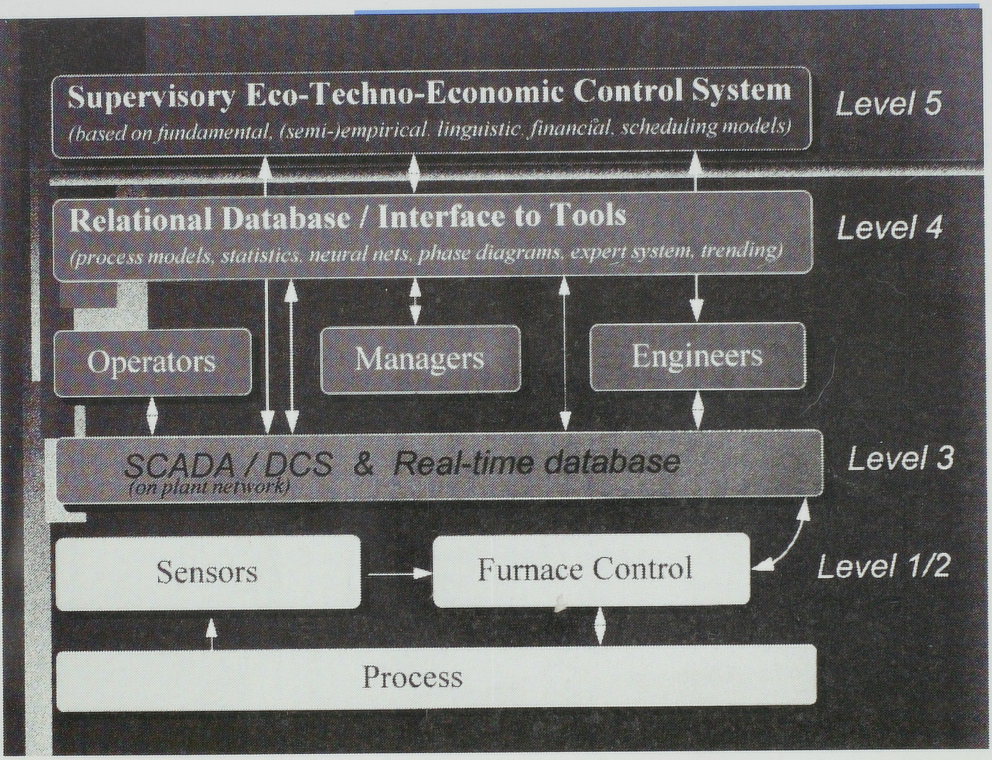
Carbon and Eco-techno-economics

Intreerede

June, 1997

Markus A. Reuter Pr.Eng, Ph.D., Dr. Habil



TU Delft
Delft University of Technology

Faculty of Applied Earth Sciences

Carbon and Eco-techno-economics

Inaugural speech on the acceptance of the

Professorship Raw Materials Processing at the Faculty of Applied Earth Science

of the Technical University of Delft

Friday June 20th, 1997

by

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Rector Magnificus,

Members of the College van Bestuur,

Professors and other co-workers of the University,

Ladies and Gentlemen,

Family, Friends and other Guests

In the next forty-five minutes or so I will be presenting to you what I intend to build up in Raw Materials Processing at the Faculty of Applied Earth Sciences. In a nutshell; I have a vision of closing the cycles of ecology, technology, economics *(eco-techno-economics)* in the fields of process metallurgy and recycling by the application of the various techniques available to us such as experimental work, process modelling, process simulation and process control.

1. Introduction

Ladies and Gentlemen, we are all one, between ourselves and with nature. This is perhaps very much a non-engineering statement, however, if you consult all the great religions of the world and their respective Avatar, e.g. Krishna (Hindu), Buddha (Buddhism) and Jesus (Christianity), they all say precisely this. It is very interesting that this oneness exists in all religions although these great Avatar lived many years apart, in different places of the world.

Well, you may say, this is engineering not philosophy I have to talk about during this inaugural speech. However, I cannot start my talk by questioning the philosophical soundness of our technological age. Perhaps the best way to test the philosophy (religion?) of Technology is by asking the question: “Does Technology advance the oneness of mankind and nature or is oneness inherently part of Technology; or not?” For now I would like to let this question hang in the air and I would like to get down to the business of extractive metallurgy. However, Ladies and Gentlemen, please keep the above question in your mind and try to answer it at the end of this talk. Perhaps I can attempt to illustrate our oneness by discussing the golden thread in our existence that connects us all, carbon.

Not only does carbon through ^{14}C-dating provide us with clues about our origins during excavations at archaeological sites (which I will discuss later), but also its multitude of manifestations in compounds and other materials make it an integral part of our lives. The following list

- graphite and diamonds,
- fuels (glucose, coal, oil, gas, etc.),
- organic materials (human, animal, plant tissues etc.),
- engineering materials (steel, composites, electrodes, refractories, vapour deposited carbon, etc.) and
- off gasses (respiration, energy, industry, wine making, agriculture, etc.)

represents but a brief overview of the compounds in which carbon appears, from which is clear that carbon touches the very fabric of our lives.

On a philosophical note it could be argued that carbon’s manifestation as graphite and diamond can be considered to represent two poles of our existence on earth, viz. softness and hardness, darkness and light, evil and live, Mephisto and Faust, Devachan and Nirvana - the list is endless. For metallurgists this epitomises carbon - the play between making metals from ore by the use of coal as a reductant and/or energy from coal-fired power stations, at the same time producing carbon containing off-gases and other residues that are placing our planet at great peril. Thus two poles can be distinguished, viz. “advancement” of our society due to metal production or the demise of our planet due to our uncontrolled greediness. How does one control this greed? How does on control the effects on the environment? These are probably questions asked frequently by many of you.

Not only does carbon touch our very existence, but also all the metals to name but a few such as (also many still produced/refined in Europe/The Netherlands) gold, magnesium, antimony, silver, bismuth, mercury, copper, nickel, iron steel, tin lead, zinc, tungsten, aluminium, and platinum are produced by the chemical energy or reducing gases made available by carbon. I think you would all agree and it has long been proven that the many elements in nature play an integral part in the functioning of our body and many have a very specific role to play. I found a very nice text, an ode to metals, which I would like to read to you in Dutch:

> *"Metalen zijn geschenken des hemels, die ons van de Zon, de sterren en de planeten worden toegezonden. Zij worden in de Aarde en al haar schepselen opgenomen en veranderd, waarna zij de dragers zijn van alles wat wij zelf uitzenden en wegschenken, de ruimte in. Door onze bloedstroom, door onze handen en door de ziel gaan de metalen, vast, vloeibaar, gasvormig of etherisch. Wij leven met hen en zij met ons. Wat de mens nog aan het leren is, dat is het bewust zijn van hun wezen."* (Uyldert)

Perhaps too idealistically I ask myself how we can bring ourselves closer to nature at the same time exploiting it to such an extent that we can live in harmony with our mother earth, very much like the Khoisan (Bushmen) in the Kalahari Desert have done for so many aeons. How do we control ourselves, our processes, so that this can materialise? This is the central circle in my mind, concisely expressed as the cycle between ecology, technology, economy and people. The harmony we have to achieve is depicted by Figure 1, which highlights that all disciplines should be considered simultaneously in an eco-techno-economic paradigm which I recently coined [Reuter and Sudhölter (1996)]. One aspect should never out-balance the others, for this will topple the pyramid.

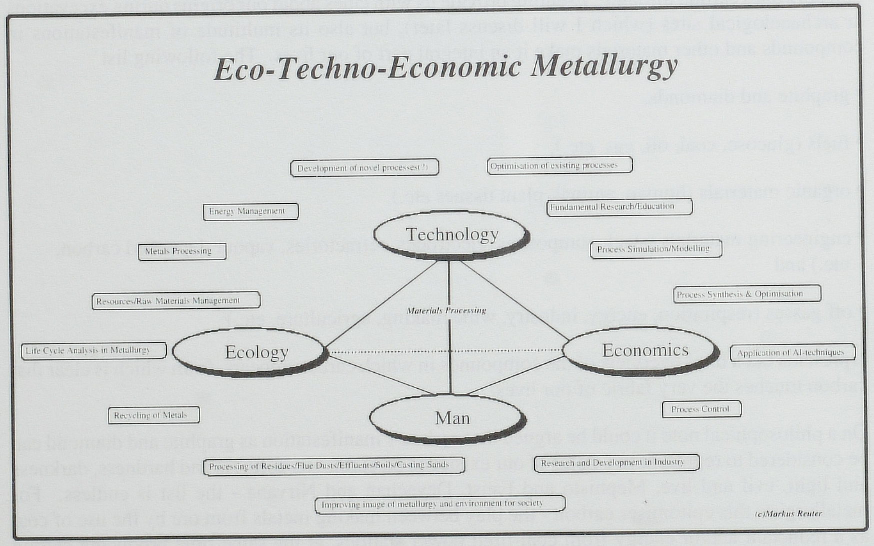

Figure 1 A holistic eco-techno-economic framework for and inter-relationships between Ecology, Economics, Technology and man in Process Metallurgy and Materials Processing

Before I start painting the picture and providing colours to some of the aspects in Figure 1 (e.g. Energy Management, Metals Processing, Raw Materials Management, Life Cycle Assessment, Recycling of Metals, Processing of Residues / Flue Dusts / Casting Sands, Process Control / Synthesis / Optimisation, Environmental Management etc.), I would like to map shortly the history of process metallurgy. Without going into too much detail and without discussing the bronze age (production of copper and tin alloys), I would like to dwell on the iron age and then more specifically how it developed in South Africa, the country of my origin. In this country, technology and nature lie so close to one another and this makes one acutely aware of the implications of Figure 1. Just for a moment imagine a landscape with a majestic eland, gemsbok, an ambling herd of elephants or a ravenous pack of lions in a cloud of dust in front of a fiery red sun, which could be setting between the belching chimneys of a factory. Perhaps you can feel what I am getting at.

