Slutrapport för projekt

Optifines – Optimised sludge recycling using OXYFINES-technique

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Optifines – Optimerad slamåtervinning med OXYFINES-teknik
Optifines – Optimised sludge recycling using OXYFINES-technique

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Preface

The project *Optimised sludge recycling using OXYFINES-technique*, includes the verification of performance and operational optimisation of the OXYFINES technique and the development of a recovery concept for 100% recycling of zinc containing sludge from ore-based steelmaking. The project's financiers and constellation have greatly contributed to the project's deliveries and good results, contributing the technique, equipment, knowledge, competence, and resources. The project partners and founders were: SSAB Europe which is a steel producer with ore-based metallurgy and SSAB Merox (now included in SSAB) who works to optimise SSAB's by-products, scrap, and waste management. Linde (formerly AGA/Linde) is a company with technique and production of industrial gases, and the developer of the OXYFINES technique. The base metal industry was represented in the project via Boliden Mineral. Project leader has been Swerim (formerly Swerea Mefos) a metallurgical research institute owning and running large pilot facilities. Further the project was co-financed by the Swedish Energy Agency via RE:Source – *Innovations for sustainable material use: Development and demonstration.* The specific call was intended towards actors seeking support for projects aiming to contribute to sustainable material use and, in particular, projects for reduced waste and/or contributing to an improved working environment in waste management and recycling.

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Sammanfattning

AGA/Linde har utvecklat OXYFINES-tekniken vilken är lämplig för upparbetning och förädling av zinkinnehållande finpartikulära material såsom stoft och slam och därigenom genererandet av användbara produkter. Tekniken är relativt flexibel, enkel och kostnadseffektiv och har bevisat hög grad av zinkseparering. Materialet matas till en speciellt utformad OXYFINES-brännare varigenom dess zinkinnehåll förångas till ett stoft, i detta fall avsett som ett råmaterial i zinkproduktion. Icke-förgasningsbart innehåll, såsom järn, bildar en i princip zinkfri sinterprodukt för användning som råmaterial i stålproduktionen.

Masugnsslam är ett restmaterial från gasreningssystemet för masugnen. Slammet deponeras idag i slambassänger på produktionsområdet, främst på grund av processrelaterade begränsningar kopplade till slammets zinkinnehåll. Masugnsslam är ett mycket finkornigt material med högt fuktinnehåll vilket generellt medför nödvändig förbehandling, såsom torkning och agglomerering, innan återvinning. I svensk malmbaserad stålproduktion produceras upp till 20 000 ton masugnsslam (torrvikt) varje år från råjärnsproduktion i masugn. Slammet består huvudsakligen av järnoxid och kol, varvid ett nyttiggörande skulle förbättra resurseffektiviteten genom minskat behov av jungfruligt råmaterial och minskad deponi, i detta fall i kostsamma och utrymmeskrävande slambassänger.

Projektets mål var att utveckla och demonstrera ett koncept med AGA/Lindes OXYFINES-teknik för upparbetning och ett nyttiggörande av zinkinnehållande masugnsslam. Genom konstruktion av en pilotanläggning, Figur 1, och genom utförda försök, verifierades OXYFINES-teknikens prestanda och potential. Effekterna från förändring av olika processparametrar utvärderades för utveckling av ett optimerat koncept. Pilotförsökens resultat visade de nödvändiga processinställningarna för att uppnå en hög grad av zinkseparering från slammet och för generering av en sinterprodukt med idealiska egenskaper för enkel insats till stålproduktionsprocessen, dvs. till masugn eller till LD-konverter.

Sinterprodukten testades, med goda resultat, i industriförsök genom insats som råmaterial i LD-konverter hos SSAB. Det zinkinnehållande stoftet utvärderades teoretiskt av Boliden för dess lämplighet som råmaterial i zinkproduktion. Stoftets sammansättning är liknande andra järnstoft som används vid zinkproduktion, men zinkkoncentrationen i stoftet måste vara högre för att stämma överens med kraven på zinkhalt. För detta krävs ett fortsatt arbete för att hitta ett optimalt tillvägagångsätt genom analys av processjusteringar såsom minskat avgasflöde, ökad zinkhalt i masugnsslammet och återcirkulering av stoft i OXYFINES-processen.

Genom kommersialiseringsarbetet och systemanalys utvärderades olika implementeringsmöjligheter för konceptet, dess potential och effekter i syfte att presentera den mest fördelaktiga lösningen. En implementering av OXYFINES-konceptet ger positiva effekter ur ett hållbarhetsperspektiv främst genom förbättrad materialeffektivitet och förebyggandet av avfall. Återvinningen av masugnsslam minskar deponin och användningen av genererade OXYFINES-produkter bidrar till värdekedjan genom minskat behov av jungfruliga råvaror. Riskerna för ökad

energianvändning och emissioner genom att implementera OXYFINES-konceptet kan uppvägas av de totalt sett positiva hållbarhetseffekterna i ett livscykelperspektiv. Med hänsyn till ett helhetsperspektiv bör även effekter på koldioxidutsläpp och energianvändning i stålproduktionssystemet och vid produktion av råmaterial beaktas. Vidare, medverkar en implementering till en hållbar energi- och materialförsörjning genom att utveckla tekniken för att på ett optimalt sätt nyttja och förädla värdefulla komponenter i restmaterial samt genom samarbete och industriell symbios mellan stål- och basmetallindustri.

Summary

AGA/Linde has developed the OXYFINES technique suitable for recovery and refining of zinc containing materials, such as dust and sludge, and thereby generating usable products. The technique is relatively flexible, simple, and cost-effective and has proven a high degree of zinc separation. The material is fed to a special designed OXYFINES burner where its zinc content is evaporated to a dust, in this case intended as a raw material in zinc production. The non-gasifiable contents, such as iron, forms a virtually zinc free sinter product for utilisation as a raw material in the steel production.

Blast furnace sludge is a residual material from the blast furnace gas purification system. The blast furnace sludge is today deposited in sludge ponds at the steel production site, mainly due to process-related restrictions linked to its zinc content. The blast furnace sludge is a very fine-grained material with high moisture content, thereby in general requiring pre-treatment, such as drying and agglomeration, prior to processing. In Swedish ore-based steel production, up to 20,000 tonnes of blast furnace sludge (dry weight) is generated each year from hot metal production in blast furnace. The sludge consists mainly of iron oxide and coal whereby a recovery would benefit the resource efficiency by saving virgin raw materials and decreasing material to deposits, in this case expensive and space-consuming sludge ponds.

The project’s aim was developing and demonstrating a concept, using AGA/Linde’s OXYFINES technique, for upgrading and utilising zinc containing blast furnace sludge. By construction of a pilot plant, Figure 1, and performing trials, the OXYFINES technology performance and potential were verified. The effects of different process parameters were evaluated to develop an optimised concept. With the required process settings, a high degree of zinc separation from the sludge was obtained, and thus a sinter product with ideal characteristics could be generated for straightforward charging to the steel production, i.e. blast furnace or basic oxygen converter.

The sinter product was tested, with good results, in industrial trials by its input as a raw material in the basic oxygen furnace at SSAB. The zinc containing dust was theoretically evaluated by Boliden for its suitability as a raw material in zinc production. The overall composition of the dust is similar to other iron dusts used in zinc production. Nevertheless, the zinc concentration in the dust must be further increased to meet the requirements. For this, a continued work is required to establish

the optimised way by evaluating process adjustments such as decreased off-gas flow, increased zinc in blast furnace sludge and recirculating dust in the OXYFINES process.

Through commercialisation work and system analysis, various implementation possibilities for the concept, its potential and effects were evaluated to present the most advantageous solution. Implementation of the OXYFINES concept has positive effects on sustainability mainly by improved material efficiency and by waste prevention. The recovery of blast furnace sludge decreases landfill and using generated OXYFINES products contributes to the value chain by reduced need for virgin raw materials. The risks of increased energy use and CO_2 emissions by implementing the OXYFINES concept can be outweighed by the overall positive sustainability effects in a life cycle perspective. In view of a holistic perspective, effects on carbon dioxide emissions and energy use in the steel production system and in the production of raw materials should also be considered. Furthermore, an industrial implementation will contribute to a sustainable energy and material supply by developing the technology to optimally utilise and refine valuable components in residual materials as well as through cooperation and industrial symbiosis between the steel and base metal industries.

