CHARACTERISATION AND
CONTROL OF THE ZINC
ROASTING PROCESS

JENS NYBERG

Faculty of Technology,
Department of Process and
Environmental Engineering,
Systems Engineering Laboratory,

University of Oulu

OU LU 2004
JENS NYBERG

CHARACTERISATION AND CONTROL OF THE ZINC ROASTING PROCESS

Academic Dissertation to be presented with the assent of the Faculty of Technology, University of Oulu, for public discussion in Kuusamonsali (Auditorium YB210), Linnanmaa, on December 17th, 2004, at 12 noon.

OULUN YLIOPISTO, OULU 2004
Nyberg, Jens, Characterisation and control of the zinc roasting process
Faculty of Technology, University of Oulu, P.O.Box 4000, FIN-90014 University of Oulu, Finland,
Department of Process and Environmental Engineering, Systems Engineering Laboratory,
University of Oulu, P.O.Box 4300, FIN-90014 University of Oulu, Finland
2004
Oulu, Finland

Abstract
Increasing efficiency is a necessary target for an industrial roaster nowadays. This thesis presents some studies on efficiency improvement in the zinc roasting process - process characterisation, control design, implementation and testing.

The thesis focuses on the roaster, i.e. on research regarding the phenomena in the roaster furnace. By learning more about the roasting mechanism, particle size growth and dynamics of the furnace, new control implementations have been developed. More measurements, analyses and calculated variables have been added to give more information on the state of the furnace. New control variables have been introduced to give the operators more opportunities to set the conditions so that they are more suitable for the actual concentrate feed mixture. Equipment modifications have also been done.

In this research, both laboratory and plant experiments have been performed together with thermodynamic evaluations and calculations. It has been necessary to make plant trials in order to obtain information about the impacts of different variables on the process. Only full-scale experiments give reliable results of the behaviour of an industrial furnace. The experiments with the roaster furnace have emphasised the study of both the metallurgy and the dynamics of the roasting process. The on-line calculated oxygen coefficient and its active control have proved important. The particle size distribution analysis of the furnace calcine has been shown to be a significant source of information for evaluating the state of the roasting furnace.

The main target is to improve the economic performance. The key is to be able to be flexible in using different kinds of raw materials, because the main income is the treatment charge. The trend is that concentrates are becoming finer, which increases the challenges for roaster furnace control. The capability to use low-grade concentrates is also a major challenge and improves the economic result.

Research and development on the boiler and mercury removal has also been part of this work for many reasons. Improved boiler performance and mercury removal gives more freedom in choosing concentrates and operating the roaster furnace. The approach has been the same as in the roaster furnace research and development work.

Control improvements based on existing knowledge, such as fuzzy control systems for controlling the furnace temperature and mercury removal, did stabilize the process, but they did not solve all the problems regarding process stability. The research and development concept of this thesis has provided the extra knowledge needed for further improvement of process control. The results of the process characterisation have led to the implementation of a new and effective control strategy.

The research and development carried out has improved performance in a number of ways: increased running time of the furnace and boiler, in-depth knowledge of roasting phenomena which led to new control methods and instructions for the operators, improved quality of sulphuric acid and a method to control its quality, measurements and analyses that give valuable information of the state of the process – all of which are now in use.

In the future, the emphasis will be placed on the research and development of roaster furnace performance, which will be a great challenge. Control of the roaster furnace is the key to the economic success of the roasting process and more information about these phenomena is needed for improving and optimising control.

Keywords: control applications, control methods, process dynamics, roasting process
Acknowledgements

The theme of this thesis is to improve zinc roaster efficiency. Characterisation of the process has led to better control of the process. The process that has been developed is in use at the zinc roaster of Boliden Kokkola Oy in Kokkola, Finland, now a part of the new Boliden Group.

The work was supervised by Professor Urpo Kortela. I would like to thank him for his advice, comments and support. He was the initiator of my postgraduate studies. I was also made welcome by other postgraduate students and the personnel at the systems engineering laboratory at the University of Oulu. This period in my life has been challenging and interesting in many ways. It has entailed a lot of work. To combine daily work with studies requires energy, however sometimes it can give energy too.

I wish to thank my boss, Mr. Kullervo Myllykoski, for the trust he showed during the research and development period. The freedom to do full-scale plant experiments was both challenging and necessary. Kullervo’s support was invaluable, because this kind of development requires both time and money.

I would like to thank my colleagues for their dedication and encouragement during this research and development process. I am especially grateful to Dr. Pekka Taskinen and Mrs. Maija-Leena Metsärinta for this long-term research co-operation, their comments on my work and their positive attitude. I would also like to thank other colleagues, such as Dr. Antti Roine, Dr. Björn Saxén, Mr. Juha Järvi, Mrs. Heljä Peltola, Mr. Heikki Siirilä, Ms. Aija Rytioja and Mr. Hannu Vainonen. Their contribution has been of great importance. Many other people have also contributed and special thanks goes to the whole personnel of the roaster department. The performance and attitude of the operators, both during the testing periods and in implementing the results, was excellent. I am also grateful for the support and encouragement of my friends and nearest and dearest.

For correcting the text I would like to thank Ms. Margaretha Niemi. The proofreading of the text into correct English was done by Mr. Mike Jones and Ms. Sue Pearson at Pelc Southbank Languages. I wish to thank Mike and Sue for their excellent work.

My son Daniel and my daughter Johanna have been in my thoughts during this period.

Kokkola, 21 November, 2004

Jens Nyberg
**List of abbreviations**

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Full Form</th>
</tr>
</thead>
<tbody>
<tr>
<td>ESP</td>
<td>Electrostatic Precipitator</td>
</tr>
<tr>
<td>HR</td>
<td>Human Resources</td>
</tr>
<tr>
<td>ISF</td>
<td>Imperial Smelting Furnace</td>
</tr>
<tr>
<td>LME</td>
<td>London Metal Exchange</td>
</tr>
<tr>
<td>ORC</td>
<td>Outokumpu Research Centre</td>
</tr>
<tr>
<td>R&amp;D</td>
<td>Research and Development</td>
</tr>
<tr>
<td>SEM</td>
<td>Scanning Electronic Microscope</td>
</tr>
<tr>
<td>SOM</td>
<td>Self Organizing Maps</td>
</tr>
<tr>
<td>TC</td>
<td>Treatment Charge</td>
</tr>
<tr>
<td>WHB</td>
<td>Waste Heat Boiler</td>
</tr>
</tbody>
</table>
List of figures

Fig. 1. Key elements in the development of the new control strategy .................. 19
Fig. 2. High roasting performance can only be reached through broad
development. Many factors must be taken into consideration to
reach the targets, as shown in the diagram ................................. 20
Fig. 3. Roasting research and development procedure ......................... 21
Fig. 4. Boiler research and development procedure has also been diverse ....... 24
Fig. 5. Experimental apparatus of furnace and boiler (scale 1:20) built for
flow model testing .............................................................. 24
Fig. 6. Thermodynamic equilibrium calculations were essential in the mercury
removal research and development procedure ............................. 25
Fig. 7. A block diagram of the Kokkola zinc process (Takala 1999).
Concentrates are fed both to the roasting process and
concentrate leaching, which increases flexibility. Concentrates
more suitable for roasting are fed to the roaster, while those more
suitable for leaching can be fed to concentrate leaching .......... 29
Fig. 8. Schematic diagram of a Lurgi type fluid bed roaster furnace
(Themelis & Freeman 1983/1984) ........................................... 30
Fig. 9. The particle size distribution varies for different concentrates ........ 34
Fig. 10. Microscope picture of Aznacollar concentrate. The pellets contain
mostly small particles ............................................................ 35
Fig. 11. Microscope picture of Trzebionka concentrate. The pellets also
contain large particles ............................................................ 35
Fig. 12. Schematic drawing of the reaction principle. The sulphide mineral
particle reacts with oxygen. The product is calcine (mostly ZnO).
During the reaction SO2 gas is formed ..................................... 36
Fig. 13. Schematic drawing of a calcine agglomerate formed of many small
calcine particles. Bonds are formed between particles due to molten phases.. 36
Fig. 14. Agglomerate from the furnace (November 2001) – origin Aznacollar
concentrate ................................................................. 37
Fig. 15. Agglomerate from the furnace (November 2001) – origin
Polaris concentrate ............................................................. 37
Fig. 16. Grain size distribution of concentrate versus calcines.
The formed calcine is coarser than the concentrate, especially the overflow calcine from the furnace.

Fig. 17. The Geldart classification of particles into their fluidisation behaviour in air at ambient conditions (Geldart 1986). The density of calcine in the fluidised bed gives the working area in the upper part of B.

Fig. 18. Fluidisation characteristic diagram, velocity versus particle diameter (Geldart 1986). The diagram shows the working area for a fluidised bed.

Fig. 19. Basic and advanced measurements of the furnace.

Fig. 20. The control of the furnace is a multivariable system. Many aspects must be considered. Knowledge of the dynamics and the thermodynamics of the process is essential.

Fig. 21. Control inputs of the different control levels for the furnace control.

Fig. 22. The calculation scheme for the oxygen coefficient and its use for control. This has been adopted and is now in use in the control of the furnaces at the Kokkola roaster.

Fig. 23. A furnace control diagram is shown with advanced control and measurements. It includes among others a fuzzy control loop, the calculated oxygen coefficient, oxygen measuring from the gasline, calculated calcine overflow amount and grain size distribution analysis of the furnace calcine. The possibility of feeding water to different spots and oxygen is also available.

Fig. 24. The drop in windbox pressure and the increased proportion of fine calcine indicate an unstable bed.

Fig. 25. Temperature drop indicates an unstable bed. Temperatures measured from the sidewall fell while the temperature measured from the bottom remained stable.

Fig. 26. Sulphide level of the calcine (WHB, Cyclone and ESP) decreases when the oxygen coefficient is high.

Fig. 27. Sulphide level of the WHB calcine is lower when the oxygen coefficient is high.

Fig. 28. High oxygen coefficient increases the amount of sulphates. Difference SO₄ = the amount of sulphates minus PbSO₄ and CaSO₄, which are always sulphates in roasting conditions.

Fig. 29. High oxygen level in the WHB gas increases the sulphate amount.

Fig. 30. High oxygen level in the WHB gas decreases the sulphide amount.

Fig. 31. Oxygen feed versus fine and coarse particles in the bed. During oxygen feeding the amount of fine particles decreased, while the amount of coarse particles increased.

Fig. 32. The oxygen coefficient versus fine and coarse calcine in the bed. Higher oxygen coefficient decreased the amount of fine particles and increased the amount of coarse.

Fig. 33. On-line gas measurement from the roaster bed on the feed side. The O₂ level in the bed is very low.

Fig. 34. On-line gas measurement from the roaster bed on the overflow side. The O₂ level is higher on the outlet side of the furnace.
Fig. 35. High moisture of the concentrate mixture decreases the feed. The water makes agglomerates and transfers the burning more to the bed. The feed is reduced because otherwise the temperature would rise in the furnace, due to the furnace temperature control application.

Fig. 36. Water fed to the concentrate before the furnace decreases the concentrate feed. In this case too, water makes agglomerates and transfers the burning more to the bed. The feed is reduced because otherwise the temperature would rise in the furnace, due to the furnace temperature control application.

Fig. 37. Water injection into the bed increases the feed. Water sprayed (500 l/h) into the furnace bed cools the bed and more concentrate has to be fed to keep the temperature in the furnace at the set point value due to the furnace temperature control application.

Fig. 38. Water fed into the concentrate before the furnace decreases the sulphide level of the boiler and cyclone calcine. The feed decreases due to the water feed and this increases the oxygen coefficient.

Fig. 39. Increasing the water feed (*1) before the day bins increases the sulphate amount in the bed. (*1 = The concentrate feed rate to the day bins is about 350 t/h and water is fed to this stream).

Fig. 40. SEM picture (left) of an overflow calcine 10.4.2002 (40 x). The coating around the inner part (=ZnO) is PbSO₄. The other picture (right) shows that copper behaves differently to lead. A Cu₂S core is formed in a copper rich concentrate pellet in a laboratory roasting experiment at 950°C. The coating around the Cu₂S core is ZnO.

Fig. 41. The Cu level of the feed versus the amount of calcine overflow of the concentrate feed. The proportion of the overflow calcine has decreased when the Cu level has increased.

Fig. 42. Oxygen coefficient versus the amount of calcine overflow of the concentrate feed. The proportion of the overflow calcine has increased when the oxygen coefficient has been increased.

Fig. 43. Bed temperatures and oxygen coefficient of roaster furnace No. 2 in August, showing the effect of oxygen coefficient alterations on stabilisation. By increasing the oxygen coefficient, the stabilisation of the bed temperatures can be seen.

Fig. 44. Oxygen coefficient and wind-box pressure in furnace No. 2 (September–October 2002). When the wind-box started to drop, the oxygen coefficient was increased in order to raise the wind-box pressure back to the normal level.

Fig. 45. Wind-box pressure and the total moistening water feed in roaster furnace No. 2 (September–October 2002). Water feed correlates with bed pressure, thus the wind-box pressure is low, i.e. unstable bed, when the water feed is low.
Fig. 46. Oxygen coefficient and bed temperatures (# 4 & 5) of roaster No. 1 (July–August 2002). The correlation is not so good, i.e. the temperatures stay stable even if the oxygen coefficient drops. 

Fig. 47. Water feed before the day bins and bed temperatures of roaster No. 1 (July–August 2002). The temperature drops (Thermocouple element No. 5) after the water feed is stopped. After the water is again fed to the concentrate mixture, the temperature value returns back to the normal level.

Fig. 48. Increasing the oxygen coefficient stabilized the bed temperatures (the negative trend stopped).

Fig. 49. Changes of the oxygen coefficient were made by changing the feed rate. This was done by changing the set point value of the furnace temperature. The fuzzy controller then decreased or increased the feed rate.

Fig. 50. Increasing the oxygen coefficient stabilized the bed pressure. The drop in bed pressure was stopped and a slight increase back to the normal level can be seen. The period is the same as in Fig. 49.

Fig. 51. Increasing the oxygen coefficient brought the bed pressure back to normal.

Fig. 52. The structure of the installed fuzzy control system (Rauma et al. 2000).

Fig. 53. The scope of the simulator made for training start-up and shutdown situations. A dynamic model for the furnace pressure was made (Toskala et al. 2001).

Fig. 54. Responses of gas temperature and bed temperatures, when water is fed to the concentrate mixture before the table feeder. The temperature rises in the bed when water is fed to the concentrate mixture. At the beginning there is a slightly inverse reaction in the bed temperatures. The top temperature decreases when water is fed to the concentrate mixture.

Fig. 55. Water feed before the table feeder stabilises the bed, which can be seen from the fact that the temperature measurements in the furnace are closer to each other when more water is fed.

Fig. 56. Response of water injection into the bed. The furnace temperature decreases due to the cooling effect of the water injection.

Fig. 57. Divergent effect of oxygen on bed temperature measurements. The oxygen seems to have a divergent effect on the temperatures, which could be explained by an increase of the reaction rate in some parts of the furnace. Where there is a temperature drop, the reaction rate decreases.

Fig. 58. Tracer content in the furnace overflow calcine for two experiments. The Ti-oxide tracer was fed as an impulse at time 0 h. A first order model with a time constant of 20 h is shown for comparison (Saxén et al. 2004).

Fig. 59. The tracer tests shows that the time constant in the gas line is very short, i.e. the Ti-oxide tracer fed as an impulse to the furnace is almost immediately detected in the calcine from the cyclone after the boiler.

Fig. 60. The effect of the baffle wall on the boiler behaviour (radiation section of the boiler) is shown here. The velocity vectors are shown.
The Fluent model calculation was made by Foster Wheeler (= the boiler manufacturer). ........................................... 80

Fig. 61. The effect of the baffle wall on the boiler behaviour (radiation section of the boiler) is shown in this figure. The temperature gradients are shown. The Fluent model calculation was made by Foster Wheeler (= the boiler manufacturer). ............................ 81

Fig. 62. The feed increases when the temperature is higher in the furnace. The increased feed decreases the oxygen coefficient and the result is that the sulphide level of the formed calcine is higher, as shown here (Nyberg et al. 2000). .................................................. 87

Fig. 63. By increasing the amount of air, the feed increases due to the cooling effect of the air (graph on right). Due to the lower oxygen coefficient the sulphide level of the calcine increases (graph on left). The furnace temperature in the experiments was 950°C (Nyberg et al. 2000). .................................................. 87

Fig. 64. By using oxygen the feed increases, due to the cooling effect of the oxygen. In the experiments with additional cooling (C and D), more cooling coils had been added to the furnace. The furnace temperature in the experiments was 950°C (Nyberg et al. 2000). .......... 88

Fig. 65. Higher top temperature increases the feed and due to the lower oxygen coefficient the sulphate level of the formed calcine is lower, thus the sulphate load on the WHB decreases. ......................... 88

Fig. 66. In both cases the feeds and the oxygen coefficient are the same. By injecting water, the temperature can be lowered in the furnace, without decreasing the concentrate feed. In cases with high impurity levels, a temperature level of about 900°C might be necessary. .... 89

Fig. 67. The operating range in the furnace is narrower if the concentrate mixture contains high impurity levels. The temperature and the oxygen coefficient are the main control variables. ................................. 90

Fig. 68. The figure shows the developed control strategy. The target is to build a control application that maximizes the feed based on this control strategy. The aim is to optimise the feed and the process conditions (temperature and oxygen coefficient), based on metallurgical knowledge and knowledge of the dynamics. Measurements, analyses, the dynamic model and control variables are also key elements in the control application ......................................................... 91

Fig. 69. In order to achieve sustainable results, the issues shown in the diagram must be considered in the development process. ................................. 94
## Contents

Abstract
Acknowledgements
List of abbreviations
List of figures
Contents

1 Introduction .......................................................... 17
   1.1 Background of the research and development work .............. 17
   1.2 Research problem and asserted hypothesis ....................... 19
   1.3 Content of the research and development work .................. 20
      1.3.1 Roasting research and development procedure ............. 21
      1.3.2 Boiler research and development procedure ................ 23
      1.3.3 Mercury removal research and development procedure ........ 25
   1.4 Contribution of the author ...................................... 26

2 Process description .................................................... 28
   2.1 Zinc process ..................................................... 29
   2.2 Roasting process ................................................ 30
   2.3 Gas cleaning and sulphuric acid production ..................... 31
   2.4 Roasting and direct leaching ................................... 32

3 Main phenomena of the roasting process .......................... 33
   3.1 Mineralogy ....................................................... 33
   3.2 Main reactions and thermodynamics ............................... 35
      3.2.1 Sulphates and molten phases ............................ 38
      3.2.2 The sulphide analysis of the formed calcine ............ 39
   3.3 Heat transfer .................................................... 39
   3.4 Fluidisation ..................................................... 40
   3.5 Gas cooling and dust handling .................................. 41
   3.6 Gas cleaning ..................................................... 41
   3.7 The dynamics of the process ................................... 42

4 Targets for control system development ........................... 43

5 Measurements and control of the fluidised bed furnace ........... 46
   5.1 Measurements and analyses of the fluidised bed furnace ....... 47
5.2 Control specification of the fluidised bed furnace .................................. 49
5.3 Aspects relating to the boiler and mercury removal ............................. 55
6 Results of the control strategy development for the Kokkola zinc roasting process 56
  6.1 Furnace development ................................................................. 56
  6.1.1 Factors correlating to bed instability ..................................... 57
  6.1.2 Oxygen coefficient control .................................................. 58
  6.1.3 Oxygen use to control bed quality ....................................... 61
  6.1.4 Bigger nozzles and oxygen measurements from the bed ............ 62
  6.1.5 Effects of water on the furnace behaviour ............................ 64
  6.1.6 Control of the furnace when Pb and/or Cu is high .................. 66
  6.1.7 Controlling unstable situations .......................................... 69
  6.1.8 The dynamics of the roaster furnace .................................. 74
  6.2 Boiler development ............................................................... 79
  6.3 Mercury removal development ............................................ 81
7 Discussion ............................................................................. 82
  7.1 Summary of the results .......................................................... 83
  7.1.1 Summary of roasting development ...................................... 84
  7.1.2 Summary of boiler development ......................................... 85
  7.1.3 Summary of mercury removal development .......................... 86
  7.2 Control strategies and further research and development ............ 86
    7.2.1 Increasing the capacity of the furnace ............................. 87
    7.2.2 Example of flexible control ........................................... 88
    7.2.3 Operation conditions for different feed mixtures ............... 89
    7.2.4 The developed furnace control strategy ............................ 90
8 Conclusions ................................................................. 93
References ................................................................. 96
Appendices ............................................................... 103
1 Introduction

Roasting is an essential part of the electrowinning zinc process. A typical Zn process line comprises the following sub-processes: roasting, leaching and purification, electrowinning and the last step foundry (Kajiwara et al. 1995, Morris 2000). During the last few decades, the direct leaching of concentrates, pressure or atmospheric, has been introduced as a parallel and/or alternative process stage to roasting. Besides typical electrowinning processes there are also other methods to produce zinc, with the ISF (Imperial Smelting Furnace) being a method used by some plants (Bendieck et al. 2002, Brook Hunt 2003, Canham & Charles 1981, James et al. 2000, Lee 2000).

