# The tapping process in silicon production

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This paper presents some of the work carried out in order to improve the tapping process in silicon production, with special focus on the environmental and the safety standards. Some of the modelling work that has been done to improve the understanding of the process is described, together with the resulting implementation to improve tapping standards.

## Introduction

The tapping process has seen improvement over the past 30 years, and some important tools such as simple automated tapping equipment have been introduced. However, further developments are still required, particularly in reducing operators' exposure to diffusive emissions.

## Challenges of the industrial silicon tapping process

Silicon production consists of a series of critical processes, the major ones being raw material handling, furnace operation, and refining and casting. Tapping is one of the critical processes and affects the overall process in several ways. In the tapping process, molten silicon at a temperature above 1500°C is drained from the furnace through a tap-hole, either continuously or discontinuously, using different tapping equipment. Keeping this critical process under control has several challenges:

- Good drainage of silicon from the smelting furnace is a prerequisite for stable furnace operation and optimal silicon yield. If silicon is allowed to accumulate in the furnace over time, it will react with either carbon or silicon dioxide, which in turn will disturb the furnace process and reduce the silicon yield (Schei, Tuset, and Tveit, 1998)
- Utilizing the right kind of tapping equipment is important to obtain the correct product quality. The tapping process may also have an adverse effect on the production yield and the total revenue
- The tapping area has several safety challenges. Operators are in close proximity to molten silicon, high temperatures, moving equipment, and complex logistics. The risk of burns and crush injuries is high unless preventive action is taken
- The tapping process performance affects the working environment. The tapping area is one of the largest sources of internal air pollution at the smelting plants.

Elkem has worked on the dust exposure challenges of the process through several different research programmes, both internally and in cooperation with other parties such as the Norwegian Ferroalloy Producers Research Association (FFF). Figure 1 shows the result of mapping the main dust-exposed areas at Norwegian ferroalloy smelting plants. The Norwegian Labour Inspection Authority has increased its focus on chronic obstructive pulmonary disease (COPD) with the objective of reducing dust exposure for workers in the Norwegian smelting industry (Arbeidstilsynet, 2011).

Elkem started its process dust mapping programme 1999, and the final report was presented in 2005 (Hetland, 2005). This work showed that exposure to excessive dust levels at a smelting plant over a prolonged time increases the risk of reduced lung capacity. The tapping area was found to be one of the highest risk areas. The health risks were confirmed by Johnsen (2009). These findings prompted an increased effort within Elkem to improve the working environment.

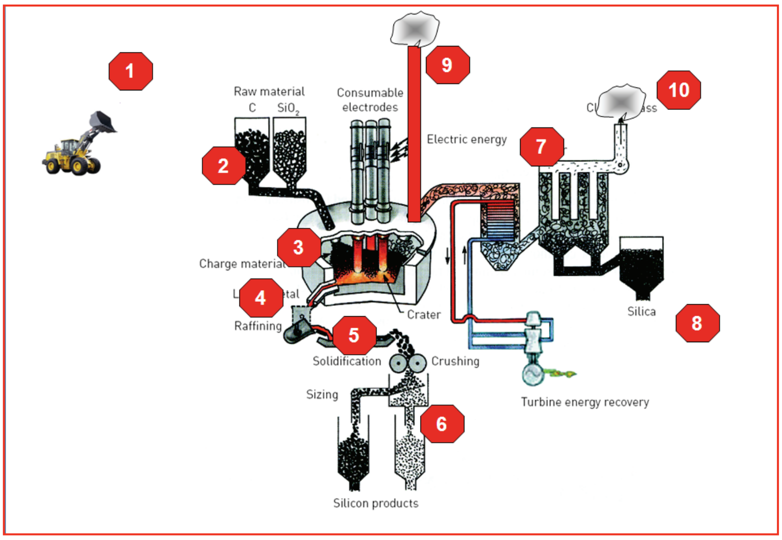



***Figure 1. Main dust source areas at Norwegian ferroalloy smelting plants***

As an initial step, the use of dust masks at the Elkem smelting plants became mandatory from 2005. In addition, resources were allocated to process understanding and possible technical solutions to the challenge. In 2006 the project ‘Promiljø’ was initiated (Norwegian Ferroalloy Producers Research Association, 2011), followed by the ‘Fume’ project in 2009 (Norwegian Ferroalloy Producers Research Association, 2013).