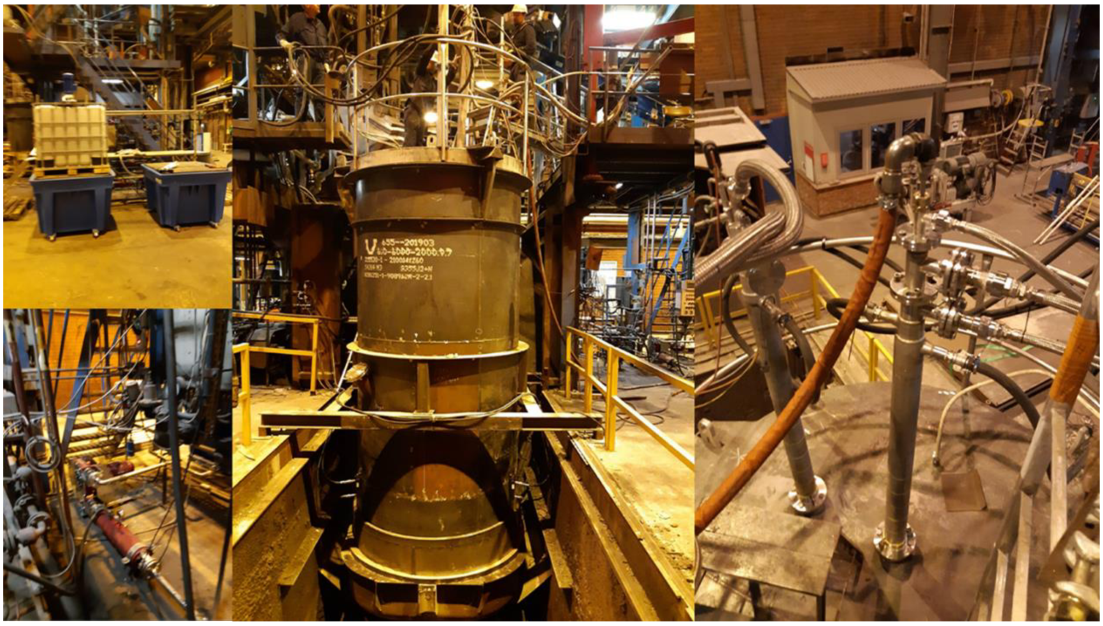


Figure 1. OXYFINES pilot trials set-up with the reactor (middle), burners through the lid at the top (right), pump (bottom left) and IBC containers (top left).

Introduction and background

Introduction and project scope

The process route of SSAB Europe, Luleå's steel production system, illustrated in Figure 2, can roughly be divided into ironmaking and steelmaking. Ironmaking consists of blast furnace (BF) and desulphurisation (deS), whereas steelmaking is performed in the basic oxygen steelmaking process (BOS) including the basic oxygen furnace (BOF) and ladle metallurgy (LM) followed by continuous casting (CC). There is also a coking plant located at the site which produces coke for BF, and the iron ore pellets used in BF are delivered from LKAB Malmberget by train.

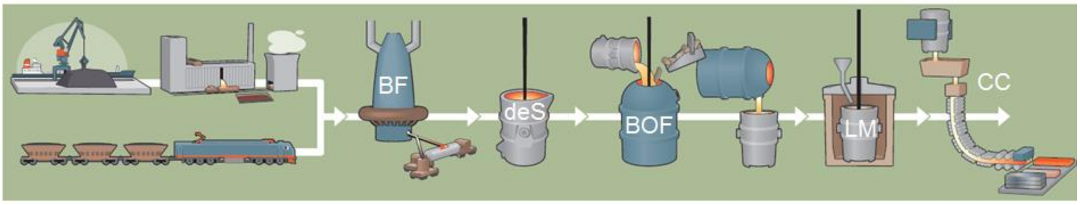


Figure 2. Outline of SSAB Europe, Luleå steel production plant.

Despite persistent recycling work some residual materials from the steelmaking process route are currently deposited due to difficulties in recycling or finding possible utilisations. This applies to zinc containing sludge generated from the blast furnace's gas purification system. In Swedish ore-based steel production, up to 20,000 tonnes of blast furnace sludge (dry weight) is generated each year from hot metal (HM) production in blast furnace. The largest sources of zinc from external raw materials are iron ore pellets for HM production in blast furnace. However, the major source of zinc in the blast furnace charged materials is from the residual materials recovery via BF dust briquettes.

Even though the BF sludge has a substantial amount of valuable contents, such as iron (about 35%) and coal (about 25%), all freshly generated blast furnace sludge is today deposited in sludge ponds. The reason for this is the zinc content, which, due to process related restrictions, makes it unsuitable to return to existing internal processes. Furthermore, the blast furnace sludge, if taken directly from the gas purification system, has high moisture content which requires efficient ways to lower the moisture content to such levels suitable for agglomeration and for safe addition into metallurgical processes. If the sludge could be recirculated to the steelmaking system, e.g. to the blast furnaces, by estimation this would lead to a reduced need for iron ore pellets by up to 12,000 tonnes per year.

Increasing expectations through sustainability perspectives and companies' pursuit of the "zero waste" vision, together with costs and space for the construction of new intermediate storages/landfills, motivates the development of effective techniques for increased material recycling. For example, the construction cost of a sludge pond with a capacity of approximately 55,000 tonnes sludge (corresponding to 5 years of HM production) is estimated at between 25 and 50 million SEK, depending on prevailing land conditions. Therefore, it is of great economic and environmental value to increase internal recycling as long as this does not lead to process disruptions and compromised steel product quality.

Zinc is an easily evaporated element, and therefore follows with the process exhaust gas and is enriched in the dust/sludge formed in the gas purification system. The main issue of blast furnace sludge for internal recycling is process restrictions on zinc-containing materials. This applies especially to the blast furnace process since all recovered dust/sludge is charged to the blast furnace via a cold bonded briquette and by direct injection of recirculated blast furnace dust to the blast furnace. In recent times also parts of old blast furnace sludge, i.e. with considerably lower zinc content, have been used in the blast furnace briquettes. Over time an increasing amount of zinc-containing materials is recycled to the blast furnace whereby in turn the zinc content, mainly accumulated in the generated blast furnace sludge, has increased. A limit has been set for the maximum permitted load of zinc in the blast furnace, today some 150 grams of zinc per tonne of hot metal produced. The limit has been set to avoid costly operational and production disruptions such as hangings due to zinc condensation on the inner wall and raw materials in BF, thereby causing e.g. disintegration of furnace linings and raw materials [1] [2]. Furthermore, the zinc content in the blast furnace sludge (less than 1% Zn) is too low for external recovery for instance in zinc production, which requires a desirable Zn content of at least 30%.

This project aimed to demonstrate a concept for 100% recovery of zinc-containing blast furnace sludge by developing and applying AGA/Lindes OXYFINES technique. Pilot trials with OXYFINES technique for recovery of blast furnace sludge was performed in a scaled-up test set-up for an optimised concept and producing a zinc rich dust, intended as a raw material in zinc production. From the non-evaporated contents, such as iron, a zinc free product for utilisation as a raw material in the steel production (i.e. BF or BOF) was formed. Important factors for the OXYFINES process optimisation include the moisture content and chemical composition in the BF sludge feed such as its coal content for reduction of the zinc oxides. The process parameters are set for separating the maximum amount of zinc, from the blast furnace sludge to produced dust, at the same time keeping temperatures low enough not to form a melt but generating a sinter product suitable for the intended use.

The project attempts were for an upscaled facility to obtain industrially transferable results. The technology under development was of readiness level (TRL) 6 for demonstration and optimisation of existing technology with OXYFINES burner.

The main objectives of the project were to be achieved via the following sub-objectives based on the project's activities:

- Demonstrated and optimised concept for OXYFINES technology by process knowledge and evaluated parameters to obtain products suitable for utilisation.
- Recyclable products based on pilot trials results of the OXYFINES technology and evaluated through industrial trials, theory, and system analysis.
- An implementation plan of the concept based on the pilot- and industrial trials results, system optimisation, cost analysis, planning and effects on sustainability.

An industrial implementation of the concept would improve the resource efficiency by preventing waste and returning material to the value chain thereby decreasing the use of virgin raw materials. Furthermore, the project contributes to sustainable energy use and material supply by optimising the technology and refinement through the use of valuable components of the materials (hereby means coal, iron, and zinc).

Potential recipient of zinc-rich dust

Boliden Rönnskär in Sweden uses residual materials from other industries as raw material in their base metals production. Currently, steel mill dust from three different suppliers in Sweden are used in the zinc production i.e. fuming process. A fuming plant consists of fuming furnace, settling furnace and clinker furnace. The fuming furnace is a water-cooled rectangular furnace in which finely ground coal and preheated air is injected into the liquid slag, forming CO gas, thus reducing metal oxides, e.g. zinc oxide and lead oxide, in the slag. Certain resulting metals are in the vapour state, thereby possible to be stripped from the liquid slag. Nitrogen in the injected air supports the stripping of zinc vapour from the slag. Zinc vapour is re-oxidised to zinc oxide directly above the foaming bath of liquid slag. The reduction process further recovers metals such as lead and arsenic and extracts halogens from the slag. The resulting oxides are de-halogenated in the clinker furnace. The slag is further treated in the settling furnace in which the remaining copper in the liquid slag is separated into liquid phases containing copper and other precious metals. These are either recycled to the copper smelter or sold to specialised metallurgical plants [3].