Zinc concentrates from the mines are fed to and roasted in fluidised bed furnaces. The most common roaster furnace in zinc roasting is the Lurgi furnace (Brook Hunt 2003). The main reaction is $\text{ZnS} + 1.5 \text{O}_2 \rightarrow \text{ZnO} + \text{SO}_2$. The main components of the roasting process are: the furnace, waste heat boiler (WHB), cyclone, electrostatic precipitator (ESP), Hg removal and sulphuric acid plant. Essential process equipment includes: conveyors, bins, calcine cooler, ball mill, fans and steam handling equipment (Magoon et al. 1990). The fluidised bed roaster furnace has been used on commercial scale since the middle of the 1950s (Heino et al. 1970, Themelis & Freeman 1983/1984). The zinc process and roasting process are more thoroughly described in chapter 2.

Zinc processes are continuously being developed and the trend is that they are becoming bigger and more efficient. New possibilities like direct leaching of concentrates is one trend in this development work. Roasters are also being developed and one reason for this is that the concentrates are tending to become finer, which has an impact on roasting behaviour. The capability of using impure concentrates is another objective for development work.

1.1 Background of the research and development work

In this study the roasting process has been developed using intensive and extensive research. The goal has been to improve the process control of the roasting process. The aim is to understand the behaviour and to evaluate both details (micro level) and the
entire roasting process (macro level) to reach the target of increasing the efficiency of the process. To be able to do this many aspects must be considered. The focus in the thesis is on the actual fluidised bed roaster furnace behaviour, but developments in the boiler and mercury removal are also discussed to some extent. The roasting mechanism is a very complex process and therefore requires knowledge of many fields. Matters like the mineralogy of concentrates, thermodynamics, fluidisation, heat transfer and dynamics must be studied to gain more knowledge. These are discussed in chapter 3. Normally the feed to the furnace is a mixture of concentrates and every mixture behaves differently, which increases the difficulty (Brown et al. 1995). Flexibility is required to be able to handle different feeds. This flexibility means the possibility to run the process in optimal conditions by having the control tools to change the operation conditions. The key to reaching optimal conditions is to have a thorough knowledge of the process.

The behaviour of the roasting furnace is influenced by several parameters and the complexity is vast. If, for instance, the impurity levels for certain elements exceed certain limits or the process conditions are not suitable for the feed, this will lead to instability. The boiler is closely connected to the roaster furnace and by making the boiler performance effective, more freedom in roasting conditions is achieved and thus the constraints due to the boiler are smaller. The same applies to mercury removal; more efficiency gives more freedom when choosing concentrates.

The reasons for development work are the need to avoid disturbances in the furnace (build-ups, defluidisation and instability), to increase the running time of the furnace and boiler without cleaning and to avoid quality problems with the sulphuric acid (too high a level of mercury).

The need to increase process knowledge was clear, as the problems could not be handled merely by adopting stabilizing control applications like fuzzy system applications. The fuzzy systems developed for temperature control in the furnace and for controlling the acid concentration and temperature in mercury removal work well but they do not solve problems caused by changes in concentrate mixtures. It is important to know the optimum process conditions and to have measurements showing the state of the process. It is also essential to have the necessary control tools.

The primary goal was to improve the economic result of the operation. Other major goals were to decrease the environmental impact of the operation and to reduce safety problems. An increase in feed capacity, running time and improved product quality were the intermediate targets of the work. Achieving this would enable the primary goals to be reached. The treatment charge (TC) is the major input and optimisation of this is the most important factor. The greater quantity of concentrates treated, the higher the revenues from the TC. This means that if concentrates with low Zn levels are used to produce a certain amount of zinc metal, then the income is larger. Decreasing production costs was another goal and maintenance costs also had to be optimised. The targets are discussed more thoroughly in chapter 4.

Flexibility in using different types of concentrates along with the possibility and capability of using impure concentrates is the key to success. Another major factor is the ability to handle fine concentrates. The trend is that concentrates are becoming finer. The basic platforms for reaching the goals include process knowledge, working skill, control possibilities, and equipment performance.
1.2 Research problem and asserted hypothesis

The roasting process of zinc sulphides is very complex. In order to improve the efficiency of an industrial roaster many aspects must be considered and characterisation of the process performed. More metallurgical knowledge is needed, e.g. about the roasting mechanism, calcine particle size growth and the effects of impurities. More knowledge must also be gained about the state of the process and the dynamics of the furnace. Knowledge about the optimum process conditions is required. New measurements, equipment modifications and control variables are needed. The impacts of changes must be studied and experiments have to be performed to provide the necessary information.

Both laboratory and full-scale plant experiments are necessary. Besides knowledge about the dynamics knowledge in process metallurgy is also essential. Knowledge about the state of the process requires measurements (both new and old), but also understanding of process phenomena. The effects of control variables must also be studied. Adding more control variables and equipment modifications has also been a part of this development. These additions make it possible to create optimal conditions and increase the flexibility of the control. The chosen procedure has been to proceed step by step.

In order to reach the goal, i.e. increased efficiency in the control of the roasting process, a new control strategy has been developed. Essential parts of the new control strategy are process characterisation, dynamic models, new analyses and new measurements, new control variables and equipment modifications. The key elements of the basis for the new control strategy are shown in Fig. 1.

Fig. 1. Key elements in the development of the new control strategy.
1.3 Content of the research and development work

Increasing the efficiency of an industrial roasting process requires that many phenomena and many variables must be studied, as shown in Fig. 2. The main focus has been on improving roasting by studying furnace behaviour and roasting mechanism. Much attention has also been paid simultaneously to boiler and mercury removal performance. These three elements have a great bearing on success. Development of the boiler is essential, because if the boiler performance is good, then there are fewer constraints in furnace control. Mercury removal is necessary to produce sulphuric acid of high quality. Good mercury removal gives more freedom in choosing concentrates, which is essential when evaluating the whole process.

The development that has been made is based on the results of laboratory experiments, full-scale plant experiments, calculations, thermodynamic evaluations, experiments with models and extensive chemical analyses.

![Diagram](image)

Fig. 2. High roasting performance can only be reached through broad development. Many factors must be taken into consideration to reach the targets, as shown in the diagram.

Control loops and algorithms have been improved by studying the dynamics of the process and using advanced methods like fuzzy systems. By doing this, the process has been stabilized. Good examples of such are the fuzzy control of the roaster furnace temperature and the fuzzy control of the mercury removal towers to stabilize the
temperature and acid content (Rauma et al. 2000, Rauma 1999). Both applications work well and they stabilize the process, i.e. the temperatures and acid content fluctuations are small. However they do not solve all the problems: for the furnace i.e. how to handle fine and impure concentrates; for mercury removal how to make good sulphuric acid consistently, i.e. to keep the mercury level low in the sulphuric acid produced.

New control variables had to be found, as did ways of knowing the right process conditions for different concentrate mixtures and how to maintain them. Besides more process knowledge new measurements, new control tools and methods are needed to improve the control of the process. Control and control aspects are presented in chapters 5 and 6. Measurements and analyses are also presented in chapters 5 and 6. Possible methods are discussed in chapter 7.

1.3.1 Roasting research and development procedure

It is essential to have a good and stable bed in the roaster furnace. Defluidisation due to a fine bed is one problem. Another problem is the formation of build-ups due to molten phases or sulphates, which can lead to sintering of the bed or part of the grate area. Heat transfer, oxygen need and fluidisation vary due to differences in the concentrate mixture. The aim of the research and development concerning roaster furnace performance has been to gain more knowledge about the different mechanisms and to design a control strategy. The most important research stages are described below and shown in Fig. 3.

Mineralogical Analysing Laboratory Plant

evaluations calcine experiments

terodynamic evaluations

Heat balance calculations

Active surveillance of special situations in the Roaster

Applications and operating rules

Fig. 3. Roasting research and development procedure.

Mineralogical studies of all concentrates used in Kokkola have been made. Chemical analysis and microscope analysis were made to get information about the concentrates and to determine what kind of minerals they contain. The basic results from the studies were the oxygen requirement and the heat energy of different concentrates.

Evaluations of thermodynamic phase diagrams and Kellogg diagrams have been made on a large scale. In roaster furnace conditions, impurities (Pb, Cu, Si) form molten phases. Sulphates are also formed (Pb, Ca). These have a negative impact on roasting and therefore it is important to study the phase diagrams of the different combinations of impurities. The aim is to find the best roasting conditions and the limits for impurities. Different types of molten phases can be formed: sulphide melts (Pb, Cu, Fe, Zn), sulphate melts (Na, K, Pb) and oxide melts (Pb, Cu, Si, Zn). The formation depends on the
conditions in the furnace. The main variables are temperature, oxygen pressure and amount of impurities (Appendix 1).

Analysis of calcine samples has also been made. During plant experiments and also during normal operation, calcine samples have been taken mainly from the furnace but also from the boiler, cyclones and ESPs. Chemical analyses, particle size distribution and microscopic analyses have been made (see chapter 6 and Appendix 4). Only by doing this, can more information about growth mechanisms and what is actually going on in the furnace be acquired. In particular, analysing samples under the microscope gives valuable information.

Thermodynamic heat balance calculations have also been made. The effects of different variables can be estimated by these calculations. Therefore a model using HSC Software has been made for the furnace boiler system (Roine & Nyberg 2000, Björklund 2001). The model has gradually been improved to be more user-friendly and accurate. The impacts of different variables can be tested such as temperature, feed composition, air flow, use of oxygen and water injection to the bed. By doing this kind of testing, evaluations of the impacts can be made before real changes in the equipment or operating parameters are made. This has been useful in the case of both the furnace and the boiler.

At Outokumpu Research Centre experiments have been carried out in small laboratory furnaces (Taskinen et al. 2002, Metsärinta et al. 2003, Metsärinta et al. 2005b) where tests to study the effects and the limits for impurities have been made. Also, different roasting conditions were tested, for example roasting with a high oxygen coefficient. High impurity levels were also tested. These experiments were very often pre-tests made before performing full-scale plant experiments. During these laboratory experiments, samples were taken for chemical and X-ray diffraction analysis.

During the research and development period (especially during 1999–2004) many full-scale roasting experiments were performed (Chapter 6, Lepistö 1999, Nyberg et al. 2000, Metsärinta et al. 2005a). Full-scale experiments are necessary in order to get information and knowledge before making decisions on how to increase the performance of the roaster furnace; otherwise actual knowledge of how the furnace will behave cannot be gained. Different items were tested such as impurity levels, temperature levels, air amount, water feed to different spots and oxygen feed. Risks are involved in plant experiments. If for instance too high impurity levels are used, it can lead to too many agglomerates and furnace instability. In the worst case the furnace must then be cleaned, i.e. causing production losses of several days and the ensuing extra costs. Due to this there are constraints in full-scale plant trials on how high the impurity levels are that can be tested and therefore it is safer to make experiments first on laboratory scale.

During the research and development period (especially during 1999–2004) many full-scale roasting experiments were performed (Chapter 6, Lepistö 1999, Nyberg et al. 2000, Metsärinta et al. 2005a). Full-scale experiments are necessary in order to get information and knowledge before making decisions on how to increase the performance of the roaster furnace; otherwise actual knowledge of how the furnace will behave cannot be gained. Different items were tested such as impurity levels, temperature levels, air amount, water feed to different spots and oxygen feed. Risks are involved in plant experiments. If for instance too high impurity levels are used, it can lead to too many agglomerates and furnace instability. In the worst case the furnace must then be cleaned, i.e. causing production losses of several days and the ensuing extra costs. Due to this there are constraints in full-scale plant trials on how high the impurity levels are that can be tested and therefore it is safer to make experiments first on laboratory scale.

The plant trials lasted from one to several weeks. The experiment plans included sampling, an analysis plan and variable changing intervals. During the trials a vast amount of data was collected and active surveillance was made. Measurements and analyses were collected on the database of the process computer and the plant information system. On-line analysis of the gas composition in the roaster bed was also made during several tests (Chapter 6, Parkkinen et al. 2002). Many samples were taken for chemical and X-ray diffraction analysis. The results from the tests were thoroughly evaluated and reported.

The emphasis in the full-scale plant experiments has been on the process metallurgy. By learning more about the particle size growth mechanism and the effects of the
impurities, new means to control the furnace behaviour have been developed and also new process operation conditions have been chosen.

The dynamics of the process have also been tested to get information about the effects of different variables on the process. By studying the dynamics, information for developing and tuning control loops has been gained. The information has also been invaluable in understanding the behaviour of the furnace. By making step trials, i.e. changing the air flow, concentrate feed, water addition, oxygen feed etc. stepwise and by letting the furnace respond to the changes, the dynamics of the furnace have been identified. These results have been used to make simulators, a state variable model and tuning control loops (Rauma et al. 2000, Toskala 2000, Toskala et al. 2001, Härkönen 2003, Saxén et al. 2004, Valo 2004).

Every now and then the roaster furnace becomes unstable. Active surveillance of these special situations has been done. During those periods active measures have been taken to correct the situation back to normal. During such abnormal situations samples have normally been taken and analyses of the samples made. Often these situations have been successfully corrected by control methods, i.e. using oxygen, decreasing the furnace temperature, using water etc. Sometimes a change of concentrate mixture has been the only way to get the furnace back in equilibrium. Such periods have been thoroughly analysed and reported. These special situations have provided excellent opportunities for testing the new control strategies and process knowledge.

During shutdowns, yearly maintenance shutdowns or boiler cleanings, samples have been taken from the build-ups and analysed. After analysis, the results have been evaluated and explanations for the build-ups have been made (Appendix 4).

1.3.2 Boiler research and development procedure

The pattern for boiler development has been similar to that of roasting and is shown in Fig. 4. The conditions of the furnace influence the boiler. The main goals are to have separation of the calcine coming from the roaster furnace gas through the upper part of the furnace, effective gas cooling and a high degree of uptime for the boiler. These are the prerequisites for good results in roasting performance.

Before major modifications were made in the boiler a flow scale model was built. A picture of it is shown in Fig. 5 and the model has been presented in a paper (Järvi et al. 2002). The biggest issue that was tested with this flow model was the impact of the baffle wall. The shape, size and the location of the baffle wall were tested.
Fig. 4. Boiler research and development procedure has also been diverse.

As a complement to the model, numerical calculations were also made to confirm the results gained from the laboratory experiments. These calculations showed both the temperature and the flow gradients of the boiler. The calculations gave similar results as those with the laboratory model. Two commercial programs were used for calculations. Outokumpu Research (ORC) used the CFX programme (Järvi et al. 2002) and Foster Wheeler (the boiler manufacturer) used the Fluent programme (Chapter 6). The results of the flow model calculations are similar to those in published papers (Peippo et al. 1999, Yang 1996).

During the last decade there has been intensive and close co-operation between the roaster department and the boiler manufacturer. Several meetings and planning sessions have been held where the results have been evaluated and new modifications have been planned. Changes and additions to the boiler have been considered together before implementation. Often changes have an impact on the stress factors in the boiler system. Therefore the risk is that without thorough evaluation new problems can arise. In addition, follow-up has been done together and based on the evaluation of the progress, new plans to develop the boiler have been made (Kilju 2004).

Utilisation of plant operation experience has been a part of the boiler development work. The impact of the changes made can only be evaluated after a long period, several
months or years. Analysis of malfunctions is also a part of development work. By active monitoring of the boiler over long periods, valid information for further development has been gained.

Development of maintenance practice is crucial and has a great impact on the performance of the boiler. Measurements during shutdowns (e.g. X-ray) and monitoring the boiler during operation by measuring the water flows of the different circulations, are an area that should not be neglected. During shutdowns, maintenance and above all proactive maintenance are important. This means replacement in advance of parts that are not in good condition. The way the boiler is cleaned also influences the result. One example of an established practise that has increased running time is cleaning the boiler with water during the yearly shutdowns. This improves the running time of the boiler.

1.3.3 Mercury removal research and development procedure

Likewise, mercury removal research and development has been implemented using the same pattern. This is shown in Fig. 6.

Fig. 6. Thermodynamic equilibrium calculations were essential in the mercury removal research and development procedure.

Material balance calculations had to be made in order to get a clear picture of the entire process including the roaster, mercury removal and the sulphuric acid plant. The mass balance contained important elements (Hg, Se, Cl, F, Si, etc.) and all phases were included, i.e. solid, liquid and gas. Some new analyses had to be made and every input and output was calculated. The chemical analysis of every process stage (and every phase) and the material balance calculations clearly showed the amounts and, above all, this work resulted in a better picture of the process.

