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Ekaterina Polovnikova

NTNU
Norwegian University of
Science and Technology
Faculty of Engineering
Department of Mechanical and Industrial Engineering

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Contribution to Management of Safety Instrumented Systems (SIS) in Furnace Water Cooling Systems on Elkem Plants

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Ekaterina Polovnikova

Reliability, Availability, Maintainability and Safety (RAMS)
Submission date: June 2019
Supervisor: Mary Ann Lundteigen
Co-supervisor: Tor Magne Undheim
Trygve Gerhard Hanssen

Norwegian University of Science and Technology
Department of Mechanical and Industrial Engineering

Preface

This project is a compulsory part of the study plan to fulfill the graduation requirements of the two-year master program in Reliability, Availability, Maintainability and Safety (RAMS), department of Mechanical and Industrial Engineering, Norwegian University of Science and Technology (NTNU). According to the official study plan, in the fourth semester the student devotes 100 % of school workload to this paper. The Master Thesis is weighted to 30 credits points. The Master Thesis was undertaken at the request of Elkem ASA, where the student undertook a summer internship (summer work, 2018) and wrote a Specialization Project in the third semester (Autumn 2018). The research scope was formulated together with university-supervisor, professor Mary Ann Lundteigen, and industry-supervisors, Trygve Gerhard Hanssen (Manager Automation, MES and Technical Safety, Elkem ASA, Technology) and Tor Magne Undheim (senior project manager, Control Systems, Elkem ASA, Technology). The Master Thesis is based on literature study and overview of information on technical assets of Elkem relevant for the research scope .

Trondheim, 11th of June 2019

Ekaterina Polovnikova

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I would like to thank my university-supervisor in NTNU, professor Mary Ann Lundteigen, for her patient and useful guidance, and advice she has provided throughout my time as her student. She steered me in the right the direction whenever I needed help. I have been extremely lucky to have a supervisor who cared so much about my work, and who responded to my questions and queries so promptly. I would also like to thank my industry supervisors Trygve Gerhard Hanssen, Tor Magne Undheim for their great support. They consistently allowed this paper to be my own work where I could study the use case in Bremanger and were always open whenever I ran into a trouble spot or had a question about the industrial use case. I want to express my gratitude to colleagues in Elkem Torfinn Buseth, Øivinn Bruce, Thor Inge Bernhardsen, and Bente Merete Faaness for their help to understand the study case and search of the necessary information information and literature. Also, I would like to thank Håkon Leirvik for his assistance and supervision during my visit the Elkem plant in Bremanger.

E.P.

(E. Polovnikova)

Abstract

Cooling systems are widely used across different industries in order to keep the industrial processes running and ensure safety. The cooling systems are a critical part of industrial furnaces, particularly Furnace Water Cooling Systems (FWCS) are used for providing process cooling water to water-cooled furnaces. When the cooling system is out of control, damage can begin to occur to the cooling system and the components it protects. One of the most common problems associated with cooling systems is water leakage. In This Master Thesis, literature study and analysis of information on accidents related to FWCS leakages showed that it is important to look for the opportunities of improvements within safety measures and initiate projects for implementation of possible feasible safety solutions along with the existing traditional flow-based leakage detection system. Nowadays, the market and associated industrial experience, offers several solutions for water leakage detection. In this Master Thesis we discussed a pressure-based method for very small leaks detection which has already been successfully employed by a Canadian company Nickel Smelter Vale Ltd. We suggested to implement a SIF based on this method as a pilot project for some critical water-circuits (in terms of both eruption and explosion problems) as an additional measure of risk mitigation.

Key words: Furnace Water Cooling Systems (FWCS), water leakage, water-circuit, Safety Instrumented System (SIS), Safety Instrumented Functions (SIF), flow-based water leakage detection, pressure-based water leakage detection.

Contents

Preface . . . i
Acknowledgment . . . ii

1 Introduction **2**
1.1 Background . . . 2
1.2 Goal of the project . . . 3
1.3 Objectives . . . 3
1.4 Limitations . . . 4
1.5 Approach . . . 4
1.6 Structure of the Report . . . 4

2 Furnaces in industries **5**
2.1 Furnaces application in different industries . . . 5
2.2 Furnaces classification . . . 6
  2.2.1 Furnace classification based on the heat source . . . 6
  2.2.2 Furnace classification based on the method of charging . . . 8
2.3 Silicon Production in Elkem . . . 9
  2.3.1 Silicon and ferrosilicon: definition and applications . . . 9
  2.3.2 Overview of furnace smelting process . . . 10

3 Cooling systems for furnaces **14**
3.1 Furnace cooling systems: classification (open/ closed loops) . . . 14
3.2 Elkem FWCS . . . 15
  3.2.1 Cooling for casting process: granulation . . . 16
3.3 FWCS: the main associated danger . . . 17
  3.3.1 Dangers associated with FWCS failures . . . 17
  3.3.2 What is the danger of water? . . . 17
  3.3.3 Eruption due to internal water leakage . . . 19
  3.3.4 Explosion due to external water leakage . . . 20
  3.3.5 Risk associated with granulation process . . . 21
3.4 FWCS: accident accident experience . . . 22
  3.4.1 Accident at Elkem Thamshavn, 2006: water-gas reaction . . . 22
  3.4.2 Other similar accidents in industry . . . 25

4 Safety protection of FWCS 27
4.1 Safety measures after the accidents 27
4.2 Handling water leakage 31
4.2.1 Water leakage localisation 31
4.2.2 Water leakage size 32
4.2.3 Mechanism of water leakage detection and closure 32
4.3 Relevant regulations applicable for FWCS 34
4.4 Possible SIF options 36
4.4.1 Risk analysis: base for SIF implementation 37
4.4.2 SIF: side sections of the smoke hood 40
4.4.3 Pressure based leak detection system 41
4.4.4 Pros and cons of the safety measures 44

5 Summary 46
5.1 Summary and Conclusions 46
5.2 Discussion 47
5.3 Recommendations for Further Work 47

A Acronyms 49

B Raw materials and products of smelting process on Elkem plants 50

C Content of FeSi92 produced on ELkem plants 51

Bibliography 52

Chapter 1

Introduction

1.1 Background

Many industries imply large amounts of thermal energy, i.e. very high temperatures, where cooling processes play an integral role for process control and safety. Therefore, cooling systems are widely used in order to keep the industrial processes running and ensure safety [1]. The cooling systems are a critical part of industrial furnaces, particularly ***Furnace Water Cooling Systems (FWCS)*** are used for providing process cooling water to water-cooled furnaces in such applications as: pyrometallurgical industries, silicon production, and fusing materials. Even though these water-cooling systems can be different in terms of design features, all of them must be designed so that to provide both control and safety function. Safety aspects related to FWCS are not limited to an availability of water supply to perform necessary function, but there are other aspects to be controlled such as prevention of water leaks, maintaining a required level of water temperature and water flow.

As it can be observed from industry experience, such cooling systems are often overlooked until problems arise. When the cooling system is out of control, damage can begin to occur to the cooling system and the components it protects. One of the most common problems associated with cooling systems is water leakage [2].

Production of silicon in submerged arc furnaces, as a part of Elkem business, is a type of complex industrial processes where the company cannot afford downtime as the result of systems failures and, what is of paramount importance, such failures can lead to severe accidents with loss of human lives. The relevant safety issues and accident experience, associated with failures in FCWS, are discussed in this Master Thesis.

Problem Formulation

There are initiatives to consider improvement of a safety part within FWCS along with a furnace reconstruction project currently run on Elkem Bremanger plant as well as ongoing pilot projects for implementation ***Safety Instrumented Functions (SIF)*** on other Elkem plants. *However, the implementation of SIF for the cooling systems in the smelting process is a very important, yet rather ambiguous question at the same time.* Several determining factors for implementation of safe instrumented measures, along with FWCS structure and current emergency response procedures, are discussed in the Master Thesis for building a base for further discussions on SIF related pilot projects in Elkem. Thus, the main focus in the Master Thesis will be put on finding process/ emergency response/ accident experience/ FWCS structure - related opportunities to equip FWCS with additional safety equipment so that to provide additional safety loops for earlier failure detection and quicker response to any process deviations.

Literature Survey

The Master Thesis implies the survey of a literature related to application of industrial furnaces, particularly for silicon production, and importance of cooling processes. Among of the these literature sources are: *"Industrial Furnaces"* of W. Trinks [3], *"Furnaces"* of J.D. Gilchrist [4], *Metal Production in Norway"* of M. Tangstad [5], *High Silicon Alloys"* of A. Schei, J.K.Tuset, H. Tveit [6].

Another essential part of the literature survey is related to analysis of accident experience across the industry and particularly Elkem. The key literature source is an article of H. Tveit *Water Leakages and Eruption From a Silicon Furnace*" [7] where the other provides not only the information on a severe accident related to a furnace eruption, but also provides a precise description on the background and mechanism of the accident.

1.2 Goal of the project

The goal of the Master Thesis is to find and describe the scope of the opportunities for implementation of SIFs for furnace cooling systems and to suggest a design and operation philosophy of the SIFs, needed to ensure a reliable and safe furnace cooling system.

1.3 Objectives

In order to achieve the main goal of the Master Thesis, most of the efforts will be given to achieve following objectives:

1. To study and present relevant theory on industrial furnaces and, particularly, furnaces for silicon production (smelting furnace);

2. To study and present relevant information on structure and principles of operation of cooling systems applied for smelting processes on Elkem plants;

3. To study and present relevant information about the main dangers and risks associated with failures of cooling systems for the smelting process;

4. To analyse available accident data related to furnace cooling systems both in Elkem and other industries;

5. To analyse regulation / guidance base for furnace cooling systems design and exploitation.

1.4 Limitations

The main limitation met during the work on the Master Thesis was the lack of opportunity to be on the Elkem Bremanger plant sufficient amount of time in order to get a full overview of the furnace cooling system operating for Furnace N 5 and to communicate with experiences personnel when any problems within the project occur.

The analysis of accident experience, related to failures in cooling systems in other industries, did not give a sufficient amount of investigation materials due to limited access for public.

1.5 Approach

The Master Thesis implied the use of several approaches to to follow the defined tasks and obtain the practically applicable results: literature study for learning theoretical base of the study case, study of the main system (smelting process equipment and cooling system), investigation and study of industry company's technical assets and procedures related to the topic of the project as well as available information on other industries' experience. During the preliminary discussions of the scope of the Master Thesis, it was decided to split the progress into two main milestones: Phase 1 and Phase 2. The main objective of the Phase 1 implied familiarization with the cooling systems concept, existing safety practices in Elkem and other industries. The content of Phase 2 (investigation of opportunities for safety instrumented measures) was defined when the main results of the theoretical part were achieved.

1.6 Structure of the Report

The rest of the report is structured so that to follow the stated objectives of the Master Thesis. Chapter 2 *Furnaces in industries* gives an introduction to theory about application of industrial furnaces, their classification based on different criteria and provides an overview of silicon production process and its associated equipment in Elkem. Chapter 3 *Cooling systems for furnaces* contains a literature overview and analysis of Elkem local documents on operation of furnace cooling systems in Elkem and describes the safety issues associated with the failures of these systems including accident experience. Chapter 4 *Safety protection of FWCS* introduces information about available safety measures available on Elkem plants for handling safety issues associated with failures of cooling systems describe. Important part of the Chapter 4 is a summary of opportunities and limitations for SIF implementation that had been found during the literature and Elkem procedures study.

Chapter 2

Furnaces in industries

Industrial furnaces are of crucial importance for many industries where a big amount of heat energy is needed for heating raw materials and production the final product[8]. The Chapter 2 starts with a brief introduction to *industrial furnaces application,* then it gives description of the main *classification systems o*f industrial furnaces. The Chapter ends with an overview of ***silicon / ferrosilicon production in Elkem*** and description of some ***associated equipment and processes t***hat are of interest for the scope of the Master Thesis.

2.1 Furnaces application in different industries

Industrial heating processes encompass a wide range of temperatures, which depend partly on material being processed, partly on the purpose of heating operation, and partly on subsequent operations of the production process.

Many industrial processes, particularly within metal, glass, ceramic production, are based on furnaces application and there are different types of furnaces were developed as their applications and demands grew. Furnaces are used as vessels where the energy, either chemical energy of fuel or electrical energy, is converted into heat to raise the temperature of processed materials [4].

☞ **Industrial process heating furnaces**: "insulated enclosures designed to deliver heat to loads for many forms of heat processing" [3]

However, not every device for heating processes is supposed to be called as a furnace because each industry adapts the use of furnaces within a specific purpose: those operating at temperatures lower than 650 °C (1200 °F)[1] are usually called *"stoves"* or *"ovens"*, in ceramic industry furnaces are termed *"kilns"*, chemical process industry uses terms *“heaters”*, *“incinerators”* or *“destructors”*, glass is melted in so called *“tank”* [3].

Metallurgical industries are the main users of furnaces. Melting of ferrous metals, particularly production of ferrosilicon, is a process which requires very high temperatures. A term of very high temperatures may be applied differently and different industries, however in case of

---

[1] The temperature ranges might very in different literature since there are no sharp dividing between furnaces and ovens; and the terminology can often be used interchangeably.

industrial furnaces, *"very high temperatures"* usually mean a temperature over *1260 °C (2300 °F)* [3].

Depending on industry, the of temperature ranges may vary. Figure 2.1 shows the temperature ranges applied in metal industry. The process of silicon / ferrosilicon production belongs to a very high temperature range and requires attainment of a temperature of 1703 °C (2606 °F) as a melting point of silicon (the general overview of a process of silicon production will be described in Chapter 2.3).

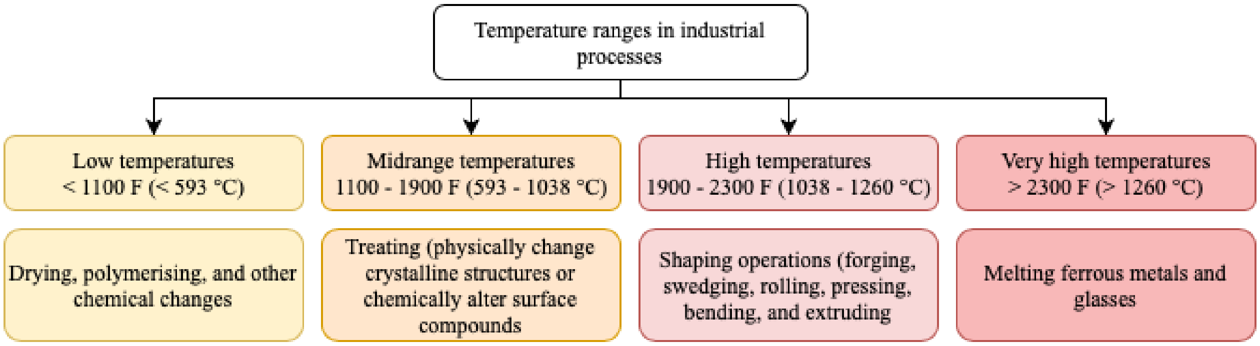

Figure 2.1: Temperature ranges and examples of their application in different processes within metal industry [3]

2.2 Furnaces classification

There is no one comprehensive classification system for furnaces, however they may be grouped in many ways, e.g. by their purpose, by temperature variance, by heat source, by type of fuel, by shape, by the method of charging (i.e. handling material), by recirculation, by heat recovery, and by other characteristics. In this Section 2.2, the following classification systems will be introduced and conceptually described:

1. Classification based on the heat source (extended part), and
2. Classification based on the method of charging (short part).

2.2.1 Furnace classification based on the heat source

Furnaces generate heat to raise the temperature by energy created by either ***(1) chemical energy of fuel*** or by ***(2) electrical energy*** converted into heat. Advantages offered by each of these types may depend on available resources, process parameters etc [4]. For instance, combustion type of furnaces (fuel-fired) are used relatively often, however electrical furnaces are necessary where fuel cost is not comparable with other advantages of electrical furnaces, e.g. a wider range of temperatures [3]. Figure 2.2 represents the classification of furnaces by heat source where the two main brunches of fuel-fired and electrical furnaces where categories, highlighted in blue color, are relevant for Elkem plants.