The fuming process at Boliden Rönnskär annually produces ca 35,000 tonnes of zinc clinker, whereof approximately 10-15% of the produced clinker originates from steel plant dust. The fuming process involves melting the dust to form a slag and the removal of halogens in a clinker furnace to produce clinker. The clinker is sent to either Boliden's Odda smelter in Norway or Kokkola smelter in Finland to be refined into pure zinc [4].

Alternative techniques for the treatment of zinc containing residual materials

The sintering process

The sintering process is a pre-treatment step, used in the production of iron. The Nordic sintering plants have been closed due to environmental issues though sintering plants are still in use elsewhere. The sintering process comprises the agglomeration of fine mineral particles (e.g. fine particles iron ores, iron oxide residuals such as zinc containing dusts and mill scale together with lime raw materials) into a porous and semi-molten lumpy mass. The temperature is typically maintained between 1150 °C and 1250 °C. In the process, heat is commonly provided by combustion of solid fuels, such as coke breeze or coal.

The moistened feed materials are placed in a layer onto a continuously moving strand where the material surface is ignited with gas burners at the starting point of the strand. Air is drawn through the moving material bed to combust the fuel. The moving strands velocity and the gas flow are regulated to ensure the complete combustion and sinter process from the top layer to the base of the material on the strand. Finally, the produced mass is air-cooled and broken into pieces of sinter in a crusher to the size and strength required for feeding into the blast furnace [5].

However, sinter plants are the main contributor to dust emissions from integrated iron and steel works e.g. from raw material handling, wind box exhausts, sinter crushers and sieves. Furthermore, polychlorinated dibenzo-p-dioxins (PCDDS) and polychlorinated dibenzofurans (PCDFs) are highly toxic compounds generated especially by combustion processes where the iron sintering process today is the principal PCDD/Fs industrial source in Europe. Legislated limits are rising whereby sinter plants are under increasing pressure for decreased emissions [5], [6].

In a study on zinc removal during sintering, two filter cake wastes, i.e. a BOF filter cake sample and a mixture filter cake sample of a 3:1 blend of both BOF and BF filter cake was analysed. The samples were sintered at 1100–1300°C in argon and air to evaluate the effects of temperature, gas atmosphere and coal content on zinc removal and on the mineral phase formation. The results showed improved zinc removal rate from increasing the sintering temperature, except for the BOF filter cake samples sintered in air where the effect of temperature on zinc removal was negligible. The best zinc removal was shown for the mixture sample sintered in a reducing argon (Ar) atmosphere. Yet, at 1150°C, the zinc removal rate was less than 20%. At 1250°C it was increased to 55%, and at 1 300°C it was 62%. For each of the tested samples the results showed that removal of zinc in argon was higher than in air. For example, the zinc removal rate of the mixed sample sintered in air at 1300°C was only 22%. From the study it was concluded that the removal of zinc in the filter cake samples was enhanced in a reducing atmosphere [7]. Based on the results from the study, sintering plants, which are operated in an oxidation atmosphere, are not effective in zinc removal.

Reduction furnaces

In the 90s, the concept of the Rotary Hearth Furnace (RHF) was developed towards recovery of zinc and alkali containing dust and sludge. Companies in Japan, such as Nippon Steel and Kobe Steel, have developed RHF technology, i.e. the Kimitzu process and the Fastmet/Fastmelt process. In the year of 2000, the first commercial plant was taken in operation by Nippon Steel, Hirohata Works. The RHF process is characterised by the requirements of drying and agglomeration of input materials. It has a good zinc removal efficiency and produces a recyclable Direct Reduced Iron (DRI) product and a zinc rich dust. However, it requires larger amounts of input materials as it generally has high maximum material treatment capacity of more than 300 ktonne/year [8] [9].

The OxyCup technology, developed by ThyssenKrupp Steel and Küttner is a smelting reduction process based on self-reducing agglomerates in a shaft furnace producing a liquid hot metal. The furnace is described to be charged with a flexible briquette feed material composed of different residual materials, preferably containing high iron and coal contents, zinc and alkali containing fines and also lumpy residuals are referred to as possible materials to be processed. The agglomerates are produced on site in the briquette making plant. The self-reducing briquettes are charged from the top of the furnace together with skulls, coke and additives whereby the direct reduction of the iron oxides is made by the coal from the residuals in the briquettes.

At about 1450 °C the briquettes are converted into solid iron sponge which is melted together with other metallic charge in the furnace hearth. Hot metal with a coal content of about 4% is continuously tapped over an iron-slag siphon system at 1500 °C. The hot metal and slag generated in the OxyCup shaft furnace are comparable to blast furnace qualities. The slag is formed from compounds as lime and silica in the residuals and described to be used for cement, road and water way construction. The zinc and most of the alkalis leave the furnace as dust and are collected in the filter cake downstream the scrubber system [10].

The Waelz kiln technology comprises the use of a revolving tubular furnace for the volatilisation of zinc. The technology was originally proposed in 1881 by George Druyeel. In 1923 Krupp Grusonwerk, in collaboration with Metallgesellschaft A.G., started developing the process. The Waelz process can treat a variety of materials such as ores, tailings, middlings, slimes, ashes, and slags. The input materials, containing zinc in the form of zinc oxide, zinc ferrite, zinc silicate, or zinc sulphide is mixed with coal containing fuel. The material is heated in the kiln at temperatures ranging from 1000 to 1500 °C whereby the zinc is reduced, volatilised, and oxidised to zinc oxide. The zinc oxide is then separated from the exhaust gases by bag filters or electrostatic precipitators and delivered to zinc smelters for zinc production. The non-zinc materials in the Waelz process, generates a so called Waelz Iron Product, which is presented to be used directly for construction purposes e.g., in road construction, cement manufacturing or it may be reprocessed in some other way for value added use of the iron content [11].

Recovery of fine-grained dust/sludge using established technologies, such as the reduction furnaces mentioned above (e.g. Rotary heart furnace, OxyCup or Waelz kiln technology) in general needs to be based on considerably large amounts of residual materials and entails high investment costs that cannot be justified by the quantities of the material in question, i.e. BF sludge in Sweden. Prior to reprocessing, the sludge also requires pre-treatment such as drying and or agglomeration. In addition, it is essential that the new residuals generated in these types of technologies, e.g. dust, sludge and or slag, are possible to be utilised.

The DK Recycling process

In Duisburg-Hochfeld, Germany, DK Recycling has developed the DK process specialised for recycling residual materials from the steel industry. The process is based on classical sintering and blast furnace operations for the recycling of steel waste oxides containing high levels of zinc and alkalis. The zinc load in the blast furnaces is as high as 40 kg/tonne pig iron and the level of alkalis are 300 g/tonne pig iron. The company processes 500 ktonne materials per year producing 300 ktonne of pig iron which is sold to the European foundry industry. The zinc is collected from the gas purification system as sludge and is declared to be sold for further use [12].

External recycling in reprocessing plants, such as DK recycling in Germany, is costly and entails long transportation and loss of in-plant gain from valuable contents of the residual materials.

Mechanical separation

Previous studies were made by SSAB Merox, on the possibility of mechanically separating the blast furnace sludge via, for example, a hydro cyclone. Sampling, sieving, and analysis showed that the zinc content of the blast furnace sludge is independent of particle size and difficult to separate as the material is very fine grained. The conclusion was, therefore, that it is not applicable to mechanically fractionate the blast furnace sludge.

The OXYFINES technique

AGA/Linde has developed the OXYFINES technique for which dust or sludge is fed to an OXYFINES burner whereby components such as zinc, sulphur, alkalis and lead to various degrees are vaporised to a generated dust phase. Other contents in the ingoing material forms an oxidic bottom phase, in either molten or sintered form, depending on process temperature. The technique is a relatively simple and cost-effective method where previous tests have shown a high degree of separation of zinc (about 97%) and with which no pre-treatment of sludge, such as drying, is required.