## The tapping gas problem – root causes

The process gas in most reduction furnaces is mainly CO as shown in Equation [1]. Normally the furnace interior is under slight positive pressure due to the conversion of solid materials (ore or quartz plus reductants) into the liquid state and gas phase. The process gas has a much higher volume than the solid materials.

$$Me_xO_y + YC = XMe + YCO(g) \quad [1]$$

In the silicon and ferrosilicon processes this problem is exacerbated due to the existence of SiO gas, which is an inevitable product of the process. The total reaction is shown in Equation [2]–[4] Equation [3] shows the reaction that takes place in the upper part of the furnace and Equation [4] the reaction in the crater zone near the tips of the electrodes.

$$SiO_2(s;\,l) + 2C(s) = Si(l) + 2CO(g) \quad [2]$$

$$SiO\,(g) + 2C(s) = SiC + CO(g) \quad [3]$$

$$SiO_2(s;\,l) + SiC(s) = Si(l) + CO(g) + SiO(g) \quad [4]$$

The SiO(g) is stable only at very high temperatures and creates the following problems in the tapping area:

- In a large industrial (ferro)silicon operation, 1 litre of solid materials is converted to around 3000–5000 litres of gas. This creates a positive pressure inside the furnace, which has been measured to be in the order of 0.01–0.07 bar. If the tap-hole condition is unfavourable this may create a tapping gas problem
- The tapping gas, consisting mainly of CO  and SiO , combusts outside the tapping area, creating heat that may be harmful to operators and equipment if appropriate protection is not installed
- The combustion of the SiO gas outside the tap-hole generates amorphous $SiO_2$ particles that pollute the plant environment and give rise to diffusive emissions. These particles are generally smaller than 2.5 $\mu$m, making them respirable, and a fraction of these particles is also under 100 nm (Kero, Næss, and Tranell, 2013).

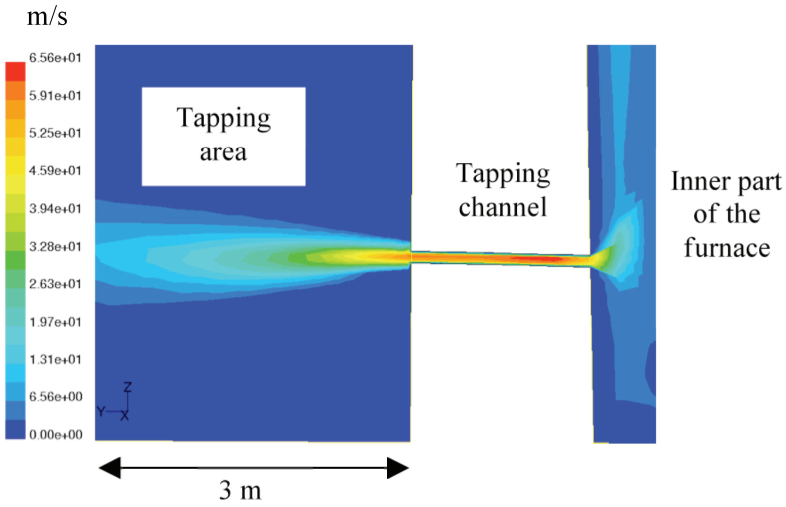



***Figure 2. Velocity distribution***

A computational fluid dynamics (CFD) simulation of velocity distribution of tap-hole exit gas on a scale from 0–65 m/s in the tapping region is shown in Figure 2. The jet will leave the tap-hole with a velocity of approximately 50 m/s and may become more than 3 metres long (Ravary and Laclau, 1999).

**Silicon and ferrosilicon furnace multiphase flow model**

To understand the problem and to find solutions a PhD project was initiated within the FFF environmental programme. The work (Kadkhodabeigi 2011) included industrial measurements as well as modelling and theoretical studies. A full 3D multiphase flow model of silicon and ferrosilicon furnaces was developed. The modelling set-up is shown in Figure 3.

The model was based on CFD and fluid flows and interactions between the phases were therefore investigated. The modelling process consisted of constructing the furnace geometry, selection of the physical models regarding the assumptions and simplifications of the real system, developing user-defined sub-models, considering proper boundary conditions, and explaining the model results.

In addition to theoretical modelling, the results of industrial tests from different furnaces were used. The industrial measurements were carried out both to achieve a better understanding of phenomena in order to develop the model and to be able to validate the model.