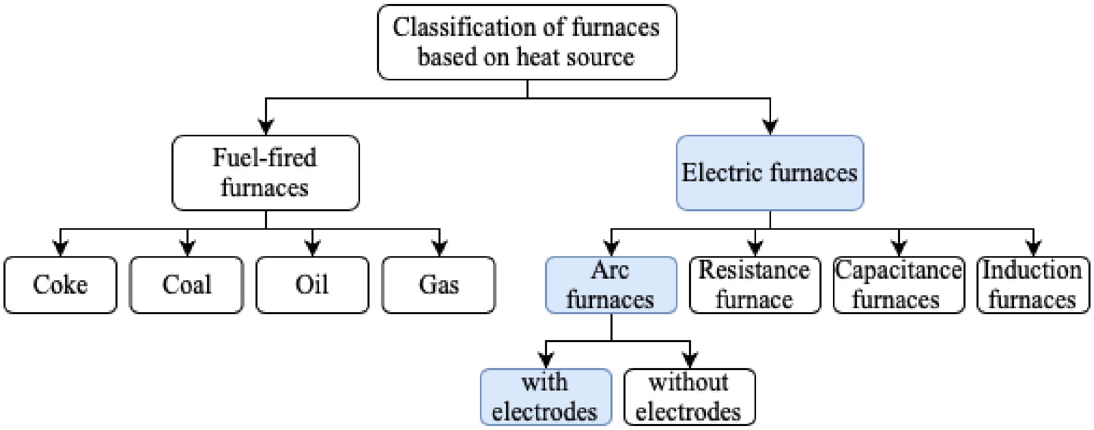

Figure 2.2: Classification of furnaces based on the heat source

Both fuel-fired and electrical furnaces can be classified further. In this Section 2.2, *the classification based on type of fuel is introduced for fuel-fired furnaces*, and *the classification based manner of energy transformation – for electrical furnaces.*

Classification of fuel-fired furnaces:

Fuel-fired furnaces operate by combustion of ***(1) coke***, ***(2) coal*** (which are the commonest solid carbon fuel), ***(3) oil***, and ***(4) gas*** [4].

Along with this classification, *coal-fired furnaces* can be grouped by the form of supplied fuel, i.e. *(1) solid fuel beds* and *(2) pulverized fuel*, while operation process of coke-faired furnaces is always based on solid fuel beds method. Pulverized form of coal (also known as powdered coal) is considered rather like a gas. The fuel, in the form of fine powder, is injected into the furnace along with the hot combustion air stream [4].

Oil furnaces: The burning mechanism in oil furnaces may be grouped as:

1. Oil is burned like a gas, being vaporized prior to introduction to the ignition process,
2. Oil is broken into fine droplets and they are injected into hot air stream [4].

The first type of oil furnaces is not much used since it requires oil to be refines which significantly effect the cost of operation. However, the method of oil droplets easily works with cheaper heavy oils or other liquid fuel. The oil is broken into droplets by different methods: mechanically by rotating discs or swirler, by high pressure injections from a orifice of a small diameter, or by application of air or steam [4].

Gas furnaces: Gas, as well as oil, may be used for furnaces operation in different ways. Thus, gas and air may be pre-mixed before burning process or may be introduced into the furnace in separate streams.

Classification of electric furnaces:

Based on the manner in which electric energy is converted into heat energy, electric furnaces may be classified as [4]:

- Resistance furnaces,
- Induction furnaces,
- Arc furnaces, and
- Capacitance furnaces (or dielectric furnaces).

Of these the first three are important in metallurgical industries. Even though *electric arc furnaces are the main interest for scope of the Master Thesis*, the brief description of other types is given in this Section 2.2.

Resistance furnaces: Resistance heating process requires a conductor (i.e. resistor) as a component through which a current is passed. There are many types of materials (e.g. nichrome, carbon, molibdenium) which may be used as resistors and the choice depends on required properties such as resistivity itself, melting point etc [4]. This type of heating is associated with the relatively high electricity cost ans may require additional functional devices, e.g. circulating fans to assure the achieved temperature uniformity [3].

Induction furnaces: Induction heating is similar to resistance heating, but, in this case, current passes through an water cooled coil that surrounds the piece to be heated. This furnaces usually consume less electricity, however, sometimes, it becomes expensive due to cost of water that is necessary for cooling of induction coil [4] [3].

Capacitance or dielectric furnaces: Unlike resistance and induction furnaces, capacitance furnaces applies only to non-conducting (insulting) materials. The method is widely employed in plastic and ceramics industries for heating of materials [4] [9].

Electric arc furnaces: Heating mechanism in electrical arc furnaces is an another form of resistance heating. In such furnaces the resistor is the ***"plasma"*** (i.e. ionized atmosphere) which is formed in the space between two electrodes. Electric arc furnaces develop *extremely high temperatures which about 5000 °C (9032 °F)*. Such furnaces are used in production of special steels, smelting processes (e.g. ferrosilicon), one of the stages of the production of sound ingots of refractory metals (e.g. titanium), and other manufacturing processes [4]. Electric arc furnaces are also sub-classified as those *with electrodes*, and *those without them*. Operation of furnaces without electrodes is based on energy transfer to the plasma by induction [1]. *Elkem Silicon Materials division use submerged electric arc furnaces* and the process of silicon production along with the furnace structure are introduced in Section 2.3.

2.2.2 Furnace classification based on the method of charging

There are two main methods applied for delivering charge material to the furnace: ***(1) Batch method*** and ***(2) Continuous method***.

Batch-type furnaces: The process of batch charging may be performed by manually or by automatized systems (e.g. manipulator or robot). In such furnaces, the charge material (i.e. load) is placed in the furnace and heated for a fixed time and then the load is discharged – through a single charging-and-discharging door or two charging and discharging ends of the furnace [3].

Continuous-type furnaces: Continuous charging process implies delivery of the load when the furnace is being heated.

2.3 Silicon Production in Elkem

Elkem ASA is the largest silicon and ferrosilicon producer in Norway and one of the major producers on the world market [5]. ***Silicon (Si)*** is the most abundant metallic element and the second most abundant element in the earth's crust. However, the element very rarely occurs as the pure element in the nature, but it is the major component of quartz and sand stones [10]. Around 1950, extremely pure silicon was produced and was commercially used in computer industry for production of many key elements and electronic devices. Even though, for public, silicon is mostly known as a raw material for semiconductor industry[2] and as a symbol of the Silicon Valley, there are other applications of silicon which play an important role in many industries [6]:

- Raw material for some of the processes in chemical industry,
- Alloying of aluminum and other widely used metals,
- Deoxidation and alloying of steel and cast iron [6].

This Section 2.3 introduces *silicon and ferrosilicon (as one of the most important silicon alloys)* and gives a survey of *the technology of its production.* The main focus will be put on the common technology which is also applied in Elkem, however the other methods are worth brief discussion within the Master Thesis paper for the expanding general knowledge about the industry scope.

2.3.1 Silicon and ferrosilicon: definition and applications

In engineering terminology, particularly in metal industry, *the product "silicon" does not mean that it is a pure product with 100% of silicon content.* In practice, it contains some tramp elements such as iron *(Fe), calcium (Ca), aluminium (Al)* and others [5].

Silicon metal [3] and ***ferrosilicon*** are used in different industries such as steel production, foundry, electronic, chemical industry which finally provide society with building materials, heavy machinery, vehicle, medicine devices and many other things (see Figure 2.3).

Metal industry uses different metallic and non-metallic elements for alloys for changing (improvement) physical or chemical properties of a base-metal. ***Iron (Fe)** is the most common metallic alloying element.*

☞ **Ferrosilicon (FeSi)**: an alloy which consists of Silicon *(Si)* [4] (as the main element) and iron *(Fe)* [5] [5].

The leading countries in ferrosilicon production are China, Russia, Norway, Brazil, and USA [11].

The amount of iron may vary depending on the desired properties of the final product (i.e. ferrosilicon) and is shown in percentages. For example, *FeSi92* means an iron-silicon alloy with

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[2] Electronic devices, photovoltaic cells [6]

[3] The solid silicon is not a metal. However, in metal industry, pure silicon with less than 1 – 2 % of other elements, is called silicon metal)

[4] The most important products contains 65 % and more content of silicon

[5] A small percent of other elements presents

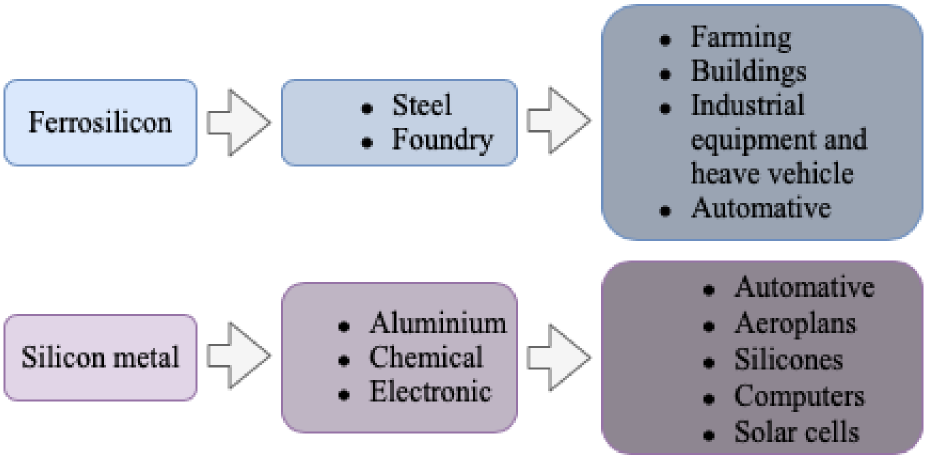

Figure 2.3: Examples of the most common applications of silicon metal and ferrosilicon) [6]

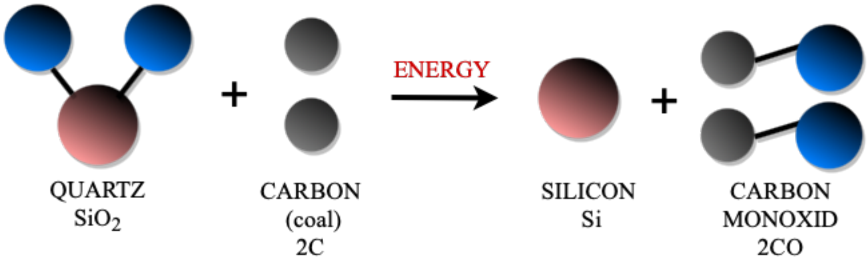

Figure 2.4: Representation of the carbothermal reaction in ferrosilicon furnaces [12]

92 % of pure silicon content, and 8 % weigh iron. However, in practice, silicon and iron are not the only elements presenting in the alloy, but several other elements may constitute a small percent [6].

☞ **High Silicon Alloys**: silicon-containing alloys (including ferrosilicon) where the silicon is the dominant element in the alloy [6].

The high silicon alloys are produced in industrial furnaces (see Section 2.3.2 for description of production process).

Elkem produce both ferrosilicon (with different silicon content from 87 % to 92 % of silicon content (Appendix C shows the content of the product FeSi92).

2.3.2 Overview of furnace smelting process

The two products of smelting process on Elkem plants (*division Silicon Materials*) are *silicon (Si99%)* and *Microsilica®*. Appendix B shows the scheme of the main raw materials and products produced in Elkem Silicon Materials.

Elkem produce ferrosilicon in *submerged electric arc furnaces.*

☞ **Submerged Arc Furnace**: "vessel in which a combined arc / resistance heating is used to melt the charged material" [13].

The whole process of Si and FeSi production can be decomposed into several steps:

1. Raw materials (SI, C, Fe) reception and storage,
2. Charge mix,
3. Smelting process in the furnace,
4. Casting process and metal tapping[6],
5. Metal cooling and crushing,
6. Product packing and storage,
7. Shipping to market [14].

Since *the danger of leakage from furnace cooling systems* (will be discussed further in Chapter 3.3) is relevant for only some of the mentioned processes, the main area of the interest related to the main problem in this Master Thesis is limited to *smelting process, casting and tapping of smelted metal, and metal cooling process.*

The main components (equipment) of silicon production plant in addition to the smelting furnace are (see Figure 2.5 for graphical representation):

- The mix unit for pre-mixing of raw materials (Si, C, Fe),
- Electrical system (including electrodes) giving necessary amount of energy for furnace operation,
- Energy recovery and the gas cleaning equipment (the off-gas units)[7],
- Furnace cooling system,
- The product processing units for tapping, casting, and crushing of produced liquid alloy [5] [6].

Further in this Section we will look through the key components of the production process following the mentioned structure of the production plant.

Charge material handling

There is a chain of operations for handling of the charge material and it is usually organized in the following operational cycle: stoking of the furnace charge burden and charging of raw materials [15]. The the raw materials (i.e. quartz (SiO2) and carbon materials (C) such as charcoal, coal and coke) *are transported, stored, weighted, and mixed* before being added to the top of the furnace through the furnace silos. The storage equipment for the charge material is often called *"day bins"*. It is important to protect carbon materials from humidity and, therefore, they are stored indoors bins. Variations in water content significantly complicates the furnace control [5] [6].

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[6] Production of Microsilica®is going in the parallel with Si production

[7] Includes equipment for Microsilica®separation

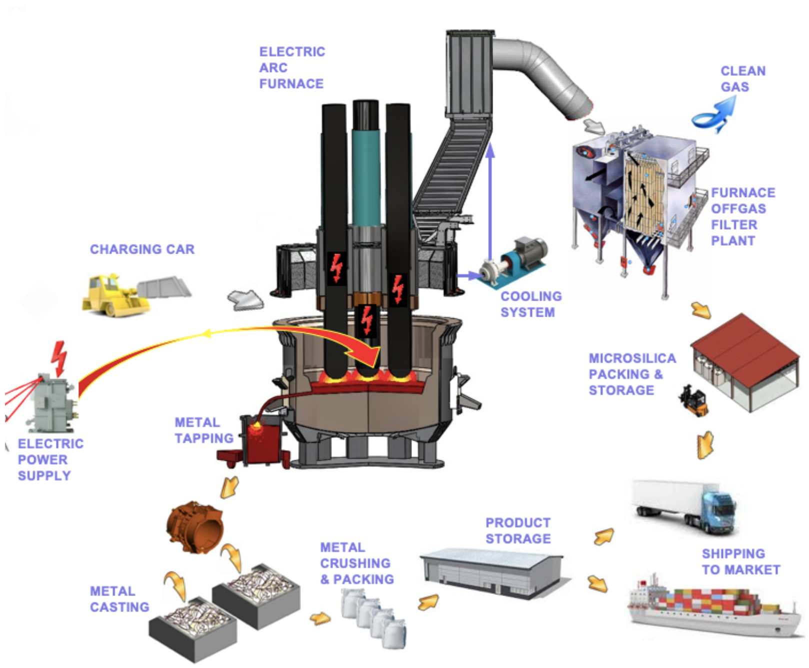

Figure 2.5: The main components and processes of the smelting process on Elkem silicon plants [14]

Energy for the furnace operation

Inside of the furnace there are three *electrodes* which serve as energy providers. During the operational process the electrodes are heated, and are slowly consumed. Therefore, the life cycle of the electrodes implies their periodic replacement. Elkem uses ***Søderberg electrodes*** [8] which are based on so called *electrode paste briquettes* [9] [5].

Energy recovery and gas cleaning

The off-gas from the furnace is suitable for energy recovery. Therefore, ***the off-gas cleaning system*** (e.g. Elkem Thamshavn) can include energy recovery unit which includes a cooler and a filter. The condensed silica fume (Microsilica®) is separated from the gas flow in special baghouse filters [5] [6].

Furnace cooling system

The overview of furnace cooling systems, applied in Elkem furnaces, will be introduced in a separate Chapter 3.

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[8] This type of electrodes was invented by Elkem engineer Carl Wilhelm Søderberg and his team in 1919. The type of electrodes is patented and widely used in ferrosilicon production [16]

[9] ELSEP®- Elkem Søderberg electrode paste [17]

The product processing

The ***tapping*** of the liquid metal is carried out through the tapholes situated around the furnace pot [15]. Depending of the process structure, the process of the liquid silicon ***casting process*** can vary. Some of the methods are [6]:

- Casting into big (0.5 – 2 m) beds lined with fine particles of solid silicon,
- Casting into iron molds,
- Granulation (gentle pouring the liquid silicon into a water pool). Section 3.2.1 describes the operation.

After the casting process, the liquid metal should be cooled to the solidified form and crushed to a more convenient size for further processing [5].

Chapter 3

Cooling systems for furnaces

Many industries, particularly metal and silicon industries, imply large amounts of thermal energy, i.e. very high temperatures, where cooling systems play an integral role for process control and safety. Cooling water systems affect both production process quality and safety. The extraction of heat, i.e. cooling process, is a crucial component of many manufacturing processes in different industries. Therefore, cooling systems are widely used in order to keep the industrial processes running and ensure safety. Whether it is water cooling systems or air cooling systems, both types require control so that to minimize any associated risks. The Chapter 3 is devoted to description of principles of operation of ***furnace water cooling systems (FWCS)***, which operate on Elkem plants, and provides an overview of the ***safety issues associated with the operation of such cooling systems***.

3.1 Furnace cooling systems: classification (open/ closed loops)

There three two types of water-cooling systems based on their loops structure:

- Open-loop cooling systems,
- Closed-loop cooling systems.