Promising results were demonstrated by AGA in an earlier study where trials with blast furnace sludge were carried out on a smaller scale at temperatures of 1300-1500 °C. In this trial a molten product of iron oxide and other components were generated (containing in general 74% FeO_x, 7% CaO, 9% SiO_2, 4% Al_2O_3 and 4% MgO). The generated melt was reported possibly to form into lumps suitable for the recovery in blast furnace. The coal content of the sludge proved to be sufficient to heat and melt the sludge and to reduce the zinc content. The prevention of zinc from adhering to the bottom product (i.e. the melt or the sinter product) requires reducing conditions in the OXYFINES flame and in the reactor. Volatile substances in the residual material, such as zinc, lead and alkalis, accompany the exhaust gases to form the dust product.

Zinc evaporation is enhanced by higher temperature and lower oxidation potential in the process. By increasing the utilisation of the coal content of the blast furnace sludge, the degree of oxidation is also increased, which, however, leads to increased oxygen potential in the reaction zone. Consequently, the increased oxygen potential has a negative effect on the zinc evaporation which takes place in the form of elemental zinc vapor. In this regard, an optimal level of oxidation can be found in the process, measured with CO_2/CO ratio (and H_2O/H_2 ratio) or with oxygen potential, Lg (pO_2/bar) (or RTln (pO_2/bar)) [13] [14].

Method

Project partners

The project's partners were SSAB Europe which is a steel producer with ore-based metallurgy and SSAB Merox (now included in SSAB) who worked to optimise SSAB's by-product, scrap, and waste management. Linde (formerly AGA/Linde) is a company with technique and production of industrial gases, and the developer of the OXYFINES technology. Further, the base metal industry is represented by Boliden Mineral, a company producing base metals, including zinc. Project leader has been Swerim (formerly Swerea Mefos) a metallurgical research institute with pilot facilities. The project partners and constellation of roles, competences, resources, and functions in the project are presented in Table 1.

Table 1. Constellation (companies, roles, competences, resources, and function in utilisation).

Company	Role in the project	Competences	Resources	Function in utilisation
Swerim	Project management, pilot trials and systems analysis	Metallurgical research institute, with long experience of conducting pilot scale trials and system analysis	Pilot trial facility. Models for system analysis for metallurgical industry.	Technological development and increased knowledge
AGA/Linde	Supplier of OXYFINES technology	Manufacturer and technology for uses of process gases	Competence from previous applications	Supplier of technical solution
SSAB Europe	Industry partner, problem owner	Iron and steel manufacturer	Supplier of sludge and recipient of "zinc-free" product	Recipient of technical solution
SSAB Merox		Residual materials handling, recycling, and use		
Boliden Mineral	Industry Partner	Manufacturer of base metals (zinc)	Evaluation of the use of zinc-rich dust product	Recipient of zinc-rich dust product

Project activities and plan

The project work was divided into five activities, with the respective execution and results delivery, carried out according to Table 2 and to the following schedule with planned start and end dates:

1	Project Management	Start: 2018-06-15	End: 2020-06-30
2	Pilot trials	Start: 2018-10-01	End: 2019-08-30
3	Industrial trials	Start: 2019-08-01	End: 2019-12-20
4	System Analysis	Start: 2019-08-01	End: 2020-02-15
5	Commercialisation	Start: 2019-10-01	End: 2020-05-15

Table 2. Project activities, execution, and results/delivery.

Activity		Execution	Results/delivery
1	Project management	Planning/coordination (Swerim) Risk analysis, examinations, reporting (all)	Collaboration and dissemination of knowledge
2	Pilot trials	Construction of pilot set-up with OXYFINES technique and performing trials (Swerim, AGA, Merox). Evaluation of results (all)	Operational optimisation, performance
3	Industrial trials	Industrial trials in BOF with zinc-free product and in BF with changed briquette (Swerim, SSAB) Evaluation of zinc-rich dust (Boliden) Evaluation of results (all)	Usable products
4	System analysis	Process/system data and material analyses (SSAB, Merox, Boliden) System modelling, optimisation (Swerim) - recovery to BOF alt. BF - process efficiency, economy, CO_2 emissions and energy Evaluation of results (all)	Knowledge of system effects from using the iron-rich sinter product
5	Commerci-alisation	Business plan (AGA/Linde SSAB, all) Sustainability analysis (Swerim, all)	Implementation plan, business plan

Pilot trials

Construction of the pilot plant

Work on the construction of the pilot set-up was carried out during the first three quarters of the project. In general, the construction and preparation work for the pilot plant included:

Material handling:

- Installation of IBC containers for 10 m^3 of sludge and one hose pump (FPSH 32 with pulsation damper, Appendix 1a and 1b) including frequency control and hose system with manual shut-off as well as mixers (CR 300, Appendix 1c) and scales systems (accuracy 1kg).
- Pre-tests regarding sludge moisture content effects on stirring, pumping and sedimentation.

Mechanical construction, installation, and preparation:

- Construction and installation of reactor shaft, Figure 3a and 3b, and lid, exhaust, scaffolding, trolley in tapping pit, hydraulic lift for removal and insertion of the sinter collecting sandboxes.
- Construction of new OXYFINES burner and support burner by AGA/Linde.
- Installation and burner setting tests of AGA/Linde's burners.
- Installation of operating pump, hose system and valve from IBC tanks to the OXYFINES burner attached through the reactor shaft lid, both burners connected to cooling water system.

- Preparation of existing media system for oxygen, nitrogen, and propane.
- Preparation of gas purification system, hose filter.
- Three sandboxes are lined and covered with a sand layer.

Instruments and electrical installation and preparation:

- Preparation of LabVIEW system for process monitoring and logging of operational data, (Appendix 2).
- Preparation of process systems for the media system.
- Preparation of exhaust gas analysis equipment of CO, CO_2, O_2.
- Preparation of reactor gas analysis equipment of CO, CO_2, O_2, H_2.
- Installation of pressure measurement and temperature measurements in the reactor shaft and lid. Thermocouples adapted for process temp (1200-1300 °C).

(a) (b)

Figure 3. (a and b) Reactor shaft with exhaust duct, preparation for casting the lining.

Design of reactor and pilot set-up

The dimensions of the reactor shaft were based on a proper size to be adapted to the existing converter pit and related sandboxes used for the sinter product, Figure 4 (Appendix 3a-3g). The reactor shaft had a height of 4.65 m, and a diameter of 2.03 m corresponding to a total volume of 15 m³. The inside diameter of the shaft depends on the choice of lining material.

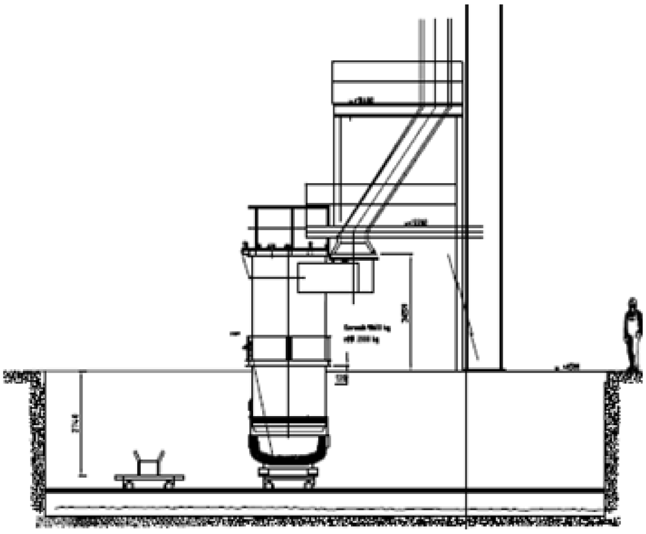


Figure 4. Sketch for reactor in converter pit.

The principle of the pilot arrangement, Figure 5, was that blast furnace sludge is fed to the OXYFINES burner together with oxygen and propane. In the first stage, the sludge is atomised, and the water content is evaporated in the burner flame. A few seconds after the sludge enters (depending on residence time in the reactor), a zinc-free sinter product is generated in the bottom sandbox of the reactor. Zinc and other volatile elements exit via the exhaust gases to form a zinc-rich dust product.