Alas, things can go wrong so very soon if we do not take care quickly... May I, therefore, complete this chapter by formulating a provocative question: **"Should a society that does not have a very strong relationship to nature be practising and using technology?".**

2. Iron Age in Southern Africa

There is convincing evidence that humanity started in and distributed from central Africa, however, the picture is largely incomplete. What is known is that one of the earliest hominids *Australopithecus* roamed the southern parts of Africa and that *Homo sapiens sapiens* evolved from these hominids between 1.5 million and 200,000 years ago. From archaeological finds it is clear that stone tools were used as well as indications that fire was used in a controlled way for a variety of tasks. This led to iron making that can be traced back to the 5th century BC in West Africa and ultimately to South Africa to about 270 AD. This is not too far off the beginnings of the Iron Age in East Anatolia around 1200 BC. It may be noted that the Stone Age in Africa was followed by the Iron Age. For example, close to Pretoria, a whole city was excavated containing dumps of iron ore, slags, furnace debris, iron ingots and a copper chain, dated to between 350 and 650 AD. The Iron Age in South Africa lasted to the early 19th century, the latter stages from the 16th century being characterised by large scale mining activity and metal production and working. This activity eventually ceased to exist when the European settlers arrived. [Mintek (1994)]

The production of iron products in furnaces as depicted by Figure 2 typically followed the steps of heating the broken iron ore and charcoal, the carbon in my talk, to about 1100°C during which a bloom, a spongy mixture of unreduced iron ore, slag and charcoal is formed. The charcoal here has the pivotal roles of providing the fuel, making it possible to reach the high temperatures together with a blast of air, but at the same time providing the chemical conditions which convert the iron oxide ore (hematite) to iron. This bloom is removed and by repeated heating and hammering, slag is expelled and unreduced material converted to iron to produce a variety of products such as spear heads, chisels and hoes. Unfortunately even at this time iron was used for making weapons true to the planet Mars this metal is associated with. Just for comparison, compare the remains of a blast furnace from Norway dated to the Roman Iron Age as depicted by Figure 3. It is self evident that although separated by more than 10000 km, the furnace operations are similar, as well as the materials used and naturally also carbon, which plays the pivotal role.

At this early age liquid iron could not yet be produced (liquid steel making would only be demonstrated by Sir Henry Bessemer in the mid-19th century), although copper was already successfully cast as early as 770 AD around Palaborwa in South Africa, presently the location of a large open pit copper mine.

Developments have been steady from these small beginnings and presently pig iron is created in blast furnaces that are many meters high (in the order 20 to 30m). These furnaces are slowly making way for more advanced and ecologically more friendly furnaces such as the industrial

Corex process in South Africa or the Cyclone Converting Furnace at Hoogovens in The Netherlands, now in pilot scale. These environmental friendly processes come in addition to recycling of steel, that already forms part of most steel works.

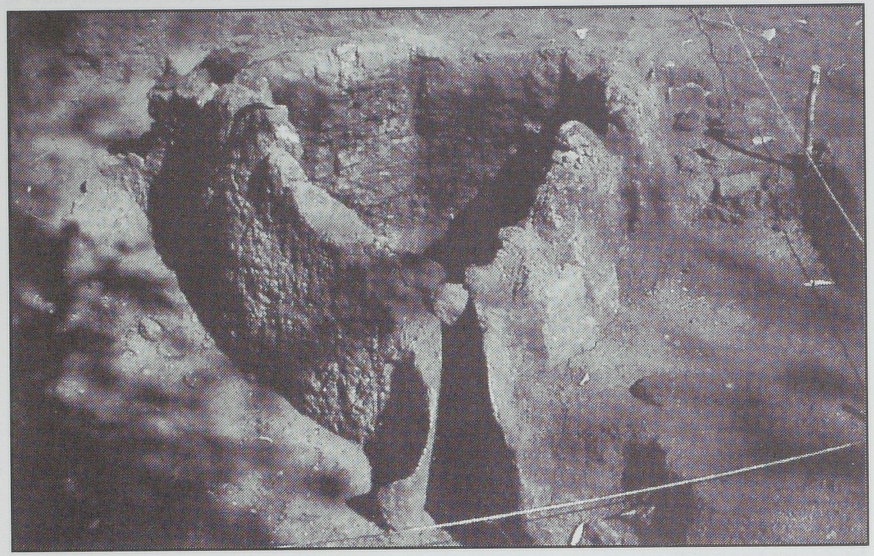

Figure 2 Remains of an iron blast furnace in South Africa (Mintek (1994) - *with permission*)

Figure 3 Battery of five furnaces for making iron (Espelung (1995))

From the above it is clear that carbon has already been in active use for many thousands of years all over the world for making iron and steel, as is still the case today, as the ca. 650.8 million metric tonnes of steel produced in 1995 (also in The Netherlands) would testify. This will rise to approximately 748.0 million metric tonnes in the year 2000 [Szekely, 1996)], generally also a trend forecast for a variety of other metals depicted by Figure 4.

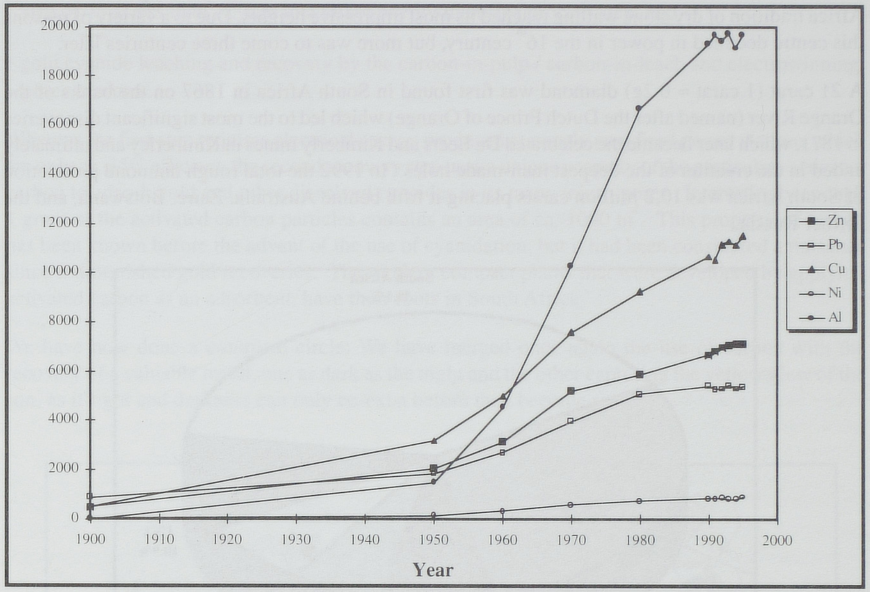

Figure 4 Metal production in thousands of metric tonnes according to the Metallgesellschaft

In summary, we have come all the way from the iron age to modern processes in steel production. These processes also form an integral part in the process of recycling your car and it can, therefore, be stated that; **recycling of metals is impossible without metallurgy or more specifically without pyrometallurgy.** This philosophy I was confronted with while working in Germany. You can no doubt see that there are still very exciting metallurgical times ahead, Ladies and Gentlemen!

Above you have been given a brief overview of metal production over the years as well as the role that carbon plays. How does one represent the generally poorly defined properties of carbon and other metallurgical particulates in a control structure permitting ecological furnace optimisation? I would like to use gold extraction, the first metallurgical process I became involved in as a chemical engineer for Anglo American Corporation in South Africa, to illustrate the complexities inherent in formalising our multi-phase systems in extractive metallurgy.

3. Gold

Iron is associated with the warlike Mars, gold on the other hand, is associated with the Sun. It has always had a magical attraction to the human ego and played such an integral part in Inca culture as in ours e.g. in monetary systems, jewellery etc. It is common knowledge that gold has played a significant part in South Africa's history. Figure 5 gives a typical indication of the gold reserves in the World from which it is clear that at least 40% of the ring on your finger has its origin in South Africa.

Although iron has been part of Southern Africa for many years, gold could only be proven to be part of society from the 12th century on. A burial site at Mapungubwe in Northern South Africa from this era revealed a variety of gold ornaments and gold plated wood figurines. (Compare the durability of this artifact to that of computer disks!) This probably formed part of a growing centre of wealth based on gold and ivory trade with Arab city-states on the coast of East Africa, Middle and Far East. This economic centre reached its zenith in hte Great Zimbabwe, where the indigenous southern Africa tradition of dry stone walling reached its most impressive heights. Due to a variety of reasons this centre declined in power in the 16th century, but more was to come three centuries later.

A 21 carat (1 carat ≈ 0.2g) diamond was first found in South Africa in 1867 on the banks of the Orange River (named after the Dutch Prince of Orange) which led to the most significant discoveries in 1871, which later became the celebrated De Beers and Kimberly mines in Kimberley and ultimately ended in the creation of the deepest man-made holes. In 1992 the total rough diamond production of South Africa was 10,2 million carats placing it fifth behind Australia, Zaire, Botswana, and the former Russia.

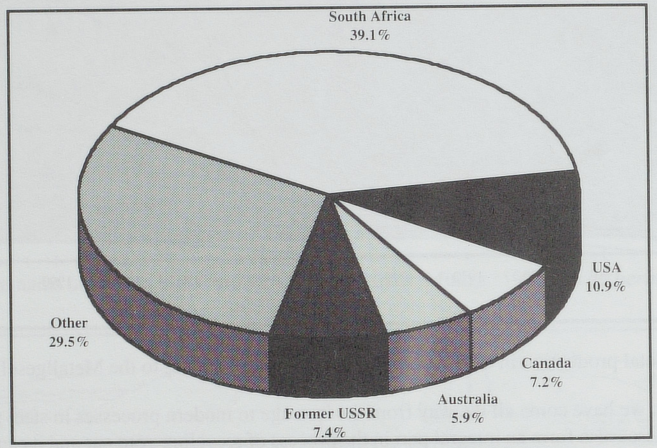

Figure 5 Gold reserves in the world (1994)

The diamond discovery was soon overshadowed by the discovery of gold in 1871 in northern South Africa and subsequently alluvial gold in the eastern part of South Africa at Lydenburg. Sluice boxes and panning were at the order of the day in gold rush cities now long gone and almost forgotten. This Pilgrims Rest Reef was exploited for about hundred years but soon the attention turned to the hard-rock ores from which the alluvial gold had weathered. This led to the discovery of the Pioneer Reef in 1883, the Sheba Reef in 1885, and then the Main Reef in March 1886. This ore (Witwatersrand conglomerate containing large pebbles of quartz, pyrite, uranium, kerogen *(which collected heavy metals)*) had to crushed and ground from which the free gold could be recovered by amalgamation with mercury placed on copper plates. Soon, however, the gold recoveries fell to below 50% due to a changing geology and gold being locked up in pyrite which made the gold price fall considerably. However, a new invention in 1888 saved the Witwatersrand from disaster, i.e. the dissolution of gold from finely milled ores with cyanide in wooden vats and then subsequently precipitating from solution by zinc shavings, by raising the recovery to over 90%. Eventually the whole expanse of the "golden arc" was established (a 60 km arc on which all initial mines were situated), which is the northern outcrop of a large basin some 350 km long and 150 km wide. This

basin was mapped already in the 1930s by a German geophysicist to ultimately produce the ultra deep gold mines near Carltonville (more than 4 km deep) and the gold mines in the Orange Free State (Figure 6). Presently a typical gold (metallurgical) production plant consists of the following steps:

- crushing and (semi) autogenous milling circuits, during which the lumpy ore is milled to a particle size of 75% less than -75mm in a rather energy intensive process step, and
- gold cyanide leaching and recovery by the carbon-in-pulp / carbon-in-leach and electrowinning process routes.