Open-loop furnace water cooling system does not imply circulation of water. Water, used during the cooling process, is directed into drainage and is not returned to the cooling process. Unlike the open-loop structure, closed-loop furnace water cooling systems are based on the principle of the water forced circulation.

Which type of loop for the cooling system to choose depends on several factors. In terms of FWCS operation, the most important factor would be an resilience of equipment, i.e. valves, to dirt build-up because an open-loop water cooling system may collect debris which provokes valves clogging [18].

The main advantages of the closed-loop cooling systems, as compared to open-loop systems: higher water quality (i.e. cleaner and softer), less risk of corrosion and clogging, lower water consumption, relatively sensitive leakage detection [18].

3.2 Elkem FWCS

Silicon and ferrosilicon production process requires a water-cooling system integrated with the process equipment. Elkem furnaces require cooling systems to balance thermal load and associated wear of the inner lining, to protect the electrode system, shell and other components.

As a rule, the structure of FWCS of submerged electric arc furnaces is complex, even though for the scope of the Master Thesis is limited to a specific type of problem – water leakages. Therefore, this Section 3.2 contains information about FWCS which is relevant in terms of *water leakage issues*.

At Elkem Bremanger there is an ***open-loops water cooling system***, which implies discharge of water after use. Central water supply is split into eight large water ***manifolds*** which ensure water supply, separated into different flows, to furnace equipment. Each of the manifolds consists of a certain number of ***water-circuits***. Figure 3.1 is a photo of a manifold N3 at Elkem Bremanger.

Figure 3.1: Manifold N3 at Elkem Bremanger (The photo is published with permission)

Critical[1] for process safety water-circuits can be:

- Controlled (Pressure and Temperature),
- Adjusted (regulating valves, back-flow prevention valves, pressure control valves, 3-way control valves),
- Shut-off (stop valves).

---

[1] The concept of water circuits criticality is introduced in Section 4.2.2

Usually one water-circuit would have an inlet valve to open/close and an outlet regulation valve to trim in the flow volume.

Each of the manifolds has a certain cooling function depending on an equipment to be cooled. Table 3.1 shows the distribution of manifolds functions and the components of silicon/ ferrosilicon furnaces.

Table 3.1: Eight manifolds of FWCS of Furnace N5 at Elkem Bremanger

Manifold N	Cooled equipment
1	gas outlet, smoke stack, smoke hood, charging tubes, emergency damper
2	gas outlet, smoke stack, smoke hood, charging tubes
3	Pressure rings
4	Electrode shield
5	Contact clamps
6	Side sections, smoke hood, electrodes-system sealing
7	Various
8	Various

3.2.1 Cooling for casting process: granulation

Cooling processes within silicon production also include granulation and water mist as types of casting processes. This operational processes are necessary to be introduced since they *(1)* water-consuming and, therefore, *(2)* they pose a certain degree of risk along the silicon production process.

☞ **Granulation**: a type of silicon and ferrosilicon solidification by pouring the hot alloy directly in a large amount of cold water. During the method allows to break to hot metal into droplets of s shape and size required by the customer [19] [20].

The method of granulation is used in Elkem Rana. This process is based on the gentle and controlled pouring the ferrosilicon alloy into cold water (see Figure 3.2).

Granulation method has its advantages such as:

- Quicker solidification,
- Finer granules and stronger alloy,
- No need of further crushing,
- Prevents formation of dust created during the crushing process [19].

Even though the method is well developed and the technologies allow producers to make the granulation process in a safe and reliable way, more and more silicon and silicon producers try to replace the method with less risky processes.

This process is also included into the hazards related to silicon industry (see Section 3.3.1, Figure 3.3)

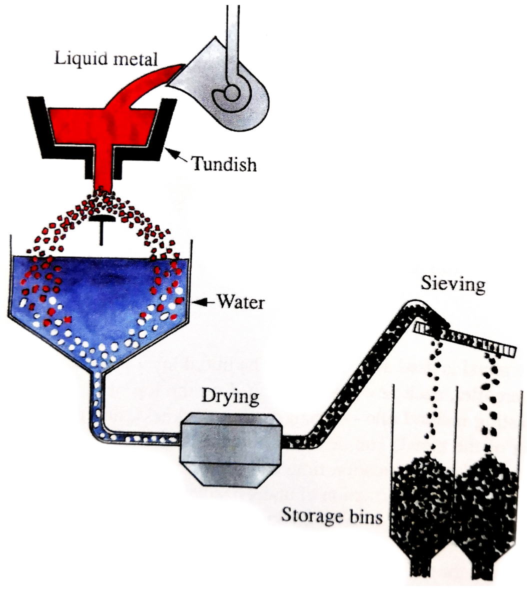

Figure 3.2: Granulation process applied on Elkem Rana plant [6]

3.3 FWCS: the main associated danger

3.3.1 Dangers associated with FWCS failures

Cooling water systems in any applications may have some operational problems and the most common of them is water leakage. The danger of these leakages is that they can interfere with substances or zones (e.g. electronics) which may lead to undesired outcomes, and/or reduce cooling efficiency [21].

It is important to understand the role of such water-cooling systems malfunctioning and failures in the scale of silicon and other metal production industries. The hazards, relevant for these industries, may be divided into five types where water leakages are a significant part (Figure 3.3 demonstrates the hazards, and water leakages are in yellow boxes) [7].

Based on the Figure 3.3 content, it is reasonable to limited and mark the scope of the water-related issues within the Master Thesis. As it was said earlier, *the simultaneous presence of water and a hot metal is one of the major dangers for ferrosilicon process*, however this danger might occur in different parts of the process and are not necessary associated with FWCS leakages itself. Figure 3.4 demonstrates the water-related issues to be discussed further in this Section 3.3.1.

3.3.2 What is the danger of water?

The simultaneous presence of very high amount of heat energy and a water in the same process poses *a risk of severe explosions or eruptions* [7]. This risk is very likely to be realised when any malfunctioning or failures in water-cooling system occur and lead to a water leakage. This risk is very likely to be realised when any malfunctioning or failures in water-cooling system occur and lead to a water leakage.

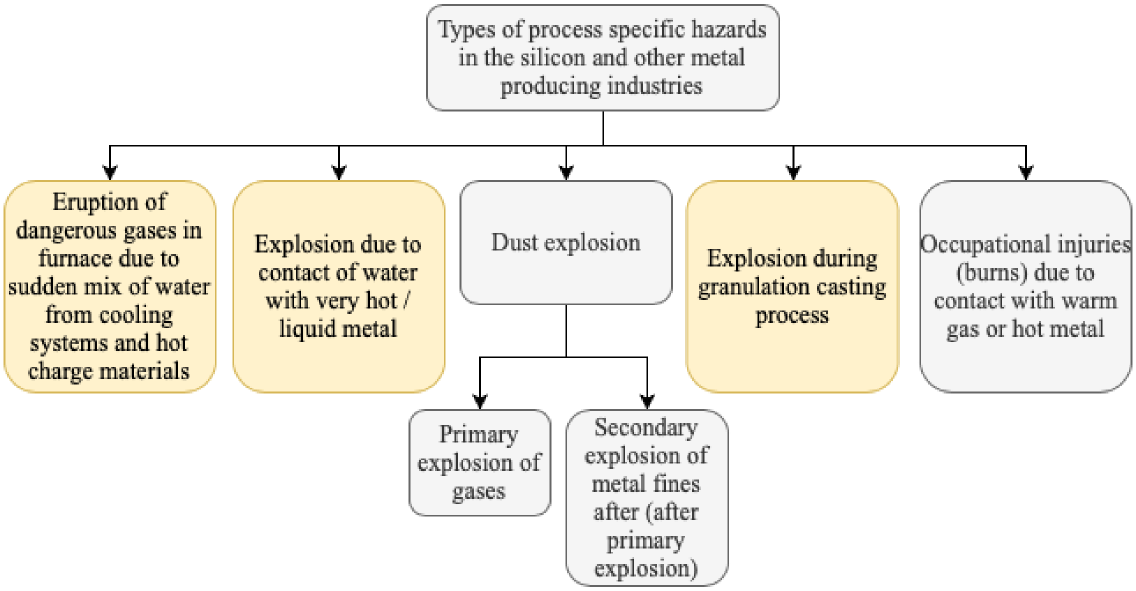

Figure 3.3: Classification of hazards in silicon and other metal industries according to [7]. Categories, highlighted in yellow, are subjects to discuss in this Master Thesis

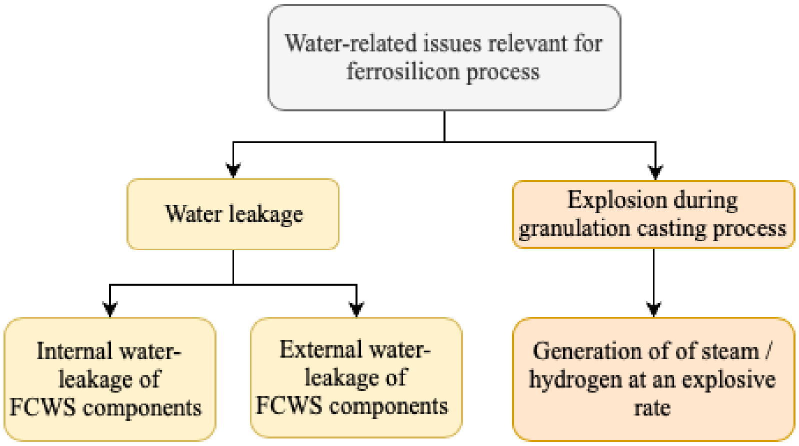

Figure 3.4: Water-related issues in ferrosilicon production related to water issues

The accidents related to water leakages in metal industry (particularly in Elkem) can be grouped based on the type of dangerous exothermic reaction (see Figure 3.5):

- Water-metal reaction, and
- Water-gas reaction (eruption-like events).

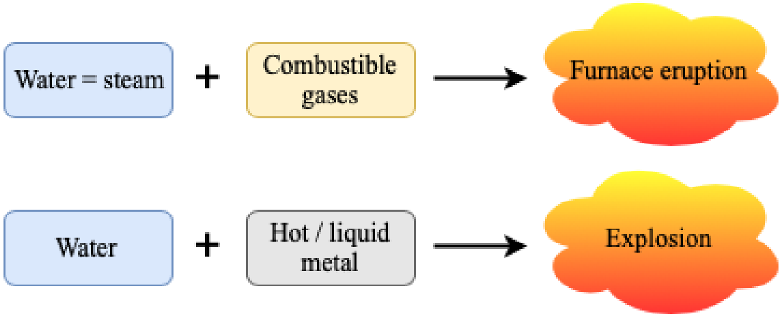

Figure 3.5: Types of dangerous reactions of water with substances leading to accidental events

3.3.3 Eruption due to internal water leakage

Furnace eruption is a result of water-gas reaction. The mechanism of water-gas reaction is precisely described in Section 3.4.1 and demonstrated on the example of a severe accident, happened in Elkem Thamshavn in 2006. However in this short subsection, it is important to discuss the ***tolerable water leakage limits in the furnaces***. The information, provided below, will be used in the Section 3.4.1 (Elkem Thamshavn accident, 2006).

Safe limits of water leaks

Based on a set of calculations (more precise in [7]), it is defined that a silicon furnace can tolerate up to 4800 kg of water, i.e. the furnace can evaporate it in a safe manner. This means that the *hot charge, being mixed with the water, is able to take the load and evaporate in the order of 5 m3* [7]. *It is possible to detect a water leakage in the order of 1 m3 per hour*, which means that the safe limits are being kept and monitored [7].

Important modes of operation in terms of leakage

In terms of leakage inside of the furnace, it is important to consider several key furnace modes of operation: ***(1) active load mode), (2) load shut-down (not load process)***, and ***(3) furnace shut-down)***, i.e. maintenance load.

Load shut-down mode: It is reasonable to start with the second mode (load shut-down), because the calculations of tolerable leakage limits (5 m3) are performed with regards to this mode. The reason is that, during the load shut-down mode, there is less amount of thermal energy of the charge that evaporates the water [7]. Hence, this mode is less tolerable, and therefore more dangerous, compared with active load mode.

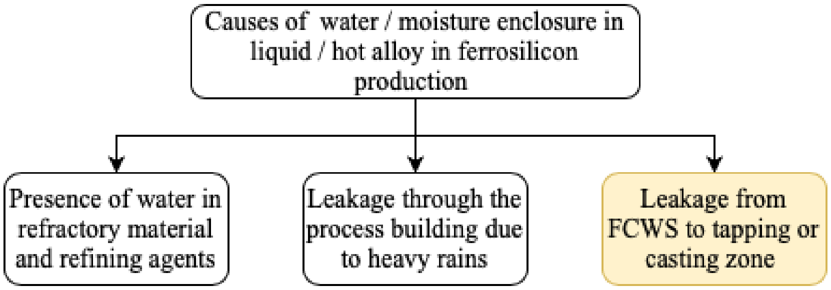

Figure 3.6: Common causes of water-related accidents in osilicon production [7]

Active load mode: In contrast to the load shut-down mode, the active load mode has larger amount of thermal energy, and therefore it allows the furnace to tolerate, i.e. evaporate, a bigger amount of water [7].

Furnace shut-down mode (maintenance): This mode is rare operation, but yet the most dangerous one. The reason is that the crater of the furnace remains very hot for a period of several weeks after the furnace shut-down. This poses a serious risk in case any failures in FWCS occurs, i.e. even a minor leak into the furnace can lead to an accident [7].

3.3.4 Explosion due to external water leakage

These type of accidents is the most frequent of the others which are discussed in this Section 3.3.4. Even though the Master Thesis is focused on the issues related to FWCS and particularly on water leakage from FWCS elements to the tapping zone, it is necessary to introduce other possible causes of such accidents (see Figure 3.6).

The tapping area, as a part of the ferrosilicon process, has several safety challenges. One of these is the possibility of contact between a cooling water, leaking from the external elements of the FWCS, and a hot ferrosilicon being poured from the furnace tapholes.

The prevention of leakages from the external parts of the FWCS is a critical issues because *a certain amount of water or even a humidity, being in contact with the hot metal, immediately evaporates and create dangerous conditions in the production area.* These are sudden expansion of the formed vapor and high pressure in the environment which eventually leads to an explosion. These type of accidents is the most frequent of the others which are discussed in this Chapter [7].

It is important to understand that the tapping process has literally *zero tolerance to an amount of water being enclosed in the molten metal.* This means that any amount of water and even moisture, mixed with the hot metal, lead to large explosion. The severity of such explosions has been investigated in metal and aluminium industry where the energy released in the explosions is expressed in ***Trotyl (TNT) Equivalent*** (see Table 3.2) [22]. In addition to TNT Equivalent expression, it is reasonable to compare the theoretical energy release with after-effects of such accidents (see Table 3.3) [7].

Table 3.2: TNT Equivalent of the energy released in the explosion caused by Interaction of 1000 kg of Molten alumunium with water” [22]

Metal	TNT Equivalent according to the amount of water, laters		
	1 liter	10 liters	100 liters
Aluminium	3.17 TNT	32.00 TNT	200.00 TNT

Table 3.3: TNT Equivalent of the energy released in the explosion caused by Interaction of 1000 kg of Molten aluminium with water” [7] [22]

TNT Equivalent	After-effect of explosion (with a radius, m)		
	Breakage of windows	Collapse of roof	Destruction of interior walls
1 kg	30 m	-	-
80 kg	250 m	40 m	23 m

3.3.5 Risk associated with granulation process

Nowadays, water granulation method is *a common method of hot alloys treatment* in silicon industries. Even though it allows to achieve better results in some parts of the silicon process (as it was listed in Section 3.2.1), it was recognized that the granulation method has a relatively big potential of hazards leading to explosions [6]. The explosions may be caused by high power generation and thereby an uncontrolled rapid formation of vapor at an explosive rate.

Compare to the hazards during the external leaks of water from FWCS (Section 3.3.4), granulation process has relatively small amount of metal, but a large amount of water which is not a serious risk itself. However occasionally out-of-control conditions may occur, and the risk of explosion will be realized [23]. The mechanism of such explosions is difficult and can hardly be called as fully understood, but several factors are often considered:

- Formation and expansion of steam at an explosive rate: if the process runs out of control, loss of cold granulation water and uncontrolled accumulation of hot alloy may result in a severe steam explosion [20],
- Formation of hydrogen gas (*H2*) at an explosive rate: granulations of ferrosilicon releases hydrogen gas. This exotherm reaction is not a desired component of the process, but yet cannot be avoided [19],
- Formation of hydrogen which reacts with oxygen (oxy-hydrogen gas): The urgent issue in this process is to prevent the formed hydrogen gas from mixing up with the air. This dangerous reaction generates an explosive atmosphere (detonating gas) which can be ignited by a single hot drop of the alloy [19].