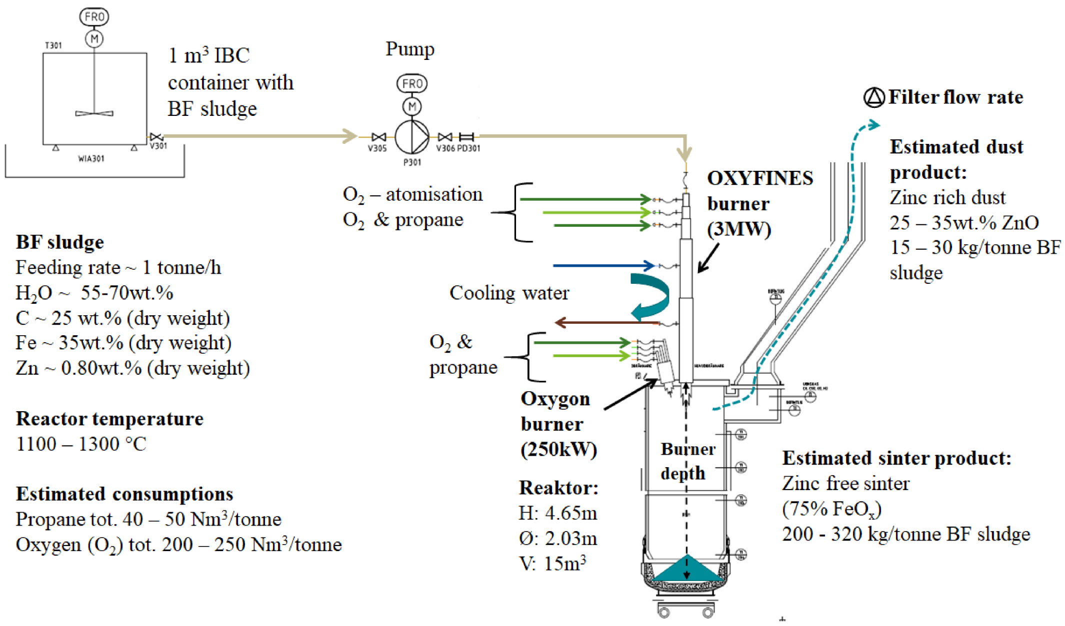


Figure 5. The principle of pilot set-up for blast furnace sludge processing.

The sludge was kept in IBC containers of 1 m^3, one by one placed on scales, using a hose pump with a pulsation damper for an even material feed of ca. 1 tonne sludge per hour to the OXYFINES burner mounted in the centre of the reactor lid.

The OXYFINES burner is a water-cooled main burner with variable insertion depth in the reactor and with atomisation of sludge via oxygen. The media for the burner is oxygen and propane depending on the required CO content in furnace gas analysis and is operated via the process control system.

The Oxygon burner is a water-cooled support burner with a simpler regulator and flame guard. Media to the burner for heating and flame retention (250 kW) are oxygen and propane. The support burner is used to heat the reactor shaft, up to 800 °C, and then burning continuously during trials.

The primary product, estimated to ca. 350 kg per hour, is collected in a sandbox on a trolley. The dust product was collected in barrels. Chemical analysis of the blast furnace sludge and generated products from the process is performed at SSAB via XRF analysis from melt iso formation, Leco (for C and S) and wet chemical analysis (i.e. most analysing is done in the liquid phase) for the zinc content.

Temperature measurements were made via four thermocouples placed through the furnace wall for measuring the temperature profile in the furnace shaft. Furnace pressure is measured at a measuring point in the furnace lid. Furnace gas analyses are carried out online for CO, CO_2, O_2, and H_2. Exhaust gas analyses (i.e. CO, CO_2, and O_2) as well as temperature and flow measurement are taken in the exhaust duct and hose filter (Appendix 4). The expected exhaust gas flow prior to tests was assumed to be approximately 6000 m^3/hour. The estimated reduction and evaporation temperatures for oxides and metals are presented in Table 3.

Table 3. Estimated reduction and resp. evaporation temp for oxides and metals (AGA/Linde).

	Estimated reduction temp	Estimated evaporation temp (metal)
SiO2	1550	2477
MnO	1450	2097
P2O5	800	431(350 Oxid)
Cr2O3	1250	2222
NiO	>2000	2837
MgO	1600	1126
CuO	>2000	2595
V2O5	1500	2527
TiO2	1600	3127
Al2O3	1900	2327
FeO	650	2727
CaO	>2000	1482
Na2O	1000	914
K2O	900	779
ZnO	950	907
PbO	300	1737 (1477 oxid)

Refractory in furnace shaft and lid

The refractory lining material for the furnace design was chosen with respect to the process-specific operating conditions and temperature range. The sinter generated in the process is potentially aggressive against the lining material due to content of FeO. Decisions on lining materials were made in consultation with experts from RHI Magnesita and Luleå Industrimontage AB (LIMAB).

The starting position was to use brick refractory lining in the lower parts (about 1/3 of the reactor height) whereas using a casted lining material in upper parts and for the reactor lid. This was further suggested as a possibility for a full-scale installation. In order to evaluate the optimal refractory material, Merox sent a sample of the blast furnace sludge to RHI Magnesita for making corrosion tests. The tests were carried out for 6h and at 1400 °C, with different types of refractory materials and, after obtained results, a second test series was performed for 6h and at 1600 °C.

The results from corrosion tests showed best performance found in COMPAC ROX A99-6 (chemical-bonded), followed by RESISTAL KSP95-1 (ceramic-bonded), COMPRIT A97-6 (hydraulic-bonded) and RESISTAL RK10 (chemical-bonded), Table 4. The other tested brands may be an option if the temperature does not exceed 1400°C. After corrosion tests at 1600 °C, four refractory materials were chosen for further detailed mineralogical investigations in order to get more information about their corrosion resistance.

Table 4. Conclusions from corrosion tests at 1400 and 1600 °C of blast furnace sludge with different refractory materials at RHI Magnesita.

		Test 1 1400°C	Test 2 1600°C
Sample 1	RESISTAL KR85C	+	-
Sample 2	RESISTAL RK10	++	+
Sample 3	RESISTAL B85	+	-
Sample 4	RESISTAL KSP 95-1	++	+
Sample 5	DURITAL E90	o	-
Sample 6	COMPAC ROX A99-6	++	++
Sample 7	DIDURIT K89-6	o	--
Sample 8	COMPRIT A97-6	++	+

Due to time limits, for the completion of the pilot plant reactor, decisions were taken that a casting mould material were to be used in the whole reactor shaft and the reactor lid. LIMAB, and their refractory supplier Gothia Eldfast AB, presented two alternative castable lining materials based on requirements:

- G-1850T is a tabular (TAB) Alumina 1800 °C material that has low porosity and high impact resistance.
- G98CS is a colloidal silica material with high impact resistance and is easy to dry.

The RHI corrosion tests results suggested the COMPRIT A97-6 and a 97% Al_2O_3 brick for the lower 1/3 part of the reactor. However, the castable lining used as lining in the reactor for the pilot trials, Gothia G98CS, is also composed of 98% Al_2O_3.

The final decision for lining material, based on requirements from sludge material, and thermal heat transfer calculations, were a two layer castable lining comprising of 75 mm Gothia's G98CS (Appendix 5), on another 42 mm inside lining labelled ILW13. This generated an acceptable outer furnace wall "cold face" temperature of ca 250 °C, at inside "hot face" temperatures of 1400 °C.

Blast furnace sludge

Blast furnace sludge from sludge pond number 8 at SSAB, Figure 6, was used in the trials. Chemical analysis of the blast furnace sludge for knowledge of expected sludge contents and amounts such as iron, and zinc are presented in Table 5. Pre-trial tests on blast furnace sludge and moisture measurements were made by SSAB Merox. The tests resulted in a moisture content of 55%. Performed ultrasound sieving showed that 73 wt.% of the blast furnace sludge is <5µm, (Appendix 6).

Table 5. Average blast furnace sludge analysis for pre-trial tests.

BF sludge	
Content	**(%)**
Fe (tot.)	34.78
CaO	8.08
SiO_2	5.25
MnO	0.22
P_2O_5	0.19
Al_2O_3	2.15
MgO	1.43
Na_2O	0.15
K_2O	0.06
V_2O_5	0.24
TiO_2	0.26
Cr_2O_3	0.03
C_Leco	25.80
S_Leco	0.38
B2	1.54
Zn	0.57

Figure 6. Bucket with blast furnace sludge for pre-trial tests.

Tests on bulk density of the blast furnace sludge showed an average of 1.40, Table 6. Calculations based on processing of 1 tonne of sludge per hour with 55% moisture content corresponds to 1.18 tonnes of sludge per cubic metre or 0.85 m^3/tonne.

Table 6. Calculation of volume per tonne blast furnace sludge based on density.

Density, tonne/m³			
	Particle	Bulk	Porosity
Dust	2.50	1.40	0.44
Water	1	1	
Moisture, %	Slurry tonne/m³	m³/tonne	m³/day
0	1.40	0.71	7.14
10	1.36	0.74	7.35
20	1.32	0.76	7.58
30	1.28	0.78	7.81
40	1.24	0.81	8.06
50	1.20	0.83	8.33
55	1.18	0.85	8.47
60	1.16	0.86	8.62
70	1.12	0.89	8.93

Due to the collection of blast furnace sludge directly from the sludge pond it contained lumps, gravel, and stones. Hence, sieving the sludge was required, using a 5 mm sieve. This was made by manual sieving from container to container during the first campaign. A sieving table was built for the second campaign.