Whereas the first step requires electrical energy produced at mostly coal fired power stations which are only ca. 35% efficient, the second recovery step uses a unique property of the particulate activated carbon to adsorb gold and other dissolved cyanides in its many micro-pores. Interestingly enough 1 gram of the activated carbon particles contains an area of ca. 1000 m^2. This property of carbon has been known before the advent of the use of cyanidation, but it had been considered a nuisance since it diminished gold recoveries. The modern compact plants that were developed by applying activated carbon as an adsorbent, have their roots in South Africa.

We have now done a complete circle: We have merged once again the use of carbon with the recovery of a valuable metal, one as dark as the night and the other capturing the yellow glow of the sun, as if light and darkness can only co-exist before they become reality.

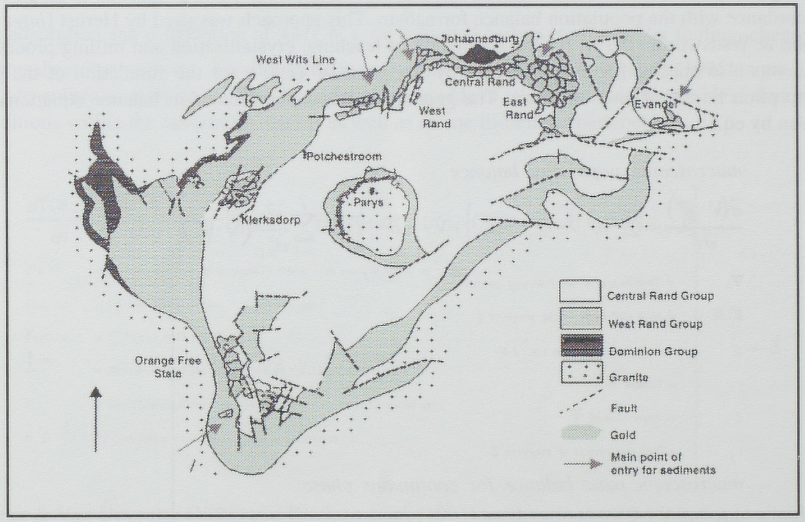

Figure 6 Simplified map of the Witwatersrand basin (Mintek (1994) - *with permission*)

South Africa took the lead in the development of the carbon-in-pulp and carbon-in-leach processes. Soon after the plants started to operate a number of efforts followed to optimise the process economically and ecologically, i.e. to optimise the recovery of gold, at the same time minimising activated carbon and energy consumption. The question is, how can these multi-phase systems consisting out of a leach liquor, activated carbon and a fine particulate ore slurry be controlled, in which every carbon and ore particle basically has its own properties such as particle size, density, mineral content, refractoriness, etc. This multi-phase nature of our systems really sets us apart from other disciplines in process engineering. I started off as a chemical engineer who could, so I thought, model and simulate everything. Tempered by the reality of our particulate and high temperature processes, I have become far more pragmatic. The next pages will demonstrate this.

Before I go into more detail regarding the ecological, technological and economic process control, I would like to present you shortly with a typical equation, from which the models for particulate systems may be derived, which define the changing properties with time, i.e. the change of particle sizes, change of activated carbon loading, abrasion of activated carbon, etc. This is especially interesting for defining systems in minerals processing and extractive metallurgy since it provides a deeper insight into the nature of these systems.

3.1 Multi-phase and particulate systems

For the multi-phase and particulate systems encountered in extractive metallurgy it is always necessary to consider the population balance approach to represent systems. However, one should always be aware of the fact that the parameterisation of these models is generally always rather difficult. At this point I would just like to demonstrate to you for example what the equations look like for modelling gold adsorption. The adsorption system consists of particles, the dispersed phase, and a metal containing liquor, the continuous phase [Sohn & Wadsworth (1979)]. In the micro-fluid approach one usually uses average particle sizes, average retention times as well as average reaction rates. In macro-fluid systems distributions of these properties is assumed in accordance with the population balance formalism. This approach was used by Herbst [*inter alia* Sohn & Wadsworth (1979)] for the simulation of leaching, crystallisation and milling processes, and was also applied for linear kinetics by Stange *et al.* (1990) for the simulation of the gold adsorption in stirred tank reactors. The general macroscopic population balance equations are given by eq.1:

macroscopic population balance

$$\frac{\partial\left(V\cdot\overline{\psi}\right)}{\partial t}=Q_{in}\cdot\psi_{in}-Q_{out}\cdot\psi_{out}+V\cdot\left[\left(\overline{B}-\overline{D}\right)-\sum_{j=1}^{J}\frac{\partial}{\partial\xi_j}\left(v_j\cdot\overline{\psi}\right)\right]$$

$\overline{\Psi}$ = *Distribution of the balanced property*

$\overline{B}.\overline{D}$ = *birth and death of the property* ξ

Q = *Volumetric flow rate* (m^3/h)

V = *Volume* (m^3)

ξ = *Dimension of* $\overline{\Psi}$

v_j = *Time rate change of property* ξ

macroscopic mass balance for continuous phase

$$\frac{d\left(V\cdot C_i\right)}{dt}=Q_{in}\cdot C_{i,in}-Q_{out}\cdot C_{i,out}+r_i\cdot V \qquad \text{—1}$$

There are many kinetic expressions that define well-defined processes in extractive metallurgy and minerals processing. However, changing mineralogy, changing chemical conditions, make it rather difficult to generalise these equations. In order to cater for these scenarios, the author attempted to generalise by formulating eq. 2 [Reuter (1992-1994)]. This equation was formulated to be able to define the kinetics of

- leaching, reduction, flotation and precipitation reactions, and
- adsorption and similar reactions,

as a function of all poorly-defined process parameters. This equations has the following form for non-pivot / non-standard conditions *[k(C, t) is the state variable, R is the final recovery,* α *&* β *the adjustment parameters]*:

$$-\frac{dC}{dt}=\alpha\cdot k(C,t)\cdot(C-C_o\cdot(1-\beta\cdot R_{Pivot}))=-r \qquad \text{—2}$$

C(0)=1 *(when dimensionless)* or C_o,

for the transformation of C to $1-\beta\cdot(1-C)$ for C(0)=1; $C(\infty)=(1-\beta\cdot R)$,

$\alpha,\beta\geq 0$ the adjustment factors which relate changing conditions to the kinetics by neural nets called adjustment factor neural nets, and

the state variable $k(C,t)=-\frac{dC}{dt}\cdot\frac{1}{(C-C_o(1-R_{Pivot}))}=f(neural\ net)$, calculated from smoothed pivot data for which a =1 and b=1

(calibration of the model).

The adsorption and distribution of $Au(CN)_2^-$ on activated carbon is affected by fouling, changing chemical environment, etc. For this scenario eq. 1 could be generalised by Reuter (1995) to produce eq. 3 by substituting by eq. 2. This formulation is capable of taking care of the non-ideal changing conditions within the adsorption reactor as well as define ill-defined parameters.

$$\frac{d\overline{y}(d,t)}{dt}=\frac{Q\cdot\varepsilon^{in}(d,t)}{V\cdot\varepsilon(d,t)}\left[\overline{y}(d)^{in}-\overline{y}(d)\right]+\alpha\cdot\overline{k}(d)\cdot\left[C(t)-C_o\cdot\left(1-\beta\cdot R_{Pivot}\right)\right]$$

$\overline{y}(d,t)$ = *Average loading on activated carbon with particle size d at time t*

$\varepsilon(d,t)$ = *Carbon concentration* = $f(neural\ nets)$

$\overline{k}(d)$ = $\int_0^\infty P(y,d,t)\cdot k(y,C,d)\,dy$

P = *Distribution of the property* $\Rightarrow P(y,d,t)=f(neural\ net)$

k = *Distribution ofr the adsorption rate* $\Rightarrow k(y,C,d)=f(neural\ net)$

$\alpha.\beta$ = f *(operating conditions)* = $f(neural\,net)$ = *eq. 2* —3

Reuter & Van Deventer (1991) and Petersen *et al.* (1991) used various methodologies to simulate gold adsorption reactors as well as packed bed columns. A typical result of such a simulation using eq. 3 is depicted by Figure 7, in which the average gold concentrations in solutions and on activated carbon are compared to simulated values for 10 industrial reactors in series. In the first four reactors the gold concentration increases due to leaching. In reactors 5 to 10 the concentration in the solution decreases, while the gold concentration increases on the counter-current flowing activated carbon.