Chemical analyses of process samples were performed in order to get a better picture of the process. Samples were taken from all process stages. The challenge here was proper sampling. This is due to the fact that the temperatures are high in some steps and the content of some elements is very low, both in the liquid and gas phase. If sampling is not done properly, the analysis is of no value. Due to the low level in some steps the chemical analysis was also demanding. One example of this is the determination of Hg$^{0}$ and Hg$^{2+}$ concentrations in the gas phase. This plays a significant role in the process.
chemistry, but due to the low concentration levels in some process stages, analysis is difficult.

Based on the material balance calculations and chemical analysis, massive thermodynamic equilibrium calculations for every process step were performed by personnel from ORC. These calculations were performed using commercial programs such as HSC, ChemCalc, ThermCalc, etc. The results from the thermodynamic calculations and the results from the chemical analyses were similar and showed that the gas phase is in a steady state in the different process stages. This information was vital for the development of the process.

Based on the above, i.e. material balance calculations, chemical analyses and thermodynamic calculations, experiments on laboratory scale were performed. Different chemicals such as Se solution and thiosulphate were successfully tested (Peltola et al. 2000, Berg et al. 2003).

After the laboratory experiments, feeding of Se solution was carried out to different parts of the process chain, both Hg removal and the acid plant. The most effective location was found to be feeding Se solution to the acid plant process. The quality of the sulphuric acid improved and the process became more stable and manageable.

1.4 Contribution of the author

The author of this thesis worked as manager of the Kokkola roaster department during the research and development process presented in the thesis. As manager of the department, the author was responsible not only for production but also for the research and development of the process. The main partner in this research and development process was Outokumpu Research (ORC). Universities and others have also participated, e.g. through Master’s theses. The necessity of continuous development is paramount and the target has been to increase efficiency. In order to achieve good results, a broad development in many fields has been necessary. The goals are discussed in chapter 4. The author was the initiator of the research and development projects described in the thesis.

The author has created the control concept presented in this thesis for improving the control of the process and has also been responsible for carrying out the implementation. The main contribution of the thesis has been the process characterisation and the combination of the process knowledge gained with the control system development.

Active participation and contribution in all the projects has been an essential part of the author’s work. The research and development work consists of both basic and applied research. Applied research, i.e. full-scale plant trials, has also involved risk-taking. As manager, the author has been responsible for this risk-taking. Therefore, the author participated actively in the planning of the plant trials.

The results of the research have led to applications, e.g. equipment modifications, new control methods, changes in operation practices, new measurements and analyses taken in use, which have increased efficiency and also improved quality.

Some of the results of the research and development work have been presented in scientific publications. These publications are referred to in the thesis. The aim has been to present some of the key elements and achievements of the research and the
developments made. In the papers the procedures of the research and development work have also been presented. The author has acted as the initiator in the publishing process. The author of this thesis has been active in creating the structures of the papers and in the writing process of the presented papers.

As previously mentioned, the research and development work has led to practical applications. This has also resulted in patents and patent applications have been made. These patents and patent applications are referred to in the thesis. The author is a participant in seven patents or patent applications. In the others patents, that are in use at the Kokkola roaster, the author has played a supportive role and been active in the testing of these systems.

Master’s theses have also been part of the research and development work. The Master’s theses are referred to in this thesis. They have been both theoretical and practical. The theses have been an important part of the research and development process. They have helped to achieve practical applications and new research results valuable for continuous development. The contribution of the author of this thesis has been as the initiator, helping in the process characterisation, giving feedback and supervisor of the Master’s theses.
2 Process description

The zinc business is changing all the time. It is a complex network consisting of mines, zinc plants, zinc market, end users and authorities. The price of zinc is of major importance. The London Metal Exchange (LME) zinc price and the size of the LME zinc storage are relevant factors influencing the business. The treatment charge (TC) changes yearly and is influenced by the zinc price. It is the factor that determines the income and survival of both mines and zinc plants.

Zinc plants are becoming bigger and more efficient. The major costs, especially in electrowinning Zn plants, are as follows:

- Zn concentrates
- Electricity costs
- Labour costs
- Maintenance costs
- Chemicals

The major income for zinc plants is received from treating concentrates, i.e. TC payment. Other incomes are gained from selling zinc plus premium, sulphuric acid and in some cases steam. The demand for more efficiency has led to an increase in the automation level and production capacity but also to the development of the process. Development work includes all zinc plant departments. Major improvement targets are to increase the running time and leaching yield, which means better Zn recovery. An important target is to make a purer solution in purification, because then the electric efficiency increases in the cellhouse. Challenges in roaster development include new concentrates, which tend to be finer, impurities in the concentrates, the need to increase running time and reduce maintenance costs.

The continuous development work being done by the zinc industry has also led to new process stages such as the direct leaching of concentrates. Environmental aspects have also been an issue for development with one major issue – how to treat iron residue. For this reason, great demands have been placed on the entire zinc industry in many countries.

Cooperation between zinc plants, mines and end users is also necessary in order to meet the demands from society and the authorities.
2.1 Zinc process

There are different types of zinc processes. Among plants treating sulphide zinc concentrates, the most common type is the electrowinning zinc plant. There are also ISF plants operating, though these are diminishing in number. The electrowinning plants differ as to the kind of leaching process in use and the iron residue precipitated (jarosite, hematite or goethite) (Brook Hunt 2003). There are also differences in the purification processes. In the cellhouse the major difference is the size of the cathode.

There are normally four sections in an electrowinning zinc plant. They are: Roaster, Leaching and Purification, Electrolysis (i.e. the cellhouse) and Foundry. In the roaster the concentrates are roasted in a fluidised bed furnace. The SO₂ gas from the roaster is cleaned (mercury removal) and then sulphuric acid is produced. In leaching the calcine from the roaster is leached using sulphuric acid. Iron is precipitated and the solution from leaching is then purified, i.e. Cu, Co, Ni, Cd, Ge, Sb etc. are precipitated out. The purified solution is then pumped to electrolysis, where zinc is precipitated on aluminium sheets using electric power. The Zn is stripped from the aluminium sheets by automatic stripping machines. The zinc produced is then melted in the foundry.

As mentioned in chapter 1, direct leaching of concentrates has become an alternative or parallel process to roasting. In the Kokkola zinc plant both are in use and this gives more flexibility to the operations (Takala 1999). The advantage lies in the fact that some concentrates are more suitable for roasting and others are more suitable for leaching. A block diagram of the Kokkola plant is shown in Fig. 7. A flow sheet with more details is presented in Appendix 3.
2.2 Roasting process

In the thesis the furnace type studied is the Lurgi furnace. Fig. 8 shows a schematic diagram of a Lurgi furnace. There are also other types of furnaces used for zinc sulphide roasting and some plants use the Dorr Oliver furnace (Yoneoka et al. 1998). The feed to the zinc roaster furnaces is normally a mixture of several concentrates. Concentrate composition is discussed in the mineralogy section of chapter 3. The main phenomena regarding roasting are also described in chapter 3.

In the roaster the nozzle grate area of the furnace has gradually expanded and today there are some Lurgi furnaces in operation with a grid area of 123 m² (Berg & Pape 1978, San Martin et al. 2000). A typical nozzle grate area for Lurgi furnaces is nowadays about 72–77 m². The two furnaces in Kokkola that have been the objects tested in this work are both 72 m².

The concentrates are stored in warehouses and the feed mixture is prepared daily and transported by conveyors to the day bins. Screening and crushing equipment have been installed ahead of the day bins to take care of lumps. From the day bins the concentrate is fed to the table feeder and after that high-speed transport belts, i.e. slinger belts, throw the material into the furnace. Air is fed from the bottom of the furnace to the furnace grate through nozzles. This air makes the bed in the furnace fluidise. The oxygen in the air reacts with the concentrate mixture. The reaction is exothermic and the heat is generated to the calcine and SO₂ gas that are formed. The roasting temperature is about 920–960°C.
The cooling coils in the furnace remove some of the generated heat, but the boiler removes most of the heat. The heat is recovered, both from furnace and boiler, by the water-steam system of the boiler. The SO$_2$ gas formed in the furnace leaves the furnace from the upper part and enters the boiler. The inlet temperature is about 850–950°C. The boiler cools the gas to approximately 320–380°C, which is the inlet temperature to the cyclones. The majority (60–70 %) of the calcine is also included in the gas from the furnace. The boiler removes part of the calcine from the gas and the rest is removed in cyclones and in ESPs. Some (about 30–40%) of the calcine leaves the furnace via the overflow of the furnace. Some plants also have a furnace underflow to remove the calcine partly from the furnace.

The calcine from the furnace is cooled in a cooler, normally a section cooler but in Kokkola a fluidised bed cooler is used. The calcine from the furnace and boiler is crushed in a ball mill. All calcine from the roaster is collected together in an intermediate silo and transported pneumatically to the calcine silo.

The SO$_2$ blower that controls the pressure in the roaster furnace is situated after the ESPs. A slight underpressure is kept in the furnace.

A good stable bed and good fluidisation are essential for the performance of the roaster fluid bed furnace. Many factors determine the optimal temperature value, but the impurity levels are the crucial parameters. Therefore the chemical analysis of the calcine formed is important. Major impurities in roasting are Cu, Pb, Si, Ca, Na and K. The sulphide level of the generated calcine, normally in the range of 0.1–0.3 %, is a major indicator of the roasting process. Good control and measurements are required to avoid forming of builds-ups, sinters. Issues regarding control and measurements are discussed in chapter 5. In the furnace there are several temperature measuring devices, pressure and windbox pressure measurements. There are several control loops such as draft control, air flow control and concentrate feed control. The key for the behaviour of the furnace is the calculated feed mixture. The main phenomena regarding the roasting process are discussed in chapter 3. The Kokkola Roaster process is presented in Appendix 2.

2.3 Gas cleaning and sulphuric acid production

After the electrostatic precipitators, the SO$_2$ gas with an SO$_2$ concentration of 7–9 % is cleaned. Mercury is the major impurity to take care of. There are different types of gas cleaning processes and many zinc roasters use the Boliden-Nor zinc process for mercury removal (Dyvik 1994). In Kokkola the Outokumpu mercury removal process is in use (Mukherjee 1999). Besides mercury other important elements to take care of are F, Cl and Se. The processes used for mercury removal are discussed in chapter 3.

The incoming temperature of the gas to the cleaning section is over 300°C. The gas is cooled and in Kokkola the outlet temperature of the gas after mercury removal is about 60–65°C. The sulphuric acid plant also has washing towers and the final removal of mercury occurs in this stage. In the mercury removal process the mercury is removed from the gas and ends up in the slurry. The control of mercury is complex and the balance between the gas phase, liquid phase and solid phase is influenced by many parameters. The levels of mercury are very low in some phases and it is quite demanding to measure...
them accurately. In order to produce sulphuric acid with low mercury, the whole process, i.e. mercury removal and the sulphuric acid plant, must be taken into account. The amount of mercury varies in the concentrates a lot (0.001–0.19 %). The trend is, however, that the product, sulphuric acid, must be low in impurities (Ludtke 2001). Nowadays the trend is that the mercury level should be lower than 0.1 mg Hg / kg H₂SO₄.

2.4 Roasting and direct leaching

Direct leaching of zinc concentrates has gradually become more common during the last decades as a parallel or alternative process to roasting (De Nys & Terwinghe 1990). There are two types of direct leaching, pressure leaching and atmospheric leaching (Buban et al. 2000). Pressure leaching (autoclave leaching) has been in use since the 1980s (Ashman & Jankola 1990, Collins et al. 1990, Dreisinger et al. 1990, Masters et al. 2002, Mollison & Moore 1990, Ozberk et al. 1995). There are some plants that have added pressure leaching as a parallel process to increase the capacity, but there is also a zinc plant that treats all the concentrates using pressure leaching without any roaster capacity (Collins et al. 1994, Collins et al. 1995, Krysa 1995). In the 1990s, direct atmospheric leaching of concentrates has been adopted and increasing interest towards this process has arisen (Adams et al. 1990, Takala 1999).

The use of direct leaching (pressure or atmospheric) of concentrates, as a parallel process to roasting, gives more freedom when choosing concentrates. Some impurities, such as Cu and Pb, can be higher in leaching while concentrates with high mercury and chlorine are more suitable for feeding to the roaster. The sulphur in the concentrate ends up in the sulphuric acid in the roasting process and in direct leaching the sulphur ends up in the sulphur residue. Here the sulphuric acid market and the possibility to store the additional residue influence the process choice.
3 Main phenomena of the roasting process

In the roasting process the following issues are of great importance: mineralogy, thermodynamics, heat transfer, fluidisation, gas cooling, dust handling and gas cleaning. In development work, i.e. when aiming to increase the efficiency of the process, knowledge about these issues and their effects is essential. In addition, the dynamics of the process are diverse. The dynamics of some changes are very rapid (pressure, temperature) while some changes are slow (formation of build-ups). In this chapter an evaluation of these issues is made.

3.1 Mineralogy

Normally, the feed to the roaster furnace is mainly a mixture of zinc concentrates. Some secondary materials like oxides are sometimes blended with the feed. Zinc ash from the casting department is also fed to the furnace. The main variable for the behaviour of the roasting furnace is the concentrate mixture. Since the feed composition is very significant for the behaviour of the furnace it is important to know the composition of the concentrates, of which the basic factor is the mineralogy of the concentrates. Most Zn concentrates are sulphides but there are also oxides.

The most common Zn minerals are the following:
Sphalerite, zinc sulfide, ZnS, (Zn,Fe)S, cubic, trimorphous with martraite and wurtzite.
Wurtzite, zinc sulfide, ZnS, (Zn,Fe)S, hexagonal and trigonal polytypes, trimorphous with martraite sphalerite.
Marmatite, (Zn,Fe)S ferroan sphalerite.
Martraite, ZnS, trigonal, trimorphous with sphalerite and wurtzite.

There are also many other zinc minerals (Fleisher & Mandarino 1991, Mandarino 1999).

The chemical analysis and grain size distribution of the concentrate are important. They influence the behaviour of the roasting and above all the behaviour of the roasting bed. The Zn content for concentrates is in the range of about 45–60%. The S content is about 30%. The impurity level has a great impact on roasting and important elements
include Cu, Pb, Si, Ca and Fe (Taskinen et al. 2002, Metsärinta et al. 2003, Metsärinta et al. 2005b). Other components that have an impact on roasting are the amounts of FeS₂ and FeS (Taskinen et al. 2002). The most important elements with regard to gas cleaning are Hg, Se, Cl, F and C (Yazawa et al. 1980). For the rest of the plant there are many important elements that must be handled in leaching and purification to avoid problems in electrolysis and even in the end product. These elements are for instance Co, Ni, Cd, Ge, Sb and Tl.

Typical analysis ranges of zinc concentrates are as follows:

<table>
<thead>
<tr>
<th>Element</th>
<th>Analysis Range</th>
</tr>
</thead>
<tbody>
<tr>
<td>Zn</td>
<td>45–60%</td>
</tr>
<tr>
<td>Fe</td>
<td>1–12%</td>
</tr>
<tr>
<td>S</td>
<td>28–33%</td>
</tr>
<tr>
<td>Pb</td>
<td>0.2–4%</td>
</tr>
<tr>
<td>Cu</td>
<td>0.2–4%</td>
</tr>
<tr>
<td>Cd</td>
<td>0.05–0.35%</td>
</tr>
<tr>
<td>Hg</td>
<td>0.001–0.19%</td>
</tr>
<tr>
<td>Ge</td>
<td>0.001–0.09%</td>
</tr>
<tr>
<td>Ca</td>
<td>0.05–1.1%</td>
</tr>
<tr>
<td>Si</td>
<td>0.3–1.5%</td>
</tr>
<tr>
<td>Pb</td>
<td>0.2–4%</td>
</tr>
<tr>
<td>S</td>
<td>28–33%</td>
</tr>
<tr>
<td>Cu</td>
<td>0.2–4%</td>
</tr>
<tr>
<td>Cd</td>
<td>0.05–0.35%</td>
</tr>
<tr>
<td>Hg</td>
<td>0.001–0.19%</td>
</tr>
<tr>
<td>Ge</td>
<td>0.001–0.09%</td>
</tr>
<tr>
<td>Ca</td>
<td>0.05–1.1%</td>
</tr>
<tr>
<td>Si</td>
<td>0.3–1.5%</td>
</tr>
<tr>
<td>Co</td>
<td></td>
</tr>
<tr>
<td>Ni</td>
<td></td>
</tr>
<tr>
<td>Cd</td>
<td></td>
</tr>
<tr>
<td>Ge</td>
<td></td>
</tr>
<tr>
<td>Sb</td>
<td></td>
</tr>
<tr>
<td>Tl</td>
<td></td>
</tr>
</tbody>
</table>

Because of the analysis and mineralogy, the heat energy and the oxygen requirement differ for different concentrates, and the range varies (Taskinen et al. 2002). The values for sulphidic zinc concentrates lie in the following range:

- Heat energy: 980–1430 kWh/t
- Oxygen demand: 280–380 Nm³/t

The particle size of the concentrates affects roasting significantly. The particle size distribution varies for different concentrates as shown in Fig. 9. There is a tendency towards finer concentrates as the mines crush them more nowadays to increase recovery. The d50-values (= mass median diameter) for concentrates are in the range of 5–70 µm.

Fig. 9. The particle size distribution varies for different concentrates.

Figs 10 and 11 show microscope pictures of two concentrates. From these pictures it can be seen that the Aznacollar concentrate (Fig. 10) contains more fine particles than the Trzebionka concentrate, which contains more coarse particles (Fig. 11).
3.2 Main reactions and thermodynamics

The product of roasting is called calcine and the reaction is exothermic. The reaction occurs in the particles through the diffusion of $O_2$ on the surface of the concentrate particles (Ajersch 2000, Beveridge 1962, Dimitrov et al. 1981, Fukunaka et al. 1976, Hattori et al. 1980). During roasting ferrites are also formed, such as $ZnFe_2O_4$, $CuFe_2O_4$ etc. (Graydon & Kirk (1988a, 1988b, 1988c), Richards 1995). Some major reactions are presented below:
The main reaction in roasting: 

\[ \text{ZnS} + 1.5 \text{O}_2 \rightarrow \text{ZnO} + \text{SO}_2 \]

Other reactions of importance: 

\[ 2 \text{FeS} + 3.5 \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 + 2 \text{SO}_2 \]
\[ 2 \text{FeS}_2 + 5.5 \text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 + 4 \text{SO}_2 \]
\[ \text{PbS} + 2 \text{O}_2 \rightarrow \text{PbSO}_4 \]
\[ \text{Cu}_2\text{S} + 2 \text{O}_2 \rightarrow 2 \text{CuO} + \text{SO}_2 \]
\[ \text{CaCO}_3 + \text{SO}_2 + 0.5 \text{O}_2 \rightarrow \text{CaSO}_4 + \text{CO}_2 \]

The ferrite formation reaction: 

\[ \text{ZnO} + \text{Fe}_2\text{O}_3 \rightarrow \text{ZnO} \cdot \text{Fe}_2\text{O}_3 \]
\[ \text{CuO} + \text{Fe}_2\text{O}_3 \rightarrow \text{CuO} \cdot \text{Fe}_2\text{O}_3 \]

Also, agglomeration between particles takes place in the bed, which leads to larger particles (Benlyamani & Ajersch 1986, Condina et al. 1980, Richards 1995). The growth mechanism is essential for the behaviour of the bed, but due to its complexity, understanding of the mechanism is limited (Constantineau et al. 2002). Control of the bed particle size distribution is of major importance for stable roasting conditions. Thermal analysis has also been carried out in roasting research (Sarveswara Rao & Ray 1999).