Planning of pilot campaigns

The purpose of the pilot study was to obtain industrially transferable results through which a design for a full-scale plant can be made and to identify an optimal mode of operation for the generation of useful products.

Functional description of the workflow in the process were prepared by AGA/Linde e.g. start and stop sequences regarding the burners were prepared. Further, calculations for consumption figures on propane and oxygen, were made for different temperatures, moisture, and coal contents in sludge.

The trials were initially planned for two campaigns, of each three days, with a calculated blast furnace sludge processing time of maximum 10 hours per day. Based on the assumption of processing ca one tonne sludge per hour, with 50% moisture, this would have resulted in 3.5 tonne sinter per day and a total of 21 tonne from the two campaigns. To produce a dust product with ca 30% zinc, based on the calculated sludge processing time and amount, a total dust amount of ca 720 kg would have been generated in the pilot campaign trials.

The two pilot trial campaigns were carried out at Swerim's facilities in Luleå during the summer months of 2019 (i.e. week 19 in May and week 35 in August) with the corresponding three trial days each. The daily planning for the pilot trials in campaign 1 and campaign 2, respectively, is illustrated in Table 7 and Table 8.

Table 7. Daily planning, campaign 1.

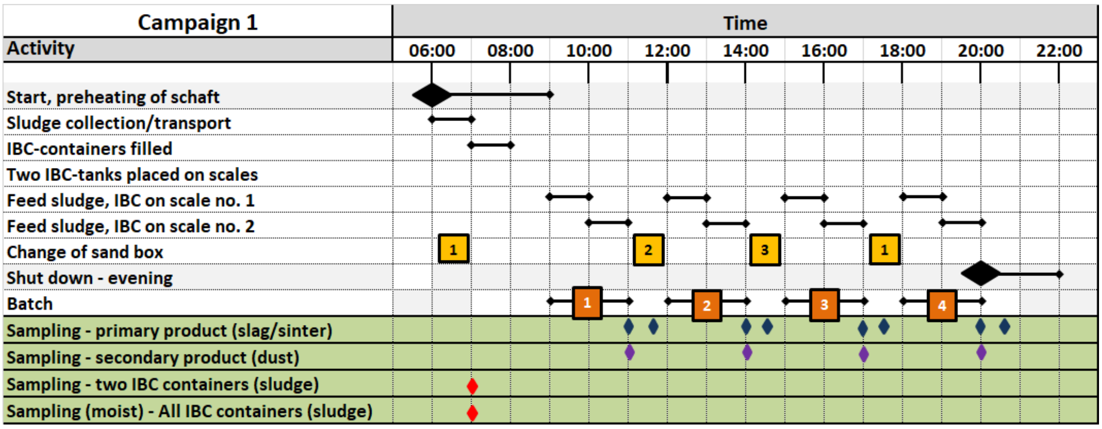
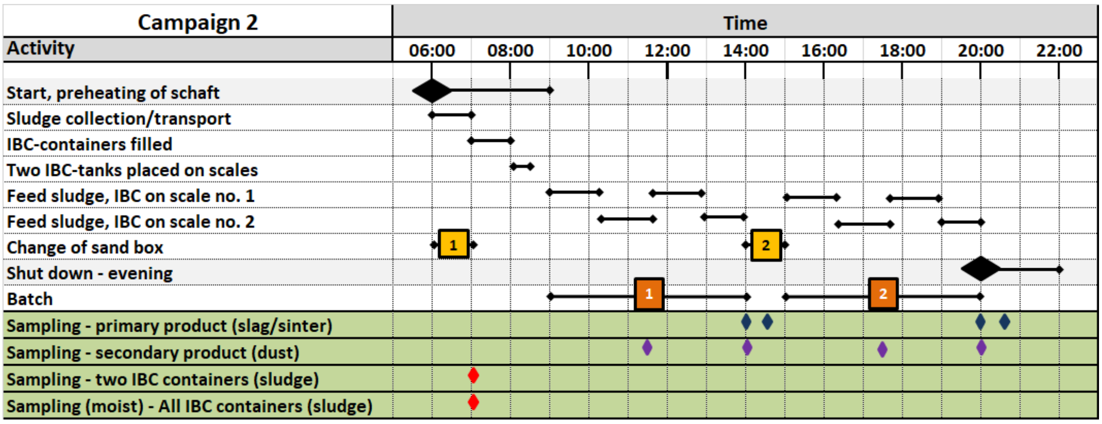


Table 8. Daily planning, campaign 2.



During pilot trials, trucks were filled from a suitable area in sludge pond number 8 at SSAB and transferred to IBC containers, Figure 7. To achieve the best conditions, for a pumpable and homogeneous material with uniform moisture content, a sieving table, and a container for stirring and homogenising the sludge before transfer to IBC containers, was installed to be used in campaign 2.

Figure 7. Blast furnace sludge transferred from the truck to IBC containers.

Decisive for the suitability of the dust product as a raw material in zinc production is a zinc content corresponding to > 30%. Any components of the dust with potentially negative effects in the zinc production were also considered. Important for the utilisation of the sinter product and its application as a raw material, either in BF or in the BOF, is the chemical composition but also the physical characteristics. The OXYFINES process had not previously been tested at lower temperatures, so it was not known prior to the trials, whether the sinter product would be formed as a massive "piece" or possibly as granules.

The process temperature in the pilot trials was intended to be operated as low as possible (down to 1100 °C) to minimise energy consumption, but at the same time operating at a temperature sufficient to produce a zinc free sinter product. A probable appropriate operating temperature was assumed to be around 1300 °C. Depending on the process conditions, parts of the iron in the produced sinter would be reduced to a lower oxidation state. Estimated reduction and evaporation temperatures for oxides and metals were compiled by AGA/Linde. At temperatures below 1300 °C, lead (Pb) is less likely to be separated into the dust phase. Expected results according to previous trials made by AGA/Linde:

- Content of Sinter product
  - Iron oxides - FeO_x ~ 74 wt.%
- Degree of separation
  - Coal - C ~ 100 wt.%
  - Zinc oxide - ZnO ~ 97 wt.%
  - Potassium oxide - K_2O ~ 39 wt.%

- Sodium oxide - Na_2O ~ 0 wt.%
- Sulphur - S ~ 61 wt.%

Prior to the trials, knowledge of the moisture content and composition of the sludge was crucial for manageability and for the evaluation of the processing. Moisture measurements and preparatory tests were made to evaluate the required moisture content for a pumpable sludge and to simultaneously avoid unnecessarily high moisture content in terms of energy requirements and eventual moisture problems in the exhaust duct. A suitable moisture content was assumed to be about 55% for manageability.

Conducting pilot trials

The pilot trials were carried out as a series of batch tests with altered process conditions to evaluate the influence on e.g., primarily the zinc separation degree, the quality as well as the amounts of generated sinter and dust products. A couple of studies initially included in the trial program were:

- Tests at different temperatures and stoichiometry to evaluate the zinc separation rate and product generation.
- Evaluation of the trials impact on the lining material in furnace and lid.
- Gas purification system optimisation to identify the performance of a full-scale system (e.g., effects on fan, filter, air dilution, flow rate).

Process conditions regarding temperature and stoichiometry were evaluated in eight different batches during campaign 1, keeping different constant temperatures, from 1300 °C to 1100 °C, and stoichiometry (ratio CO/CO_2), with a value of CO in furnace gas analysis from ca 2 to 10 Vol.%. This was made to identify an optimal relationship between temperature and CO for which the best products were obtained.

In campaign 2, five batches were performed, with the focus on reducing the amount of non-gasifiable contents following to the dust phase, thus increasing its zinc concentration. In the pilot trials, the distance of the OXYFINES burner to the bottom of the reactor was adjustable. This, in combination with altered operating temperatures and stoichiometry contributes to opportunities to influence the generation of products. Trial batches in campaign 2 were conducted with reduced sludge feeding rate, with adjusted distance of the OXYFINES burner to the sandbox in the bottom of the reactor, and with reduced oxygen for the atomisation flow.

During the campaigns, material samples were taken for analyses on the blast furnace sludge moisture content in the separate batches and on sludge and generated sinter and dust products for chemical analysis, according to the sampling schedule in Tables 7 and 8. The samples of the sludge for analysing moisture contents were weighed, dried overnight at 100°C and then weighed again. Logging of process parameters and operating data (e.g., sludge feeding rate, oxygen rate for the atomisation, temperature, energy use and carbon monoxide in furnace gas analysis) were made and related to respective batch with results from analysis of sludge and generated material, Table 9.

During the campaigns also the off-gas filter flow, i.e. regulating the under pressure in the reactor, was altered by using three different flow rates.