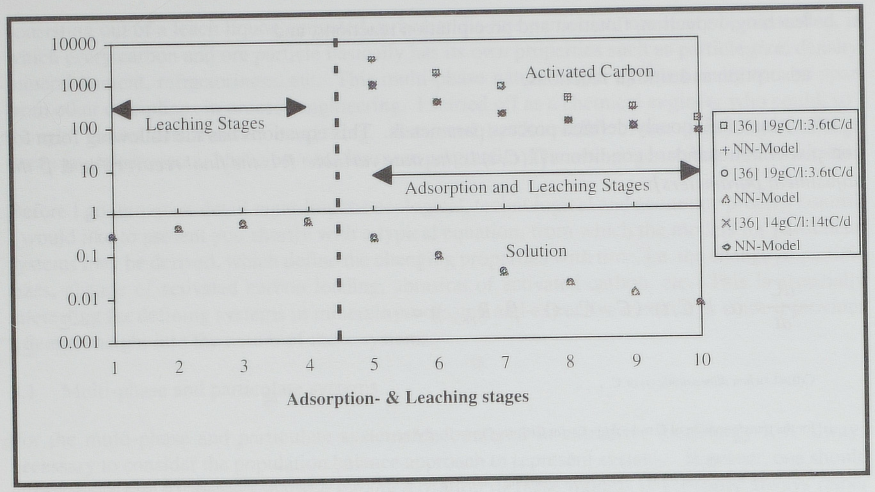

Figure 7 Comparison between plant data [36] and the generalised population balance eq. 3 for two different carbon concentrations and flow rates for an industrial carbon-in-leach operation

4. Eco-techno-economics

The discussion on gold has given you a glimpse into the multi-phase and property nature of our metallurgical systems. It has demonstrated that the system cannot be characterised by average parameters and properties only, but also parameters and properties that are defined as distributions are needed too. In a nutshell, this is what metallurgists are confronted by if they want to optimise their processes or if they want to control their plants optimally in an eco-techno-economic sense. Ladies and Gentlemen, I would now like to explore the concept of eco-techno-economics by referring to two of a number of industrial examples that I have been involved in and in which we have attempted to apply this philosophy.

To refresh your memory I would like to refer back to Figure 1 and extended it to an octahedron, the crystal structure of a diamond in Figure 8. This form has always had a fascination for me, especially since having had a hand full of many ca. 100 carat industrial diamonds while working in the high security area of a De Beers diamond recovery plant. I will like to leave the general interpretation of Figure 8 to you, however, let me concentrate on the interaction between ecology, economy, technology and man in nature.

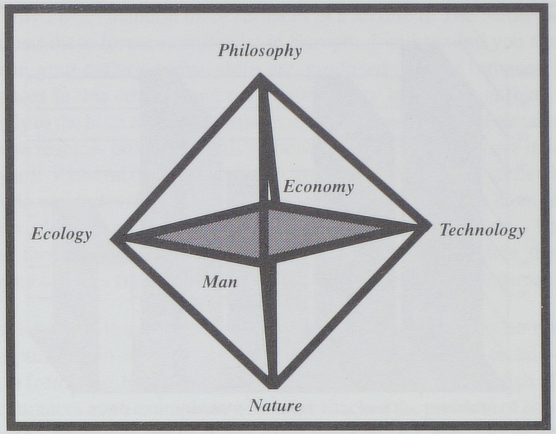

Figure 8 Eco-techno-economics and diamonds

4.1 Technology and Economics

Have you ever wondered where the silicon in your PC chip, or the chrome and manganese in the steel of your car comes from? What about nickel in the money in your purse? Well, above 70% of the estimated chromite world reserves are found in the Bushveld complex, depicted by Figure 9.

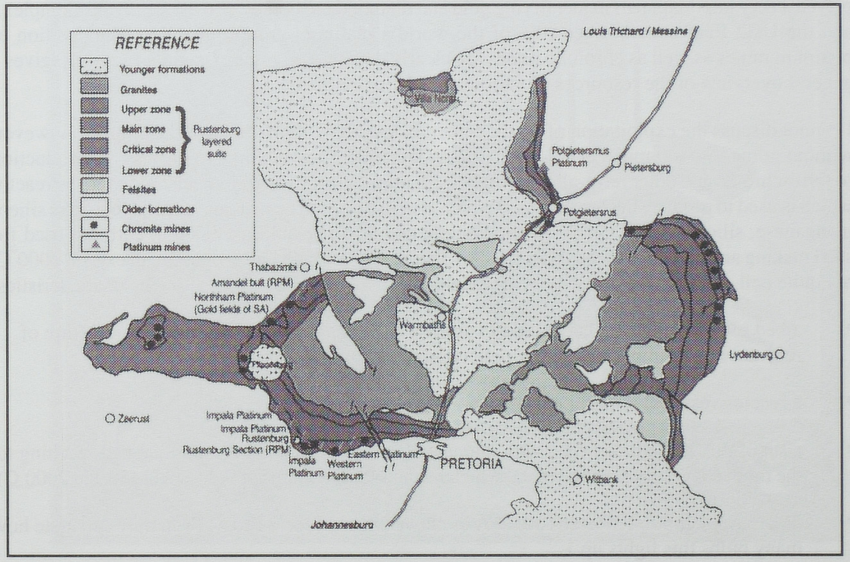

Figure 9 Bushveld complex (Mintek (1994) - with permission)

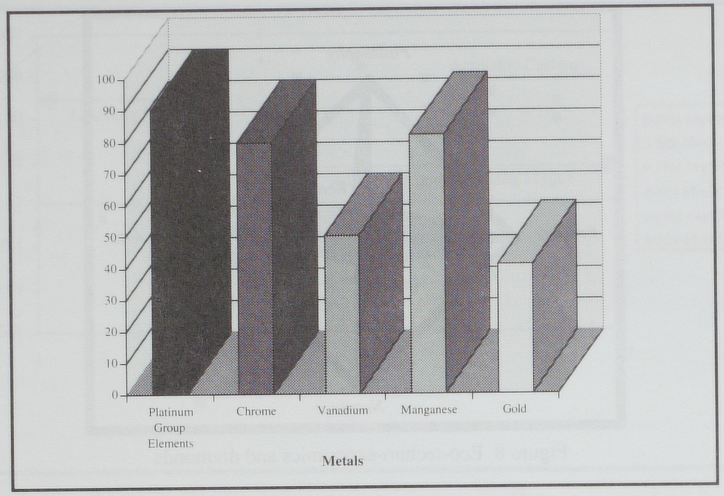

Figure 10 Metal reserves in South Africa - special reference to Bushveld Complex

Not only is this Bushveld complex a Pandora's Box for chromite but also among others for platinum group elements, copper, cobalt, nickel, gold, tin, fluorite and vanadium. It is truly one of the world's geological wonders. Some 2000 million years ago enormous volumes of molten magma intruded into the earth's crust. On slow cooling through a process of magmatic differentiation saucer shaped layered sequence of different rock types 9 km deep were created. The major platiniferous horizons, the Merensky Reef (Named after the geologist Dr. Hans Merensky, who played a very important part in identifying gold and diamond ore bodies, and the Bushveld Complex.) and the UG2 Reef contain over 80% of the world's platinum-group minerals. The position of platinum mines as well as chromite mines are clearly depicted on Figure 9, while Figure 10 gives a general overview of the resources of various metals in South Africa.

I cannot discuss the exploitation of all the minerals locked up in the Bushveld Complex, however, without going into too much detail, Ladies and Gentlemen, I would like to discuss the production of ferro-chrome and other ferro-alloys, which form important alloying elements in steel. The reactor which is used to produce the ferro-alloys (which also include ferro-manganese, ferro-chrome, silico-manganese, silico-chrome, ferro-silicon, silicon, and also phosphorus, calcium carbide) used for steel making and other products, is depicted by Figure 11, in which temperatures can exceed 2000°C, not quite hell, but probably close to it. Typically these furnaces have the following characteristics:

- a bed of particulate feed containing various coals, chars, charcoal, coke and a mixture of relevant ores (lumpy, sintered or pellets) up to 5 m in depth,
- a reactor vessel measuring up to 10 m in diameter,
- a set of three electrodes each with diameters up to 2 m sticking through the bed reaching to the molten layers of slag and metal which reaches temperatures of between (1450 and 2000°C),
- power consumption of over 100MVA or above 50MW (cos ø f≥0.5) (You may calculate how many bulbs this lights up.),
- and producing up to a few hundreds of tonnes of molten ferroalloy per day, the stuff that makes any real pyrometallurgist's heart go soft.

You may wonder why I even mention these furnaces in a lecture in The Netherlands and you may even question whether these furnaces still exist in Europe. I will remind you that not only are the elements in your car, your cutlery, trains, ships etc. produced in these furnaces, but also there are three of these furnaces in this country and may I add, pretty large ones at that. Furthermore, the same principles apply to the blast and other furnaces at Hoogovens and other metallurgical operations. You may think, these reactors produce metals somewhere in the World where it does not bother me or affect my backyard! Remember, however, each molecule CO_2 emitted somewhere in this world, does affect you, as do emitted residues, and as long as you use objects that have been manufactured somewhere in the world, you are accountable for any damage to our planet. Think of the ripples created by a stone thrown into a water pond. Therefore, it is imperative that the control and management systems of these furnaces be optimised no matter where the furnaces are situated.

In summary it can be stated that control systems that optimise a process no matter where in the world, should be optimised in such a way that they always address eco-techno-economics. This aim is rather easy to formulate, however, much more formidable to accomplish. I would like to use the submerged-arc furnaces as an example in which we attacked the problem of eco-techno-economic process control (same principles apply to the blast furnace). **By controlling these furnaces we could decrease energy consumption by more than 10% in the best example, which has direct economical and ecological benefits**. These furnaces have the interesting property that on the one hand one can control the electric side of the furnace rather well, but on the other hand one cannot characterise the particulate feed or define the process metallurgy very well. In short, in order to be able to control these furnaces well (feed-forward and feedback), one has to combine the electrical and metallurgical aspects in such a way that both aspects are taken care of in the most optimal way.