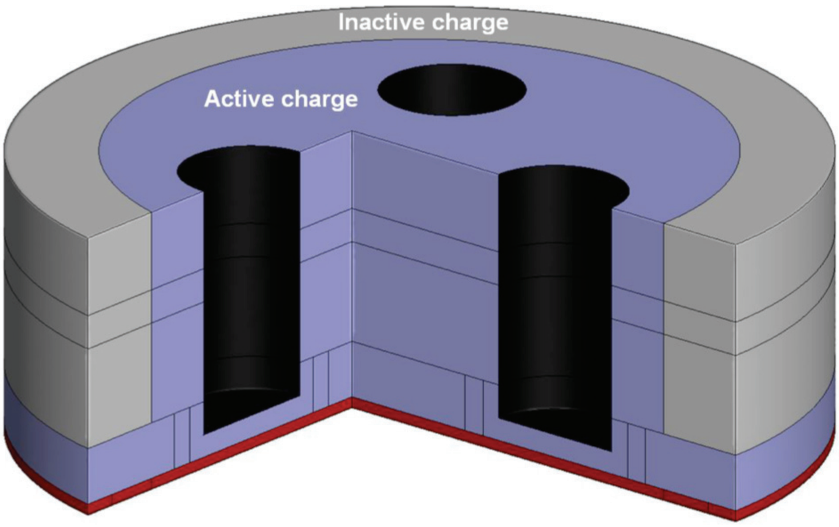



***Figure 3. The 3-D dynamic model of the reaction zones, the electrodes, and the charge***

The results from the modelling work are presented in Figure 4 and Figure 5. Figure 4 shows the static pressure and the silicon and gas distribution at a given time. Figure 5 shows the distribution of silicon during the whole tapping process. Note the 'doughnut' shape of the silicon distribution, and also that the draining of the silicon is partly along the periphery of the furnace.

The model parameters are presented in Table I.

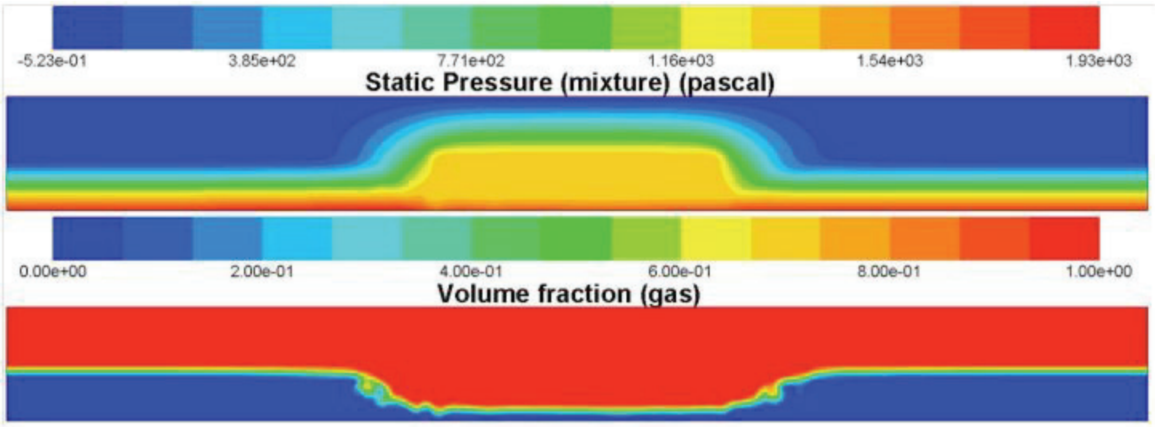



*Figure 4. The calculated static pressure in the furnace above the liquid area and the volume fraction of gas. Note the clear depression of the silicon level in the centre of the furnace due to the static gas pressure*