To sum it up, the granulation process poses the risk of severe explosions which can result in significant production loses and even loss of people lives. Therefore, a plant, where the granulation method applies, should be designed so that to perform the control of the process remotely from the outside of the special separated room which is designed so that to handle minor explosions [7].

3.4 FWCS: accident accident experience

Each industry has its specific hazards which pose specific health and safety risks. Regarding metal and ferroalloy industry, the accidents are of generic type which can be relevant for many other industries. However, the presence of hot metal and large amount of thermal energy pose a specific risk for this industry. Elkem are aware of the danger water poses when it comes in contact with molten metal. It is a common problem for metal industry and there have been several serious accidents were water leakage was the root cause [24]. One of the major accidents in metal industry, caused by water leakage, happened March 2011 at the Carbide Industries LCC facility located in Louisville, KY, USA [25]. A closed calcium carbide furnace exploded due to a water leakage, ejecting a huge amount of solid and powdered debris, flammable gases, and extremely hot (molten: 3800 F / 2100 C) metal and completely ruining the adjacent control room, killing two people [24].

3.4.1 Accident at Elkem Thamshavn, 2006: water-gas reaction

Elkem has experienced several accidents caused by water leakage both inside and outside the furnaces. Further in this Section we will look through the most severe accident, happened in Elkem - Accident at Elkem Thamshavn, 2006. The mechanism of the accident, happened in Thamshavn furnace N1 in 2006, was an eruption due to mix of humid and warm combustible gases and steam after a critical water leakage (see Figure 3.7) [7]. As the result of the severe accident, one operator got critically injured and subsequently died of severe burns, and four other operates got minor injuries [24].

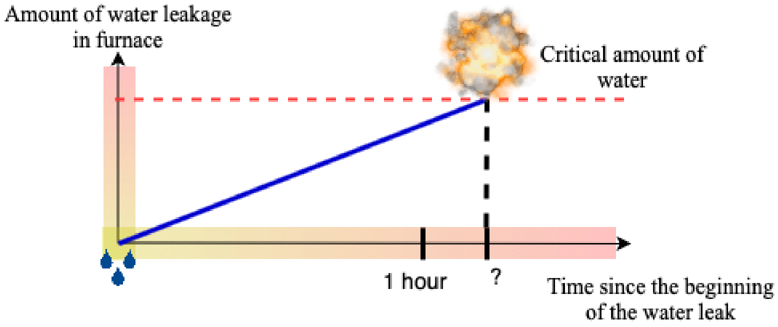

Figure 3.7: Furnace eruption process at Elkem Thamshavn, 2006. The time is not clearly defined, but it is known that it took more than 1 hour form the moment of leakage started to the moment of eruption

It is important to define the difference between terms "explosion" and "eruption". An explosion applies as a general term for a physical process of sudden release of energy, while eruption is more specific for the study case.

☞ **Explosion**: "sudden increase in volume and release of energy in an extreme manner". The typical length time of an explosion is milliseconds [7].

☞ **Eruption**: in terms of metal and silicon industry, the accidents, caused by internal leakage in a furnace, are better called as "eruption" of gas form the furnace. Furnace eruption is a relatively slow process, i.e. eruption takes place over a period of several seconds [7].

In Thamshavn, the eruption of the furnace was caused by a major leakage when a water-cooled bolt connection in the furnace electrode system failed. The leakage is termed as major because it exceeded the safe limits: it took more than one hour to identify the leakage and to close specific water line [24]. A critical amount of water got enclosed in the hot charge of the furnace and it expanded dramatically in volume as it flashed into steam, resulting in a spray of hot steam, process gases, hot charge and furnace debris [26].

Figures 3.8 and 3.9 illustrate the mechanism of accident in Elkem Thamshavn. i.e. how a major water leakage in the furnace developed into an accidental event. Particularly, Figure 3.8 represents the situation when the water leakage is within safe limits, and the water initially evaporates which does not pose a significant risk [7].

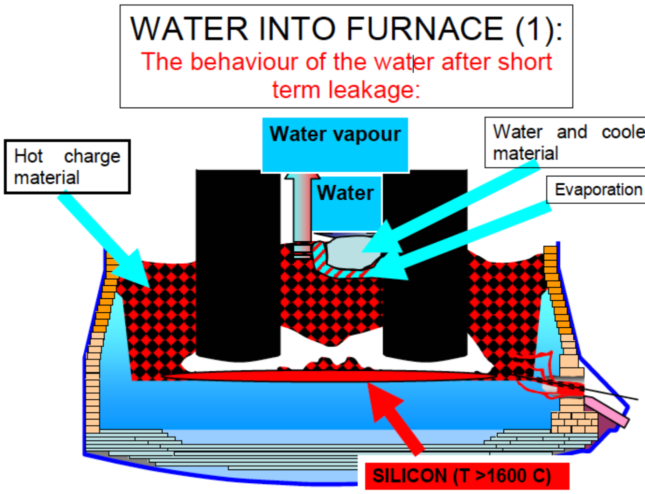

Figure 3.8: The effect of a not significant water leakage in the submerged electric arc furnace for silicon production (Elkem Thamshavn) [7]

The situation is worsen when the amount of the water, enclosed into to the furnace, exceed the safe limit (Figure 3.9 illustrates the described situation). The water mixes with incoming raw materials and, subsequently, raw materials "get wet". However, the critical situation is yet to come: the wet raw materials mixes with the hot charge which has a very high temperature and high thermal energy content. It provokes formation of a huge amount of water vapor which subsequently mixes with dangerous combustible process gas in the shaft and crater of the furnace. This movement of the mixture of the vapor and the process gas violates the normal process conditions in the furnace and provokes even more active mixing of leaking water and the hot charge. This potentially leads to a new, but more severe eruption which maybe fatal.

As it is follows from investigation materials of the Elkem Thamshavn accident, there were three sequential eruptions, and the second was the most severe [7]. Figures 3.10 and 3.11 describes the general process of prime and violent eruptions. Figure N is relevant for Thamshavn accident.

To sum it up, and to cover the whole accident, including aftermath of the eruption, the fol-

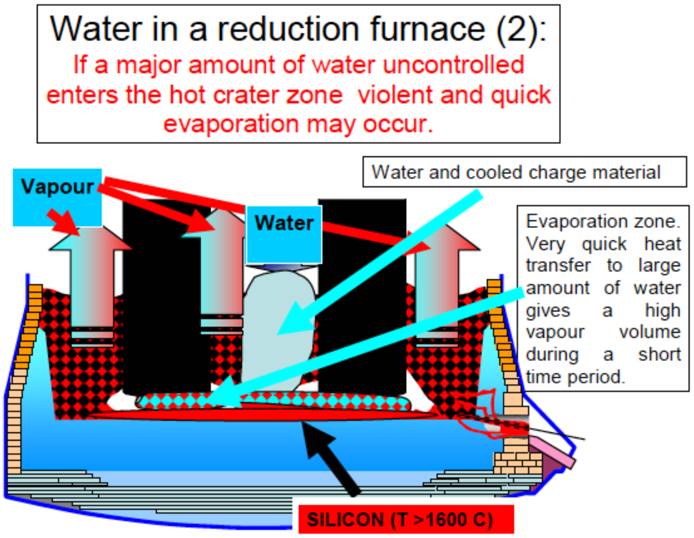

Figure 3.9: The effect of a major water leakage in a submerged electric arc furnace for silicon production (Elkem Thamshavn) [7]

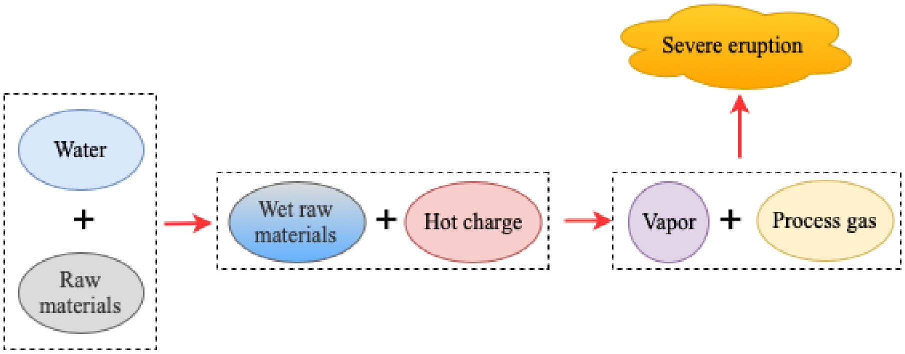

Figure 3.10: The short sequence of reactions in furnace leading to immediate eruption of the furnace.

lowing sequential events can be listed:

1. Water leakage exceeded tolerable limits and mixed with the raw materials. Raw materials got wet and accumulated dangerous amount of humidity.
2. Wet raw materials and water cooled the hot charge which provoked intensive evaporation.
3. Vapor and process gas accumulated in the furnace and provoked **prime eruption:** vapor and process gas flow out the furnace.
4. This prime eruption violated the process conditions in the furnace and provoked more intensive mixing of water and hot charge, and the bigger amount of vapor and process gas accumulated in the furnace,
5. **Violent eruption (accident):** raw materials, hot charge, the mixture of vapor and process

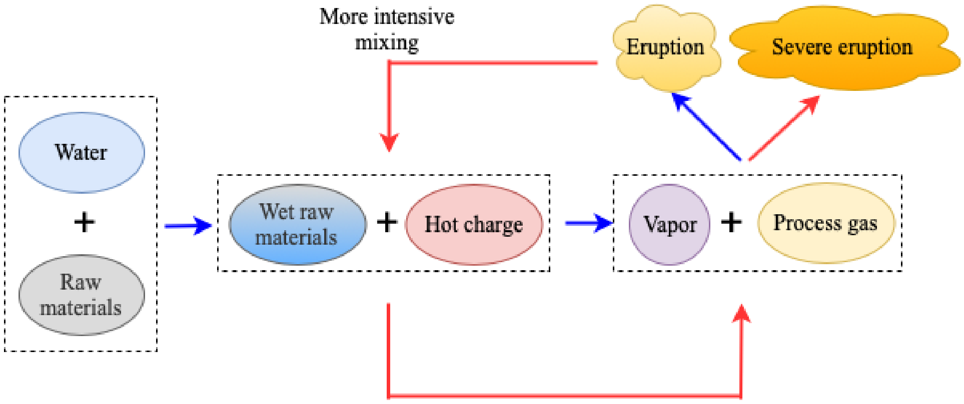

Figure 3.11: The sequence of reactions in furnace leading to eruption of the furnace: there might be several the same reactions consequently leading to the eruption.

gas burst out the furnace with the dangerous intensity, and it created a very hot and lethal atmosphere with high temperature and high humidity,

6. People, being exposed to this atmosphere, got severe or lethal skin burns and traumas damage.

3.4.2 Other similar accidents in industry

Precise information about all accidents and documents on investigations are limited for public, but a brief information was found on local news websites and in the article [7] where the author had several private conversations with the witnesses and victims of the accidents.

- **Silicon plant of Electro Bosna in Jajce, Bosnia and Hercegovina, 1973 [7]:** furnace eruption due to major water leakage. The accident killed six operators.

- **Tinfos Notodden, Norway, 1982 [7]:** Eruption of FeSi furnace due to major water leakage. Several people were injured.

- **Samancor Crome's Middelburg ferro-chrome smelter, South Africa 2005 [27]:** furnace eruption due to water leakage. Two people were killed immediately, five people died in a hospital after severe injuries, and four people were got injuries. In 2002, the same plant had another severe accident (explosion) where three workers were killed.

- **Minera Autlán's Tamós ferroalloy plant, Mexico, 2007 [28]:** furnace eruption due to water leak. Three workers were killed immediately, three other workers dies subsequently in a hospitality and five workers got severe injuries.

- **Assmang Cato Ridge Work (furnace N6), South Africa, 2008 [7]:** furnace eruption due to water leakage into the furnace. Six employees were killed. Operation of all seven furnaces were terminated for the period of investigation.

Patterns in findings

There are several patterns (see Table 3.4.2 following from the findings from the listed accidents in the previous subsection and accident in Elkem Thamshavn, 2006.

Table 3.4: Patterns in findings in accidents related to water leakages in metal industry, including accident at Elkem Thamshavn, 2006 [7]

Pattern	Description
Cause	Major water leakage: water is evaporated and reacts with explosive gases
Problem detection	Water leakage is not defined during a safe period of time, and therefore the amount of water entering the furnace exceeds the tolerable limits
Mechanism of the accidental event	Even though the cause of the accidents is contact of water/ steam with explosive gases, the accidents did not follow the "explosion" process. The accidents are eruption of the furnaces
Eyewitness	The operators, eyewitnesses of the accidents, claim: “without any bang or sound of an explosion – but a “puffing sound” from gas streaming out from the furnace. There were gas flames, water vapour and glowing raw material flowing out from the furnace doors. Then the whole area became black”
Lives loss and damage to health	The accidents result in loss of people´s lives and severe injuries. Most of the victims were not killed immediately after the accident, but the injuries (damaged skin and lung system) worsens during days and weeks and people die in hospitals. The injuries to the workers are not typical of explosions, i.e. hit by debris from furnaces or a shock wave. The furnace eruption process causes burnes to people.

Chapter 4

Safety protection of FWCS

As it was discussed in in Chapter 3.3, for silicon production process, water leakages pose a very serious risk and, therefore, the cooling systems should be designed, built and maintained so that to avoid any associated dangerous situations. This Chapter 4 introduces main aspects of safety insurance in FWCS applied at Elkem plants. The Chapter begins with description of ***safety measures i***mplemented on Elkem Thamshavn based on the accidents experience related to water leakages. ***water leakage detection*** is a main concept for discussion in this Chapter since this mechanism is relevant for the concept of Safety Instrumented System (SIS). In addition, the Chapter contains an overview of ***relevant regulatory base*** which is applies for electric arc furnaces and, particularly, to their FWCS operation.

4.1 Safety measures after the accidents

Elkem's goal is to increase process safety at our facilities in order to avoid injury to personnel and materials (from PP Thor Inge). Safety barriers management plays an integral role in safety insurance in Elkem processes, particularly in terms of water cooling systems functioning. Elkem follow the strategy of three types of barriers [29]:

- *Organisational:* work processes, standartisation of procedures, reporting.
- *Physical / Technical:* Safety Instrumented Systems (SIS), detection systems, alarms, Basic Process Control Systems (BPCS),
- *Human / Operational:* competence, communication, management.

In this Master thesis, *the focus is technical barriers which imply Safety Instrumented Functions (SIF).*

Elkem divide safety measures based on the zone of water leakage: in the tapping zone and inside of the furnace. The tragic accident, happened in Thamshavn in 2006, induced a major evaluation of the silicon production process in terms of safety and new risk assessment [7]. Elkem performed several risk assessment procedures, particularly after the accident in Thamshavn in 2006 and Fesil Rana in 2008, and the summery of the risk assessment is shown in the Table 4.1.