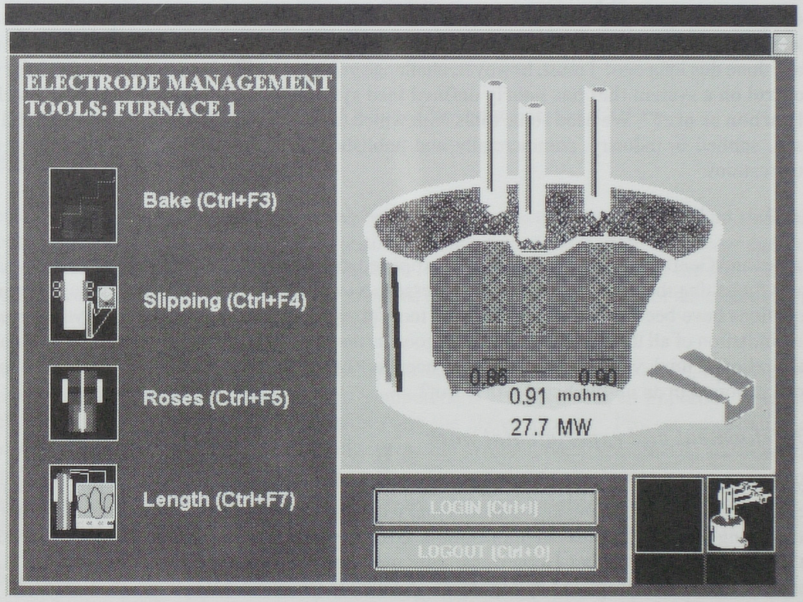

Figure 11 Typical schematic of a ferroalloy furnace with various (semi-)empirical process control tools as per FurnStar™

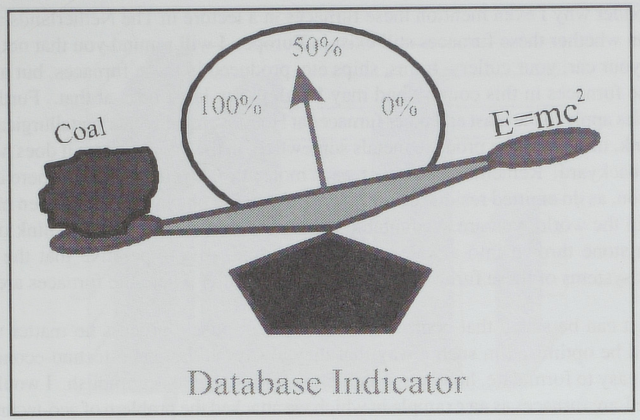

Figure 12 Well-defined and ill-defined systems

Permit me for the moment to return to my golden thread, carbon. If one considers Figure 12, two distinct systems are apparent, i.e. the well-defined system *(for which the parameters can be determined very accurately)* and the ill-defined system *(for which the parameters can only be determined very poorly, input and output relationships are only poorly known and equations can at most be semi-empirical)* So many of our metallurgical systems can be classified as such. The question is how do you optimally operate and control a system that only has very poorly defined parameters, such as the parameters that would define a chunk of coal? As Figure 12 suggest, for poorly defined systems, a well structured database forms the pivot and vice versa. This will become clear once we discuss a control structure for a poorly defined process below. You may say, but we have done this long ago! I must, however, challenge you by asking, **"Have you done feed-forward control on a system that has poorly defined feed systems especially particulates like a chunk of carbon or ore?"** We need some tools with which to accomplish this task, most of which I have used, applied in industry, commercially and published results on in various of my close to 70 publications.

4.1.1 Tools

Ladies and Gentlemen, the computer age has opened many doors with regard to the development of tools for testing theories and models of processes. Nice pictures created by the solving of complex equations have become a rather persuasive tool for engineers and scientists, however, remember the limitation of all these; these tools are as good as the boundary conditions and the sets of data for calibration. I think you can all relate to the accuracy of weather forecasts - how often have you not been captured in an un-predicted rain storm?

Development and experimental work

Let me start with the tool experimental work, as this is so important for determining fundamental relationships. Much testing and experimental work has been done and still will be done in future on existing plants to optimise their operation. Even new processes will be and are being developed at this moment - remember Hoogovens' new more environmentally friendly reactor for making raw iron and steel as depicted by Figure 13.

In addition to the various process developments so many basic relationships found in practical systems have not been explored and formalised in input-output relationships. It is imperative that these basic relationships be explored so that fundamental models could be calibrated. For example,

Figure 14 depicts the relationship between the liquidus temperature and various slag properties, which are so critical for optimal ferro-manganese production. This constitutes typical fundamental research in extractive pyrometallurgy, which unravelled the reason why furnaces of this type tend to sometimes explode. The subsequent formalisation of these measured experimental data is done with the aid of variety of analytical tools. These tools will now be discussed, from which it will become apparent how regions of optimal chemistry, physics and process and plant operation could possibly be identified.

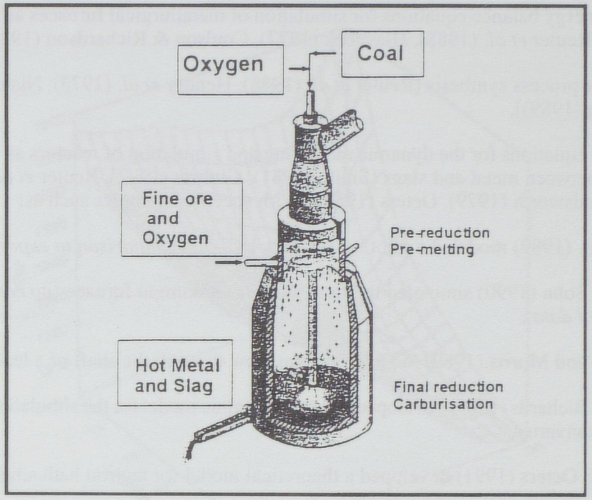

Figure 13 Hoogovens' Cyclone Converter Furnace (CCF)

Modelling and Simulation

Mathematical modelling and simulation has been part of extractive metallurgical and minerals processing for a long time now. As hinted at above, developments have often been slow due to a variety of reasons among which the following are a few (i) multi-phase nature of the systems, (ii) poor parameterisation possible of feeds and products, (iii) multi-dimensionality of the systems, and (iv) poor characterisation of particulate systems.

Due to ever stricter demands on product quality, stricter environmental legislation, tighter profit margins, flood of process data from process computers, it becomes ever so important to create models that can assist in alleviating and addressing the above aspects. Process computers are fortunately becoming faster and faster, making it possible to treat more and more data and simulate with models which are becoming ever more complex. The question to ask; Is it necessary to develop complex models for systems for which parameters are often only poorly defined? Well, there are a variety of modelling techniques available:

- *phenomenological models (fundamental models), i.e.* models that are based on physical and chemical fundamentals of the processes being modelled *(parameters can be derived independently e.g.* $E=Mc^2$*),*

- *semi-empirical models, i.e.* fundamental models, of which the parameters are estimated by calibration by e.g. least squares fitting of existing data *(the validity of these models are limited to the range represented by the fitting data and may not be generalised) e.g.:*

⇒ Navier-Stokes equations to model fluid flow in metallurgical reactors [Szekely (1988), Guthrie (1992), Ottow *et al.* (1989)],

⇒ finite element methods for simulating metal milling operations,

⇒ mass and energy balance equations for simulation of metallurgical furnaces as well as chemical processes [Reuter *et al.* (1988), Hlavacek (1977), Coulson & Richardson (1983)],

⇒ methods for process synthesis [Reuter *et al.* (1988), Hendry *et al.* (1973), Nishida *et al.* (1981), Westerberg (1989)],

⇒ differential equations for the dynamic modelling and simulation of reactors as well as diffusion processes between metal and slags [Smith (1981), Guthrie (1992), Reuter *et al.* (1992-1993), Sohn & Wadsworth (1979), Oeters (1989)], with specific examples such as:

◊ Barr *et al.* (1989) modeled a pilot scale rotary kiln *(no comparison to experimental data),*

◊ Hahn & Sohn (1990) simulated the shaft of the Outokumpu furnace *(no comparison to industrial data),*

◊ Hussain and Morris (1989) modeled the gas flow through the shaft of a lead blast furnace,

◊ Kyllo & Richards (1989) developed a thermodynamic model for the simulation of an industrial Nickel converter,

◊ Zhang & Oeters (1991) developed a theoretical model for an iron bath smelting furnace.

⇒ mass and energy transfer correlation [Guthrie (1992), Coulson & Richardson (1977, 1978), Reisener *et al.* (1993)], and

⇒ modelling of thermodynamic equilibria [Rao (1985), Reuter *et al.* (1992b), Bale & Eriksson (1990)].

- *empirical models, i.e.* models that have at their basis empirical equations with parameters that mostly reflect no physical meaning *(mostly application specific),*
- *regression analysis, i.e.* statistical methods that permit the approximation of functions and classification of data by the use of non-parametric methods *(application specific),* which include (i) *regularization nets* [Poggio & Girosi (1990)], (ii) *additive modelling* [Friedman & Silverman (1989)], (iii) *projection pursuit* and *recursive partitioning* [Friedman (1991)], (iv) *multiple adaptive regression splines - MARS* [Friedman (1991)], (v) *principle component analysis'* [SYSTAT (1992)], (vi) *group method of data handling - GMDH* [Ivakhnenko (1971), Ikeda *et al.* (1976)], and (vii) neural nets [Lippmann (1987), Rumelhart *et al.* (1986), Hornik (1989), Baum und Haussler (1989), Kramer (1991)].

A variety of examples using neural nets in chemical engineering and extractive metallurgy have been documented:

⇒ modelling and simulation of equilibria in metallurgy [Reuter (1994a), Reisener *et al.* (1993), Reuter *et al.* (1992b, 1993), Aldrich *et al.* (1994)],

⇒ diagnosis and simulation of reactors [Reuter & Bernhard (1994b), Reuter *et al.* (1993), Hoskins & Himmelblau (1988 & 1989), Moolman *et al.* (1995), Van der Walt *et al.* (1993), Leonard *et al.* (1992), Ungar *et al.* (1990), Bhat & McAvoy (1990)],

⇒ simulation of hydrometallurgical and minerals processing reactors [Reuter (1992 & 1993), Jämsä-Jounela (1991)],

⇒ process diagnosis of chemical processes [Hoskins *et al.* (1991), Pollard *et al.* (1992), Watanabe *et al.* (1989), Venkatasubramanian *et al.* (1990)] and

⇒ process control [Reuter *et al.* (1995, 1996), Moolman *et al.* (1995)].