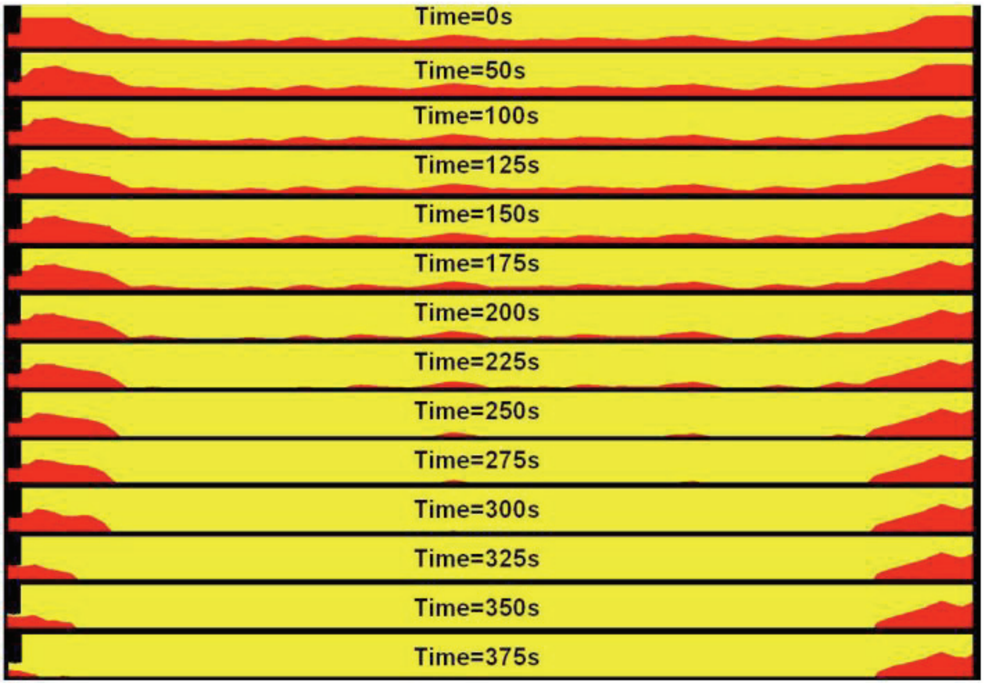



*Figure 5. The ferrosilicon level during the tapping process. The gas phase is represented as yellow. The ferrosilicon (shown in red) is forced to the furnace periphery due to the static gas pressure in the furnace*

**Table I. Structure of the comprehensive model of tapping process in the submerged arc furnaces used for high-silicon alloy production (Kadkhodabeigi 2011)**

| Insight into the Structure of the CFD Model | | | | |
|---|---|---|---|---|
| Parameters | Parameter Type | Detailed Parameter | Accuracy | References / Comments |
| Input | Geometry | Furnace diameter | High | Industrial data |
| | | Furnace height | High | Industrial data |
| | | Electrodes diameter | High | Industrial data |
| | | Taphole diameter | High | Industrial data |
| Input | Process information | Metal production | High | Industrial data / (Schei et al. [1998]) |
| | | Gas production | High | Industrial data / (Schei et al. [1998]) |
| | | Crater pressure | Medium | Industrial tests (Ingason [1994] and Johansen et al. [1998]) |
| | | Formation of charge zones | Low | Furnace excavations (Zherdev et al. [1960]), (Otani et al. [1968]), (Schei [1967]),(Myrhaug [2003]) and (Tranell et al. [2010]) |
| | | Melts density and viscosity | High | (Rhim and Ohsaka [2000]) and (Klevan [1997]) |
| Tuning Parameters | Physical properties | Particles size (Outer zone) | Medium | (Schei et al. [1998]) and Johansen et al. [1991] |
| | | Particles size (Inner zone) | Tuned | Furnace excavations (Zherdev et al. [1960]), (Otani et al. [1968]), (Schei [1967]),(Myrhaug [2003]) and (Tranell et al. [2010]) |
| | | Packed bed porosity | Tuned | Furnace excavations (Zherdev et al. [1960]), (Otani et al. [1968]), (Schei [1967]),(Myrhaug [2003]) and (Tranell et al. [2010]) |
| Output | Results of model | Tapping speed | High | Industrial tests |
| | | Average metal height | Predicted | |
| | | Metal pattern | Predicted | Industrial accident for leakage of melt from the furnace which confirms high metal heights close to the furnace wall |
| | | Gas flow in the charge | Predicted | Industrial observations and (Tranell et al. [2010]) |

### *Learning outcomes of the modelling work (Ravary and Laclau, 1999; Kadkhodabeigi 2011)*

The model for tapping has proved useful for the training of operators in order to improve their understanding of the behaviour of the tapping process. Of special importance is the quality of the taphole repair in order to avoid direct gas emission from the crater. The understanding of the 'doughnut' shape of the liquid silicon in the furnace has been useful for optimizing the tapping process and improving operational standards. The doughnut' shape also provided a welcome explanation of some important process phenomena – why the process seems more stable and gives less SiO loss in the first 30–60 minutes after tapping. The reason for this may be explained by the reduced level of liquid silicon in the centre of the furnace and consequently little reaction with the added quartz.