Table 9. Process parameters and operating data in OXYFINES pilot trial campaigns (C) and the respective batches.

C	Batch	Index	Feeding rate	H_2O	Lance length	O_2 atom.	Oxygon burner	Temp	CO	Filter flow
No.	No.	No.	kg/min	wt.%	m	Nm^3/min	kW	°C	Vol.%	Nm^3/h

Industrial trials and evaluations of OXYFINES products

The totally generated sinter product from the two pilot trial campaigns of ca 6.5 tonnes was evaluated via industrial tests in the two 130 ktonne top-blown Basic Oxygen Furnaces (BOF) i.e. the LD-process at SSAB Europe, Luleå. The trials at SSAB were performed at two occasions (during week 42 in October and week 45 in November) by charging the sinter product via the scrap chute to the BOFs as a potential exchange material for parts of the cooling scrap charged in the start sequence of the heat. The amount of added steel scrap is typically in the range of 10 to 20% of the total metal charge (i.e. hot metal and scrap).

The simplified principle of the LD-process is that coal rich hot metal is refined into low coal liquid steel by blowing oxygen onto the metal bath at a temperature reaching approximately 1700°C and oxidising the coal to CO and CO_2. The BOF is initially tilted while a smaller amount of steel scrap is charged. Subsequently, hot metal is poured into the BOF from the hot metal ladle and the furnace is raised to its vertical blowing position, after which blowing commences and basic slag formers are charged. Most impurities in the charged hot metal will be oxidised, forming a slag together with added basic slag formers, such as burnt lime and dolomitic lime. When the correct end-analysis and temperature are reached the liquid steel and slag are tapped in separate ladles.

In the trials the total charged steel scrap amount was ca 13% of the total charge. The OXYFINES sinter were charged in amounts of 1.2%, 1.6% and 2.4% of the total charge weight based on a constant Liquid Steel (LS) net. weight of 128 tonne. The effect of the sinter addition and its contents on the LD operations and generated slag and steel composition, was analysed by sampling at end of the blow and compared to the reference analysis.

Boliden Mineral made a theoretical evaluation of the dust product based on the chemical analysis of the dust generated during the pilot trials and based on the requirements for a zinc raw material for their fuming process. The analysis was regarding primarily the dust analysis zinc content with the requirements of at least 30% zinc in the dust. Further contents in the dust were assessed by comparison to the contents of other steel mill dusts used in the fuming process at Boliden.

A one-week campaign with full-scale test in blast furnace 3 at SSAB was carried out during week 50 in December. The trials consisted of tests charging dust briquettes with altered composition and higher zinc content than normal to the blast furnace. The tests were made to assess the effects on blast furnace operation and the effect on zinc contents in blast furnace dust and sludge as a result of a higher zinc content in the raw material. During the week, a total of 2,633 tonnes of dust briquettes (99.1 kg/tonne of hot metal) were charged with an average zinc content of 0.14%, compared to an annual average of 0.086% zinc during 2019.

In the blast furnace, hot metal is produced at 1400-1500°C using raw materials charged into the furnace from its top in the form of iron ore pellets, reductant coke, limestone and other additives such as blast furnace briquettes and basic oxygen furnace slag. Complementary reductants, such as pulverised coal, and blast furnace dust, are injected via tuyeres in the lower part of the blast furnace. The blast furnace gas departing via the furnace top also carries dust, with particle sizes from about 6 mm to only a few microns. The gas is firstly cleaned by entering a primary dust catcher in which heavier dust particles are captured after which the gas then enters a wet scrubber system where the finer particles are collected as a wet sludge. About 25 kg of total dust (as dust and sludge) is emitted per tonne of hot metal produced.

The cement-bound dust briquettes consist of a variety of iron-, coal- and lime-containing fine-grained residual materials such as fine-grained scrap, dust and sludge. The materials that are dry, such as blast furnace dust, filter dust and cement are stored in silos. In the briquette factory mixer, the dry materials are mixed with water and a premix of moist materials e.g. scrap, mill scale and zinc-rich sludge. This pre-mix is manufactured during the summer and the production is continued during the winter season provided that the materials are not frozen. The composition of the pre-mix cannot be significantly altered for a shorter test during the winter, so to increase the zinc content of the briquettes during the trial week, the proportion of blast furnace dust in the briquettes was increased. The week before the trial, week 49, parts of the generated dust was "saved" so that it was possible to use more of the dust in the briquettes prepared for the test week. During week 49, the zinc content of the briquettes was only 0.023% versus 0.14% during the trial week. During the trial week, blast furnace dust, corresponding to 7 kg per tonne hot metal produced, was also injected, which further contributed to the total zinc load to the blast furnace.

The results of the experiment were used for analysing any negative effects on the blast furnace operation based on the potentially increased zinc load, and hence to identify opportunities of improving the dust product generated in the OXYFINES process. This, from the effect of the dust briquette on possibilities to increase the zinc content in the generated blast furnace sludge to the OXYFINES concept. The further evaluation based on the briquette trials was used in the system analysis to create a comprehensive picture of various opportunities for material recycling in a full-scale implementation of the concept.

System analysis

The system analysis performed within the project was intended to assist in the OXYFINES concept assessment. The analysis was made to indicate the effects, both positive and negative, from using the OXYFINES sinter product as a raw material in blast furnace iron making or in the steelmaking converter. The calculations were made based on one option for full-scale OXYFINES process concept, calculating the effects on raw material, energy and CO_2 and the related unit process and system cost effects (i.e. to indicate the OXYFINES sinter value in BF and BOF process and the system). Also, the intentions of the performed system analyses include the effects on blast furnace zinc load and potential for the improvement of the OXYFINES dust product.

The process route in the SSAB Luleå system model is the ironmaking, by blast furnace (BF) and desulphurisation (deS), and the steelmaking including Basic Oxygen Furnace (BOF). Other associated parts essential in the analysis is the BF briquettes. The reference system of SSAB Europe, Luleå, is schematically illustrated in Figure 8. The freshly generated BF sludge (i.e. with higher zinc content) is put in sludge pond deposit, and lesser parts of the old sludge (i.e. with lower zinc content) is used in the BF briquette.

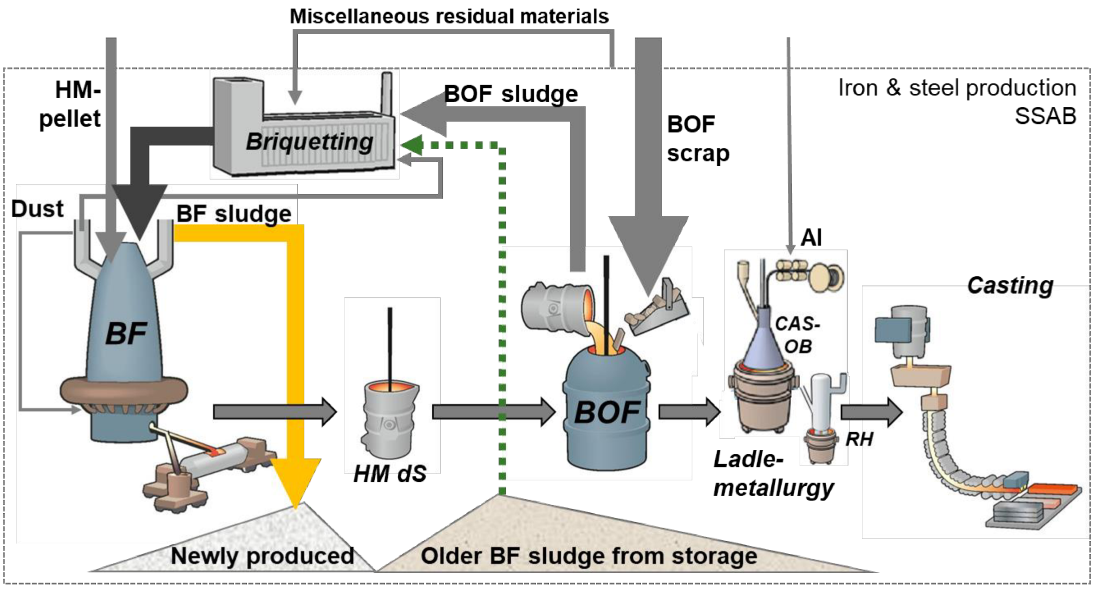


Figure 8. Reference production system SSAB Europe, Luleå.

Figure 9 illustrates the production system with the implemented OXYFINES concept and the possibilities for using the OXYFINES sinter in either blast furnace, BF, or in basic oxygen furnace, BOF, and using the dust product in the zinc producing industry.