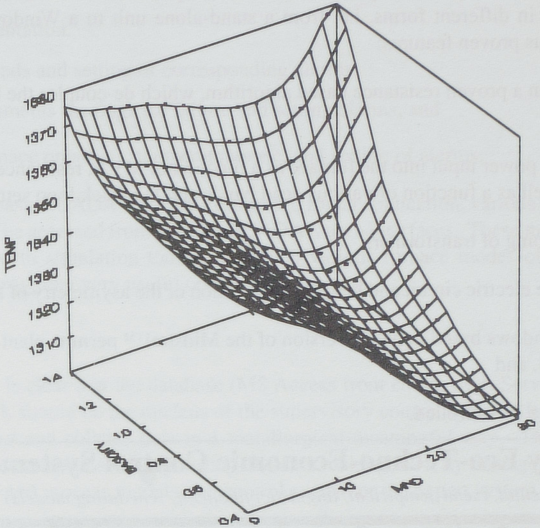

Figure 14 Liquidus temperature as a neural net function of basicity, %MnO and a variety of other factors which are constant for this 3D representation

- *knowledge based modelling i.e.* models that are based in symbological representation of data and information *(application and domain specific)*, e.g. expert systems for (i) selecting catalysts [Banares-Alcanatara *et al.* (1987)], (ii) process design and synthesis [Beltramini & Motard (1988),Lakshmanan & Stephanopolous (1988), Stephanopolous *et al.* (1987)], (iii) process modelling and control [Ungar *et al.* (1990), Bhat *et al.* (1990), Bhat & McAvoy (1990)], (iv) process diagnosis [Rich & Venkatasubramanian (1987), Venkatasubramanian & Rich (1988)] also with the aid of neural nets [Hoskins & Himmelblau (1989), Venkatasubramanian *et al.* (1990), Watanabe *et al.* (1989)], and (v) in extractive metallurgy for various applications [Reuter (1989-1992), Jämsä-Jounela (1991), Tucker & Lewis (1988), Sumitomo (1992), Ynchausti & Hales (1990)].
- *combined or hybrid models i.e.* a combination of two or more of the above mentioned models.

Process control

The aspect of process control ties on to the last point above, i.e. the hybrid modelling and simulation of processes. To illustrate process control for poorly defined processes let me present you a control technology my colleagues and I developed and implemented on industrial ferroalloy furnaces, in which we attempted to address ecological and economical optimisation of furnaces, all with one aim, i.e. to minimise damage to nature. From Figure 15 [Reuter *et al.* (1996) and Reuter (1997)] various levels can be discerned, each containing a mixed bag of the methodologies discussed above.

- **Levels 1 & 2**

The patented low-level control system (Minstral™) for submerged-arc furnaces has an international proven track record, having been implemented in various plants all over the world. This control system, packaged in different forms, i.e. from a stand-alone unit to a Windows based network version, has various proven features:

⇒ control based on a proven resistance based algorithm, which de-couples the movement of electrodes,

⇒ optimisation of power input into the furnace as a function of MVA, resistance, MW and current set-points as well as a function of various dead bands and feedback loop settings,

⇒ differential tapping of transformers,

⇒ balancing of the electric circuit and hence minimisation of the asymmetry of the electric circuit,

⇒ the TCP/IP Windows based network version of the Minstral™ permits plant wide maximum demand control, and

⇒ electrode baking is controlled.

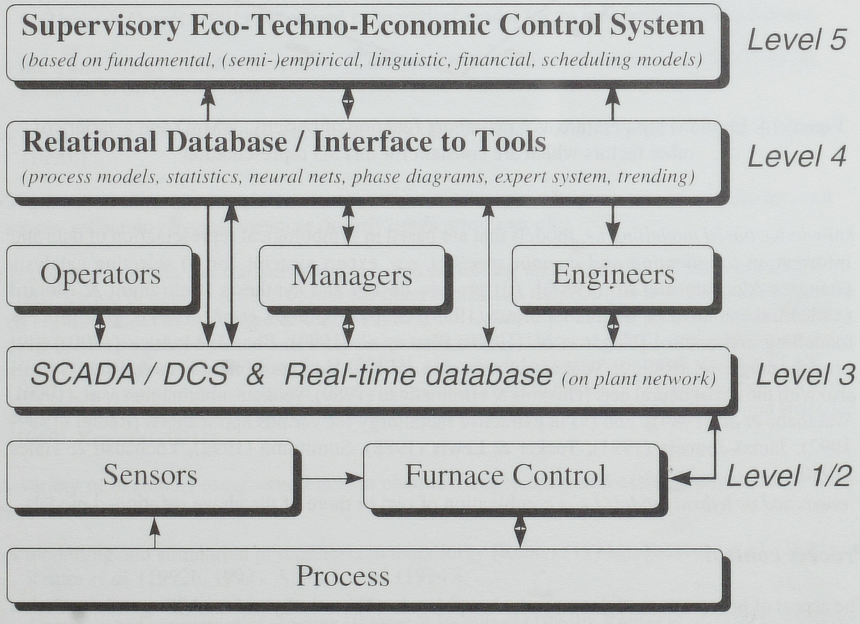

Figure 15 Control structure for a metallurgical furnace

- **Level 3**

The networked SCADA system (Intellution's FIX DMACS™ and Wonderware's InTouch™) provides all the standard features of such state-of-the-art packages, e.g.:

⇒ graphical interfaces, data logging, historical trending, and SQL-features,

⇒ intelligent multiple symptom alarming e.g. through the command language,

⇒ statistical process control,

⇒ on-line documentation,

⇒ checking of trends and setting of corresponding alarms,

⇒ checking instruments readings for failure and setting alarms, and

⇒ monitoring furnace pressures, temperatures etc. and setting of alarms.

In addition to the basic SCADA software customised for an application, various modular Windows utilities could also be accessed from the user-SCADA's user-interfaces. These model based utilities provide the user with simulation tools with which various furnace modes of operation can be simulated hence providing very useful operator guidance.

- **Level 4**

From Figure 15 it is clear that the database (MS Access front end to SQL Server) residing on the server of a network should be the nucleus of the supervisory control system. It accommodates all furnaces on a plant and collates data in a metallurgical meaningful way. This ensures that all datacan be considered simultaneously during decision making, be it by management, metallurgist, operator, fundamental process models, the control system or the expert system.

> *If you consider Figure 12 again, you will now understand why this level is of such utmost importance. Since the furnace system, its feeds and products, are only poorly defined, one requires accurate process data sets to be able to calibrate semi-empirical models, create statistical models, etc. Therefore, the more poorly our system is defined the more heavily the control system makes use of a well structured database.*

For this reason we built a variety of features into our database (Figure 16) and should be accessible from the database ensuring its metallurgical usefulness:

⇒ An interface is provided to input raw material and raw materials analyses into the database if automatic downloading is not catered for via a SCADA.

⇒ All electrical and other real-time data are acquired from the model based control system by the application of the SQL-facilities of the SCADA package.

⇒ An interface is provided to input production data as well as metal and slag analyses from the laboratory and the control room, which could also be automated if the analysis equipment is linked to the database.

⇒ The slag data is presented in a visual form by superimposing the slag Basicity on suitable phase diagrams.

⇒ Mass and energy balances are calculated automatically as a function of the various feed materials and production outputs and compared to actual values.

⇒ Trends in any combination of data in the database can be shown in order to investigate the interrelationships that exist between the various data collated by the database.

⇒ The data are presented in a visual three dimensional form by the application of techniques such as neural net regression modelling and neural net data classification by Kohonen feature maps or Sammon neural nets.

⇒ Expert guidance is provided by the expert system (interacts with the database) on electrical aspects such as (i) suggestions on how, why and when furnace operating limits set by the model based control system can or may be changed, and (ii) reasons why and how to combat electrodes climbing out etc.

⇒ Expert guidance is also given on metallurgical/electrical aspects such as (i) relating feed compositions to given products and (ii) fault diagnosis, i.e. suggesting changes to feed or operation as a function of product quality, specific energy input, metal recovery/losses to slag, materials input, type of reductant, etc.

⇒ An automatic interface is provided to Windows based statistical packages that permit the macro-driven advanced statistical analyses of data as well as the three dimensional data interpolation of data to investigate the interrelationships of three variables at a time.

⇒ Reporting facilities generate shift, daily and monthly reports.

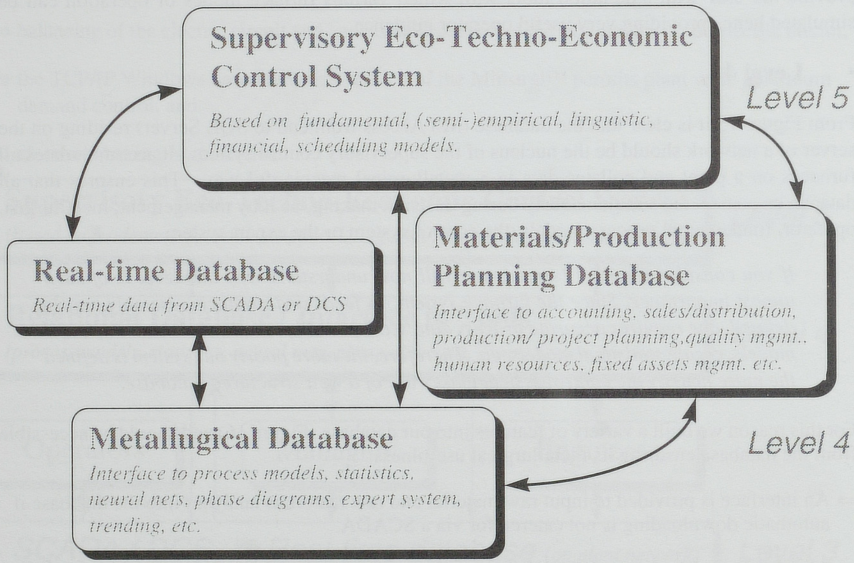

Figure 16 Details of the different databases

In addition to the above features the following utilities will also be accessible (i) interface to a thermodynamic simulator, (ii) linear programming modules to perform plant wide optimisation, and (iii) real-time data mapping by neural nets such as Sammon nets linked to an expert system, which makes use of dimensionless feed and reductant numbers (Figure 17). Metallurgical know-how that is integrated into this database sets it apart from the normal database which any non-metallurgist database builder would provide.

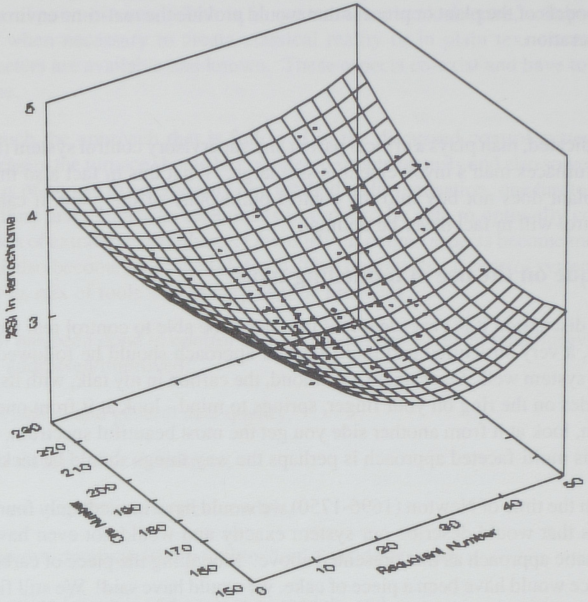

Figure 17 Industrial ferro-chrome quality as a neural net function of dimensionless ore and reductant feed numbers that characterise the particulate feed

- **Level 5**

As is clear from Figure 15 various types of on-line models can be developed for this level, a list which could include expert systems, neural nets, scheduling, ecological simulation and plant wide optimisation models.