Regarding risk of furnace eruptions due to major water leakage in cooling systems, along with organizational and human /operational safety barriers, Elkem has a range of technical measures for prevention of this type if accidents:

Table 4.1: Overall risk assessment of water leakages in Elkem Thamshavn [30]

Risk elements	**Furnace eruption**		**Explosion in tapping zone**	
	Risk value	**Description**	**Risk value**	**Description**
Frequency of water leakage	🟥	Frequency of a major leakage: 5 -10 per year	🟥	Frequency o water leakage in tapping zone: 1 - 3 per year
Probability	🟨	Requires a large water leakage that goes on over time as long as the furnace is in operation. All furnaces have installed meters for the detection of water leakage on most critical equipment in the furnace. Eruption probability significantly reduced as the water leakage can be closed manually before the critical amount of water comes into the oven.	🟥	Even small amounts of water can cause a large explosion if the water is enclosed in silicon. No meters have been installed for detecting water leaks on critical equipment that can provide water in the tapping zone. Manual closure of water leaks often takes relatively long time that the amounts of water are so large that the water at any time reaches the tapping zone. There are too few barriers that prevent water from flowing from the furnace and into the taping zone.
Exposure of personnel	🟩	Improvements to the New Safety Standard have reduced the exposure of personnel who are in the risk zone during leakage from furnace (mostly design and location of operator rooms). There is a high probability that the leakage will occur on equipment with leakage detection meters, where there is an alarm with subsequent evacuation and blocking.	🟨	Taps are present in the risk zone and water can get into the tapping zone (and ladle) without warning. Few plants have alarms in the tapping zone in case of water leakage
Risk of injury	🟨	Leak detection and reduced exposure of personnel have reduced the risk of personal injury due to debris from the furnaces significantly.	🟥	Without measures, it is only a matter of time before a water leakage occurs that gives an explosion in ladle with personnel in the risk zone

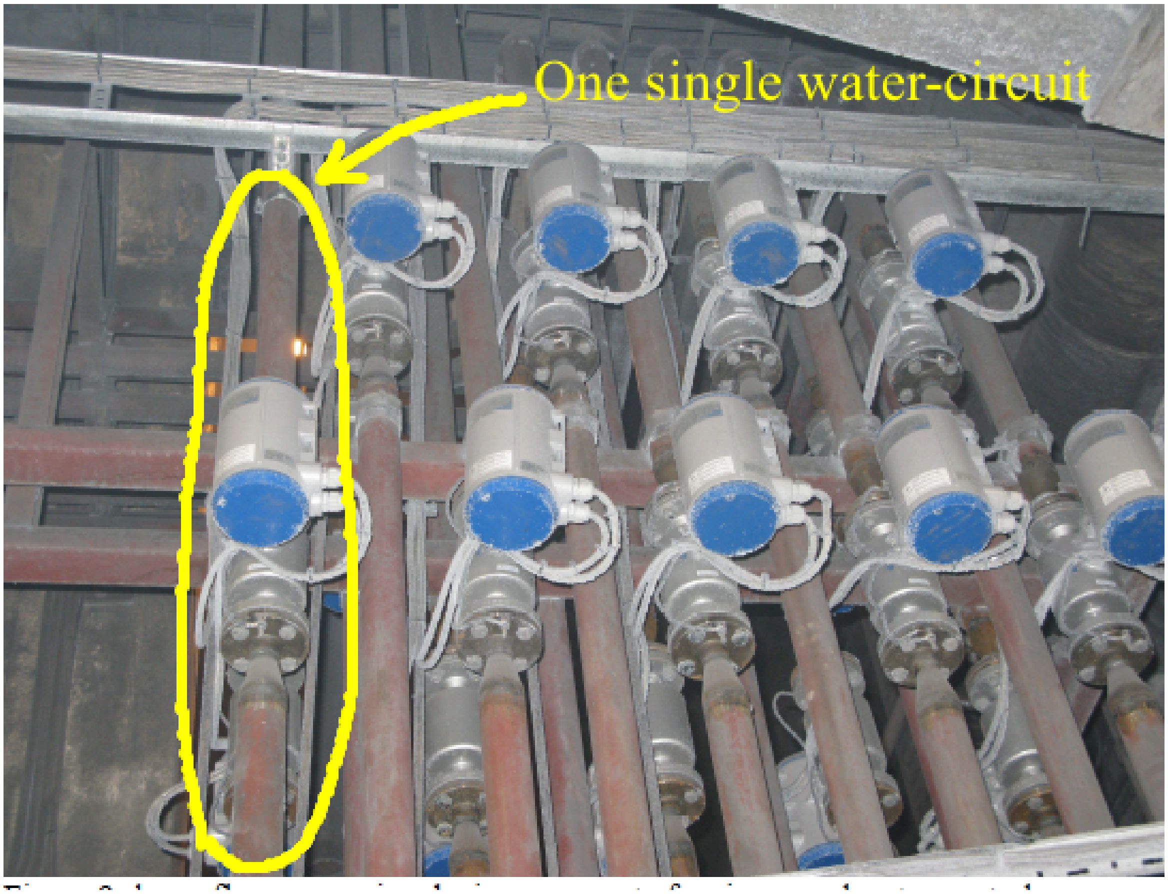

Figure 4.1: Cooling water flow measuring devices as a part of an improved water control [7].

- Continuous monitoring of the total water inventory for immediate water leakage detection.
- Continuous monitoring of all critical water-circuits for immediate water leakage detection (see Figure 4.1).
- A set limit (1000 liter per hour) for tolerable water leakage which can be easily detected, but yet far from the critical limit (5000 liters).
- A system of water-circuits shut-off in case of leakage (safety valves).

A very representative example of safety measures for prevention of accidents due to water leaks is set of safety measures for prevention of water leakage into the tapping zone in Elkem Thamshavn. This risk is posed by water, running over the furnace into the dangerous zone – tapping zone. The risk management for this situation is described below, divided into phases “before” and “after” safety measures were implemented.

Before the safety measures were implemented:

The water, leaking from the cooling elements, had many *“opportunities”* to reach the tapping zone. Figure 4.2 represent the general scheme of water leakage flow around the furnace. The following safety issues posed the risk:

- Water that runs over the furnace can flow further between the furnace and the stacking deck.
- Water on the fence will flow into the furnace due to a fall in the wrong direction on the floor.
- Water needs buffering inside the furnace and through expansion chains in the stacking deck.

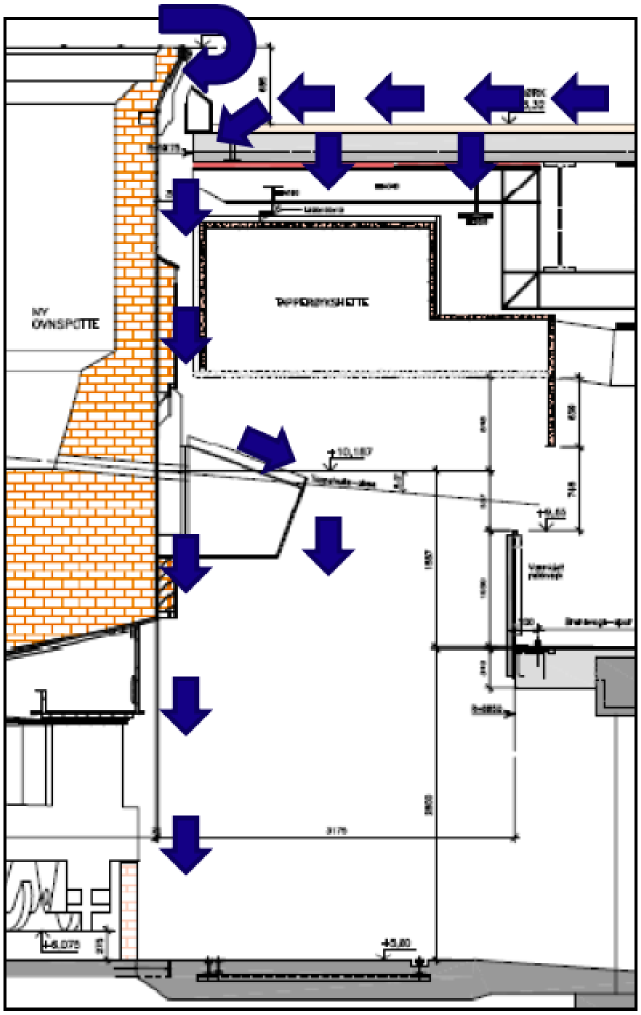

Figure 4.2: The situation in water leakage safety before special water drainage system was installed [30].

After the safety measures were implemented:

It was decided to design and install an effective water drainage system for the furnace. There were three barriers implemented in order to prevent contact of water, leaking around the furnace, with hot metal in tapping zone. The set of implemented water drainage elements (see Figure 4.3) significantly reduced the risk of water leakage into the taping zone.

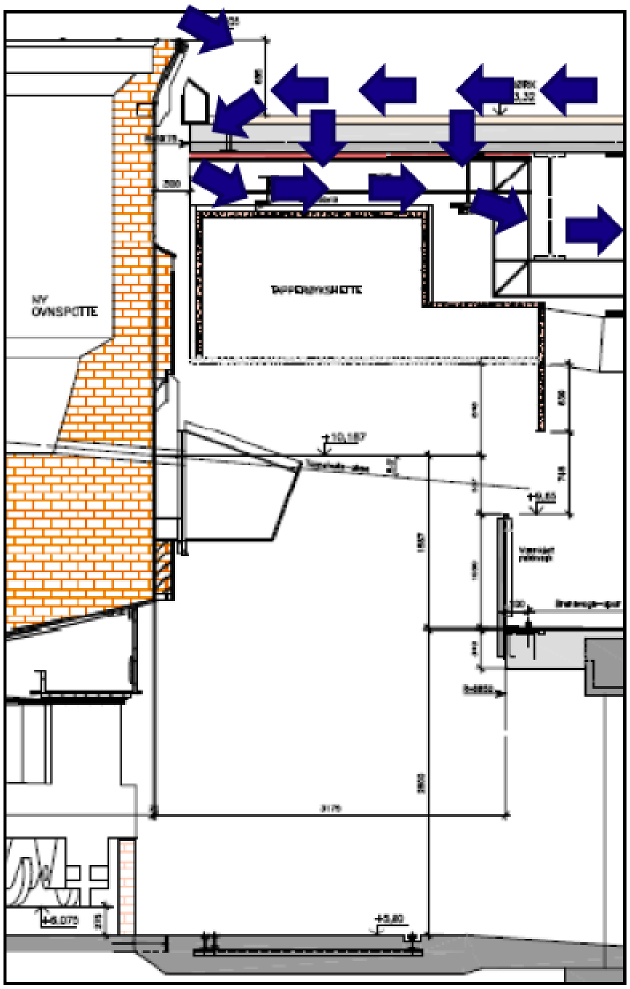

Figure 4.3: Water drainage system around the furnace for prevention of dangerous situations during external water leakages [30].

4.2 Handling water leakage

The general process of safety assurance regarding water leakages in Elkem production processes can be summarized as: ***detection, localisation***, and ***shut-off***.

For the proper response to water leakages in the FWCS, it is necessary to know:

- Where the leakage occurs, and
- How large the leakage is.

4.2.1 Water leakage localisation

Water circuits can be grouped as critical and non-critical. For the critical water lines, there are monitoring systems to detect water leakages (see Figure 4.4). Elkem uses leakage detection systems based on flow rate comparison. Critical water circuits are equipped with flow meters for water leakage detection which show the size of water leakage and give alarm when a large water leakage is detected.

In case of leakage on the water-circuit without flow meter, personnel should use equipment-overview maps to identify water-circuits based on localization water leakage. It is necessary to note numbers on water-circuits and manifolds for closing the water-circuits [31].

4.2.2 Water leakage size

Elkem sets a boundary *0.200* m^3 */ hour* between a small [1] and a large water leak for electrodes system.

Based on the information about the leakage location, size, availability of flow meters[2], Elkem apply a set of special procedures for water leakage response. The procedures are documented and used as local documents:

- Stenging av Vannlekkasje (*eng:* Closure of water leakage)
- Vannlekkasje på Ovner (*eng:* Water leakage in furnace)

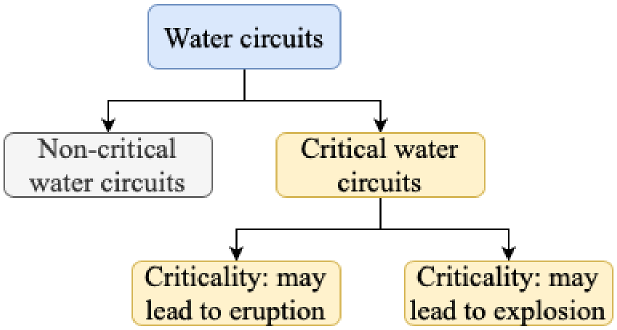

Figure 4.4: Criticality of water-circuits within FWCS based on zones of water leakage

4.2.3 Mechanism of water leakage detection and closure

In this Section 4.2.3, the brief overview of main procedures of water leakage closure and response is introduced. In terms of water leakage issues, there is an important component of FWCS – flow indicators. Leakage in a water line is detected based on the flow readings before and after the water line passes the equipment to be cooled. The generalized scheme of water line is shown on Figure 4.5.

Operators monitors the process parameters, measured by the control system, and see the information on a panel. The core information, shown on the panel, is illustrated on Figure 4.6. There are all main elements shown to the operator: the exact function of a water circuit, the water flow inside of the water circuit before and after it passes the cooled elements, difference between these two flows, and a status (either normal or emergency).

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[1] An incoherent jet (drip) is considered as a small water leak

[2] Elkem has different procedures for water leakage closure for water circuits equipped with flow meters and without them

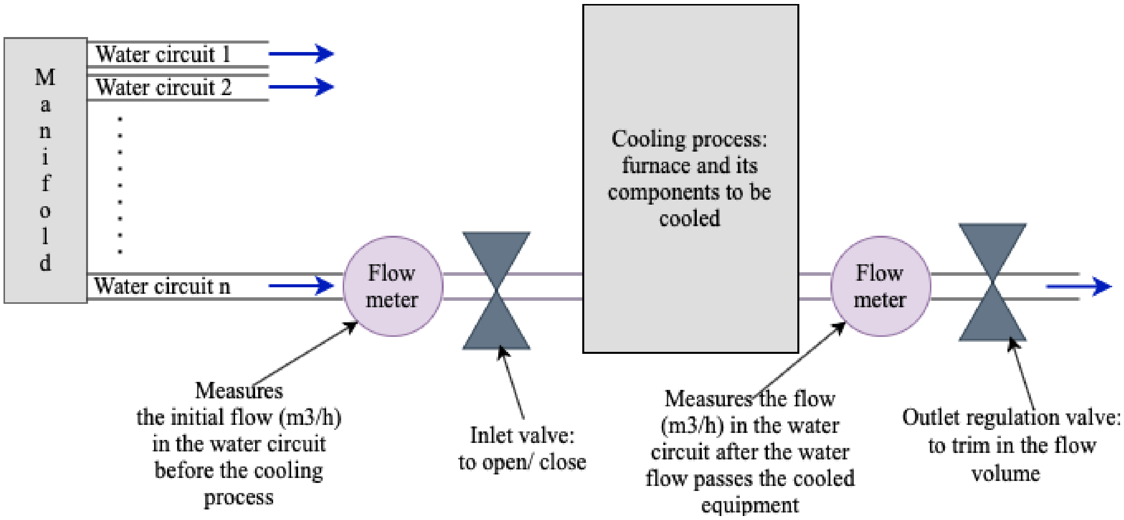


Figure 4.5: General scheme of water-circuit role in FWCS process

As soon as the exceeding limit of difference in flows is detected, the control system gives an alarm. As it follows from the characteristics of the water detection and accident prevention process, the instrumented signal, i.e. signal about water leakage given by the control system, is followed by manual actions and observations of operators (see Figure 4.7).

The general process of water-circuit shut-off consists of three main steps:

1. After the leakage detection in a certain water circuit, inspect the outlet of this circuit to confirm low volume, high temperature, or steaming,
2. Shut-off the inlet valve of the water circuit to remove the pressure,
3. Check the outlet spout in order to confirm that the correct water circuit is closed.

Emergency response procedure: relevant issues

Emergency response upon water leakage in side the furnaces is a complicated process where the main role is played by a proper human decision making.

Elkem local document *Vannlekkasje på Ovner* (*eng:* Water leakage in furnace) [32] has a set of procedures for water leakage inside of a furnace. Even though the document lists the sequence of actions for prevention of an accident (furnace eruption) after leakage has occurred, there is still a certain level of risk associated with measures. The scheme on Figure 4.8, the main decision making process, was made based on the information given in the document. It is shown that the furnace shut-down is a key procedure within the emergency response. However, not every furnace shut-down mode is considered to be safe. As it is shown in *yellow boxes* on the Figure 4.8, furnace shut-down is relatively risky due to (1) uncertainty in amount of water accumulated in the furnace, and (2) impossibility to close leakage immediately. The *green boxes* represent comparatively lower risk of furnace shut-down because the main conditions (i.e. amount of water in the furnace is defined, and the damaged water-circuit is shut-off) are met. It is obvious that the process of emergency response crucially depends on staff decision making because it is necessary to take into account critical parameters such as time of leakage, flow measurement,

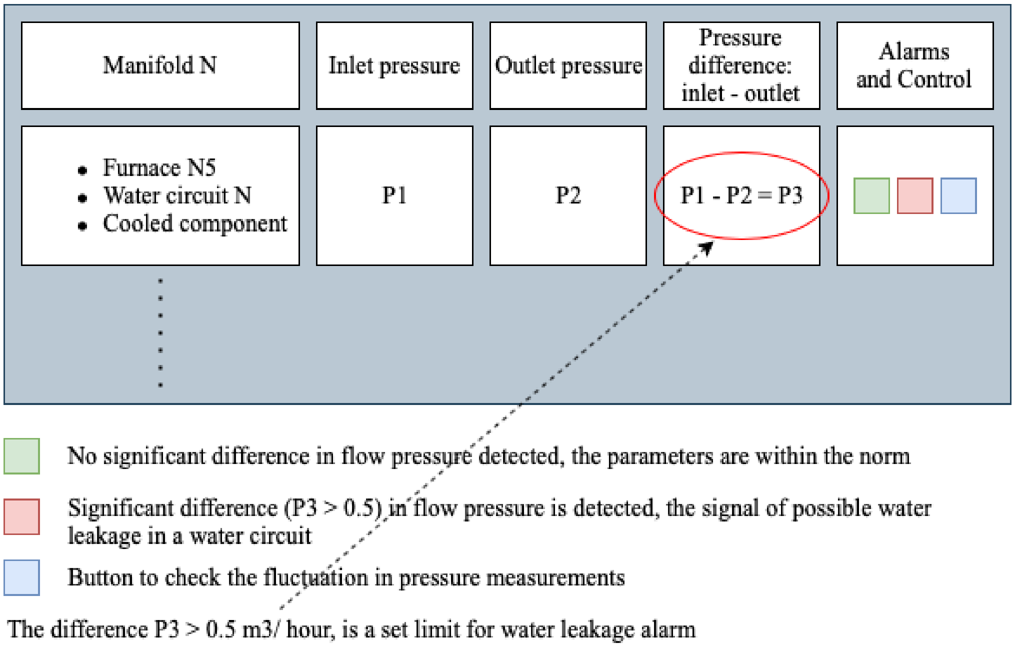


Figure 4.6: General parameters shown on the control panel of FWCS control system (parameters necessary for leakage detection and localisation)

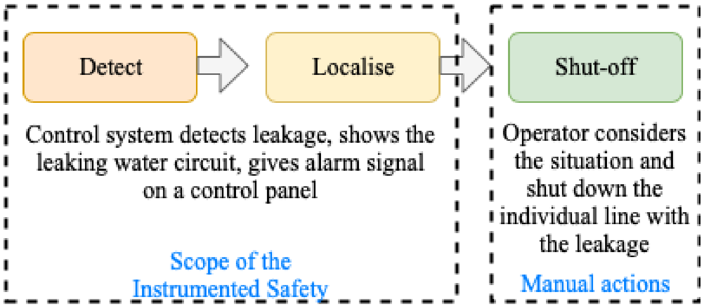


Figure 4.7: General algorithm of actions in case of water leakage detected in a water circuit

amount of water in the furnace, mode of operation (see Section 3.3.3 about important modes of operation). This pose the main problem for implementation any Safety Instrumented Functions for emergency response upon water leakage inside the furnaces (as it was shown earlier on Figure 4.7).