In Fig. 12, a schematic drawing shows how the reaction in a particle occurs. Many small particles agglomerate together to form a bigger particle and this is shown schematically in Fig. 13.

**Fig. 12.** Schematic drawing of the reaction principle. The sulphide mineral particle reacts with oxygen. The product is calcine (mostly ZnO). During the reaction SO₂ gas is formed.

**Fig. 13.** Schematic drawing of a calcine agglomerate formed of many small calcine particles. Bonds are formed between particles due to molten phases.
Figs 14 and 15 show microscope pictures of agglomerates. The outer layer in the microscope pictures is ZnO and in the middle there is non-reacted ZnS. Based on microscopic studies of concentrates, the origin of the pellets can be recognized. During the sample interval, the feed to the furnace was a mixture containing both Polaris and Aznacollar concentrate. The same structures can be seen in the calcine pellets.

![Fig. 14. Agglomerate from the furnace (November 2001) – origin Aznacollar concentrate.](image1)

![Fig. 15. Agglomerate from the furnace (November 2001) – origin Polaris concentrate.](image2)

When the main reaction takes place in the bed and above the furnace bed, calcine is formed. The calcine formed in the bed is coarser than the concentrate as is shown in Fig. 16. For good fluidised bed furnace performance, it is significant to have a bed with the right particle size distribution. The bed should not be too fine nor too coarse. If the bed is too fine, then the furnace becomes unstable due to defluidisation for example. The key question is: How can the particle size distribution of the bed be controlled?
Fig. 16. Grain size distribution of concentrate versus calcines. The formed calcine is coarser than the concentrate, especially the overflow calcine from the furnace.

### 3.2.1 Sulphates and molten phases

If the feed mixture contains many impurities such as Cu, Pb, Si, Ca and Mg, then the formation of sulphates and molten phases occurs more easily (Appendix 1, Freshcorn 1976). This can lead to the formation of build-ups on the roaster furnace grid and walls. In the worst case this leads to sintering of the bed and then the feed to the furnace has to be stopped. The furnace must then be emptied, which takes several days. The formation of build-ups and molten phases is a very complex combination of different elements. Therefore there are limits in roasting for these elements. There are maximum limits for Cu, for Pb, for a combination of Cu and Pb, etc. It is not easy to determine precise limits and mostly they are based on operating experience in zinc roasters. A commonly accepted “rule of thumb” in roasting is that “Pb + Cu + SiO$_2$ < 5 %” to avoid bed agglomeration and/or a sticky bed (Grant 1994). When the impurity level in the feed is high, then the right roasting conditions are important. Variables like temperature and oxygen coefficient must be controlled carefully. Phase diagrams must be studied to know the dangers and to find the right conditions. There are many important phase diagrams and Kellogg diagrams that give valuable information for understanding roasting, which should be evaluated (Elvers & Hawkins 1996, Mäkinen 1972, Appendix 1).

An essential reaction that occurs in the gas phase is SO$_2$ + 0.5 O$_2$ → SO$_3$. This reaction needs some catalysts, such as Cu. Due to this reaction, sulphates are formed in the boiler. The formation reaction of ZnSO$_4$ could be ZnO + SO$_3$ → ZnSO$_4$ (Gales & Winand 1973). Sulphates are also formed in the furnace due to leakage air on the walls. The formation of sulphates starts when the temperature is reduced to below about 850 °C.
3.2.2 The sulphide analysis of the formed calcine

The sulphide level of the calcine is normally in the range of 0.2–0.3 %. Increasing the capacity increases the sulphide level. Some plants keep the calcine sulphide level in the range of 0.3–0.5 %. Then the danger is that the oxygen coefficient is too low. The oxygen coefficient is defined in chapter 5. The sulphide level of the calcine produced is a quality indicator of the roasting process. The sulphide level is one of the main variables in control aspects and is discussed more in chapter 5. Typical analyses of calcines formed from different process stages are shown in Appendix 4. The level of sulphates in different process stages can be seen from the analyses. Analyses of samples taken during shutdowns are also shown in Appendix 4.

3.3 Heat transfer

The concentrate mixture is fed to the furnace from the side via slinger belts, and air comes from the bottom of the furnace through nozzles. The reaction between the concentrate and the air generates heat. The normal roasting temperature is between 920–960°C. There are cooling coils in the furnace that partly take away the heat that is generated. These elements take about one third of the heat away to the water/steam system. The rest of the generated heat is in the outgoing gas with some in the calcine. The gas is cooled in the boiler and in gas scrubbing. The calcine from the bed is also cooled. To increase the capacity of the furnace, the area of the cooling coils can be extended.

As mentioned above, the roasting reaction occurs both in the bed and also above the bed. If the concentrate mixture is very fine then more burning takes place above the bed than when the mixture is coarse. If the bed fluidisation is good then the heat transfer to the cooling coils is effective.

The temperature gradient of the bed is a good indicator of roasting and bed behaviour. The temperatures are measured from the bottom and the side of the furnace with several thermocouples. The more homogenous and stable the bed, the more homogenous the values from the different temperature measurements, i.e. only small differences between the values of the readings from the different temperature sensors. The gas temperature in the upper part of the furnace, that is, the part between the furnace and boiler, also reveals a lot about the situation in the furnace. If the top temperature rises, then water can be added to the concentrate feed mixture before it is fed to the furnace to lower the temperature. The water can be fed both before the concentrate enters the day bins and after the day bins but before the furnace. The effects of the different locations are somewhat different due to time delays but also due to how the water is absorbed into the concentrate. To increase the capacity, water injection to the bed can be used. Compared with cooling coils, this gives more flexibility to control the feed rate. If oxide materials are in the concentrate mixture, then the feed increases because oxide materials have a cooling effect on the bed.

After the furnace some of the calcine, about 30–40 %, comes out via the overflow of the furnace. This calcine is cooled in Kokkola in a fluid bed cooler, but more often in zinc roasters in a sectional drum cooler (Svens et al. 2003). After this the calcine is transported
by water-cooled redlers to the ball mill. Some zinc roasters remove part of the furnace calcine by some kind of underflow system.

The gas enters the boiler at a temperature of about 850–950°C and is cooled to about 320–380°C. The heat transfer that occurs in the boiler, cooling the gas and the calcine in the gas flow, is both radiation and convection.

### 3.4 Fluidisation

The amount of air and air velocity are very significant for fluidisation behaviour (Kunii & Levenspiel 1969). The particle size distribution of the bed also affects fluidisation. If the bed has too many fine particles they tend to go with the gas flow to the boiler. A very coarse bed also affects fluidisation and the heat transfer to the cooling coils. Impurities in the feed have an effect on the bed and can make it sticky, in which case the fluidisation behaviour is poor and the fluidity of the calcine is bad. If the fluidising of the bed is weak it can lead to channelling, i.e. a pressure drop in the bed because gas flows through the channels. In that case the bed will also be badly mixed. The particle size, particle size distribution, the shape and density of the particles all influence fluidisation behaviour. The Geldart classification is presented in Fig. 17 (Geldart 1986). The density difference of particles and gas is shown as a function of particle diameter. Fig. 18 presents a fluidisation diagram from the same source.

![Fluidisation Diagram](image)

**Fig. 17.** The Geldart classification of particles into their fluidisation behaviour in air at ambient conditions (Geldart 1986). The density of calcine in the fluidised bed gives the working area in the upper part of B.
3.5 Gas cooling and dust handling

The gas is cooled in the heat recovery boiler from about 850–950°C to about 320–380°C. The calcine dust is removed from the gas in the boiler, cyclones and hot electrostatic filters. The walls in the boiler are membrane cooled and there are also bundles, screens and a baffle wall inside the boiler. Effective spring hammers are installed to remove the calcine dust from the walls and bundles. These spring hammers shake the equipment resulting in the calcine falling down to the redler transporter (Peippo et al. 1998). The energy goes to the water and steam system of the membrane boiler. The steam generated goes to the power plant or is used for heating purposes. Conveyors transport the produced calcine further. As mentioned previously, a fluid bed cooler cools the calcine from the furnace overflow. In most plants a sectional drum cooler cools this calcine overflow. The furnace and boiler calcine is coarse and is therefore ground in a ball mill. All the calcine goes into a bin and then the calcine is normally transported pneumatically to the calcine storage bin.

3.6 Gas cleaning

The SO₂ gas contains impurities that must be taken care of in order to make pure sulphuric acid at the sulphuric acid plant. In gas cleaning the most important impurity to remo-
ve is mercury. For this purpose there are different processes of which the Boliden-Nor-zink method is one of the most common (Mukherjee 1999). Another process is the Outokumpu process, which is used in Kokkola. Final mercury cleaning methods are the Dowa tower and the Se filter (Abe et al. 1980, Mukherjee 1999). Other important elements in gas cleaning are Cl, F and Se. For Hg removal the important elements are Hg, Se and Cl. These elements have an impact on Hg removal efficiency. The halogens, Cl and F, must also be taken care of because they are corrosive elements.

In Kokkola the chain is very long and the gas pipe from the Hg removal towers to the acid plant is 800 m. The process in Kokkola can use concentrates with a very high Hg level e.g. up to 800 ppm in the concentrate mixture has been used. The normal mercury level in the concentrate mixture is about 100–400 ppm. The quality of sulphuric acid is also important and the Hg level should be below 0.1 mg Hg/kg H₂SO₄. The trend is to make sulphuric acid with a mercury level of 0.01 to 0.05 mg Hg/kg H₂SO₄.

### 3.7 The dynamics of the process

The dynamics of the roasting process are very complex. A slight underpressure is kept in the furnace. The dynamics of the underpressure are very fast (seconds), i.e. changes in the air feed and valves connected to the fans change this pressure very quickly. Controlling the underpressure is therefore a challenge for the operators. Start-up and shutdown situations are especially demanding. This was the main reason for building a simulator (Toskala 2000). The pressure dynamics were studied thoroughly before the simulator for the operators was built. This simulator enables the operators to practise start-up and shutdown situations (Toskala 2000, Toskala et al. 2001).

Changes in feed rate, air amount and feed water amount influence the gas temperature very quickly (seconds) whereas changes in the bed temperature are slower (minutes). The dynamics of the furnace were studied with the purpose of identifying the process. Based on this identification a model was built (Härkönen 2003, Saxén et al. 2004). Further development based on the model has been made with the target of optimising the furnace control (Valo 2004).

The dynamics that are much slower are more difficult changes to observe and control. Build-ups in the furnace or instability in the bed become fine phenomena where the time delay is very long, i.e. several days. The major challenge is to obtain information about phenomena that occur in the furnace slowly. Formation of build-ups in the boiler is also a slow process.

In mercury removal the time delay is also very long, several days, before anything can be seen in the end product. Correcting the process also takes several days.

The dynamics of the process are discussed further in chapter 6. Some results are presented from the step tests, from which it can be seen how quickly the different variables have an effect e.g. bed and gas temperatures.
4 Targets for control system development

The overall target of the research and development done has been to improve the economic result by running the roaster efficiently, including quality, environment and safety issues (Nyberg 2001, Fugleberg 1999). The main target is to increase flexibility in the use of concentrates, i.e. increase the treatment charge income, by developing the control strategy. The sub-targets include running time and feed rate. The sub-targets promote the main targets, such as the economic result and quality.

One of the main goals for every zinc plant is to achieve a good economic result. The major income of zinc plants is the treatment charge for treating zinc concentrates. When selling the zinc ingots they have produced, the plants are paid for the zinc plus they get a certain premium, which is additional income. The price of zinc is a relevant factor, both when concentrates are bought and when zinc is sold. The concentrates are a major cost factor and the purer the concentrates are, i.e. the higher the Zn content, the more expensive they are. Besides concentrates the other main costs of the zinc plant are electricity costs, personnel costs, maintenance costs and costs of the chemicals used. The treatment charge (TC) income should be optimised. To achieve this the performance of the roaster is critical. During the last decade, the TC-value has been in the range of $140–220 /t concentrate. The capability of using different kinds of concentrates along with the smooth running of the process is the key to success. Production of the same amount of zinc using low-grade zinc concentrates, i.e. compensating for the low grade with a high feed rate, increases the income. Knowledge and control options are required to increase the feed rate and to be able to use low-grade concentrates.

The general price functions for zinc concentrates are:
1. When the Zn level of the concentrate = Zn % > 53.3% then
   Price of the concentrate = Zn price * 0.85 * Zn level (%) – TC – fines
2. When the Zn level of the concentrate = Zn % < 53.3% then
   Price of the concentrate = (Zn level (%) – 8%) * Zn price/100 – TC – fines

In order to reach the economic target the operation of the roaster should be smooth. A high concentrate feed rate and high uptime are the main sub-targets. There are several ways of increasing the feed rate to the furnace, such as increasing the temperature, adding more cooling coils to the furnace, water injection to the bed and using oxygen. The challenge is to know what the optimal conditions are for each concentrate mixture. It is
essential to have a good, stable bed in the furnace. The fluidisation should also be good, because it has an impact on the heat transfer. It is therefore important to gain knowledge about how the quality of the bed can be controlled. When coarse concentrates and concentrates with a low amount of impurities are used, this is easier to achieve than when the concentrates are impure and fine. The main impurities that must be taken into account are Cu and Pb. The feed mixture is the most important control variable and planning the feed mixture is the key to success, both in short- and long-term planning. The kinds of concentrates used influence the roasting performance. The advantage of the zinc plant in Kokkola is that concentrates more suitable for roasting are used in the roaster and those more suitable for direct leaching are used in leaching. When concentrates are chosen, there are many other viewpoints that must be considered besides the main goal, i.e. a good economic result. In fact, the whole plant must be considered when evaluating the impacts of the different elements in the concentrates.

The target for the control of the furnace is to optimise both the capacity and the conditions in the furnace. To reach a high degree of uptime, it is essential to maintain optimal conditions in the furnace. In zinc roasters the specific capacities of the roaster furnaces are about 6–8.2 t/m²/d (Svens et al. 2003). In the Kokkola zinc roaster the yearly average is about 7.4 t/m²/d (dry ton). The optimum feed rate depends on the concentrate mixture, the equipment capacity (furnace, boiler and ESPs) and the possibilities of setting the optimal conditions, i.e. having the necessary control tools. Too high a feed rate can lead to sinters, bad fluidisation and problems in the boiler, which will influence the uptime. The target is to optimise the capacity, i.e. the yearly concentrate feed amount, by optimising the feed rate and running time. Yearly concentrate feed versus feed rate and running time is shown in Table 1.

Table 1. Yearly concentrate feed as a factor of feed rate and running time.

<table>
<thead>
<tr>
<th>Running time %</th>
<th>Yearly concentrate feed as a factor of feed rate and running time Mt / a</th>
</tr>
</thead>
<tbody>
<tr>
<td>95.0</td>
<td>0.166 0.171 0.175 0.179 0.183 0.187 0.191 0.196 0.200</td>
</tr>
<tr>
<td>94.5</td>
<td>0.166 0.170 0.174 0.178 0.182 0.186 0.190 0.195 0.199</td>
</tr>
<tr>
<td>94.0</td>
<td>0.165 0.169 0.173 0.177 0.181 0.185 0.189 0.194 0.198</td>
</tr>
<tr>
<td>93.5</td>
<td>0.164 0.168 0.172 0.176 0.180 0.184 0.188 0.192 0.197</td>
</tr>
<tr>
<td>93.0</td>
<td>0.163 0.167 0.171 0.175 0.179 0.183 0.187 0.191 0.196</td>
</tr>
<tr>
<td>92.5</td>
<td>0.162 0.166 0.170 0.174 0.178 0.182 0.186 0.190 0.194</td>
</tr>
<tr>
<td>92.0</td>
<td>0.161 0.165 0.169 0.173 0.177 0.181 0.185 0.189 0.193</td>
</tr>
<tr>
<td>91.5</td>
<td>0.160 0.164 0.168 0.172 0.176 0.180 0.184 0.188 0.192</td>
</tr>
<tr>
<td>91.0</td>
<td>0.159 0.163 0.167 0.171 0.175 0.179 0.183 0.187 0.191</td>
</tr>
<tr>
<td>90.5</td>
<td>0.159 0.163 0.166 0.170 0.174 0.178 0.182 0.186 0.190</td>
</tr>
<tr>
<td>90.0</td>
<td>0.158 0.162 0.166 0.170 0.173 0.177 0.181 0.185 0.189</td>
</tr>
</tbody>
</table>

20.0 20.5 21.0 21.5 22.0 22.5 23.0 23.5 24.0

Concentrate feed rate t/h

In order to achieve a high running time there should be few shutdowns and the yearly shutdown should be as short as possible. The interval between yearly shutdowns should also be as long as possible, however without neglecting the required maintenance of
equipment at proper intervals. The stress and the challenge come from keeping the furnace and boiler running without cleaning for long periods. Besides the main equipment, i.e. furnace and boiler, there is also other equipment that must be taken care of, such as the big fans and ESPs. Back-up equipment (fans, ESPs etc.) is one means of achieving a high running time.

Efficient production and minimal process disturbances are the result of process knowledge, good control of the process, good equipment, good maintenance and skilled personnel.

The total concentrate feed is the result of the feed rate versus the running time as shown in Table 1 above. The table shows that increasing the running time from 93% to 94% increases the yearly feed rate by about 0.02 Mt/a, at a feed rate of 21.5 t/h. Increasing the feed rate from 21.5 t/h to 22.5 t/h increases the yearly feed by 0.08 Mt/a, when the running time is 93%.

The quality of the steam, calcine and sulphuric acid produced should be acceptable. In particular, the quality of sulphuric acid has lately become more important and the trend is that the mercury level should be low. To be able to produce sulphuric acid with low mercury and few disturbances has placed extra stress on process development. The need for a good and manageable process is also important when choosing concentrates. If the process can handle concentrates with high mercury without problems then flexibility is increased.

Nowadays, environmental issues are becoming increasingly important. Therefore running the roasting lines with as few disturbances as possible is crucial. Again, process knowledge, maintenance and skilled personnel are essential in reaching this goal. Safety issues have also become a topic of great importance. Therefore safety issues must be considered all the time.