⇒ An expert system should only perform those tasks that cannot be modelled or expressed in a fundamental way i.e. it should support the model based control and not replace it. Furthermore, it should not duplicate the functionality and features provided by state of the art SCADA packages and it should also not replace metallurgical empirical and fundamental models. If possible, the use of an expert system should be limited to aspects of the process which are well defined. This would ensure that the control strategy does not fail if the furnace operation moves into a domain that is perhaps not covered by the rules in the expert system's rule base. Areas of application of real time expert systems for well defined procedures are

◊ orchestrate start-up and shutdown procedures,

◊ assisting the model based control by downloading suitable set-points as a function of both electrical and metallurgical data,

◊ intelligent alarming and instrument checking, if this does not duplicate alarming through the SCADA, and

◊ plant wide maximum demand control via an installed network.

⇒ Online financial, management and scheduling models, and
⇒ Ecological models of the plant or process that would provide the real-time environmental impact of current operation.

- **Level 6**

Although not indicated, man plays a critical part in any supervisory control system (Figure 15). For submerged-arc furnaces man's involvement is still large. What this in fact also implies is that, if everyone on a plant does not buy into the control philosophy of the plant, it can be stated that supervisory control will in fact never be optimal.

4.1.2 A critique on the use of modelling tools

From the above discussion it is very clear that in order to be able to control real industrial poorly-defined systems, a very structured and multi-faceted approach should be followed in order to be able to control a system well. Once again a diamond, the carbon in my talk, with its many polished and sparkling sides on the ring on your finger, springs to mind - look at it from one side you get a certain reflection, look at it from another side you get the most beautiful spectrum, or heat it and it will burn. This is multi-faceted approach is perhaps the way things should be tackled.

If we had lived in the time of Newton (1696-1750) we would have immediately found our solace in sets of equations that would describe our system exactly and would not even have considered a multi-tier pragmatic approach as that presented above. Modelling the piece of carbon or ore in the feed to the furnace would have been a piece of cake, we would have said! We still find solace these days in huge sets of equations which we solve in computers that are becoming faster and faster. Alas, very much like Newton, who solved the three body problem only by approximation, we are still not quite capable of describing a chunk of carbon in such a way that we can use it in a nice set of differential equations, which optimise a metallurgical reactor.

As you know, in the last three centuries we moved from Newton to Einstein, we moved from the precise Newton mechanics to Einstein's relativistic mechanics of which one result was the famous exact equation on the right side of the balance in Figure 12. Einstein, however, also bumped his head into something called quantum reality, something that originated from him through his quantum considerations of light. The ensuing quantum mechanics talks of collapsing probability wave functions - hence creating reality. Ask yourself the question - if you have quantum physics on the one side of the scale in Figure 12 and classical relativistic physics is on the other hand, were is the wave function going to collapse, were does the classical reality start? What can be modelled and what cannot be modelled? [Gribbin, 1995]

I sometimes feel we metallurgists are walking the same path. We look at a heap of junk, and ask ourselves, what is the reality of this heap of junk? How do you characterise it? How do you parameterise it to describe it and how do you determine the parameters experimentally? Have you ever tried to describe the reality of your heap of rubbish in the trash can in you kitchen or looked into your corn flakes bowl in the morning and wondered how the flakes are digested in your stomach? What about a piece of steak?

In this macroscopic particle nature of our everyday environment, the wave-particle duality of quantum reality comes to mind as an analogy. It is this and Heisenberg's uncertainty principle that have had a very clarifying influence on me on how to consider a heap of junk or a heap of coal. There is an interesting analogy between quantum mechanics describing a probability wave function and process metallurgy using population balance modelling to describe certain systems. Do not get me mistaken and accuse me of trying to equate lofty quantum physics with particulate junk, but I think you can follow my general point of view, which is, in quantum mechanical terms, collapse the probability wave function when necessary to create classical reality or in plain text create a deterministic model if parameters are available and known. These aspects co-exist and have to be taken care of at the same time.

This is very much the approach that is followed in the discussed control system, i.e. the many aspects that represent the furnace should be considered simultaneously and also solved simultaneously in real-time. It is of no use to opt for only one method or formalisation, one has to apply the whole range of modelling and simulation techniques in order to be able to optimally control the poorly defined processes of extractive metallurgy. Obviously, as certain aspects become more well-defined, the models will also become more well-defined. This implies that a control system in itself should be dynamic, or its mix of tools should vary as time proceeds.

Although much has been done to control poorly defined processes in metallurgy, various aspects still need to be addressed/improved:

- feed characterisation and general data quality,
- real-time data visualisation techniques,
- real-time in- and output metallurgical models,
- sensors to improve data acquisition and to "look" inside reactors,
- definition of online financial and ecological models, and
- improved synthesis of different techniques in industrial multi-level control system.

Ladies and Gentlemen, you may at this point ask what is still the role of man in all this? If you can remember, man has a critical part to play in the whole metallurgical control philosophy of poorly defined systems and it is in fact he who continuously improves the system. He is really the learning machine! You may not agree with this in view of Deep Blue's accomplishment, however, remember that the boundaries of chess are rather well-defined. To conclude, just a final though in this regard with reference to the control system in planes. In relation to a metallurgical system, a plane is a rather well defined system with fairly well-established in- and outputs. In spite of having a well defined control system, sensors, models etc. two pilots still ensure that you arrive at your destination safely! When this will change, who knows? On the other hand a metallurgical process is still very much further removed from the concept of a pilotless plane!

4.2 Ecology of metal cycles

Ladies and Gentlemen, in the context of this paper I would like to concentrate the ecological aspects on energy consumption as well as mapping of hazardous materials originating from individual processes. In the previous section I discussed what a control system should look like to optimally control poorly defined metallurgical processes. Performing this process control task well has immediate spin-offs for the ecology. I would like to take this a step further by considering a number of processes at the same time and see what their total environmental impact is. Therefore, rather than considering a plant with a number of unit operations, **I would by analogy like to consider the world as my plant and different processes in the world as my unit operations**.

By following this approach I come back to my basic philosophy that everything is linked to each another, that emissions are never to be considered in isolation, that it is very debatable to place plants in places where environmental control is poor, that all decisions on this earth always have a ripple effects i.e. they always have consequences. The question is, how does one consider this problem, i.e. how can one ascertain what affects what, by how much and when?

Let my try to answer this question by considering metal cycles that are not only inter-linked by alloy production but also by the emissions they create and especially by the energy they use, which mostly has its origin in fossil fuels - i.e. we are back to consider the golden thread in this talk carbon. It is really this we are attempting to map.

Before we go into detail I would like to present a few tools available to us.

4.2.1 Tools

Process synthesis has been part of process engineering for many years [Nishida *et al.* (1981), Westerberg (1989)]. Various examples may be mentioned, e.g.

- planning and lay-out of heat exchanger plants [Nishida *et al.* (1981), Kobashi *et al.* (1971), Hendry *et al.* (1973), Hirai & Ichikawa (1972)],
- synthesis of process plants [Mahalec & Motard (1977), Nath & Motard (1981), Lu & Motard (1985)] also with the aid of expert systems [Kirkwood *et al.* (1988)],
- synthesis of flotation and gravity separation plants and gravity [Reuter & Van Deventer (1990, 1992), Reuter *et al.* (1988), Green (1984), Mehrotra and Kapur (1974), Yingling (1993a&b), Aldrich *et al.* (1993), Anthony *et al.* (1991)], and
- synthesis of zinc processing routes [Reuter *et al.* (1995, 1996), Sudhölter *et al.* (1996)].

Process design [Hlavacek (1977), Coulsen *et al.* (1983)] is a well established field with numerous simulation software packages on the market, e.g. for chemical engineering ***ASPEN PLUS***, and for minerals processing and extractive metallurgy, ***USIM PAC***®, MicroSim [Stange *et al.* (1988)] and METSIM.

4.2.2 The world as a processing plant

Metallurgy is characterised by many possible process routes [Bruch et al. (1995)]. The question often arises as to the best route not only in view of technology and economics, but also ecology. Recent papers [Reuter et al. (1995, 1996) and Sudhölter et al. (1996)] have attempted to render the process route selection for Zn production more objective by the application of an eco-techno-economic formalism. This approach basically advocates using the available processes and "optimising" the link between unit operations to achieve an environmentally as well as economically sustainable operation. At this point, this approach does not take cognisance of any interactions with production routes of other metal, e.g. steel, Cu, Al, Sn, and associated alloys. Hence, these interactions cannot be utilised to evaluate the "optimal" solutions produced with reference to the reactions of interacting metal production routes.

Environmental or eco-software (also life cycle software) could be used to establish the eco-impact of various metal production routes. However, it cannot map the various interactions that connect all metal flows in a complex web, i.e. these software cannot consider the world as a processing plant. Eco-software tools are often used by decision makers, in spite of having a number of serious flaws e.g.:

- different process route options are not included and therefore impairing generality,

- dynamic interactions between different metal cycles are not really considered,
- location of mining and metals production and the usage of products is not considered,
- the boundary is often not seen to be a global one implying that an incomplete and simplified picture of reality is presented,
- often only average values for energy and emission are used, seriously questioning validity, and
- the translation of mass balances into environmental effects is done by "black box", of which the content is not transparent.