4.3 Relevant regulations applicable for FWCS

Submerged electric arc furnaces belongs to a group electroheating installations and, therefore, the principles of their design and operation are covered by standards related to safety of installations used in electroheating industrial processes. In this Section 4.3 the main documents and their specififc relationship to FWCS operation are introduced.

The ***NEK IEC 60519-1:2015 "Safety in installations for electroheating and electromagnetic processing. Part 1: General requirements"*** does not specify any requirements for operation of

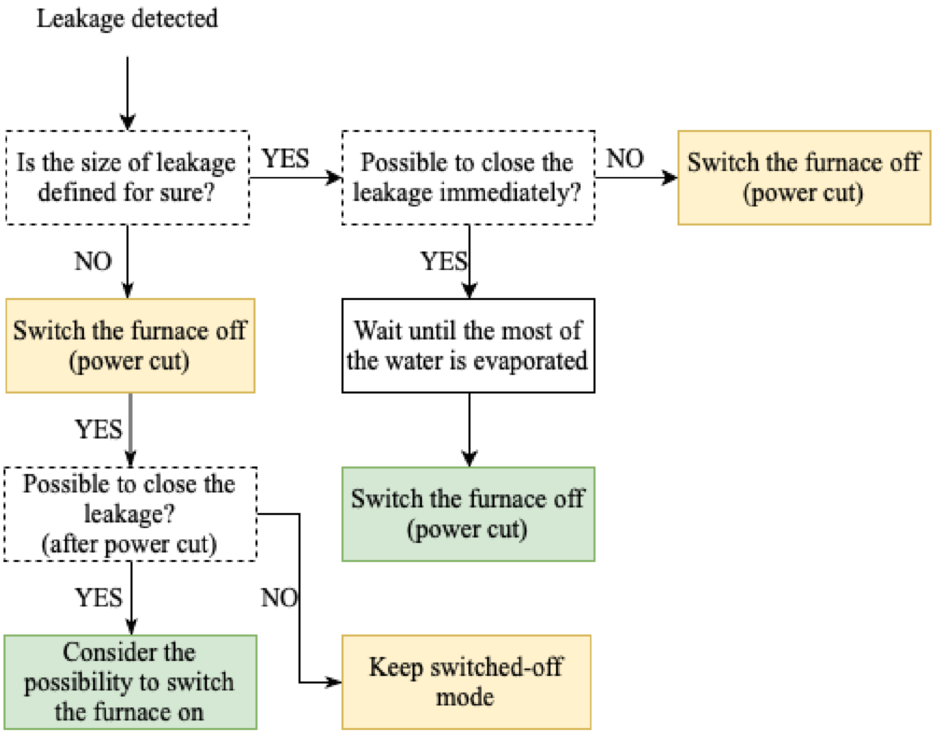


Figure 4.8: Procedure for water leakage closure inside of a furnace

furnace cooling systems, however sets a list of general requirements for *cooling processes* (see Paragraph 10.5 of the Standard) which are relevant for FWCS in industrial furnaces. Another relevant information, which is provided by the NEK IEC 60519-1:2015, is about *protection against over-temperature* (Paragraph 10.6) and *protection against hazards from fluids* (Paragraph 12.1). The Paragraph 10.6.8 can be presented as an example of requirements applies to a FWCS operation within a furnace: generally, it is relevant for process of furnace shut-down after which it is still crucially important to monitor the situation and consider the effect when residual heat stored in the furnace [33].

The ***NEK IEC 60519-4:2013 "Safety in electroheating installations. Part 4: Particular requirements for arc furnace installations"*** is another relevant part of NEK IEC 60519 which provides particular safety requirements for electric (including submerged electriac) arc furnaces and its operation and maintenance procedures [34]. An particular relevant requirement to be mentioned in this Section is about *emergency furnace shut-down* (see Paragraph 6.1): FWCS should be kept in function upon an emergency furnace shut-down. Annex BB.1 of the NEK IEC 60519-4:2013 provides additional requirements (such as structure of water circuits, flow rate, location of over-pressure valves, hoists and other outlets location) for the safety of *water cooling systems for shell and roof* of the furnace. Annex CC.3 of the standard provides a requirement for safety of water cooled-electrodes: the system should be equipped with leakage monitoring system which can interrupt the power supply to the furnace, shut-off the water supply and lift the electrode [34]. The standards also refers to another document, ***NEK IEC 60683:2011 "Industrial electroheating equipment. Test methods for submerged-arc furnaces"*** where some specific requirements for *testing* of cooling systems are listed.

Both NEK IEC 60519-1:2015 and NEK IEC 60519-4:2013 are connected (overlap in several parts) to ***ISO 13577-1:2016 "Industrial furnaces and associated processing equipment. Safety. Part 1: General requirements"*** which provides requirements for safety of industrial furnaces and other associated equipment. Particular requirements (overlap with IEC 60519-1:2015) refers to protection against hazards from fluids (water leakage) and against thermal influences (Paragraphs 10 and 12).

Figure 4.9 represents the short overview of standards, relevant for FWCS. It is also shown that the standards are mutually connected to each other.

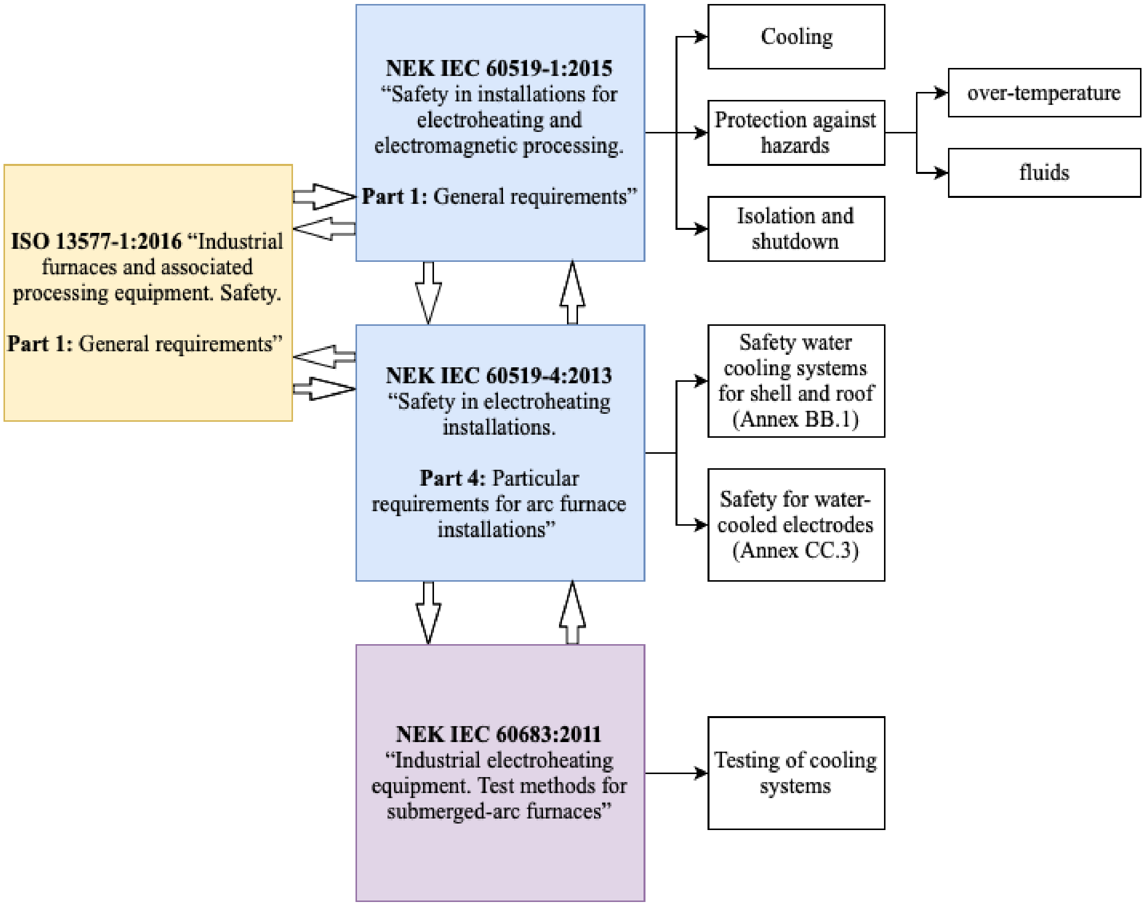


Figure 4.9: The key standards for FWCS operation within submerged arc furnaces operation and their main relevant content

4.4 Possible SIF options

Per today, Elkem seeks opportunities to improve safety aspects of FWCS. Even though, Elkem apply a set of safety measures and run on-going projects within FWCS safety, there is still a need and opportunities for other solutions. Currently, Elkem plants are equipped with flow-based leakage detection systems and some of them have a set of physical barriers, i.e. water drainage installations around furnaces, for prevention of explosion (i.e. when leaking water contacts with hot metal in the tapping zone). Risk analysis, performed in Elkem, shows that the problem of explosion (i.e. external leakage) poses a higher risk than the problem of eruption (i.e. internal leakage in the furnaces) due to the fact that the tapping zones have zero-tolerance to water content and even certain amount of moisture. It is therefore relatively difficult to handle this problem when having only flow-based detection system because it takes time to perform emergency actions. Therefore, one of the key questions is implementation of possible SIF for proper response to water leakages occur in furnace cooling systems in order to:

- prevent any water leakages,
- provide a faster emergency response in case water leakage occurs.

Regarding the issues of explosion and providing a faster emergency response where it is critically for the safety, Elkem is going to run a project for installation for a SIF for prevention of water leakage to the tapping zone through the smoke hood side sections. The idea of this pilot project is described in Section 4.4.2. Measures for prevention of water leakages can be seen in lights of testing procedures in order to increase chances to reveal leakages which cannot be detected by the basic flow-based detection system. Very small leakages can pose a significant risk for safety because, as practice of different industries shows, undetected failures (i.e. small cracks in pipes) can trigger major accidents. The literure review during the work in this Master Thesis, shows that industries apply new methods for problem related to water leakages in cooling systems within different types of equipment. One of them, a SIF for water-circuits testing, is presented in Section 4.4.3.

As for Elkem Bremanger, there is an on-going project for equipping of water-circuits with flow meters. Currently, not all water-circuits are equipped with flow meters and the procedures of emergency response upon water leakage are different depending on where the leakage is: whether water-circuit with flow meter (see Section 4.2.2 or without. It is planned to equip other water-circuits with flow meters in Autumn 2019.

4.4.1 Risk analysis: base for SIF implementation

Elkem performed risk analysis in terms of the problem of water leakage to the tapping area in Elkem Rana (2018). If water contacts with hot metal in the tapping zone, it will lead to an explosion (the danger of the explosions were described in Section 3.3.4). Since the problem of such water leakage is urgent, any possible methods for prevention of the accident should be considered in light of risk assessment. Elkem consider two main directions for the prevention of the accidents: *frequency reduction* and *consequences mitigation*. Figure 4.10 shows the key methods behind this idea.

Behind the idea of *frequency reduction* there are mostly use of proper materials, maintenance strategy, testing, water quality [35]. The strategy of *consequences mitigation*, particularly shut-off damaged water-circuits, is more relevant for the scope of the Master Thesis.

During the risk assessment, Elkem project managers considered two options of water-circuits shut-off [35]:

- Flow measurement and manual shut-off valve, and

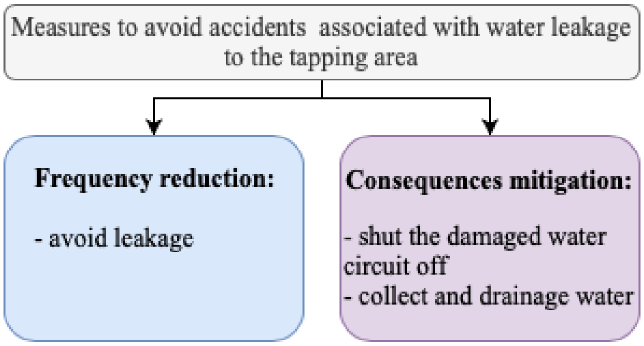
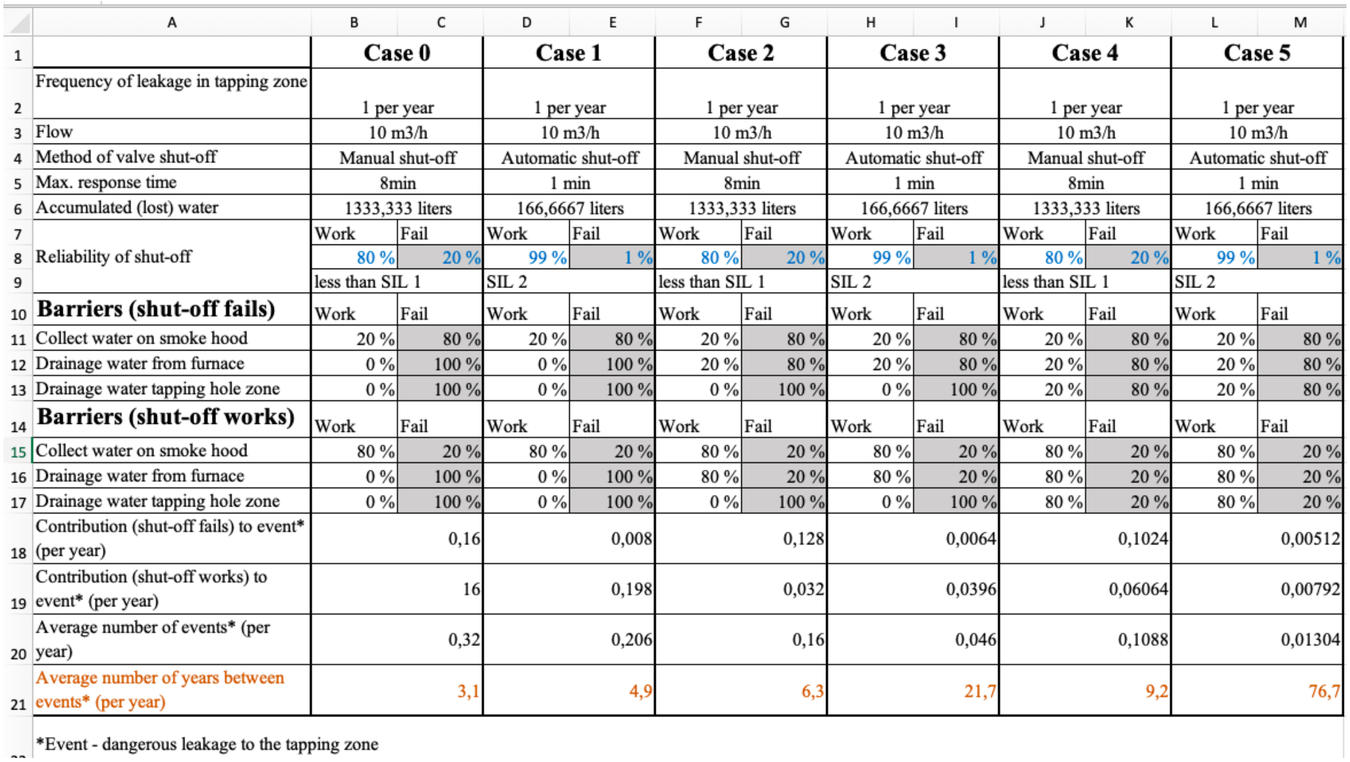


Figure 4.10: Methods to avoid accidents due to water leakage into tapping area [35]

- Flow measurement and automatic shut-off.