In roasting, the target has been to obtain more information about the roasting mechanism, the impacts of impurities, the dynamics of the process and the influences of different control variables. More knowledge is needed in order to be able to treat fine and impure concentrates in the roaster fluid bed furnace. One important target has been to adopt new measurements and analyses that give more information about the state of the roasting process. Adding the means to control the process has also been a significant target. Another goal has been to increase the skill and performance of the operating personnel by training and creating new instructions using the knowledge gained.

In boiler development, the target has been to modify the boiler based on research and development work and operational experiences in order to increase efficiency and uptime. Reaching this target improves the overall performance and gives more freedom for roasting furnace control.

In mercury removal the target has been to gain more knowledge about the process by doing research and development work. This has been the platform when creating the means to control the process.
5 Measurements and control of the fluidised bed furnace

In this chapter measurements and control of the fluidised bed furnace are discussed. It was part of this work to establish what kinds of measurements and analyses give valuable information for the control system development. Based on more knowledge, more measurements and more analyses, the control strategy, loops and means of control could be developed. A computer system for monitoring and controlling the process is a necessity. The need to gather measurements and analyses in a system that contains both short-term and long-term trends is necessary.

The major goal of the control strategy development is to improve the economic result and the treatment charge (TC) is the key factor that should be optimised. The target is to be flexible in the use of concentrates, which is necessary to reach the economic goal.

As discussed in chapter 3, the quality differs between various concentrates which are generally known to behave differently in the furnace. The major factors are the impurity levels and the particle size distribution of the concentrates. The concentrate mixture is the most significant control factor. When no other control tool works, then this control tool must be used, i.e. the concentrate mixture must be changed.

For example, a broad range of different concentrates is used in the Kokkola roaster. Calculation of the concentrate mixture is made both in short- and long-term planning. Long-term planning means that the concentrate mixture for a period of about one year is calculated. The key in long-term planning is to optimise the economic result, but also to make a plan that is realistic, i.e. to keep the impurity levels and particle size distribution within a safe range. A short-time plan made on a weekly basis enables changes to be made when needed, according to the response of the process and the optimisation of the use of the concentrates that are actually in the concentrate storage.

Control of the roaster furnace is the essential factor allowing flexibility in the use of concentrates. There are several limits to the operation of the furnace, as the process is quite varied and many aspects have to be considered. Having the tools to change roaster furnace behaviour, i.e. control tools, is essential in order to achieve flexibility.

Developing the boiler and mercury removal process has increased the flexibility in running the roaster furnace and choosing concentrates. The flexibility in choosing concentrates is higher when constraints due to these two stages are low. For the boiler this means long running periods with few shutdowns due to build-ups or leakages in the
boiler. An effective boiler also allows more flexible running of the furnace, i.e. the operation parameters in the furnace can be chosen so that they are optimal for the furnace, but not necessarily for the boiler. By making the boiler effective it can cope with a high dust load and high sulphate load. The target is to make sulphuric acid with low mercury content, but having a process that allows the use of a concentrate mixture with a high mercury level is also essential for optimising the concentrate mix, i.e. optimising the TC income.

5.1 Measurements and analyses of the fluidised bed furnace

Many measurements and analyses are required to know the state of the roasting process as shown in Fig. 19. Calculated variables give additional information. In this evaluation mainly those measurements and analyses are discussed that are of importance for roasting. Basic measurements give a good overview of the state of the process. The basic measurements are:

- Temperature (many measurements in the furnace bed, in the gas line and in calcine cooling).
- Pressure (furnace wind-box, furnace, boiler and gas line).
- Flows (air, water, steam, oxygen).

Besides measurements many chemical analyses are required. Chemical analyses of the concentrates form the basis for making the feed mixture calculation. There are maximum limits for many impurities. The limits set are based on zinc plant operation experience and also pilot studies (Grant 1994, Constantineau et al. 2002).

Pressure measurements indicate the state of the process. The wind-box pressure is essential for evaluating furnace behaviour. Many things affect the actual value of the
wind-box pressure. The actual amount of the bed, the particle size distribution (coarseness), fluidisation and sinters formed in the furnace influence the wind-box pressure. Thus a change in wind-box pressure can be a result of many factors, and many times experience and the ability to analyse trends are required in order to draw the right conclusion. Draft pressure is another pressure measurement that must be monitored. Pressure measurements in the gas line (boiler, cyclones, ESPs and mercury removal) are indicators of how clean the equipment is and of when manual cleaning of the equipment is required. The boiler pressure, along with the level control of the boiler drum, is necessary for the operation of the water steam system.

Different flow measurements are also among the basic measurements that are needed. The amount of concentrate fed to the furnace is normally based on X-ray measurement. Measurements of the airflow to the furnace and water flows to various locations are also required.

Furnace temperatures are measured both from the bottom and the side of the furnace. These measurements are very important when evaluating the state of the furnace. The more temperature measurements installed in the furnace, the more reliable the picture of the state of the furnace gained. At Kokkola more temperature measurements have been installed at the bottom of the furnace and also on different levels of the sidewall to get more information. Temperature measurements in many places are essential because during long running periods malfunctions due to severe conditions and/or formation of sinters always cause some of the temperature measurements to stop working.

The calculated overflow calcine amount is in use at Kokkola to give more information about the calcine flow. The calculated calcine overflow amount is based on a mass and heat balance calculation of the fluid bed calcine cooler. The calculation is based on temperature and flow measurements of the calcine, water and air system. Changes in furnace behaviour can often be seen in a changed overflow amount of the calcine flow.

The chemical analysis of the total calcine, for instance the sulphide sulphur ($S^{2-}$) analysis, gives a picture of the roasting conditions. The sulphide level of the calcine is a major indicator both of the state of roasting and the quality of the product. This was also discussed in chapter 3. It is important to monitor other analyses like Cu and Pb to avoid the problems which will arise if their levels are too high. More analyses give more information and at the Kokkola roaster the analysis of the furnace overflow calcine has proved crucial when evaluating the state of the furnace. Besides chemical analysis (Cu, Pb, $S^{2-}$, Si, Ca, $SO_4$) of the overflow calcine, the analysis of the particle size distribution also gives a lot of information. The particle size of the calcine is classified into four different areas and in particular the amount of fine particles corresponds with furnace behaviour; thus, for example, there are normally problems when the proportion of fine particles in the bed is high. The importance of monitoring the particle size distribution is discussed further in chapter 6.

Besides temperature, the second most important factor for roasting conditions is the oxygen coefficient. The determination and calculation method of the oxygen coefficient are presented later in this chapter (in the control section). Oxygen pressure is the general variable, in addition to temperature, when phase diagrams are evaluated and so the oxygen pressure value is essential.

The on-line oxygen measurement in the off gas line also indicates the oxygen coefficient. It is normally placed at the end of the waste heat boiler. The value of the
measurement changes according to changes in the oxygen coefficient, and the correlation is quite good (See chapter 6). However, this requires that the draft control of the furnace is stable; otherwise the result is disturbed by leakage air.

On-line measurement of the oxygen from the roaster furnace bed has been implemented at Kokkola during plant trials. Oxygen has been measured both from the feed side and the overflow side of the furnace (Parkkinen et al. 2002). During measurement campaigns done during test periods, changes have been detected in the oxygen content in the bed when making changes in the process variables. The oxygen content has been lower on the feed side of the furnace compared to the overflow side. This has also been mentioned in a report (Richards 1995). Chapter 6 includes examples of these measurements.

5.2 Control specification of the fluidised bed furnace

The control of a fluidised bed furnace and the equipment in connection with the furnace is quite varied and many aspects have to be considered. One is the necessity for a good and reliable computer system in order to reach a high level in control aspects. Large fans and many valves must be controlled. It requires a lot of attention and skill by the operators to control them, especially during start-ups and shutdowns. This was one reason why a simulator was built (Toskala 2000, Toskala et al. 2001) – to enable the operators to train and learn to understand the dynamics of the process. Pressures and temperatures must be within the correct operating range. There is also a lot of external equipment to control. There are conveyors in the roaster both for feeding the concentrate mixture to the furnace and for transporting the formed calcine to the calcine storage bin. The boiler system also requires a lot of attention. The high pressure and temperature of the boiler make the dynamics very rapid and there are also many safety aspects that the operators must be aware of. A failure in boiler control may have fatal consequences. During normal operating conditions the automation system keeps the system quite stable.

The control of the roaster furnace is a multivariable system. Changing one control variable has an impact on many variables, as shown in Fig. 20. Both dynamic and thermodynamic aspects must be considered in the development of the furnace control strategy.
The control of the furnace is a multivariable system. Many aspects must be considered. Knowledge of the dynamics and the thermodynamics of the process is essential.

The control hierarchy of the furnace control can be classified in three categories and is described as follows (Saxén & Nyberg 2003). Fig. 21 shows the main control inputs of the different control levels for the furnace.

**Conventional Control:** When the situation in the furnace is stable and the concentrate mixture is easy to handle, then standard control is enough. Changes in set points, like temperature and air flow, keep the temperature gradients stable in the furnace, the quality of the product good and also the production amount at the proper level.

**Advanced Control:** To increase the control level of the furnace control in order to increase flexibility a more advanced control level is needed. This requires more measurements and also more control tools, such as the possibility to add water to different locations and to use oxygen enrichment to keep the furnace in balance. The challenge is to know the state of the furnace. Knowing what should be done, i.e. the optimum process conditions, and having the tools to do it is part of this control level. By developing advanced control the chances of being flexible with concentrates increase. The target is to optimise the production and the process conditions.
Ultimate Control: When neither standard nor advanced control helps then the only solution is often to change the mixture of the concentrate feed, otherwise the furnace may remain unstable and lead to formation of sinters in the furnace. This ultimate control is far more expensive, because purer concentrates must be used and they are more expensive. Sometimes such concentrates might not be available at short notice.

The feed mixture is the most important control input to keep the roasting conditions stable. The impurity levels and particle size distribution of the concentrate mixture influence the behaviour of the furnace. It is vital that the mixture is homogenous; therefore the blending should be done well. Usually the blend is a calculated mixture of several concentrates and the day bins before the furnace are filled in sequences that make the content of the bin as homogenous as possible. One possible way to make the feed very homogenous is to make the concentrate mixture in the concentrate storage (Ek 1999). Pretreatment of the feed before it is fed to the furnace is essential when the concentrate is fine and contains impurities. One way to handle the problem and to stabilise the furnace is to pelletise part of the feed (Brown & Goosen 1996). Some concentrates are oxides and other materials fed to the furnace are oxides too, for example, the dust from the zinc foundry. Oxide materials increase capacity because they have a cooling effect on the bed.

Additions of water have a significant impact on roasting (Grant (1993,1994), Lightfoot 1977). Water addition to the concentrate mixture makes the particles larger and stabilises the furnace. Water injection to the bed increases the concentrate feed. In addition, spraying water into the furnace above the bed increases the feed (Longton 1998, Takayama et al. 2000).

The temperature of the furnace is one of the main control variables. When the temperature is high then the feed increases, but the risk of molten phases also increases.
A normal temperature range for the bed in zinc roasters is between 920°C and 960°C. One possibility to control the temperature in the furnace is to control the concentrate feeding system, either manually or automatically, in order to keep the temperature set point at the desired value (Rauma et al. 2000). Another possibility is to set a fixed value for the feed and to control the temperature in the bed by automatically controlling the water injection to the bed.

The other main control variable besides the bed temperature is the amount of air fed to the furnace. At Kokkola the range is normally between 41,000 and 43,000 Nm³/h per furnace for the furnaces with a grate area of 72 m². If the concentrate feed controls the temperature, then the feed increases if the air amount is increased due to the cooling effect of the air (Nyberg et al. 2000). This can be seen especially during winter when the air is cold. Changing the amount of air also has other effects; it affects fluidising and changes the oxygen coefficient.

Calculation of the oxygen coefficient and its active control has been in use at the Kokkola roaster since 2000. Definition of the oxygen coefficient:

“The oxygen coefficient determines the availability of oxygen for complete roasting of the concentrate, i.e. the ratio of total oxygen in the process gas to the oxygen requirement of the feed mixture for the formation of stable oxides and sulphates in the roaster off-gas” (Anjala et al. 1987, Asteljoki et al. 1989, Asteljoki & Muller 1987, Kytö et al. 1989, Rödolff et al. 1986).

At Kokkola the oxygen coefficient is calculated on-line by an automation system based on data fed to the system and on measurements (Taskinen et al. 2000b). The use of the calculated oxygen coefficient has proved invaluable; especially when the situation in the furnace has been critical and also during experiments when new process conditions and different parameters (impurities) have been tested. Fig. 22 shows how the oxygen coefficient is calculated. Mineralogical studies provide the basis for the calculations.

Fig. 22. The calculation scheme for the oxygen coefficient and its use for control. This has been adopted and is now in use in the control of the furnaces at the Kokkola roaster.

When phase diagrams and Kellogg diagrams are studied there are two significant variables, namely temperature and oxygen pressure or potential (Mäkinen & Jäfs 1982,
Especially when concentrates containing impurities like Cu, Pb, Si, Na and K are used, the importance of keeping both the temperature and the oxygen coefficient within the right range is highly significant. The oxygen coefficient can be controlled in many ways, with the key being the feed versus the total oxygen feed. Variables that change the oxygen coefficient are the set point temperature of the bed, the amount of air used, water mixed into the concentrate mixture feed, water injected to the bed and oxygen added to the air feed. The influence of air for instance, i.e. increasing or decreasing, is dependent on the control strategy. If, for instance, the feed is fixed, then increasing the amount of air increases the oxygen coefficient, but if the temperature is kept fixed by controlling the feed, then increasing the amount decreases the oxygen coefficient. This is due to the fact that an increase of air cools the bed and increases the feed proportionally more than the amount of air. The influence of the oxygen coefficient is presented in chapter 6. It is essential to know what the actual oxygen coefficient is and to control it. This calculation and control of the oxygen coefficient is one of the most significant parts of this work (Chapter 6, Taskinen et al. 2000b).

Feeding oxygen can be used in roasting for many purposes. The use of oxygen increases the capacity without changing the fluidisation as much as the use of additional air does (Filho et al. 1998, Longton 1998, MacLagan et al. 2000, Saha et al. 1989). The use of oxygen also increases the oxygen coefficient and thus it changes the operation parameters of the process. In some cases the possibility of using oxygen can be an advantage for the control of the roaster furnace. The disadvantage is in many cases the price of oxygen. Increased cooling capacity (increasing the capacity of the cooling coils or water injection) is needed when oxygen enrichment is used to increase the capacity, otherwise the temperature will increase in the furnace.

On the overflow side of the furnace, the height of the bed is controlled by bars. Depending on the wind-box pressure of the furnace, the height of the bed is adjusted by adding or removing bars. If the bed is high, then the cooling coils in the furnace are used more effectively and thus the capacity of the furnace increases.

The cooling coils in the furnace above the grate area cool the bed. By increasing the cooling area, the capacity of the furnace increases. This capacity is fixed and cannot be controlled during operation, thus a suitable cooling capacity must be decided when the furnace is built and can only be changed during long maintenance shutdowns. Water injection to the bed is a flexible way of controlling the cooling capacity of the furnace.

The draft control must be accurate, and a slight underpressure must be sustained in the furnace. Overpressure in the furnace leads to SO₂ emissions, dust emissions and insufficient working conditions. The underpressure should be as close to zero as possible; otherwise leakage air increases, which can lead to build-ups on the furnace wall above the slinger belt inlets. These build-ups are sulphates formed due to the low temperature in this part of the furnace. The SO₂ blower and the valves connected to it control the draft.

Some plants use the underflow outlet from the grate bottom at the side of the furnace. This can be an outlet for the very coarse material on the grate surface that does not fluidise properly. There are different types of underflow mechanisms and the advanced version that is in use in some roasters is based on an automatically controlled lance system (Svens et al. 2003). A modified version of this is in use at Kokkola. This system includes a cooling system with a system that measures the amount of calcine removed and the ability to control the amount (Siirilä et al. 2003).
The grate area is full of nozzles on the surface. The distance between the nozzles is about 10 cm and the diameter of the nozzle hole is about 6 mm. To increase the amount of oxygen at the side where the slinger belts are located, bigger nozzles can be used in this specific area (Taskinen et al. 2000a). The advantage of this is that because the concentrate comes into the furnace on this side and reacts here, the oxygen demand is high in this part of the furnace. If the nozzles are of normal type, it leads to a low oxygen coefficient and formation of build-ups on the furnace bottom.

In the overflow area there are nozzles on the surface and the pressure is the wind-box pressure of the furnace. To be able to control the overflow, the nozzles of this specific area can be connected to a pressurised system (Siirilä 2000). This makes it possible to increase the pressure and to increase the amount of calcine removed from the furnace via the overflow.

An advanced furnace control diagram is shown in Fig. 23. It includes water feed to various points, oxygen feed, a fuzzy control loop for the temperature control of the bed temperature and a top temperature control loop for the boiler inlet temperature. The diagram includes also advanced measurements (oxygen at the end of the boiler), analyses (grain size distribution analysis of the furnace calcine) and calculated variables such as the oxygen coefficient and calcine overflow amount.

Fig. 23. A furnace control diagram is shown with advanced control and measurements. It includes among others a fuzzy control loop, the calculated oxygen coefficient, oxygen measuring from the gasline, calculated calcine overflow amount and grain size distribution analysis of the furnace calcine. The possibility of feeding water to different spots and oxygen is also available.
5.3 Aspects relating to the boiler and mercury removal

In the heat recovery boiler, the water steam system requires reliable measurements, because otherwise the control of this high-pressure system can lead to severe malfunctions. The pressure control and the level control of the drum are the key control items. The feed water, circulating water and steam produced are the other main control variables. The goal regarding boiler performance is to have a high degree of uptime without shutdowns and start-ups due to manual cleaning of the boiler. To achieve this, rapping or hammering devices must be installed. At Kokkola there are more than 100 spring hammers per boiler, which effectively hammer the bundles and the walls. The hammering devices are controlled sequentially by an automation system.

There are also several measurements in the boiler gas line of temperature and pressure, which indicate how clean the boiler is and if the boiler is working properly.

The control of mercury removal requires measurements (temperature, pressure and flows), analyses of both liquids and slurries (Hg, Se, Cl, and H₂SO₄) and also control options (addition of chemicals and cooling). Often the difficulty is that the quantities are very low, especially in the gas phase, and controlling them is not so easy. The target, i.e. the quality of the sulphuric acid, is nowadays very high, which means a very low mercury level.
6 Results of the control strategy development for the Kokkola zinc roasting process

In the following the control strategy development for the Kokkola zinc roaster is described. The main parts of the development are the furnace, the boiler and mercury removal.