Considering the above flaws it is obvious that the basic structure of eco-software must be improved, i.e. one that defines the major and minor metal flows of different metal producing routes as they interact with one another taking cognisance of the source, production, usage and recycling location of the metals. The questions which should, therefore, be answered are (i) how does a modelling structure look like that can capture the above features? and (ii) how can one visualise metal flows that they become transparent to all decision makers? In view of these questions it is the objective of this paper to discuss the eco-techno-economic modelling and simulation of metal cycles by the use of

- the USIM PAC 2.1 simulation software, and
- a database containing relevant environmental, energy, economic and metal split-factor data useful for simulation (as far as possible), (in accordance with Figure 12)

in order to supplement the available eco-software and hence improve eco-impact predictions. This definition of the basic metal flows places the simulation on a metallurgical fundamentally sound platform on which it is possible to compare different process routes and interactions objectively or speak a common language. The characteristics of such an approach are with reference to the world (as far as available data permit)

- **factories**, i.e. each module in the flow sheets is defined as a factory with in- and outputs e.g.:

⇒ simplistically transport is a factory with among others fuel and ore as inputs, and among others emissions and ore as outputs

⇒ a mine is a factory with among others energy and dynamite as inputs, and emissions and ore as outputs

⇒ also see figures 17 and 18 to get a brief overview on other typical factories

- **visualisation**, i.e. the complex interactions between metal flows (Figures 17 and 18 are a sample of over 20 different interacting flow sheets for Cu, Pb, Sn and Zn) are made clear,
- **design for sustainability**, i.e. a metal processing flow sheets covering the globe can be designed by not only taking economics and ecology of particular plants into consideration, but also the economic and ecological reactions of connected flow sheets, and
- **environmental effects**, i.e. not only are the main elements visualised but also the flow of minor elements can be mapped and hence their respective interactions linked to flow sheets.

It is obvious that it is extremely difficult to model and parameterise all metal flows and interactions in the way suggested here. However, the poorly defined structure of eco-software for metal production and processing makes such an approach imperative to ensure that metal production can be sustained. In addition, this visualisation of metal flows can assist in designing/selecting better plants for the future.

4.3 The Future?

The above has discussed process control in metallurgy as well as the modelling of metals cycles in the world. All these developments have among others the principal objective to improve the environmental impact of extractive metallurgy, i.e. minimise waste and emissions not forgetting the every important economic aspects.

It may well be safely stated that the metallurgical plant of the future will form an integral part of closing the metal cycle in recycling, will be clean, minimise energy usage, will accept feed materials not only from primary but also from secondary sources, and foremost will be an eco-techno-economic discipline.

5. Summary

Ladies and Gentlemen, we have talked about mining, geology, geophysics, extractive metallurgy, recycling of materials and metals (all disciplines taught at our faculty) and, process control and its economical and ecological benefits, carbon and diamonds, and ultimately of eco-techno-economics. In view of the above I, therefore, consider the following aspects of importance for my chair:

Students

- Students are trained to become professionals that are capable of optimising and improving themetallurgical and particulate materials treatment technology. This should be done with aid of all possible tools, which include a unit-based approach to defining technology, a complete overview of all primary and secondary metal and materials cycles, process simulation, process control, process synthesis, practical know-how; at all times maintaining an acute awareness of the environment and process economics.

Research

Research work will focus on

- fundamental experimental work to calibrate developed theory to improve metallurgical process performance for primary as well as secondary (recycling) processes,
- the controlling (in a wide sense) of extractive metallurgical processes (primary and secondary) in view of optimising their economic and ecological impacts
- improve extractive metallurgical technology so that the economics and the ecological impacts are optimised, and
- integrate various of the above mentioned tools, e.g. experimental work, modelling, simulation and artificial intelligence, in order to optimally control processes or provide plant personnel with tools to do the same.

If I return to the question I posed at the start of my lecture regarding the oneness of nature and technology. Considering once again my diamond structure of earlier. Probably the only way one can start approaching this is in our consumer society is through clear control (in a wide sense) structures accommodating eco-techno-economics on a plant as well as on a global scale as discussed in this paper. The only other alternative is to diminish our uncontrolled use of raw materials.

If I may leave you with the thought that everything is connected, among others by carbon, and reminding you that Diamonds are Forever, I would like to thank you for your attention.

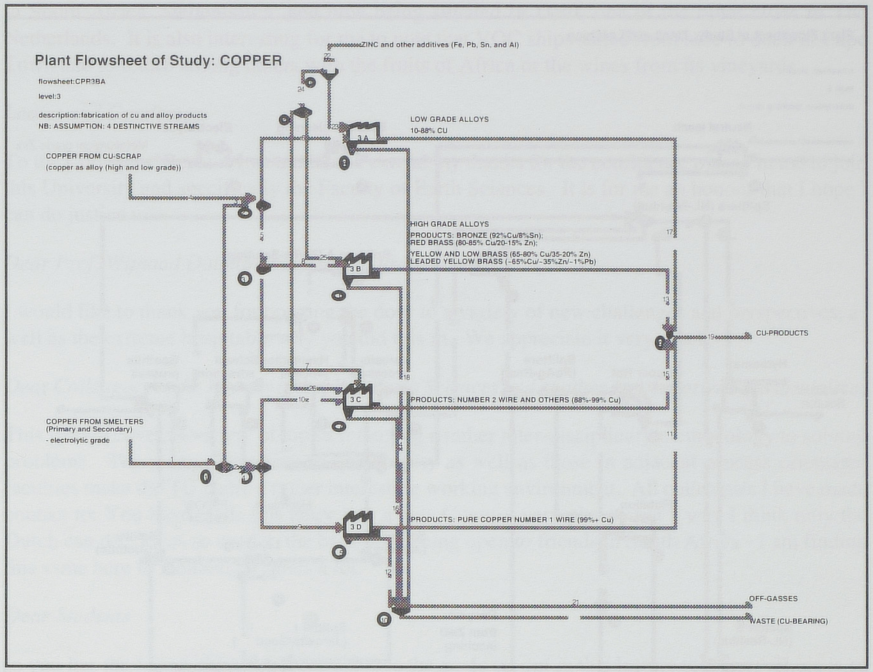

Figure 17 Section of the copper flow sheet with various factories (alloy production)

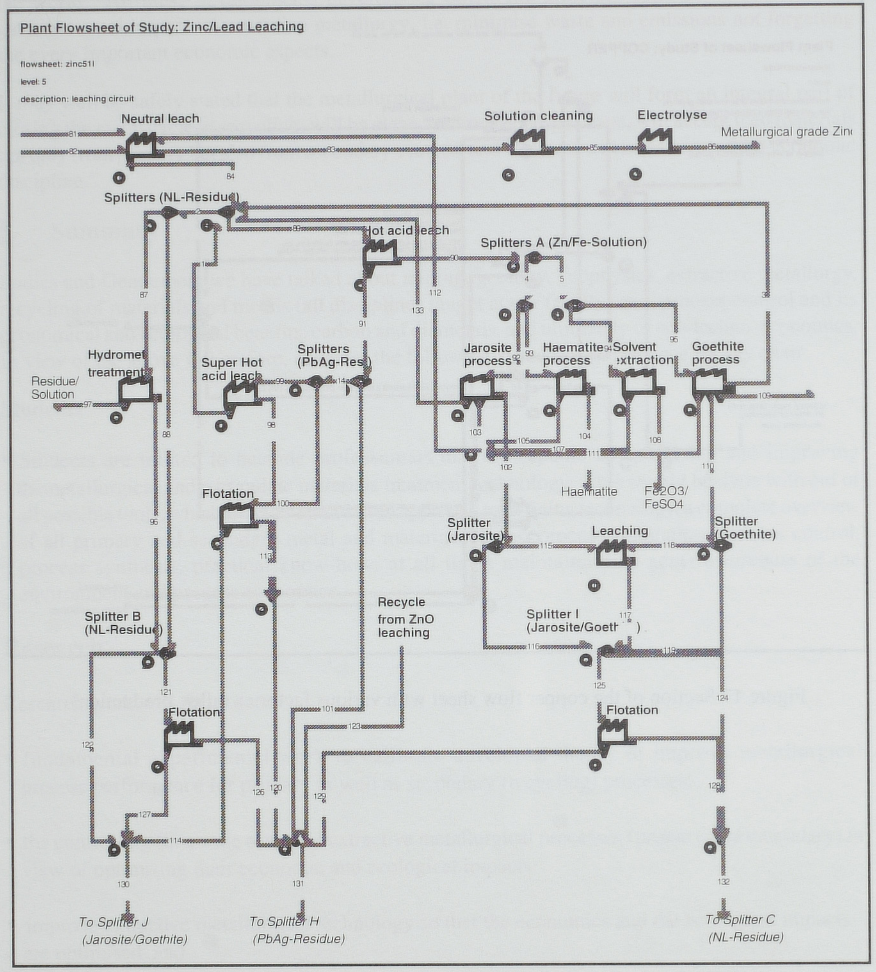

Figure 18 Section of the zinc flow sheet with various factories (hydrometallurgical zinc production)

6. Votes of thanks

For me it is a bit of a circle closing having grown up in the second oldest Dutch and European town in South Africa, Stellenbosch, and now being situated in Delft, one of the older cities in The Netherlands. It is also interesting for me to note that VOC ships sailed from here to dock in Cape Town and to return among others with the fruits of Africa or the wines from its vineyards.

Ladies and Gentlemen

To the College of Bestuur I would like to extend my thanks for the confidence placed in me to join this University and specifically the Faculty of Earth Sciences. It is for me an honour that I hope I can do justice to.

Dear Prof. Wijnand Dalmijn and Prof. Ruurd Heerema

I would like to thank you for opening the door to a variety of new challenges and perspectives, as well as the extreme hospitable way you did this in. We appreciate it very much.

Dear Colleagues at the Faculty of Applied Earth Sciences and at other process orientated disciplines

This lecture covers a variety of topics reflecting a rather inter-disciplinary methodology to solving problems. The many disciplines in our Faculty as well as those in adjacent process orientated faculties make the TU Delft a rather interesting working environment. All colleagues I have made contact to: You have made this entry into a new Country very pleasant in a way I think only the Dutch can do. I was so used to the back door being open to friends in South Africa - I am finding this same here in Holland. Thanks a lot.

Dear Students

In you lies the future. I hope we can achieve the goals set out in this lecture together. There is so much to do and still to talk about - I hope I have the privilege in sharing this with you, not only Technology but also Philosophy.

Dear Mentors all over the World

I have been fortunate to have had a number of Mentors, which are presently situated all over the world. Usually we meet over a good supper at conferences and carry on were we left off the previous time. Unfortunately they are all not present here today and Mr. Spock with his beam not either! Very much like what happens to an uncut diamond, each of these Mentors polished one of my sides. In there absence I would like thank them for their polishing.

Dear Karen

You have polished so many of my unpolished sides with your Philosophy. The music in our life especially your own and Mozart is always with me and our children, Tatjana and Jean-Michel.

Dear Nature

Let us respect you!

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