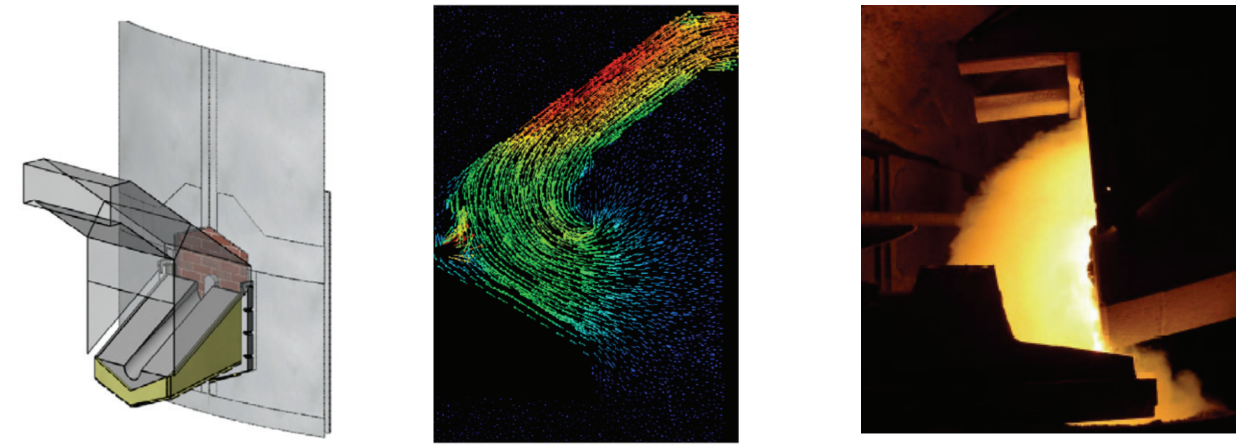
## The improvement work – reduced fugitive emissions in the tapping area

### *Theoretical principles*

In 2008 Elkem Thamshavn was ready to replace the worn existing tapping fume hood with a new hood of similar design. At the same time, Elkem was focusing on the work environment and had acknowledged that fumes from tapping were the main source of pollution, emitting fugitive dust into the work environment. A new hood was therefore followed by an expectation of reduced emissions. However discussions with the engineering companies revealed that no such reduction could be guaranteed. At that point Elkem Thamshavn made the bold decision to turn down an already approved investment and focus on the theoretical principles that govern the gas emitted from the furnace through the tapping channel.

This work was organized as a joint effort between industrial workers and engineers on the one side and a PhD student and the academic approach on the other. The result was a new understanding of flow patterns and heat stresses around the flow of SiO and CO through the tapping channel.

When new knowledge is made available and spread to industrial engineers and operators, new ideas for solution are created. After some brainstorming sessions in early 2009 a new hood design (Figure 7) was suggested.



***The idea*** ***The model*** ***The trial***

***Figure 6. Development of new tapping fume extraction hood***

***Tapping fume extraction hood - from model to practical solution***

There is, however a large step from an idea and a hypothesis based on new theoretical knowledge to a full installation on large silicon-producing submerged arc furnaces, and large steps are often associated with large risks. One of the more significant risks was that no proper mechanical solution for the hood/furnace borderline could be found. There is in addition always the possibility that assumptions made during the development of the new theory are not applicable in real life. To reduce the latter of these risks it was decided to model the suggested design in FLUENT and verify the model observations in in trials at a real furnace. Through these trials the potential of the technology was demonstrated.

A set-up with modelling and verification through trials early in the development serves several purposes. First of all, the project can be stopped early if the theory turns out to be wrong, but it also increases the motivation to overcome any obstacle that lies in the way during the technical development. When the potential of the result has been demonstrated it is easier to motivate for resources both for development and for investment at a later stage.