6.1 Furnace development

The target of the furnace control system has been to increase the capability of using different kinds of concentrates, because flexibility with concentrates is essential and economically very significant. Low-grade Zn concentrates are less expensive, but treating them is more difficult due to the fact that they contain more impurities. To reach this target, the optimal conditions for a certain concentrate mixture have to be determined. Control means and knowledge of the influence of different variables are other factors of importance. Knowledge of the state of the furnace has to increase by adding more measurements and also by taking additional samples for analysis (chemical and particle size distribution analysis).

The target has also been to run the furnace without the formation of too many build-ups and to prevent the bed from becoming fine by controlling the particle size growth of the calcine bed. The research results have led to longer running periods. Formerly the roaster furnaces were emptied once a year, but now the running period of the furnace has increased. The target, which now seems attainable, is to run the furnace for two years without cleaning.

Results from furnace research and development work are presented in the following text as well as the influence of the various major factors.
6.1.1 Factors correlating to bed instability

Factors correlating to instability have been derived from plant experiments and active monitoring of the roasting process. By adding more measurement devices to the furnace and by taking samples for analysis, information of great importance for evaluating the situation in the furnace has been acquired. Placing numerous thermocouples in the furnace at different heights has increased knowledge of the state of the furnace. Chemical analysis of the furnace calcine and above all the grain size distribution of the furnace calcine have proved to be very informative.

When the fraction of fine calcine increases in the bed, it normally correlates with other variables and with bed instability. The situation during bed instability is often as follows:

- The percentage of fine grain size of the overflow calcine grows and the fraction < 71 µm in the overflow is over 10 %.
- Bed temperature drops in the furnace due to bad fluidisation. During such situations a temperature drop can be seen in some parts of the furnace.
- The windbox pressure drops (bad fluidisation).
- The sulphide level analysed from the furnace calcine is very low.
- The overflow calcine amount (calculated variable) decreases.
- The fluidised bed becomes sticky.

Figs 24 and 25 show a situation when the bed was unstable for several days. Fig. 24 shows that the windbox pressure dropped when the amount of fine calcine in the bed, i.e. the fraction less than 71 µm, increased. At the same time, as shown in Fig. 25, the values of some bed temperatures dropped.

Fig. 24. The drop in windbox pressure and the increased proportion of fine calcine indicate an unstable bed.
Fig. 25. Temperature drop indicates an unstable bed. Temperatures measured from the sidewall fell while the temperature measured from the bottom remained stable.

### 6.1.2 Oxygen coefficient control

The importance of the oxygen coefficient has become apparent during this research. Therefore it is important to have the means to control it, to know how it affects roasting and to know the value of the oxygen coefficient. As described in chapter 5, the oxygen coefficient is calculated based on the mineralogical analysis of different concentrates. By analysing the concentrates, the oxygen requirement is determined for each concentrate and then the computer system calculates the oxygen coefficient using the available data (concentrate feed, amount of air and oxygen). Thus, the operator knows the oxygen coefficient in the furnace at all times.

There are different ways to either increase or decrease the oxygen coefficient. Different ways of changing the oxygen coefficient include: changing the temperature set point, changing the amount of air, using oxygen, using water before the furnace, feeding water to the furnace, using oxides etc. The plant experiments performed have shown the effects of different variables. Table 2 shows the alternative methods of changing the oxygen coefficient and their effects. The operators use this information when they make their control decisions.

(*1 = The control in this case, as is shown in Table 2, is such that the furnace temperature set point is fixed and controlled and kept stable by the concentrate feed. *2 = The top temperature is the point between the furnace and the boiler and is controlled by the amount of water fed to the concentrate feed before the furnace. A top temperature control loop has been added to the control system. The operator gives the set point and then the water feed to the concentrate stream before the table feeder controls the top temperature automatically).
Table 2. The effects of different variables are shown in the table. The operators have several ways to control the oxygen coefficient. Fuzzy temperature and top temperature control loops are in use in the cases shown in the table.

<table>
<thead>
<tr>
<th>Operation</th>
<th>Results</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Oxygen feed to the furnace (=oxygen enrichment of the process air to the furnace).</td>
<td>Increases the oxygen coefficient.</td>
</tr>
<tr>
<td>2  Lower bed temperature.</td>
<td>Increases the oxygen coefficient due to decreased feed.</td>
</tr>
<tr>
<td>3  Water injected into the bed.</td>
<td>Decreases the oxygen coefficient due to increased feed.</td>
</tr>
<tr>
<td>4  Water feed before the furnace to the concentrate mixture.</td>
<td>Increases the oxygen coefficient due to decreased feed.</td>
</tr>
<tr>
<td>5  Increasing the airflow.</td>
<td>Decreases the oxygen coefficient if the feed increase is proportionally larger than the increased oxygen amount.</td>
</tr>
<tr>
<td>6  Decreasing top temperature.</td>
<td>Increases the oxygen coefficient (*2).</td>
</tr>
<tr>
<td>7  Feeding oxide material into the feed mixture.</td>
<td>Decreases the oxygen coefficient because the oxide material has a cooling effect and increases the feed.</td>
</tr>
<tr>
<td>8  Increasing the cooling area of the cooling coils in the furnace.</td>
<td>Decreases the oxygen coefficient because the feed increases.</td>
</tr>
</tbody>
</table>

Some results from plant trials are presented in Figs 26–28, i.e. how different variables are affected by the oxygen coefficient.

![Graph showing the effect of oxygen coefficient on sulphide levels](image)

Fig. 26. Sulphide level of the calcine (WHB, Cyclone and ESP) decreases when the oxygen coefficient is high.
Fig. 27. Sulphide level of the WHB calcine is lower when the oxygen coefficient is high.

Fig. 28. High oxygen coefficient increases the amount of sulphates. Difference \( \text{SO}_4 \) = the amount of sulphates minus \( \text{PbSO}_4 \) and \( \text{CaSO}_4 \), which are always sulphates in roasting conditions.

The oxygen on-line measurement from the end of the WHB indicates, as is shown by Fig. 29, that the sulphate amount increases when the oxygen level increases. Fig. 29 also shows the need to calibrate the measurement device, because there is a difference in the oxygen level at different times. It is important that the boiler, cyclones and ESPs can handle the dust and the \( \text{SO}_4 \) load without any trouble, so that the freedom to choose the process parameters in the furnace and to use concentrates with high impurity levels increases. Fig. 30 shows that the sulphide level decreases when the oxygen level in the WHB gas increases.
6.1.3 Oxygen use to control bed quality

Oxygen enrichment, i.e. feeding oxygen to the process air, is used by some plants. Oxygen can be used to increase capacity (chapter 5), but also in order to increase the oxygen coefficient. The cost of oxygen is a factor that reduces its use, but if there is this opportunity, i.e. the oxygen line is installed and oxygen is available, then it is an easy way to control the oxygen coefficient. It is essential to have a bed with a good grain size distribution. During operation the bed has often become unstable, i.e. it has become fine, and by using oxygen the situation has several times been successfully corrected back to normal (Nyberg et al. 2000). Figs 31 and 32 show that by using oxygen, the oxygen coefficient has increased and this has led to an increase in the amount of coarse calcine and a decrease in the amount of fine calcine. The use of oxygen and the increase in oxygen coefficient value have not always solved the situation and other actions have also been needed. More examples of controlling instability situations will be presented later in this chapter.
6.1.4 Bigger nozzles and oxygen measurements from the bed

The concentrate feed is fed to the furnace by slinger belts from one side of the furnace and the outlet of the furnace is on the other side. This calcine amount, i.e. the overflow calcine from the furnace, is about 30–40% of the total calcine amount. The majority of the calcine formed in the furnace is carried by the gas stream to the boiler. In slinger belt tests, it became evident that the concentrate feed is not spread very far from the feed side. On many occasions it has been seen during annual maintenance shutdowns, when the furnace has been cleaned, that there are build-ups on the grate area on the feed side of the furnace. This can be explained by the fact that most of the concentrate reacts in this part of the furnace and therefore the oxygen need is greater in this part. Because an equal amount of oxygen is fed to the whole grate area there is a lack of oxygen in this area, i.e. the oxygen coefficient is low, which leads to sinters. The lack of oxygen on the feed side...
has been mentioned in a paper (Richards 1995). To avoid these build-ups bigger nozzles have been installed on the feed side of the furnace to keep the oxygen coefficient high enough (Taskinen et al. 2000a). Also, a special nozzle system has been tried to spread the concentrate better on this side of the furnace (Nyberg et al. 2001). The need for more oxygen in this side of the furnace has been confirmed by on-line oxygen measurements from the bed. Oxygen has been measured during plant experiments from the feed and the overflow side of the furnace (Parkkinen et al. 2002). Figs 33 and 34 show the very low oxygen level on the feed side, while there is oxygen present on the overflow side. The SO$_2$ level in the bed can also be seen from Figs 33 and 34. SO$_2$ measurements have also been presented in a paper (Dimitrov & Schopov 1985).

Fig. 33. On-line gas measurement from the roaster bed on the feed side. The O$_2$ level in the bed is very low.

Fig. 34. On-line gas measurement from the roaster bed on the overflow side. The O$_2$ level is higher on the outlet side of the furnace.
6.1.5 Effects of water on the furnace behaviour

As previously mentioned, the addition of water has many effects. The addition of water to the concentrate stream particularly before the day bins and also before the table feeder has a pelletising effect. Thus it should be used in cases when the concentrate mixture has a high impurity level and is fine. Feeding water to the concentrate mixture before the furnace also reduces the feed and increases the oxygen coefficient. In the cases shown in Figs 35–39, the furnace temperature set point is given and the concentrate mixture amount controls the temperature. Water can also be used to control the top temperature by feeding it to the concentrate mixture. By injecting water to the bed the feed can be increased. The water feed cools the bed and for this reason the control application increases the feed in order to keep the temperature at the set point. Some effects of water are described in the following text and can be seen in the following figures. Similar results have also been presented in a published paper (Nyberg et al. 2000).

Water fed to the concentrate mixture has the following effects:
- Stabilises sulphide combustion in a fluidised bed. This has been seen during experiments. The oxygen on-line measurements have shown that the oxygen level is stabilised when water has been fed. Other experiments have shown that the temperature differences between the different furnace temperature measurements have been decreased.
- Decreases the feed when the concentrate feed controls the temperature. This is the case when water is fed before the day bins, as shown in Fig. 35, or is fed after the day bins, as shown in Fig. 36.
- Transfers the combustion of the concentrate mixture more to the bed, i.e. less combustion over the bed, which decreases the capacity.
- Increases the total oxygen coefficient.
- Decreases the sulphide content of the boiler and cyclone calcine as shown in Fig. 38.
- Decreases the temperature of the upper part of the roaster furnace.
- Increases the fraction of overflow calcine (= the calcine furnace overflow).

Fig. 35. High moisture of the concentrate mixture decreases the feed. The water makes agglomerates and transfers the burning more to the bed. The feed is reduced because otherwise the temperature would rise in the furnace, due to the furnace temperature control application.
Water sprayed into the fluidised bed has the following effects:

- Cools the calcine bed in the furnace.
- Increases the concentrate feed as shown in Fig. 37.
- Decreases the total oxygen coefficient.

![Diagram](image)

**Fig. 36.** Water fed to the concentrate before the furnace decreases the concentrate feed. In this case too, water makes agglomerates and transfers the burning more to the bed. The feed is reduced because otherwise the temperature would rise in the furnace, due to the furnace temperature control application.

![Diagram](image)

**Fig. 37.** Water injection into the bed increases the feed. Water sprayed (500 l/h) into the furnace bed cools the bed and more concentrate has to be fed to keep the temperature in the furnace at the set point value due to the furnace temperature control application.

Fig. 37 shows that the concentrate feed is high when water (500 l/h) is injected into the furnace bed. When the water injection is stopped, then the feed drops.
Fig. 38. Water fed into the concentrate before the furnace decreases the sulphide level of the boiler and cyclone calcine. The feed decreases due to the water feed and this increases the oxygen coefficient.

The decrease in the sulphide level of the boiler and cyclone calcine, as shown in Fig. 38, is due to the fact that a low feed increases the oxygen coefficient. Fig. 39 shows how water fed before the furnace increases the SO$_4$ content. The reason for this is that the oxygen coefficient increases with the result that the SO$_4$ level of the furnace calcine rises.

Fig. 39. Increasing the water feed (*1) before the day bins increases the sulphate amount in the bed. (*1 = The concentrate feed rate to the day bins is about 350 t/h and water is fed to this stream).

6.1.6 Control of the furnace when Pb and/or Cu is high

The major impurities that should be emphasised in roasting are Cu and Pb. Many concentrates have a high Pb content, some have a high Cu content. The danger of these elements is that they can easily form molten phases as described in chapter 3. Besides Cu
and Pb, other elements also form molten phases. The molten phases lead to build-ups in the furnace and even to sintering of the bed in the worst case. The challenge in the control of the furnace is to avoid molten phases when the impurity levels of the concentrate mixture are high.

In plant experiments where the Pb level has been high in the concentrate mixture and especially when the mixture has also been fine, the need to feed water before the day bins has been obvious. Oxygen measurements from the bed have shown that the water feed has stabilized the bed. In addition, feeding water after the day bins before the table feeder stabilizes the bed, as can be seen from the fact that the temperature gradient is smaller. This will be shown later in this chapter when the dynamics is discussed. In plant experiments where there has been 3.3% Pb in the concentrate mixture and more than 5% in the bed for some time, the bed has been kept stable successfully without major difficulties. The crucial keys in keeping the bed stable have been the water feed to the concentrate mixture before the day bins, keeping the oxygen coefficient over 1.1 and running the furnace at a low temperature.

During plant experiments, numerous samples have been taken and analysed, both chemical and microscopic analyses. Microscopic analyses are important in order to get more information about what is going on in the bed. Fig. 40 shows how lead behaves in agglomerates. The coating around the particle is mostly PbSO₄ while the inner part is mostly ZnO.

Copper is a critical component in roasting. Copper behaves differently compared with lead. Copper tends to migrate in the agglomerated zinc sulphide concentrates and enrich as the least easily oxidising element in the centre of the agglomerate, as shown in Fig. 40. The Cu₂S cores formed, with very high copper concentrations, require long oxidation times and a high oxygen coefficient (Taskinen et al. 2002, Metsärinta et al. 2003, Metsärinta et al. 2005b).

During laboratory experiments the copper level in the feed has been up to about 0.9%. In laboratory experiments with a high Cu content, the need for a very high oxygen coefficient proved essential. With a high oxygen coefficient, over 1.3, the bed remained stable, i.e. no sintering of the bed occurred, even with a high copper content. Based on the
laboratory tests, plant trials were performed with a Cu level of about 0.9%. From plant experiments, as shown in Figs 41 and 42, it can be seen that the copper level and oxygen coefficient have an effect on the bed, i.e. the percentage of calcine from the overflow depends on these variables. Later, based on the good experience from the plant trials with high Pb in the feed (about 3.3%) a plant test with a very high Cu in the feed was planned and carried out. The test run with a very high Cu level in the feed mixture, which lasted about two weeks, was performed successfully. The Cu level was about 0.9–1.5% in the feed mixture. The oxygen coefficient must be high and the bed temperature low, when the copper level of the concentrate feed is high (Metsähinta et al. (2003, 2005a, 2005b)). The danger of a high temperature in the bed can be seen when phase diagrams are studied (Appendix 1). In the plant experiments (both in the case with high Pb and in the case with high Cu) the furnace bed temperature was kept at the level of about 900°C, which proved to be good, i.e. formation of build-ups on the furnace grate was avoided.

**Fig. 41.** The Cu level of the feed versus the amount of calcine overflow of the concentrate feed. The proportion of the overflow calcine has decreased when the Cu level has increased.

**Fig. 42.** Oxygen coefficient versus the amount of calcine overflow of the concentrate feed. The proportion of the overflow calcine has increased when the oxygen coefficient has been increased.
Plant experiments are necessary to gain reliable information on how the furnace behaves when the impurity levels of the concentrate mixture are high. There is always a risk that such experiments can lead to build-ups in the furnace and to other problems. Therefore, such experiments must be well planned and performed. There are also limits on how high impurity levels can be tested in full-scale furnaces.

### 6.1.7 Controlling unstable situations

When there is instability in the bed, control actions must be taken to rectify the situation, i.e. to stabilise bed behaviour. Examples of different situations are presented in Figs 43–51 and in an article (Nyberg et al. 2000). In these cases active control based on knowledge gained has been used to correct the situations. Knowledge of the roasting mechanism and also knowledge of how the particle size distribution of the bed can be controlled is essential for successful control. It can be seen from the figures that control of the oxygen coefficient has brought the bed back to a stable situation. In some cases, control and increasing the oxygen coefficient have not helped. Feeding water to the concentrate mixture has also stabilised the bed in some cases. The figures show the importance and effects of the oxygen coefficient and the water feed. Other aspects to be considered are bed temperature and impurity levels.

The fluidised bed was made stable, as shown in Fig. 43, by decreasing the bed temperature and process airflow and by increasing the oxygen coefficient of the roasting furnace by feeding oxygen. The bed temperatures rose back to normal during the period (August 2002).

![Roaster 2 - Bed temperatures and oxygen coefficient](image)

**Fig. 43.** Bed temperatures and oxygen coefficient of roaster furnace No. 2 in August, showing the effect of oxygen coefficient alterations on stabilisation. By increasing the oxygen coefficient, the stabilisation of the bed temperatures can be seen.

The fluidised bed also became unstable in September–October 2002. The wind-box pressure decreased, although the oxygen coefficient was relatively high as shown in Fig. 44. In this case the moistening water feed to the concentrate feed before the day bins was...
decreased at the same time as the wind-box pressure dropped. By increasing the water feed, as shown in Fig. 45, the wind-box pressure returned back to normal, thus showing the importance of the water feed. During this period the grain size of the concentrate mixture was fine. Increasing the oxygen coefficient failed to help in this case, but the water feed solved the situation.

Fig. 44. Oxygen coefficient and wind-box pressure in furnace No. 2 (September–October 2002). When the wind-box started to drop, the oxygen coefficient was increased in order to raise the wind-box pressure back to the normal level.

Fig. 45. Wind-box pressure and the total moistening water feed in roaster furnace No. 2 (September–October 2002). Water feed correlates with bed pressure, thus the wind-box pressure is low, i.e. unstable bed, when the water feed is low.

Figs 46 and 47 show that during this period a stable bed, i.e. stable bed temperatures, correlates more with the water feed and so the water feed is more essential than the oxygen coefficient in this case. The bed temperatures remain quite stable although the oxygen coefficient drops.
Fig. 46. Oxygen coefficient and bed temperatures (#4 & 5) of roaster No. 1 (July–August 2002). The correlation is not so good, i.e. the temperatures stay stable even if the oxygen coefficient drops.

