3 slags and Fe-Cu-S matte (Kwatara, MSc)
f. The thermodynamic behaviour and phase equilibria of the Co-Cu-Si-Fe system in the iron rich region (Banda, PhD)

ii. The measurement, modelling, and control of pyrometallurgical processes
a. A generic semi-empirical approach to the stochastic modelling of bath-type pyrometallurgical reactors (Eksteen, PhD)
b. Dynamic predictive modelling of iron and sulphur compositions in an Ausmelt converter (Georgalli, MSc)
c. The development of a dynamic model for the desulphurisation process at Saldanha Steel (Scheepers, MSc)
d. The acoustic characterisation of electric arcs in DC plasma arc furnaces and its implementation in arc length control (Burchell, MSc)
e. The CFD modelling of the thermal, electrical, chemical, and fluid flow patterns in a six-in-line matte-making furnace, taking into account the matte magneto-hydrodynamics (Snyders, PhD)
f. The systems engineering of an automated fire assay laboratory for the analysis of PGMs (McIntosh, PhD)

iii. Metallurgical accounting and reconciliation of smelter operations
a. Development of a metallurgical accounting system for PGM smelting complexes (Madonsela, PhD)
b. Characterisation of chrome losses and heterogeneity in slags associated with high carbon ferrochrome production (Nkohla, MTech)
c. Addressing metallurgical accounting challenges in the manufacture of ferrochromium based on submerged arc furnaces (Thyse, MSc)
d. Variance propagation and measurement errors in copper smelters (Cutler, MSc)

A research brochure of the department is available on the website http://www.chemeng.sun.ac.za/.

CONCLUSIONS

Stellenbosch University offers theoretical and practical courses in pyrometallurgy, but within the context of process engineering. Due to perceptions at high school levels about the pyrometallurgical and mining industries, careers specialising in extractive metallurgy do not draw sufficient numbers of good high school matriculants (especially within the Western Cape context) for a metallurgical engineering department to survive on its own. Economic class sizes dictate first year intakes of above 50 in a given engineering discipline, and most of these should graduate in the minimum allotted time to make it financially viable.

Pyrometallurgy is presented at Stellenbosch within the context that much of the knowledge related to pyrometallurgy (kinetics and reactor engineering, chemical thermodynamics, particle technology, energy and mass transfer) are taught in other core courses of the curriculum. As all chemical engineering students graduating from 2007 will have a background in pyrometallurgy, all Stellenbosch University chemical engineering graduates should be able to perform satisfactorily in any pyrometallurgical engineering environment.

Pyrometallurgy research has gained much momentum in a relatively short period of time (7 years) at Stellenbosch University. The facilities have been developed from only having to serve undergraduate education in pyrometallurgy to a fully functional research laboratory, with commensurate research outputs and postgraduate research students.

The Department of Process Engineering at Stellenbosch University will continue to build on its strengths that it has developed over the years in measurement, modelling, and control (within process and electronic engineering) and will seek to expand the research in these areas within the pyrometallurgical industry. To give more momentum to this research thrust the PMMC-lab (Process Measurement, Modelling, and Control laboratory) has been created with researchers from electronic, metallurgical, and chemical engineering backgrounds, supported by software developers, and other technical staff.

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