Project team used method of ***Event Tree Analysis (ETA)*** for demonstration of pros and cons of the two options of shut-off. The results of the ETA analysis are demonstrated on Figure 4.11 taken from the Elkem project report. The two options were analysed along with the use of *three physical safety barriers* such as [35]: *(1) collect and drainage water from the furnace smoke hood, (2) drainage water from the furnace, (3) prevent water from leaking to tapping hole zone.*



	A	B	C	D	E	F	G	H	I	J	K	L	M
1		**Case 0**		**Case 1**		**Case 2**		**Case 3**		**Case 4**		**Case 5**	
2	Frequency of leakage in tapping zone	1 per year		1 per year		1 per year		1 per year		1 per year		1 per year	
3	Flow	10 m3/h		10 m3/h		10 m3/h		10 m3/h		10 m3/h		10 m3/h	
4	Method of valve shut-off	Manual shut-off		Automatic shut-off		Manual shut-off		Automatic shut-off		Manual shut-off		Automatic shut-off	
5	Max. response time	8min		1 min		8min		1 min		8min		1 min	
6	Accumulated (lost) water	1333,333 liters		166,6667 liters		1333,333 liters		166,6667 liters		1333,333 liters		166,6667 liters	
7		Work	Fail	Work	Fail	Work	Fail	Work	Fail	Work	Fail	Work	Fail
8	Reliability of shut-off	80 %	20 %	99 %	1 %	80 %	20 %	99 %	1 %	80 %	20 %	99 %	1 %
9		less than SIL 1		SIL 2		less than SIL 1		SIL 2		less than SIL 1		SIL 2	
10	**Barriers (shut-off fails)**	Work	Fail	Work	Fail	Work	Fail	Work	Fail	Work	Fail	Work	Fail
11	Collect water on smoke hood	20 %	80 %	20 %	80 %	20 %	80 %	20 %	80 %	20 %	80 %	20 %	80 %
12	Drainage water from furnace	0 %	100 %	0 %	100 %	20 %	80 %	20 %	80 %	20 %	80 %	20 %	80 %
13	Drainage water tapping hole zone	0 %	100 %	0 %	100 %	0 %	100 %	0 %	100 %	20 %	80 %	20 %	80 %
14	**Barriers (shut-off works)**	Work	Fail	Work	Fail	Work	Fail	Work	Fail	Work	Fail	Work	Fail
15	Collect water on smoke hood	80 %	20 %	80 %	20 %	80 %	20 %	80 %	20 %	80 %	20 %	80 %	20 %
16	Drainage water from furnace	0 %	100 %	0 %	100 %	80 %	20 %	80 %	20 %	80 %	20 %	80 %	20 %
17	Drainage water tapping hole zone	0 %	100 %	0 %	100 %	0 %	100 %	0 %	100 %	80 %	20 %	80 %	20 %
18	Contribution (shut-off fails) to event* (per year)		0,16		0,008		0,128		0,0064		0,1024		0,00512
19	Contribution (shut-off works) to event* (per year)		16		0,198		0,032		0,0396		0,06064		0,00792
20	Average number of events* (per year)		0,32		0,206		0,16		0,046		0,1088		0,01304
21	Average number of years between events* (per year)		3,1		4,9		6,3		21,7		9,2		76,7

*Event - dangerous leakage to the tapping zone

Figure 4.11: Summary of ETA analysis for water leakage into tapping area [35]

Figure 4.11 represents a summery of ETA analysis, performed Elkem project team. Column A contains the conditions (estimated values are A1 - A9) and criteria (A10 - A21) of the analysis. It is estimated that the leakage on the surface of the furnace can appear once per year and the flow is estimated as 10m3/hour. The project team estimated the response times for manual actions to close the leakage and the automatic shut.off function as 8 min and 1 min respectively. Depending on the response time, there is a significant difference in the amounts of released water vary: approximately 1333 liters and 167 liters respectively for manual and automatic shut-off scenarios. ***Reliability*** (see cells in line 8 on the Figure (table) 4.11) of shut-off options, i.e. manual shut-off and automatic shut-off, were set to 80 % and 99 % respectively. The project team analysed the contribution of both options (manual and automatic shut-off) along with the physical barriers installed for prevention of water leakage to the tapping zone. Cases 0, 1, 2, 3, 4, 5 are introduced to show how the number of physical barriers effect the probability to have a dangerous leakage to the tapping area (line 21 on the Figure (table) 4.11). *Reliability of the automatic shut-off valves meets the requirement of* ***SIL2***. Further, the project team considered contribution of implementation of physical barriers (see lines 10 - 17 on the Figure (table) 4.11) to prevent dangerous leakage to the tapping area with regards to success of shut-off functions, i.e. either they work or fail. **Case 0** (for manual shut-off function) and **Case 1** (for automatic shut-off function) implied the implementation **only one physical barrier** (to collect water on smoke hood - lines 11 and 15) and its reliability is estimated to be 20 %, while the two others (drainage water from the furnace and tapping hole zone - lines 12, 13, 16, 17) are not implemented in this case (their reliability is set to 0 %). **Cases 2 & 3, 4 & 5** implied **implementation the second and the third physical barriers** respectively. As it is showed in the line 21 of the Figure 4.11 the probability of events, i.e. dangerous water leakage to the tapping area, can be significantly reduced [35]:

- If to implement all three types of physical barriers and automatic shut-off function - in this case the average number of years between the dangerous events would be almost 77 years (cell L-M 21 on the Figure 4.11). For the same number of physical barriers, but with the manual shut-off function - the probability of the dangerous event would be significantly higher (ones in 9 years) (line J-K 21).

- If there were only two physical barriers and the same automatic shut-off function, the average number of years between the dangerous events would be almost 22 years (cell H-I 21 on the Figure 4.11. For the same number of physical barriers, but with the manual shut-off function - the probability of the dangerous event would be significantly higher (ones in 6 years) (line F-G 21).

- If only one single physical barrier was implemented in addition to the automatic shut-off function, the average number of years between the dangerous events would be almost 5 years (cell D-E 21 on the Figure 4.11. For the case of one physical barrier and the manual shut-off function - the probability of the dangerous event would be higher (ones in 3 years) (line B-C 21).

One of the main conclusions to be made from the conducted analysis is that *physical barriers are critically important and their installation should be considered before implementation a SIF, i.e. automatic shut-off function.* It is shown that the contribution of the automatic shut-off function is almost zero if there are no physical scrap material barriers or even one physical barrier has been installed [35].

4.4.2 SIF: side sections of the smoke hood

Water leakage, which occur on the external parts of the furnace (e.g. smoke hood) poses a serious risk of severe explosion due to contact of water with molten metal in the tapping area (see Sections 3.3.2 and 3.3.4). Compared to water leakage inside of furnaces, leakage on the surface of furnace elements is more problematic for emergency response because tapping area has almost zero-tolerance to any water and even humidity. Elkem works on a project for implementation of a SIF for leakage detection and immediate response to water leakage on the side sections on the smoke hood (see Figure 4.12).

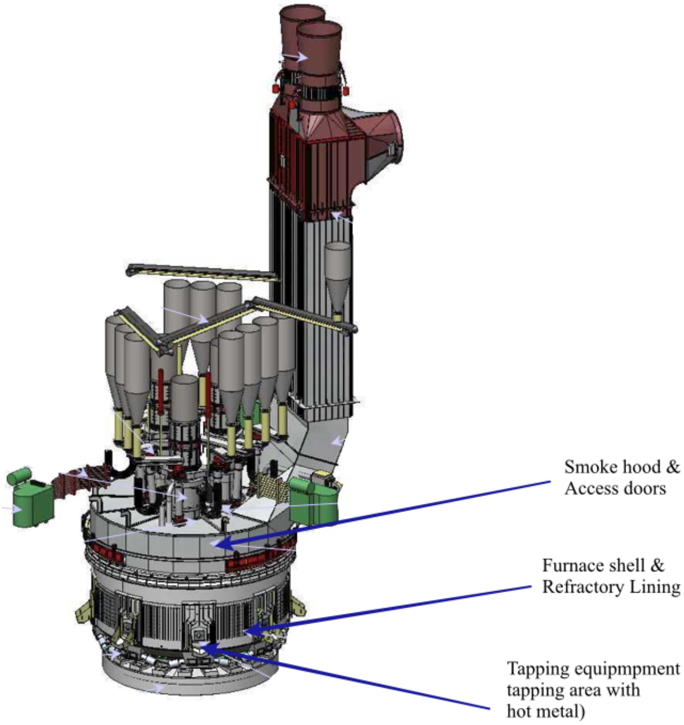


Figure 4.12: Smoke hood and vertical side sections of the silicon furnace

It is planned to perform a pilot installation of a SIF for the vertical side sections on the smoke hood. The SIF implies water leakage detection by flow meters (same system used currently) and automatic shut-off the damaged water-circuits. Side sections have thermal insulation, i.e. refractory lining, that reduces the thermal radiation and heating of the cooling water inside each side section in case of the circulation shut-off by the SIF on demand. However, the Elkem project team defined that the given SIF poses another possible problem: the water, remaining in the water-circuits [3] inside of the side sections, will most likely heat up above boiling point of water, and this will result in steam generation inside the side section and subsequent pressure build-up. It is therefore necessary to follow the SIF role with an additional safety function to release steam pressure. Elkem will provide the function to be performed by separate mechanical valves (or a two-way valves) at the manifold inlet (i.e. before the water-circuits reaches cooled equipment) or outlet (i.e. after the water-circuits reaches cooled equipment) zone to water-circuits. Figure 4.13 demonstrates the scope of the SIF and solution for the problem of steam generating.

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[3] Water-circuits which were shut-off

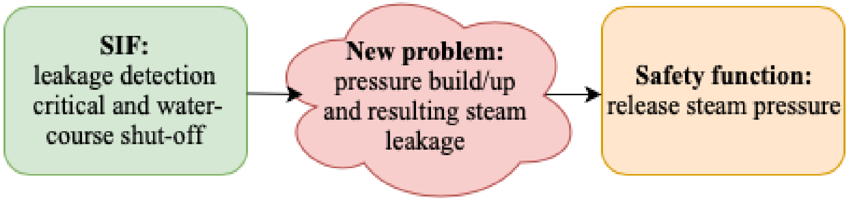

Figure 4.13: Scope of the planned SIF and additional measure

Following the general SIF structure (4.14), the new SIF will consists of flow detectors, Programmable Logic Controller (PLC), and automatic shut-off valves (see Figure 4.15).

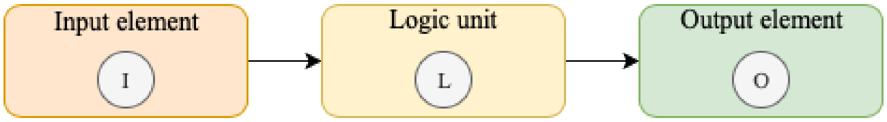

Figure 4.14: General structure of a SIF

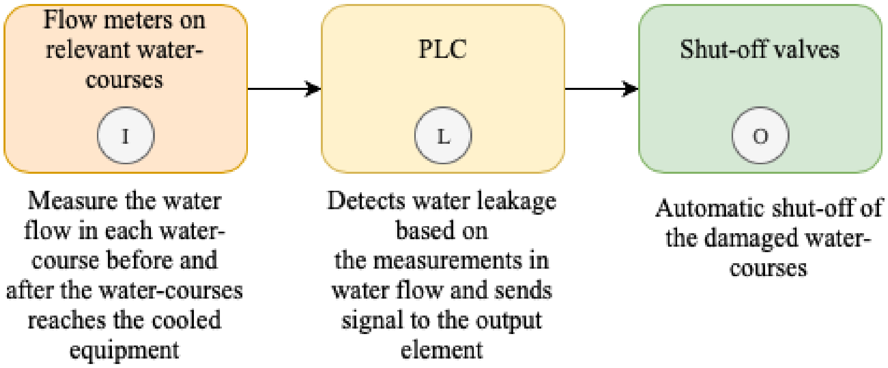

Figure 4.15: Structure of SIF for water leakage prevention to the tapping area

4.4.3 Pressure based leak detection system

This Subsection 4.4.3 introduces an improved leakage detection system for furnace cooling system, implemented at ***Vale Canada Ltd***[4]. This system is based on pressure measurement in water-circuits. This improved furnace cooling water pressure leak detection system was designed and developed by one of the world leading engineering consultancy companies, ***Hatch Ltd.***[5]. In this Master Thesis, this leakage detection method is considered as an additional measure to existing flow-based method and physical barriers so that to contribute to total risk reduction.

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[4] Nickel Smelter Vale Canada Ltd., is an wholly owned subsidiary of the Brazilian mining company Vale which produces nickel, copper, cobalt, platinum, rhodium, ruthenium, iridium, gold, and silver. Based in Toronto, Ontario, Canada.

[5] Hatch Ltd., is a global multidisciplinary management, engineering and development consultancy. The company was founded in Toronto, Ontario, Canada

This pressure-based water leakage detection system can be considered as an additional safety measure for prevention accidents due to leakages in FWCS. In addition to the existing flow-based system, Elkem plants can implement the Hatch Ltd., method to reduce probability of leakages where the flow-based method is not sensitive to. The two methods are supposed to operate in parallel and be controlled independently. The installation of this system maybe performed as a pilot project, and it can be tested only on some critical water-circuits.

The main advantage of this system is that it is *very sensitive to small leakages*, i.e. in the order of drops of water per minute. However, compared to the flow-based leakage detection system (i.e. the one used in Elkem), the pressure-based system is not a continuous water-circuits leak detection method, *but should be automatically run at regular intervals* [36].

The pressure-based leak detection system is *based on the change of static water pressure which allows to detect even small leaks*[36]. Figure 4.16 represent the principle of operation of this system where green-colored elements (i.e. entry valve, exit valve, and pressure transmitter) are the key elements of the pressure-based leakage detection system, while the gray elements are the flow-meters used for the flow-rate comparison leakage detection system. The green components are of interest. The principle is described as follows [36]:

- The system should momentarily stop the water flow in a water-circuit which allows to trap the pressurized water in a space between two newly installed (i.e. for the pressure-based leakage detection system) valves, i.e. *entry valve* and *exit valve* (as it it shows on the Figure 4.16).
- It is necessary that the *exit valve is closed before the entry valve* so that to trap the water in-between them and to maintain the pressure.
- When the water is trapped, *the pressure transmitter monitors a drop in pressure* which can be equated to a leakage in the tested water-circuit. The system allows to detect leaks as few drops per minute.
- As soon as the short test is complete, *both valves are automatically opened*, and the water circuit continues to operate.
- This is not a continuous method for leakage detection, but this testing of water-circuits by this leak detection system can be *automatically run at any regular intervals* predetermined by the Company.

At the point of the first three months since the system was installed, Vale Ltd., reported the successful operation of the newly installed pressure-based leak detection system: it detected three small leakages (two of them were concealed). It was proved that the system was functioning like it was intended and added its intended value to the safety improvement on the Nickel Smelter Vale Ltd., plant [36]. Even though the available information claims that the system was operating successfully, it is yet necessary to learn more about their experience since different problems my occur later following the commissioning.

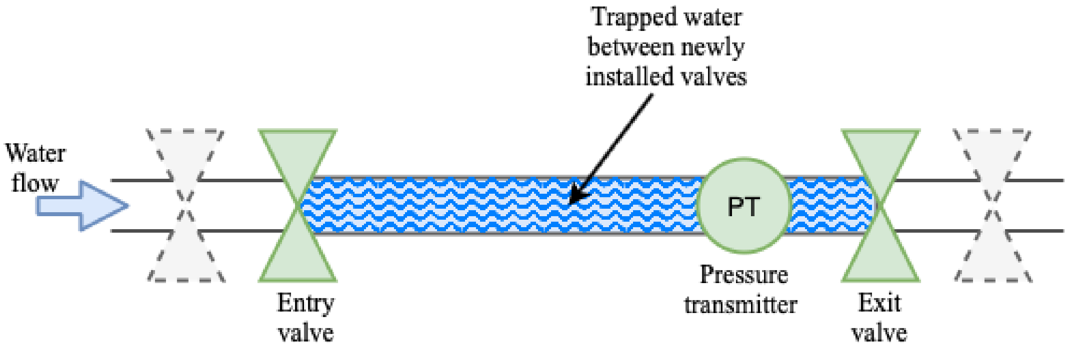

Figure 4.16: Principle of pressure-based water leakage detection system operation for furnaces, developed by Hatch Ltd.