Fig. 47. Water feed before the day bins and bed temperatures of roaster No. 1 (July–August 2002). The temperature drops (Thermocouple element No. 5) after the water feed is stopped. After the water is again fed to the concentrate mixture, the temperature value returns back to the normal level.

Fig. 48 shows that increasing the oxygen coefficient had a stabilising effect on the bed temperatures, i.e. the values of the measurements stopped falling and rose towards the normal level. The increase in the oxygen coefficient was achieved by decreasing the feed. The feed was decreased by lowering the temperature set point of the fuzzy controller for the furnace, as shown in Fig. 49. Increasing the oxygen coefficient can also be seen in the bed pressure (wind-box pressure), the low level on 8.8.2002 moves towards the normal level when the oxygen coefficient increases, as shown in Fig. 50.
Fig. 48. Increasing the oxygen coefficient stabilized the bed temperatures (the negative trend stopped).

Fig. 49. Changes of the oxygen coefficient were made by changing the feed rate. This was done by changing the set point value of the furnace temperature. The fuzzy controller then decreased or increased the feed rate.
Fig. 50. Increasing the oxygen coefficient stabilized the bed pressure. The drop in bed pressure was stopped and a slight increase back to the normal level can be seen. The period is the same as in Fig. 49.

Fig. 51 shows that the situation in the furnace was such that increasing the oxygen coefficient had a positive impact on the bed pressure. This resulted in a more stable bed.

During the period described in Figs 43–51, the feed was fine, i.e. the $d_{50}$-value ($=$ mass median diameter) was in the range of about 20–22 µm. The furnace bed became somewhat unstable occasionally during the period. The furnaces were brought back to normal by active control of the process without changing the concentrate mixture to a safe mixture, i.e. coarse and fewer impurities. The plant experiments performed have increased knowledge of the roasting mechanism. Active surveillance and control in difficult situations have also increased knowledge. Based on this, new instructions have been adopted and the operators make their control decisions accordingly.

Means of controlling difficult situations have also been increased. Thus the operators have more options to adjust the roasting conditions so that they are suitable for the concentrate feed mixture. Often it is very complicated to know what is actually taking place in the furnace. The same kind of indications can have different backgrounds and
causes. Automation systems that show both short- and long-term trends have made evaluation more effective. Monitoring and analysing the bed thoroughly is of great importance in order to get more information about developments in the furnace. Both chemical analysis (Cu, Pb, Si etc.) and the particle size distribution analysis of the calcine bed give a lot of information about the situation in the bed together with other measurements. Additional measurements are required to get a more accurate picture of the roasting furnace behaviour.

Developing systems that visualise the situation, for instance a self-organizing map (SOM) application, and then advise the operators, i.e. expert systems, are possible tools to improve performance. An on-line application of an SOM has been developed for the Kokkola roaster for detecting and predicting instability of the fluidised bed furnaces (Saxén & Nyberg 2003).

6.1.8 The dynamics of the roaster furnace

The dynamics of the roaster furnace have been studied thoroughly. The dynamics are rapid, especially the gas phase, but there are also slower processes where the response is not so fast. The time delay of the bed is much slower than the time delay for the gas phase. Information about the dynamics has been necessary for developing the furnace control. The fuzzy control of the furnace temperature and development of the simulator are cases where the dynamics have been studied before implementation (Rauma et al. 2000, Toskala et al. 2001). The fuzzy control system that was developed reduced the general deviation of the temperature from 10°C to 3°C 95% of the time (Rauma et al. 2000). The structure of the fuzzy control system is shown in Fig. 52.

In the simulator case the very rapid pressure dynamics, i.e. changes in the pressure of the furnace and boiler system, were studied by collecting data from the process during
tests. The reason for building the simulator was to give the operators a tool for practising the demanding start-up and shutdown situations. The simulator can also be used to see the effects on the furnace pressure when valves and blowers are regulated. The simulator is integrated in the automation system that is used for the actual control of the process. Fig. 53 shows the scope of the simulator.

![Diagram of the simulator](image)

Control variables:
- air blower’s vane position $U_{abv}$
- by-pass valve position $U_{bpv}$
- fluidising air valve $U_{fav}$
- SO2 blower’s vane position $U_{sbv}$
- stack valve position $U_{sv}$
- exit gas pipes valve position $U_{ev}$
- fluidising air flow $V_{fa}$

Fig. 53. The scope of the simulator made for training start-up and shutdown situations. A dynamic model for the furnace pressure was made (Toskala et al. 2001).

The dynamics of the process have been studied further. Dynamic models were identified for input-output relations in the fluidised bed furnace. Based on these experiments, a state-space model of the process has been built (Härkönen 2003, Saxén et al. 2004). In this study, step trials were performed where the influence of different variables was tested. During the tests the control loops that control the temperature of the furnace, i.e. the fuzzy control of the bed temperature and the top temperature control loop, were disconnected. The concentrate feed and air amount were fixed during the tests. In cases where the effect of the concentrate feed or of the air amount were tested, they were of course changed. The main variables that were tested are as follows:

- Water feed to the concentrate mixture before the table feeder.
- Water injection to the furnace bed.
- Air amount.
- Concentrate feed rate.
- Oxygen feed.

The aim of the tests was to collect data on how the different variables react in order to build a model, but also to develop a control system to improve the control of the furnace. Some results are presented below in Figs 54–57, which show the dynamics of the furnace behaviour. There are both rapid and slow responses.
Feeding water to the concentrate mixture increases the bed temperature (slowly) and decreases the top temperature of the furnace (rapid response). At the beginning there is an inverse response of the bed temperature before the temperature starts to rise. Feeding water to the concentrate mixture stabilises the bed and this can be seen from the fact that the bed temperatures start to converge as is shown in Fig. 54, i.e. the differences between the different measurements become smaller. The same thing can be seen in Fig. 55, where the difference between different bed temperatures is smaller when more water is used. Water injection cools the bed when water is injected into the bed, as shown in Fig. 56.

Fig. 54. Responses of gas temperature and bed temperatures, when water is fed to the concentrate mixture before the table feeder. The temperature rises in the bed when water is fed to the concentrate mixture. At the beginning there is a slightly inverse reaction in the bed temperatures. The top temperature decreases when water is fed to the concentrate mixture.
Fig. 55. Water feed before the table feeder stabilises the bed, which can be seen from the fact that the temperature measurements in the furnace are closer to each other when more water is fed.

Fig. 56. Response of water injection into the bed. The furnace temperature decreases due to the cooling effect of the water injection.

Fig. 57 shows that when the oxygen feed is started, it has a divergent effect on the bed temperatures.
Fig. 57. Divergent effect of oxygen on bed temperature measurements. The oxygen seems to have a divergent effect on the temperatures, which could be explained by an increase of the reaction rate in some parts of the furnace. Where there is a temperature drop, the reaction rate decreases.

By doing these tests a lot of information was gathered on how different variables respond when a variable is changed. The bed behaviour, fluctuation of the temperature measurements when oxygen feed was started to the concentrate mixture and the convergent effect of the bed temperatures, also provided information about the roasting mechanism and information about the advantage of using water. This research resulted in more knowledge of process dynamics and also more process know-how.

Tracer tests were made by adding Ti-oxide to the concentrate mixture to determine the residence times (Saxén et al. 2004). The tracer was fed as an impulse to the concentrate feed. The tests showed that the furnace bed behaved something like an ideally stirred reactor, i.e. a first order system. The time constant for the furnace bed was about 20 h. For the gas line the residence time was very short. The peak concentration in the cyclone was measured about one minute after the impulse in the furnace feed. Figs 58 and Fig. 59 show the results from the tracer tests.
Fig. 58. Tracer content in the furnace overflow calcine for two experiments. The Ti-oxide tracer was fed as an impulse at time 0 h. A first order model with a time constant of 20 h is shown for comparison (Saxén et al. 2004).

Fig. 59. The tracer tests shows that the time constant in the gas line is very short, i.e. the Ti-oxide tracer fed as an impulse to the furnace is almost immediately detected in the calcine from the cyclone after the boiler.

6.2 Boiler development

The work done and changes made to the boilers have been successful (Nyberg et al. 2000, Järvi et al. 2002). The running time between manual cleanings has increased from about 3–5 months to more than 9 months. Running periods of up to over 1 year have been
achieved (Kilju 2004). The baffle in the radiation section has been a success, but the long running periods are also a consequence of other development work (Peippo et al. 1999). The new type of bundles with effective hammering, section walls with hammering and installation of more hammering devices have also proved to be good solutions. In addition, effective cleaning during yearly shutdowns, i.e. cleaning the walls and bundles not only mechanically but also using water, prevents build-ups in the boiler from forming so easily. This is due to the fact that build-ups, in this case sulphates, do not stick so easily to the boiler walls and bundles when they are metallically clean. The conditions in the roasting furnace have an impact on the boiler performance. When there are more sulphates in the calcine going to the boiler more stress is exerted on the boiler.

The aim of the boiler improvements has been to reduce the constraints in roasting by having a boiler that can handle the calcine and gas load coming from the furnace. The other aim has been to increase the running time of the boiler. The targets have been reached, so the bottleneck is now more in the roaster furnace performance.

The effects of the baffle wall on the behaviour of the boiler were calculated in advance and the resulting Fluent model calculations are shown in Figs 60 and 61.

Fig. 60. The effect of the baffle wall on the boiler behaviour (radiation section of the boiler) is shown here. The velocity vectors are shown. The Fluent model calculation was made by Foster Wheeler (= the boiler manufacturer).
6.3 Mercury removal development

The quality of $\text{H}_2\text{SO}_4$ has improved significantly due to the results of the research carried out (Nyberg et al 2000). The mercury level in the sulphuric acid can be kept at about 0.02–0.06 mg Hg/kg $\text{H}_2\text{SO}_4$. Also, stability has improved and there are seldom high mercury levels in the sulphuric acid and if there are, the operators now have better means to control the quality. The main factor is to feed selenite solution to different process stages and above all to the sulphuric acid process.

Based on material balance calculations and chemical analyses from different process stages, extensive thermodynamic equilibrium calculations were performed. The chemical analyses made were very demanding because of the difficulty of making a proper analysis and the fact that the low quantities also complicated the analysis. The equilibrium calculations correlated well with the chemical analyses. Therefore, new factors of importance were learned, i.e. the role of the temperature and $\text{H}_2\text{SO}_4$ were not so critical as the role of selenium.

In addition, by studying the slurry in the sulphuric acid process it could be detected that the mercury was removed as HgSe and the need for Se was critical. Precipitation of mercury with Se solution was carried out with success in the laboratory. After that, the same was done at the plant (Peltola et al. 2000). Further research has been done and the use of thiosulphate is another possible solution (Berg et al. 2003).

Better process know-how and new means of controlling the process are the basic results of the research. The approach of carrying out both basic and applied research also proved in this case to be the right way to improve the control of the process.
The research and development presented in this study includes and is based on both laboratory and full-scale plant experiments, various studies, benchmarking, chemical analyses and calculations. Doing research and development in this way has resulted in better understanding of the process and in applications that have improved the performance.

The research must be long-term because the process phenomena are so complicated that otherwise good results cannot be achieved. Only by thorough and broad research can new knowledge be gained. The effects of the applications also often need long-term evaluation before their benefits and effects can be determined. Especially in furnace research, full-scale plant experiments are necessary to gain reliable results. Only by doing these full-scale experiments can the effects of different control variables and impurities be seen. The performance of these plant experiments must be well planned, because they involve risks. Their evaluation must also be made carefully in order to draw the right conclusions. The research must be broad in the sense that both detailed and overall research must be done. Details must be investigated to get knowledge of the roasting mechanism, boiler behaviour and mercury behaviour. Research must be overall in the sense that the whole process chain must be considered in order to reach the final targets, i.e. enhanced performance. A change in one part of the process has effects on other parts of the process and therefore a holistic view is necessary. By improving the performance in many areas, i.e. more measurements, new control variables, new instructions for the operators and equipment modifications, performance is bound to improve. The target has been to eliminate bottlenecks and make changes that do not lead to trouble in other parts of the process.

The research and development carried out has resulted in the implementation of a new overall control strategy for the roasting process. The control strategy has proved effective and is presented later in this chapter. The control strategy will be further developed and the aim is to raise the level of automation.
7.1 Summary of the results

The research carried out has resulted in improved roaster performance in many ways. The running time of the furnace and boiler has improved, i.e. there are less shutdowns and longer periods between cleaning. The quality of the sulphuric acid is better and easier to control. The flexibility in using different kinds of concentrates has increased. This flexibility is important because the treatment charge is the major source of income.

The work done to understand the roasting mechanism has been successful in many ways. More knowledge about instability situations has been gained and more measurements showing the development of instability have been added. Thus the operators know at an early stage when the bed starts to become unstable. Many times instability in the bed has been successfully corrected by active control operations based on the knowledge gained.

The target of reaching a running time greater than 95% due to better furnace practice now seems within reach. About two years’ running time (i.e. the interval between cleaning of the furnace) has been achieved and the furnace grate has remained in good shape, i.e. with only minor build-ups in the grate area. Earlier the normal running time was one year between cleaning.

More measurements, more analyses and calculated variables have increased the knowledge of the state of the furnace. Above all two things have proved to be of great importance, i.e. the calculated oxygen coefficient and the grain size distribution of the furnace overflow calcine. The calculation of the oxygen coefficient (the oxygen coefficient is defined in chapter 5) and the control of the process based on this are two of the major improvements in the control of the roaster furnace. Oxygen coefficient control has led to more stable conditions in the furnace and increased running time. The calculated oxygen coefficient is one of the main control variables for keeping the furnace stable. Other key variables are the temperature and fluidisation rate. The oxygen coefficient has been an important variable both in plant experiments and in the daily control of the furnace. The grain size distribution analysis of the furnace overflow calcine and above all the amount of fine material are good indicators of the bed quality and bed instability. Along with others, i.e. wind-box pressure, bed temperatures and calculated calcine overflow amount, it indicates changes in the fluidised bed. The grain size distribution is also important when evaluating factors that influence grain size growth.

Besides knowing the state of the furnace through measurements, analyses and calculated variables, one should also have the capability of controlling the furnace. By increasing the control options, the chances of keeping the furnace stable are increased. In this research the importance has been shown of having different means and tools to control the process and also the effects they have. Feeding water to different spots influences the furnace behaviour in many ways as described earlier. In addition, the chance to use oxygen gives more freedom. Other means such as fixed bigger nozzles in some parts of the furnace are advantageous in order to keep the oxygen coefficient at the proper level, thus decreasing the formation of build-ups. One of the key results of the plant experiments and active surveillance of the process has been new instructions for the operators on how to control the furnace in different situations. As well as calculating the oxygen coefficient, instructions have been made also on how the oxygen coefficient can be controlled by different control variables.
Better knowledge of the state of the furnace and more control options, along with knowledge of their effect, have led to longer running time of the furnace. Too much build-up in the furnace can be avoided thanks to better control. However, the formation of build-ups also depends on the impurity levels of the concentrate mixture, as too high impurity levels lead inevitably to formation of build-ups.

7.1.1 Summary of roasting development

Step by step more knowledge about zinc roasting has been gained through research. The efficiency of the roaster has gradually increased. The results of the focused research and development program of the roaster furnace can be summarized as follows:

– There is now more knowledge about the state of the process. By adding more temperature measurements to the furnace more information about the bed behaviour has been gained. Calculated variables like the oxygen coefficient and the amount of overflow calcine from the furnace have increased the on-line information about the state of the furnace. Analyses have been also added. The grain size distribution analysis of the furnace calcine is a valuable indicator of changes in the state of the fluidised bed. The new measurements (additional temperature measurements) and analyses (grain size distribution) show at an early stage when the bed starts to become unstable.

– There are now more control variables in use, which increases flexibility. There are now more opportunities to arrange the conditions in the furnace proactively: Water feed to different areas. Water agglomerates fine concentrates and thus the top temperature of the furnace can be controlled. Water injected to the bed increases the feed and thus makes it possible to control the cooling capacity of the furnace. There is the possibility of using oxygen enrichment. More oxygen is fed to the feed side of the furnace through bigger nozzles.

– More knowledge about the dynamics of the furnace has been gained. Information necessary for building simulators, models and designing control applications has been gained through the experiments performed during this work (Rauma et al. 2000, Härkönen 2003, Saxén et al. 2004, Valo 2004).

– A simulator has also been developed which operators use to keep up their skills, i.e. to practise start-ups and shutdowns. The simulator can also be used to test the process dynamics, i.e. the impacts of control variables on the furnace pressure (Toskala 2000, Toskala et al. 2001).

– There is now more knowledge about the effects of different variables on the process. This information has been gained from the experiments performed. There is now more knowledge regarding both metallurgy and dynamics (Lepistö 1999, Nyberg et al. 2000, chapter 6, Metsärinta et al. 2005a).

– There is now more knowledge about the optimum conditions for different concentrate mixtures. Full-scale plant tests with the roaster furnaces have resulted in more knowledge about the effects of different variables, such as the impact and the size of the impact on process behaviour. During experiments with impurities such as Pb and Cu in the feed mixture, new operation conditions have been tested successfully. In cases with
high impurity levels (Pb, Cu etc.), it has been found that a low bed temperature (about 900 °C) might be necessary.

- A heat balance model has been developed which has been in use to estimate the effects of different control variables such as water feed, oxygen feed and changes in the air flow (Roine & Nyberg 2000, Björklund 2001). It has also been used to evaluate effects of changes in equipment, before modifications of equipment have been made.

- The importance of the calculated oxygen coefficient has become apparent and its active control is now in use. By doing this, formation of build-ups in the furnace can be minimized or even avoided completely. As a result, a higher on-line availability of the roaster has been achieved. Even up to about two years’ running time of the furnace has been achieved and the furnace has remained in good condition, i.e. with only minor build-ups on the furnace grate.

- Opportunities for using fine concentrates have improved. Water is being used to make agglomerates in the bins and conveying systems and to control the top temperature of the furnace.

- There is now more knowledge about the effects of impurities and the optimal process conditions that are possible (Taskinen et al. 2002, Metsäranta et al. (2003, 2005a, 2005b)). Lower temperatures are necessary when the impurity levels of the feed mixture are high. The oxygen coefficient should not be too low in these cases. The limits for impurities, however, are difficult to determine exactly and they vary from one combination to another. When the levels are too high there are no optimum conditions.

- Some new tools providing data about the state of the roasting furnace process have been implemented, of which SOM is one example (Saxén & Nyberg 2003).

### 7.1.2 Summary of boiler development

The modifications made in the boilers have proved to be effective. The running time for the boiler was previously about 3 to 5 months between manual cleaning. Now the running time is 9 months or more. Over one year of running time without manual cleaning of the boiler has been achieved (Kilju 2004). The baffle wall in the radiation section has proved effective both for cooling the gas stream and also for removing calcine from the gas flow. In addition, other equipment modifications have contributed to the success, such as new effective bundles with effective hammering, hammering of the section walls in the lower part of the boiler, and installation of screens in the radiation section. Cleaning of the boiler from the inside with water during maintenance shutdowns also delays the formation of build-ups.