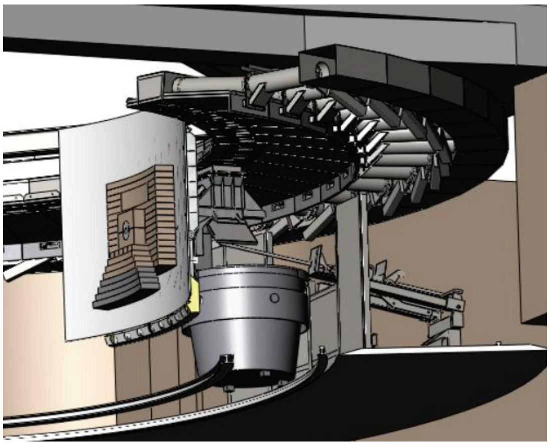


***Figure 7. The industrial pilot installation***

As a result of the promising trials made in the latter half of 2009 a project was organized and executed culminating in a full-scale pilot installation on a silicon furnace at Thamshavn in early 2010 (Figure 8). This installation was evaluated by SINTEF after start-up , and the improved fume collection rate was confirmed.

After three years in operation the new design has also proved to be mechanically robust, long lifetimes of parts and low maintenance costs. It also constitutes a starting point for a second-generation design which can be based on long-term observations of a full-scale pilot installation instead of the high risk involved in relying on new theoretical understanding.

## The Elkem DUSTEX project

To follow up the results from Promiljø, FUME, and the Thamshavn pilot installation, and facilitate the efforts at the smelting plants to reduce dust exposure in compliance with the labour authorities' requirements, Elkem decided to establish a corporate project, 'DustEx'. 'The project was divided into two stages: dust mapping and risk evaluation, and a technological part with emphasis on implementation of technology and best practice for reduction of and/or capturing of process-generated dust.

Today's solution to protect employees from dust exposure relies to a great extent in the use of personal protective equipment (PPE).

The various production plants have different conditions in the problem areas, and different prerequisites for reducing dust exposure. The main dust sources have been identified, but feasible measures to reduce dust exposure to acceptable levels are incomplete.

The main focus is on developing and implementing permanent, technical solutions for fume and gas extraction. It must be emphasized that process gas also contributes to fugitive dust emissions to the external environment, and improved gas collection constitutes a positive contribution to reducing pollution in the plant vicinity.

### *Dust exposure mapping*

In parallel with the work on technical solutions, a mapping programme for measuring personnel exposure to dust was initiated on all smelting plants. The measured dust levels form the basis for risk analysis and hence an action plan specific to each plant.

Norwegian law regulates employee dust exposure through administrative norms (ADNs) for several substances (Norwegian Labour Inspection Authority, 2013). To ensure full compliance with the norms, a separate action initiation level is set at one-quarter of the ADN. The method of measurement is a personal pump and gravimetric filter device, which is carried during an 8-hour shift. The average value from the analysis is compared to the ¼ ADN value.

| | |
|---|---|
| ADN for total respirable dust | $\leq 5$ mg/m$^3$ |
| ADN for respirable amorphous $SiO_2$ | $\leq 1.5$ mg/m$^3$ |

Also, the causes of for high intensity dust level periods will be identified, analysed, and measures taken to reduce the impact.

### *Development of a recommended practice (REP) for tapping fume extraction system*

Efficient fume extraction during tapping is necessary for compliance with Norwegian dust exposure requirements. The ultimate goal is that all fume produced in the tapping area is captured and controlled through extraction and filter systems. To contribute to knowledge transfer and utilization of best practice, a recommended practice (REP) document was compiled based on conditions at the Elkem Thamshavn pilot installation, to ensure that the best available solutions and knowledge from our tapping fume extraction projects were available for all Elkem units.

The energy in the liquid metal and the combustion of furnace gases may result in high energy flow due to radiation and combustion heat. The tapping fume installation must be designed to be robust according to local furnace conditions.

Elkem has considerable experience with tapping fume extraction systems for its furnaces, and the purpose of the REP is:

- To provide Elkem's recommended design for tapping smoke extraction systems
- To provide the recommended method(s) and information for understanding and copying the main principles and solutions for this design.

To support compliance with this recommended practice, a tapping fume design process and quality assurance checklist is used:

- Start with Elkem Recommended Design (ERD) for tapping fume extraction.
- Check if design basis is updated according to latest completed relevant projects
- Analyse and understand ERD solution with respect to key design parameters
- Analyse relevant site for key parameters and compare to ERD
- Evaluate elements from ERD solution that can be re-used
- Develop design basis for relevant site.