Length of testing procedure

There is an important factor which determines the possible longest length of the testing procedure - rising temperature inside the water-circuits upon the termination of water flow during the test.

Water-circuits can experience a certain increase in pressure during the test. The amount of the increase will vary depending on the exact location of a water-circuit (a group of water-circuits) in terms of intensity of hit flux from the furnace equipment, the and if the is leakage or not. It is therefore important to define the right length of test time. The system itself allows to perform the test in a very short time so that to not pose a risk of pressure build-up [36].

Valves

The reliability of entry and exit valves are critical for the safe operation of the system. Hatch Ltd., list following essential criteria for the valves:

- Valves shall be set to ***fail open*** to ensure that, e.g. in case of any loss of power or valve failure, the valves will not keep trapped water for long enough to effect the availability of the cooling process and, as the result, to cause the damage to the equipment.
- Valves shall be ***seal closed*** upon the water pressure in a water-circuit.
- Valves shall be ***resilient to dirty water*** (it is relevant for open-loop FWCS).
- Valves shall be easy to access, maintain, replace.

Possible challenges for implementation

Vale Canada Ltd., being the first user of this system, experienced several issues related to the process of implementation of the new method. Generally, the challenges were related to water quality and ergonomics of the installations. The most important of the concerns were [36]:

- Open-loop FWCS poses a problem of water quality. Debris can significantly effect the valves. The solution was to modify the seals of the valves to make them more resilient to dirt build-up.

- In order to prevent possible any interference with basic furnace control, the leakage detection system was set to be controlled independently.
- Installation process was complicates because water-circuits were placed so close to each other. Therefore the crew had to remove and put back some instrumentation in order to install the new instrumentation.

4.4.4 Pros and cons of the safety measures

Both currently existing safety measures, pilot-projects for SIF, and suggested SIF have their pros and cons. This small Section is devoted to a short summary on main advantages and challenges for different safety solutions against FWCS leakages.

Figure 4.17 represents the three methods available for leakage detection where the first one (i.e. visual inspection) is considered to be the least effective and not relevant nowadays due to its low reliability.

The flow-based method, which is currently applied in Elkem, is an important safety measure for continuous detection process. However, it is not effective for detection of small leakages and might have measurement errors. This is where pressure-based detection method may contribute to risk reduction. It is important to mention that the pressure-based leakage detection system cannot be the only safety measure due to availability issue - it is not a continuous method.

The SIF for side sections of the smoke hood, described earlier, poses a risk of pressure build-up which is another question for Elkem project team to address. The measure of additional mechanical valves for pressure release should be analysed in terms of proper design and reliability.

Added complexity

It is important to evaluate and consider the complexity added by all discussed safety measures to the FWCS. In this Master Thesis we discussed the following safety measures:

- Physical barriers,
- Traditional flow-based water leakage detection system (applies in Elkem),
- Pressure-based water leakage detection system (suggested for implementation),
- SIF for side sections of the smoke hood (on-going pilot project in Elkem).

Considering the commissioning of the pressure-based leakage detection system as a pilot project in Elkem, it is important to to take into account the parallel project for smoke hood SIF. Each of the systems add a certain complexity to the system, particularly to water-circuits. There are several factors might be important for the analysis of possibility to implement a certain combination of safety measures for the FWCS and separate manifolds: physical environment (i.e. available space for installation additional equipment), software issues (e.g.: if methods are supposed to share common PLC) etc.

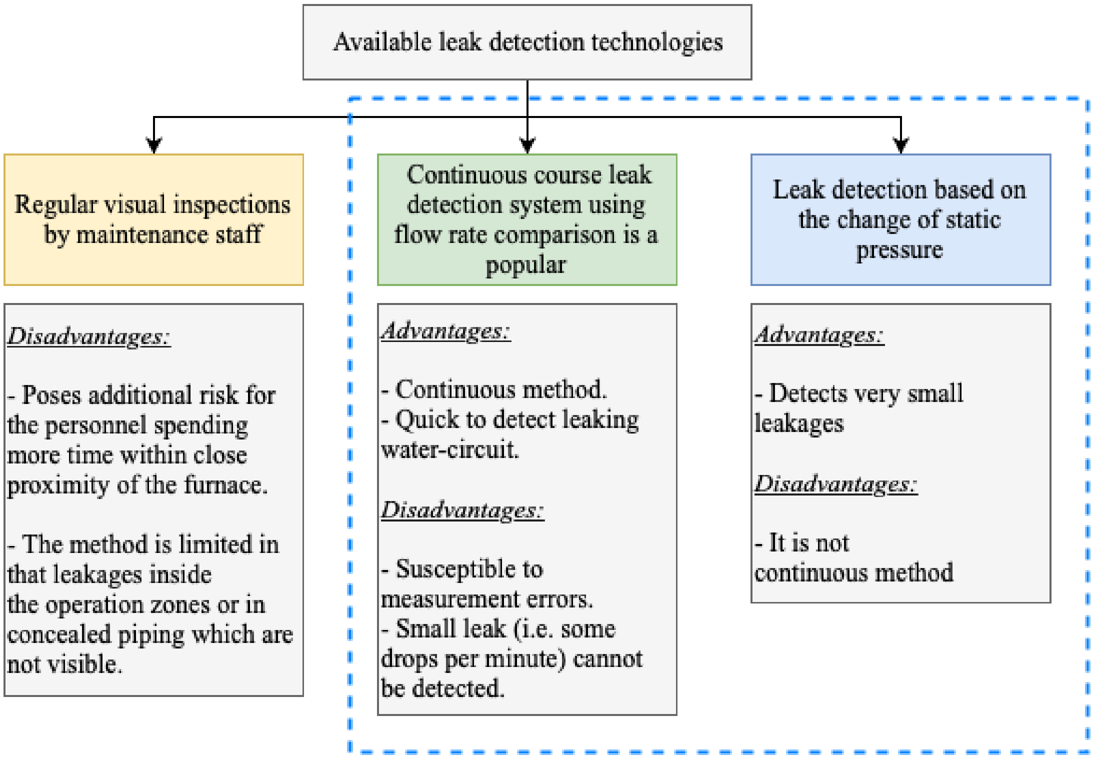

Figure 4.17: Different possible methods for water leakage detection and their advantages and disadvantages.

Qualification test shall be performed in order to evaluate the design adequacy and reliability of the solutions when being applied to the furnace smelting process in Elkem. It should be confirmed that the available solutions in their possible combinations for each single water-circuit will not interference each other's performance.

Chapter 5

Summary and Recommendations for Further Work

5.1 Summary and Conclusions

In this Master Thesis, the literature review on industrial furnaces, their classification, and description of silicon production was performed in order to show the scope of the of problem associated with cooling equipment failures, i.e. water leakages). The literature review on accident experience along the industry, particularly in Elkem, showed that water leakages in FCWS poses a significant risk of major accidents. It is therefore important to look for the opportunities of improvements within safety measures and initiate projects for implementation of possible feasible safety solutions along with the existing traditional safety measures. The flow-based leakage detection method, being widely applied across the ferroalloy and silicon industries, yet has several limitations in terms of cost, often inaccuracy, and relatively low sensitivity, i.e. small amounts of water leakages cannot be detected. Even though the traditional method allows to detect a leakage within the safety limits (unless the system fails), i.e. before the furnace accumulates a critical amount of water, it is not a "victory" for the technical safety management. Elkem seek opportunities for additional safety measure which can operate along with the existing leakage detection methods and, as the result, to contribute to the risk reduction in terms of FWCS operation.

The risk analysis, performed by an Elkem project team, showed that problem of water leakage to the tapping zone poses a greater risk rather than leakage inside the furnaces due to: (1) "zero-tolerance" for water presence, (2) relatively short time available for the emergency response. We described a concept of a pilot project to be run in Elkem for detection and immediate automatic leakage closure on water-circuits on the smoke hood which are critical for the tapping zone. This SIF should be followed by another safety function to mitigate risk of pressure build-up – mechanical pressure-release valves.

Nowadays, the market and associated industrial experience, offers several solutions for water leakage detection. In this Master Thesis we discussed a pressure-based method for very small leaks detection which has already been successfully employed by a Canadian company Nickel Smelter Vale Ltd. We suggested to implement a SIF based on this method as a pilot project for some critical water-circuits (in terms of both eruption and explosion problems) as an additional measure of risk mitigation.

We can map the contribution of the Master Thesis for current ongoing projects within technical safety aspects related to FWCS.

Since Elkem are going to run a pilot project for smoke hood SIF, it is important to consider the area, i.e. the water-circuits, to be equipped with this system when considering the possibility to run another pilot project which was suggested in this Master Thesis – Hatch Ltd., pressure-based water leakage detection. Even though this last one is considered as an additional measure of risk mitigation which is not supposed neither replace the existing flow-based method and smoke hood SIF nor interrupt them, it is necessary to perform an analysis whether the safety systems can be applied for the same water-circuits or not due to added complexity.

The results of the Master Thesis show that Functional Safety Management System is important for running the project for SIF implementation, maintaining the performance of their operation.

5.2 Discussion

Implementation of additional means for detection of much smaller leakages can be a significant contribution to reduce chances of an accident to happen. The SIF for side sections of the smoke hood will help to significantly reduce the response time in case of dangerous leakages in the tapping area and, therefore, to facilitate the process of risk reduction in terms of the most relevant problem - explosions. In case of successful implementation, the pressure-based leakage detection method will increase the overall process of leakages detection by detecting both very small leakages (i.e. which are never detected by flow-based method) and those which are uncovered by the flow-based method in case of malfunctioning. Another possible contribution of the Hatch Ltd., method to the safety assurance is that it has a potential to facilitate the process of failures reveal and maintenance of the basic flow-based detection system: in case the Hatch Ltd., method detects a leakage of a bigger size which is supposed to be detected by the flow-based method (but was not detected), it is the clear signal to examine the possible malfunctioning of the flow-based system and to perform maintenance activities.

As it was discussed in the Master Thesis, the adding of more equipment to the process of FWCS control can be complicated by the possible problem of added complexity. The concern of added complexity might be based on impossibility to equip a water-circuit with a bigger amount of safety equipment, software challenges, or other factors related to ergonomics. Despite some disadvantages, the flow-based water leakage detection method is widely used across industries and is considered as a traditional safety measure for FWCS safety assurance, and, therefore, not many companies within the same industrial sector have applied other measures, e.g. pressure-based method. Thus, the finding and anaysis of a feasible safety solution, particularly combination of safety measures for a single water circuit, can be complicated by unavailability of relevant information from industrial experience. It is recommended to implement the smoke hood SIF and pressure-based detection systems on different water-circuits groups, i.e. manifolds.

5.3 Recommendations for Further Work

The possible extension to this work can be further analysis of possibility run the projects for additional safety instrumentation as was suggested in this Master Thesis. First of all, *collabora-*

tion with the first user of the pressure-based leakage detection system, Vale Ltd., is necessary in order to learn about the system more and be aware of possible challenges which might occur during the different phases of the exploitation.

For the safe and effective operation of the Hatch Ltd., leakage detection system, Elkem should define the right values for a set of parameters of the system operation:

- *The testing time (i.e. duration of the test)*: duration of the test should be defined based on the smelting process parameters and existing equipment characteristics in order to set a time limit within which there will be no risk that the trapped water will be heated to the boiling point leading to pressure build-up.

- *Pressure drop threshold*: configuration of pressure drop threshold should be performed on order to set a set value of the threshold which will be optimal for both accuracy of the system and practical purposes in terms of maintenance. Too low pressure threshold will complicate the work of maintenance crew which might not be able to find too small leaks, or even look for leaks which do not actually exist. In contrast, too high threshold will limit early detection of small water leakages which is supposed to be the main idea of the pressure-based method application.

It is necessary to perform further analysis of the existing furnace equipment capability to be equipped with the suggested safety measures (both SIF for smoke hood and Hatch Ltd., method): *to define the possible constraints both physical and software aspects* that shall be taken into account during the design process.

The results of the analysis on suitable pressure thresholds, testing time, and constraints will be a basis for further work on *Safety Requirement Specification (SRS) set-up* for the SIFs which is one of the key processes during the design of a SIS. All important safety-related information should be collected and analysed so that to design reliable SIFs which will perform in a safe way.

The application of the SIFs will require competences of operators in control and maintenance. Thus, Elkem should prepare and perform a proper *training program* to facilitate understanding and effective use of the SIFs.

Even though the Master Thesis was focused on seeking opportunities for implementation of new safety measures, it is also important to consider *improvement of the existing flow-based leakage detection method.* The work should be focused on seeking feasible methods for extending the detection ability of the flow-based leakage detection system. In addition to literature study on existing solutions, it is necessary to investigate what kind of solutions have been implemented within the industrial sector to cope with the problem of inaccuracy and failures of the flow-based leak detection.

Appendix A

Acronyms

BPCS Basic process control system

ETA Event Tree Analysis

FeSI Ferrosilicon

ISO International organization for standardization

LS Logic solver

NTNU Norges teknisk-naturvitenskapelige universitet (Eng: Norwegian University of Science and Technology)

PLC Programmable electronic controller

PT Pressure transmitter

RAMS Reliability, availability, maintainability, and safety

SIF Safety instrumented function

SIL Safety integrity level

SIS Safety instrumented system

SRP/CS Safety related part of a control system

SRS Safety requirement specification

Appendix B

Raw materials and products of smelting process on Elkem plants

Quartz, iron, coal, coke, and woodchips are the raw materials necessary for operational process of silicon production (see Figure B.1).

☞ **Microsilica®**: the trade name (Elkem ASA) for silica fume (powder) which is a valuable byproduct of silicon and ferrosilicon production process. The fume consists of solid SiO2 particles of a small size (average size is 0.15 μm) [5].

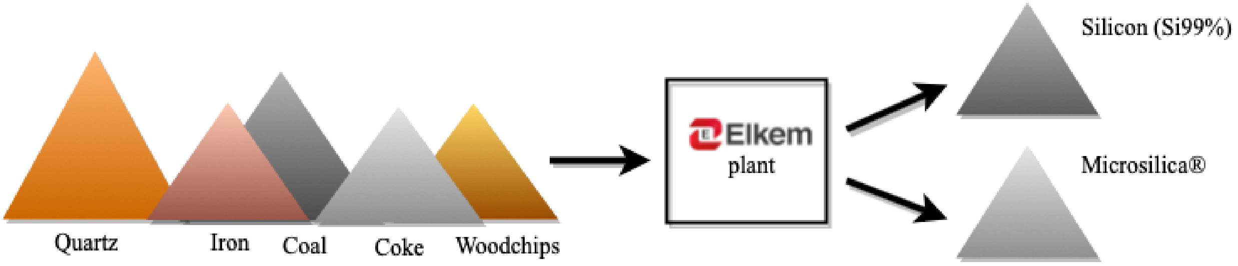

Figure B.1: General overview of raw materials and final products of Elkem Silicon Materials production process [12]

Appendix C

Content of FeSi92 produced on ELkem plants

Figure C.1 demonstrates the content of ferrosilicon (example of 92 % silicon content).

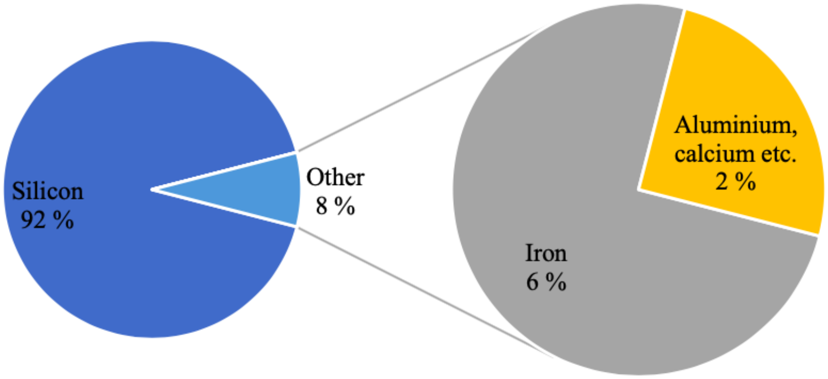

Figure C.1: FeSi92 (ferrosilicon with 92 % of silicon alloy)

FeSi92 contains 92 % of silicon content, where the rest of the alloy (8 %) is counted for mostly iron and a few percent of other elements such as aluminum, calcium, chrome etc.)[1] and silicon (99%).

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[1] Depends on Elkem division, plants, and application of furnaces (Elkem Silicon Materials or Elkem Foundry)

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