Longer running times and a more effective boiler reduce the constraints caused by the boiler, thus freedom in the control of furnace conditions increases, which in many cases is an advantage.
7.1.3 Summary of mercury removal development

The extensive thermodynamic calculations along with mass balance calculations, sampling and analyses, laboratory experiments and finally full-scale implementation have increased our knowledge of mercury removal. Sampling and analysis of mercury and other elements from the gas phase, where the levels of mercury and selenium are very low, was a demanding task. The thermodynamic calculations and analyses of samples corresponded well with each other. Both showed that gas phase of the process had reached a steady state. The result of the research and development was a new control method, i.e. the feeding of selenium to the process in liquid form. This selenium feed improved the quality of the sulphuric acid, i.e. the mercury level can be kept low and in the range of 0.02–0.06 mg Hg/kg H$_2$SO$_4$.

7.2 Control strategies and further research and development

Further research and development is necessary to gain more knowledge. The challenges lie in furnace behaviour, i.e. the roasting mechanism and particle size growth mechanism certainly need more investigation. The necessity for plant experiments has been obvious. Two types of plant experiments have been done. In some experiments the emphasis has been on studying the process metallurgy and in others on studying the dynamics. Both are needed for developing the control of the furnace. In future the emphasis will be on doing more experiments to study the process metallurgy. New measurements that show the state of the furnace and development of new means of control are some targets for further research and development. The research and development must be wide-ranging and not focus only on the control of the furnace, but also take other aspects into consideration. Pretreatment of concentrates is one example of this, which is perhaps in some cases a necessity (Brown & Goosen 1996). The challenge in furnace control is knowing the limits of the impurities, and predicting the behaviour of different concentrates is not easy.

Installing devices that prevent formation of build-ups and removing build-ups is also included in the development program (Siirilä et al. 2004). The equipment can keep the area of the slinger belt clean and prevent build-ups on the wall above the slinger belt inlet. Cleaning the furnace wall of build-ups during maintenance shutdowns can sometimes be time-consuming. Manual cleaning of the area at the top of the furnace between the furnace and the boiler during operation is a safety issue and should therefore be automated (Saarinen & Hugg 2000). Another challenge is to sustain reliable temperature measurements in the furnace during long running periods and to develop systems to replace malfunctioning devices during operation.
There are several ways to increase the capacity of the furnace (Nyberg et al. 2000). If the bed temperature in the furnace is increased, then the feed will increase. Higher bed temperature also increases the sulphide level of the produced calcine, as is shown in Fig. 62. This is partly due to formation of bigger particles at higher temperatures. An additional explanation for the higher sulphide level is that the oxygen coefficient is low due to the high feed. However, the danger of high temperatures is that molten phases are formed. This can lead to formation of build-ups, especially if the impurity levels in the feed mixture are high (Appendix 1). Another way to increase the feed is to add more air, but the limits are set by the fluidisation behaviour of the bed. More air increases the capacity, but the sulphide level of the calcine also increases in this case due to the lower oxygen coefficient, as the diagrams in Fig. 63 illustrate. Increasing the cooling capacity of the furnace is one possibility. This can be done by increasing the cooling capacity of cooling coils (fixed) and/or by water injection to the bed (flexible control of the heat balance). Feeding oxide Zn materials also increases the feed due to their cooling effect. Oxygen enrichment is used by some plants to increase the feed (Filho et al. 1998, Longton 1998, MacLagan et al. 2000, Saha et al. 1989). The increase of feed using oxygen enrichment is shown in Fig. 64. The costs of using oxygen is, however, a disadvantage. Flexible cooling capacity is advantageous when oxygen enrichment is used.

Fig. 62. The feed increases when the temperature is higher in the furnace. The increased feed decreases the oxygen coefficient and the result is that the sulphide level of the formed calcine is higher, as shown here (Nyberg et al. 2000).

Fig. 63. By increasing the amount of air, the feed increases due to the cooling effect of the air (graph on right). Due to the lower oxygen coefficient the sulphide level of the calcine increases (graph on left). The furnace temperature in the experiments was 950°C (Nyberg et al. 2000).
Fig. 64. By using oxygen the feed increases, due to the cooling effect of the oxygen. In the experiments with additional cooling (C and D), more cooling coils had been added to the furnace. The furnace temperature in the experiments was 950°C (Nyberg et al. 2000).

By keeping the top temperature of the furnace high, the feed increases and therefore the oxygen coefficient decreases. The result is that the sulphate level of the formed calcine going to WHB decreases, as shown in Fig. 65. As mentioned in chapter 4 the target is to have both optimal feed and optimal process conditions.

Fig. 65. Higher top temperature increases the feed and due to the lower oxygen coefficient the sulphate level of the formed calcine is lower, thus the sulphate load on the WHB decreases.

7.2.2 Example of flexible control

As mentioned earlier, the opportunities to arrange conditions in the furnace have been increased. Fig. 66 shows a situation when this flexibility can be used. For a certain concentrate mixture, it might be better if the temperature is lower in the furnace. Case 1 shows that the feed is A t/h, the air feed is B Nm³/h, the temperature is C°C and the oxygen coefficient is D. Case 2 shows that the same feeds and oxygen coefficient can be kept in the furnace if water (E l/h) is injected into the furnace bed. The desired temperature (C-X) °C can be achieved without decreasing the feed.
Flexible arrangement of the process conditions in the furnace

Case 1:
Concentrate feed (A t/h)
Air feed (B Nm³/h)

Temperature of the furnace
C °C
Oxygen coefficient
D

Case 2:
Concentrate feed (A t/h)
Air feed (B Nm³/h)
Water injection into the bed (E t/h)

Temperature of the furnace
(C - X) °C
Oxygen coefficient
D

Fig. 66. In both cases the feeds and the oxygen coefficient are the same. By injecting water, the temperature can be lowered in the furnace, without decreasing the concentrate feed. In cases with high impurity levels, a temperature level of about 900°C might be necessary.

7.2.3 Operation conditions for different feed mixtures

For a good economic result it is important to be able to use different kinds of concentrates. Concentrates with lower Zn content are more viable economically, but their use is more demanding as is shown in Fig. 67. The operating range is narrower when concentrate mixtures with a high degree of impurities are used.

When the impurity levels of the concentrate mixture are very high then there are no operation ranges, i.e. the furnace will inevitably become unstable. This will lead to the formation of build-ups. The difficulty is to know what are the upper limits for different impurities. The more impurities there are in the concentrate mixture, the more difficult it is to estimate the best operating conditions.
Control of the furnace bed temperature and the oxygen coefficient

<table>
<thead>
<tr>
<th>Different types of concentrate mixture</th>
<th>Safe operating conditions</th>
</tr>
</thead>
<tbody>
<tr>
<td>Clean and coarse concentrate mixture.</td>
<td>Temperature range is wide 900 – 970 °C.</td>
</tr>
<tr>
<td></td>
<td>Oxygen coefficient range is wide 1 - 1.35.</td>
</tr>
<tr>
<td>Impure and fine concentrate mixture.</td>
<td>Temperature range is narrow, too high temperatures can lead to forming of molten phases.</td>
</tr>
<tr>
<td></td>
<td>Oxygen coefficient range is narrow, forming of molten phases is a danger. The optimal oxygen coefficient level depends on the impurity types (Pb, Cu) and amount.</td>
</tr>
</tbody>
</table>

Fig. 67. The operating range in the furnace is narrower if the concentrate mixture contains high impurity levels. The temperature and the oxygen coefficient are the main control variables.

### 7.2.4 The developed furnace control strategy

The study of the dynamics of the furnace and the construction of a state space model have given results that can be used for developing furnace control (Härkönen 2003, Saxén et al. 2004). The aim has been to build a control system that optimises the feed without neglecting the results of the metallurgical experiments. The structure of the furnace control strategy that is in use is shown in Fig. 68. The target is to further raise the automation level. The aim is to build a control application that both optimises the feed and creates optimal process conditions for the concentrate mixture based on the developed control strategy (Valo 2004). The basis is to give a range both for the furnace temperature and the oxygen coefficient. The optimal values for these (temperature and oxygen coefficient) are estimated based on the knowledge gained during this development process. The control application then maximizes the feed. Measurements, analyses and knowledge about the state of the process and knowledge about the dynamics of the furnace along with control variables are parts of the application.
Fig. 68. The figure shows the developed control strategy. The target is to build a control application that maximizes the feed based on this control strategy. The aim is to optimise the feed and the process conditions (temperature and oxygen coefficient), based on metallurgical knowledge and knowledge of the dynamics. Measurements, analyses, the dynamic model and control variables are also key elements in the control application.

Many aspects must be considered in order to achieve the best result in roaster control. The entire process must be taken into account, thus in the control of the furnace boiler efficiency is also important. The control strategy could be the following:

- Optimal process conditions for a certain concentrate mixture should be chosen on the basis of metallurgical knowledge.
- The aim should be to reach long running times for the furnace-boiler system, thus minimising the number and time of the shutdowns. Therefore it is better not to overfeed, if it leads to trouble and an unstable process. By reducing the number of shutdowns the impacts on the environment are less, and the maintenance costs are also reduced.
- The state of the process must always be monitored with care (measurements and analyses) in order to make the corrections in advance.
- Control applications must be developed to maximise the feed rate, as shown in Fig. 68.
- If control actions fail to keep the furnace stable, then the concentrate mixture must be changed.

Some possible ways to further increase performance are mentioned below. Developing fuzzy control systems and/or expert systems based on the knowledge acquired is a possible development path (Ikonen 1996, Isomursu 1995, Viljamaa 2000). Optimisation
of fluid bed control has been carried out in energy-producing fluidised bed reactors (Leppäkoski et al. 1999, Leppäkoski & Kortela 1999). It could be useful to adopt their ideas, for example Combustion Power Control, or to use Learning Automata in the development (Leppäkoski et al 2000, Ikonen & Najim 1997, Najim & Ikonen 2000). The aim is to use the rules learnt from metallurgical experiments and to use the control tools available, e.g. water feed to different spots and using oxygen.
8 Conclusions

The research and development presented in this study has had the target of improving the performance of the roaster. The main aim is to improve the economic result. To achieve this goal, the capability of being flexible in using different kinds of concentrates is the main sub-target. Other sub-targets are to decrease the amount of disturbances, keep the furnace stable, increase the running time between maintenance shut downs, and improve the quality of the products. To achieve these sub-targets, equipment modifications, new control variables, new measurements and new analyses have been adopted. New instructions for the operators, development of maintenance and also improvement of the performance of the personnel have been the means employed to achieve these targets.

The implemented development concept, i.e. doing an extensive characterisation of the process has proved to be an effective way to increase the efficiency of the roasting process. The results of the process characterisation have led to the implementation of a new and effective control strategy.

The approach of the thesis has been to carry out extensive and intensive research in order to learn more about the entire process and process phenomena, i.e. process characterisation. Process knowledge is the necessary base for making improvements in process control. New applications have been developed through gaining more knowledge.

The tools used to reach the targets are the development of control methods and improvement of the process, both by equipment modifications and by adding new control variables. This improvement can be made by enhancing control, equipment and the process based on existing knowledge. Examples of such improvements are the fuzzy systems developed for the control of the furnace temperature and the control of mercury removal. These applications stabilise the processes, but are not always optimal in all cases and cannot solve all the process problems. Therefore these kinds of improvements are not enough and in this thesis the emphasis and the approach have been on improving performance based on increased knowledge. This is certainly the right approach if better performance, i.e. the optimal level, is desired.

There are several challenges for further development. More knowledge is still required about the roasting mechanism. The use of concentrate mixtures with high levels of impurities needs further research. The difficulty is to know the limits and how these limits
can be tested safely, i.e. without jeopardising the stability of the furnace. Plant experiments are necessary but they involve risks and are also expensive to perform. Therefore, they must be well planned and analysis of the results must be done with care. When high impurity levels are tested, the safest way to do these experiments is to do them just before a shutdown. Then the risk of economic and production losses are smaller. The challenge is also to determine the optimal conditions. The optimal conditions must be such that they enable long-term running of the roaster furnace, i.e. minimise the formation of build-ups. More measurements showing the state of the furnace should also be developed and more control variables should be considered. In addition, laboratory studies are needed in order to gain further knowledge about the roasting mechanism.

The impacts on the boiler system should not be neglected. Therefore, it is important to study what the impacts of the different control strategies and conditions in the furnace are on the boiler system. The need to have a better performing boiler may be required, if high impurity levels in concentrate mixture are used.

**Fig. 69. In order to achieve sustainable results, the issues shown in the diagram must be considered in the development process.**

There are also other issues that should not be neglected. Fig. 69 shows the issues that must be considered when the target is to increase the performance. Human resources (HR) should always be borne in mind during development work. Good performance can only be achieved if the personnel are skilful. Maintenance must also be of high standard and the work done during shutdowns is of great importance (Cunningham & Connock 2003). Longer running time also puts more pressure on maintenance work. Safety issues are nowadays very important and this factor must also be considered. Environment issues along with quality systems are also issues that need more and more attention. Overall, to achieve sustainable results there are many issues that must be considered in the development process.

Benchmarking, visiting other zinc plants and participating in international conferences should also be part of development work, because valuable information can be obtained from these kinds of activities (Brook Hunt 2003). In this development work, ideas and
knowledge gained from these sources have been one source for the R&D work and have in some cases led to implementation.
References


Appendices
Appendix 1: Phase and Kellogg diagrams

In this work an evaluation of the phase and Kellogg diagrams has been done in order to gain a picture of the phases that are stable or molten phases that can be formed during zinc roasting conditions. It is essential to be aware of the dangers if the impurity levels increase and to seek optimal conditions from the study of these diagrams.

From the phase diagrams it can be seen that different kinds of melts (sulfide melts, oxide melts, sulfate and silicate melts) are formed in conditions typical of a zinc roaster. The probability of melts increases as the impurity levels increase. From the Kellogg diagrams the stable phases for different elements can be seen. In these diagrams the variables are temperature, SO\textsubscript{2} pressure and O\textsubscript{2} pressure.

Some of the basic diagrams are shown below. The data sources for the diagrams are given in the reference list at the end of this appendix.

Fig. 1. Zn-S-O phase stability diagram made using the HSC program at fixed temperature. In typical roasting conditions ZnO is stable (Roine 2002).
Fig. 2. Predominance diagram for Zn-O-S at fixed oxygen pressure made using HSC (Roine 2002). The oval area marks the typical operation conditions for the furnace. Decreasing the temperature (boiler operation conditions) will result in formation of ZnSO₄.

Fig. 3. Cu-S-O phase stability diagram made using the HSC program at fixed temperature. In typical roasting conditions CuO and Cu₂O are stable (Roine 2002).
Fig. 4. Predominance diagram for Cu-O-S at fixed oxygen pressure made using HSC. The oval area marks the typical operation conditions for the furnace. Decreasing the temperature (boiler operation conditions) will result in formation of CuSO₄ (Roine 2002).

Fig. 5. Pb-S-O phase stability diagram made using HSC program at fixed temperature. In typical roasting conditions PbSO₄ is stable (Roine 2002).
Fig. 6. Predominance diagram for Pb-O-S at fixed oxygen pressure made using HSC (Roine 2002). The oval area marks the typical operation conditions for the furnace. PbSO₄ remains stable also when the temperature decreases (boiler operation conditions).

Fig. 7. Cu₂O-PbO phase diagram (Gebhart & Obrowski 1964). The danger is that molten phases are formed even if the temperature is low when there are high concentrations of Cu and Pb present.
Fig. 8. PbSO\textsubscript{4}-PbO phase diagram (Margulis & Kopylov 1969). The danger of molten phases increases when the temperature is high and the concentration of Pb is high.

Fig. 9. Zn\textsubscript{2}SiO\textsubscript{4} and PbZnSiO\textsubscript{4} liquids (Jak et al. 1999). The danger of molten phases is present when there are high concentrations of silica present.
Fig. 10. Na$_2$O-SiO$_2$ system (PED Database 1999). High concentrations of Na and Si form molten phases.

Fig. 11. PbO-ZnO-Fe-O system (Fe 1 %, p$_{O_2}$ =1 %) (Davies et al 2002).
Reference list for the sources of the diagrams:


PED Database (1998) vers. 2.1. Columbus, Ohio (USA): The American Ceramic Society.

Appendix 2: The zinc roaster of Kokkola zinc plant (The equipment of one line)
Appendix 3: Flowsheet of the Kokkola zinc plant
Appendix 4: Analyses of samples from the process

To better understand the process it is necessary to take samples for chemical analysis. Besides the daily samples, extra samples have also been taken in order to get a better picture of the process. Extra samples have been taken in particular during the plant trials and when the process has been unstable. During shutdowns samples have been taken from the build-ups in the furnaces and the boilers. Besides chemical analysis, it is sometimes necessary to do X-ray analysis too. In order to draw the right conclusions about what is going on in the process or what has happened, it is necessary to collect data over a longer period of time. Gradually more and more knowledge is built up.

Analyses from samples taken during operation and shutdowns are shown in the following tables, i.e. in Tables 3-5. It can be seen that there are some differences. Table 3, taken during normal operation, shows that the sulphate level is lower in the furnace than later in the process chain. The highest sulphate levels are in the ESP. From the samples taken during shutdowns, as shown in Tables 4-5, the sulphate levels are very high. This shows that the build-ups that were formed gradually develop to sulphates.

Table 3. Analyses taken from daily operation show that the sulphate level of the formed calcine is lower in the furnace than in the boiler, cyclone and ESP. The Pb level has also been quite high in the furnace calcine during some periods.
Table 4. Samples taken during a shutdown from the furnace and boiler build-ups show that the sulphate levels are very high, i.e. the build-ups develop gradually into sulphates. One build-up sample from the furnace (19.3.2000/second sample) shows, however, a very high Pb level, while the sulphate level is lower.

Table 5. The table shows the analyses of furnace shutdown samples taken during the yearly shutdowns. The values for the different years show how wide the range of analysis results has been.

The difficulty, in shutdown samples, is that the equipment (furnace and boiler) is large, the build-ups might be large and the build-ups have been generated during a long period. It is often difficult to take a proper sample. It might be difficult to know from what period it is. It is often difficult to find the right explanation. However it is essential to take samples and to analyse them in order to get more information. The result of the intensive collection of samples at the Kokkola roaster has been that gradually more and more process knowledge has been gained. Whenever there is instability in the process, samples are taken and analysed. Then the results are compared with similar situations in the past. Step by step more knowledge has been gained and the control actions to correct the process have been taken based on this knowledge. Over the last few years, as the result of improved furnace control, the amount of build-ups in the furnace grate area has decreased. In the shutdown of spring 2004 there were almost no build-ups in the grate areas of the two furnaces.