## Process simulation and modelling –a serious learning curve

Process engineers the last part of the 20$^{th}$ century and into the 21$^{st}$ century have been exposed to amazing developments in new technology. Knowledge of modelling, hardware development, and continual availability of improved programs and systems have revolutionized process modelling. The result of the increased possibilities has been improved concept and design in all sectors of industry, and not least in the metallurgical sector. The direct improvement may be seen in process performance, reduced costs, improved EHS standards and more. The modelling work will also provide opportunities regarding improved understanding and learning. Today the different modelling tools may give us insight into complex fluid flow patterns and convert huge amount of calculations into easily understandable presentations.

Given the background of this wonderful improvement, one may be considered as a ‘party pooper’ to write about serious learning. But unfortunately the short history of the use of computer models has included some very costly learning experiences. Some of the problem seems to be inherent in the very effective communication methods that the new modelling tools may provide. Presenting the colourful results from simulations may be very convincing. A model is normally extremely simplified compared to the physical situation. In the best case, the modelling work describes the most important phenomena and the implications of the results are fully understood by all those who will utilize the results from the modelling work.

The learning outcome is that the work before the modelling is important – but maybe the most critical phase is the work necessary afterwards in order to interpret, control, and implement the modelling results as shown in Figure 9.

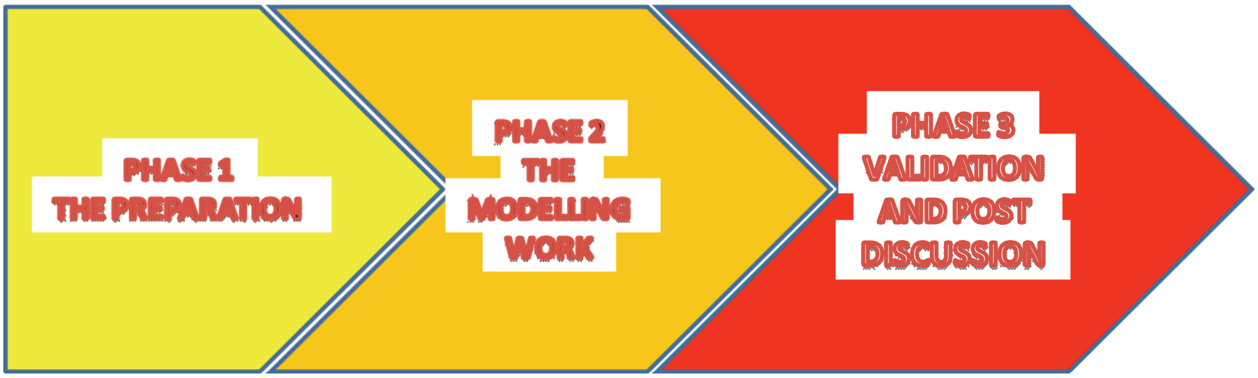



***Figure 8. The main phases in the modelling process***

The preparation phase (1) includes describing the real business case, setting of parameters, and the preparation for the modelling work. The important phase 3 includes both the control of the results, the interpretation, and the consequences of the results, as well as ensuring that the limitations of the modelling results are fully understood by the users.

On the positive side, a successful modelling exercise gives rise to increased understanding, and the modelling result such as data, graphs, and video presentations may be a helpful tool for design, construction, training and education of operators and engineers, and lead to a successful start-up and operation of the process.

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Worked in the Norwegian Iron and Steel plant 1974-1977. Elkem Bjoelvefossen 1977-1980. After that work at Elkem Thamshavn Plant and the Elkem Silicon Division.
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Several papers about different aspects of metallurgical processes – mainly FeSi and silicon production. Since 1998 I have been invited to give paper at the "Silicon for Silicones" conference that is held in Norway every 2 years. Main topic has been energy recovery, HES and silicon process and product items.

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I was educated as a process metallurgist at NTNU working with silicon and reaction kinetics. In 2010 I started working for Elkem at the Elkem Salten plant, working with furnace operation and microsilica production. After a period at Salten, I moved to Elkem's technology division where my working area was slag refining for the Solar process. Now I work in Elkem's Silicon Division's EHS&Technology team working with post taphole process's, such as tapping, refining and casting.

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