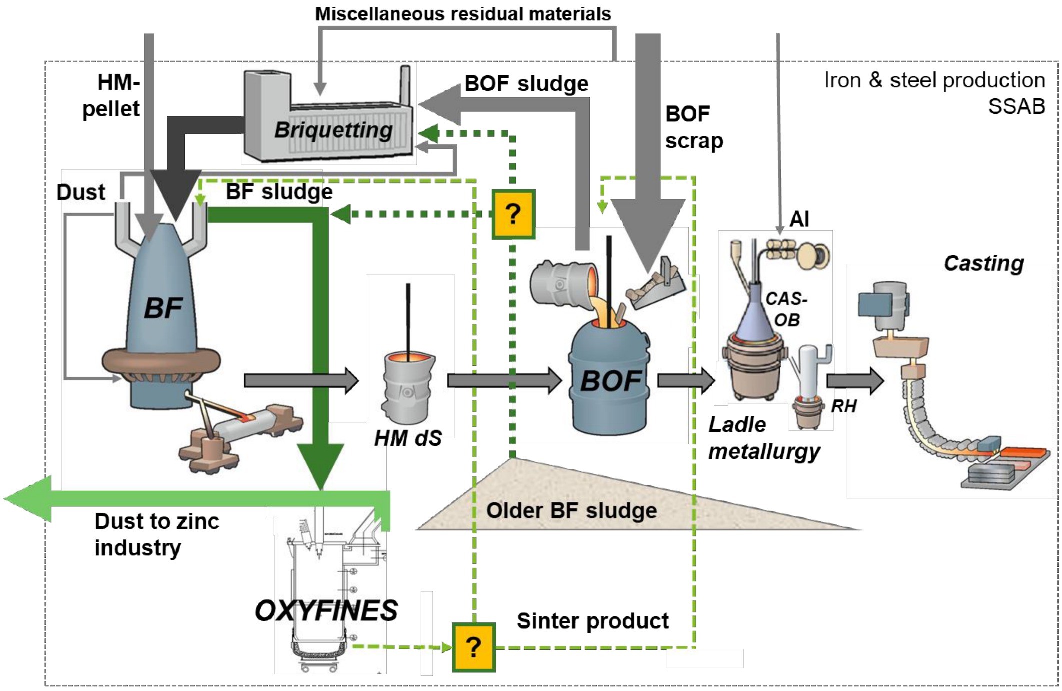


Figure 9. Production system SSAB Europe, Luleå with the integration of the OXYFINES concept.

In the performed system analysis case study, the modelling and analysis of the process chain and the use of the OXYFINES sinter product were carried out using a developed Excel spreadsheet model [15]. The model is based on iterative heat and mass balances, including element distribution to, dust, sludge, slag and metal. The model is used for process simulation and studies of various operating conditions as well as of the influence of specific process parameters. The model simulates the holistic effect on the process system considering raw materials use and quality of the final steel product, as well as the quality of generated residual materials (i.e. slag, dust, and sludge).

The case study scenarios were evaluated against a reference scenario, which is based on the calibrated Excel model, using average BF production data and operational reports from SSAB Luleå works for the weeks 51 and 52 in the year 2019. The BOF data is based on production figures of the year 2016. The approach to the calculations carried out were as follows:

- The scenarios for analysis were made according to one OXYFINES concept for full scale plant, based on 12 ktonne of sludge/year (dry weight) corresponding to a sinter amount to BF of 4.697 kg/tonne HM, and to BOF of 4.457 kg/tonne LS.
- Analysis were made of maximised BF zinc load (max 150 g/tHM) to analyse effects for increased zinc in the dust product from the OXYFINES concept.
- The calculations of sinter product value were based on average production raw material prices and primarily iron ore pellets price.

- Calculations were made for indicating energy and CO_2 analysis.
- Three different analysis of the chemical compositions for the OXYFINES sinter product were used to compare the effects in the processes from specific sinter contents. The analyses include sinter no. 1, Table 10, based on the average analysis of seven of the sinter analyses from the pilot trials with less of the sand from the sandboxes in the analysis (13 samples from 7 of the pilot batches). Sinter no. 2 is the average analysis of the batches where the best results were obtained with regards to zinc separation degree (batch O-009) and sulphur separation degree (batch O-016) (see results from pilot trial campaigns). For the comparison also one theoretical sinter analysis, sinter no. 3, was used where the sinter product was calculated with regards to separation degrees for Na, K, S, Zn, and Pb.

Table 10. Chemical contents in OXYFINES sinter analysis used in the system model.

OXYFINES sinter no.	1	2	3
Content	**Avg. of 7 batches with less sand included**	**Avg. of 2 "best batches" separation of Zn and S"**	**Theoretical calculated sinter analysis**
CaO	12.963	15.385	13.763
MgO	2.032	2.185	2.109
SiO2	9.111	8.305	7.751
Al2O3	4.514	5.690	3.190
TiO2	0.391	0.450	0.415
V2O5	0.310	0.345	0.341
Na2O	0.165	0.115	0.034
K2O	0.158	0.095	0.042
S	0.121	0.020	0.069
P	0.088	0.105	0.107
Mn	0.296	0.349	0.311
Fe	49.161	55.125	50.222
C	2.111	0.086	0.000
Zn	0.072	0.038	0.020
Pb	-	-	0.085
Cr	0.067	0.038	0.029
Cu	-	-	0.004
Ni	-	-	0.015

Process conditions of blast furnace, BF

The following conditions apply to the reference modelling and analysis of using the OXYFINES sinter product as a raw material in the blast furnace:

- 100% MPBO iron ore pellet
- Pulverised coal injection (PCI) 135.5 kg/tHM and BF dust injection 6.5 kg/tHM
- Scrap amount 33.9 kg/tHM and dust briquette amount 99.7 kg/tHM
- 0.41% Si in HM (constant)

- 0.21% Mn (adjusted with Mn slag)
- 0.035% P (adjusted with BOF slag)
- BF slag rate 167 kg/tHM, slag basicity Bell's ratio 1.3 (B2: CaO/SiO_2 approx. 1.02)
- BF dust generation ca 20.9 kg/tHM and BF sludge generation (dry weight) ca 5.5 kg/tHM

Process conditions of basic oxygen furnace, BOF
The following conditions apply to the reference modelling and analysis of using the OXYFINES sinter product as a raw material in the basic oxygen furnace:

- Addition of OXYFINES sinter product primarily made by reducing the charged amount of iron ore pellet.
- Steel scrap 17.5% of LS_{net}
- Iron ore pellet 0.7% of LS_{net}
- BOF slag rate 89.5 kg/tLS
- Basicity B2 (CaO/SiO_2) in BOF slag 3.84
- Total BOF sludge (coarse and fine) generation (dry weight) ca 30.2 kg/tLS

Cost effect and indicating sinter value evaluation
The raw material prices used for evaluating the cost effect of using the OXYFINES sinter product in BF or BOF are over time average prices for raw materials in the respective unit process, except for the iron ore price. The iron ore price in the system analysis cost calculations is 949 SEK/tonne which is based on average exchange rate 2019 of 10.115 SEK for 1 USD and the spot iron ore price of 2019, approximately 93.85 U.S. dollars per dry metric ton unit.

In the analysis, the cost for the OXYFINES sinter has been given the value 0 in order to be able to calculate the value of the material at the point of addition (in SEK per tonne) from the obtained difference cost calculated against the reference.

The calculation basis for the system analysis were a potential option of full-scale OXYFINES treatment of blast furnace sludge and the generated products, presented in the Table 11. The system analysis calculations are on a hot metal production of 1,993 Mtonnes and liquid steel production of 2,100 Mtonnes, annually. The annually OXYFINES processing of 24 ktonnes blast furnace sludge (wet weight, 50% moisture content) resulting in 1.3 tonne sinter per hour and 0.231 tonne dust per hour. The annually OXYFINES sinter production of 9,360 tonne is in the system analysis evenly distributed to the blast furnace with 4.697 kg/tonne hot metal or to the basic oxygen furnace with 4.457 kg/tonne liquid steel.

Table 11. The calculation basis full-scale OXYFINES unit for treatment of blast furnace sludge with generated OXYFINES products.

Production	
HM prod. (ktonne/a)	1,993
LS prod. (ktonne/a)	2,100
BF sludge, wet wt. 50% moisture (ktonne/a)	24
OXYFINES full scale unit	
Annually operation time (h)	8,000
90% available operation time (h)	7,200
Sludge processing, 50% moisture (tonne/h)	3.400
Sinter product (tonne/h)	1.300
Dust product (tonne/h)	0.231
Sinter product (tonne/a)	9,360
OXYFINES sinter to BF (kg/tHM)	4.697
OXYFINES sinter to BOF (kg/tLS)	4.457

Figure 10 illustrates the schematics of the system model and material flows with regards to an implemented OXYFINES concept.

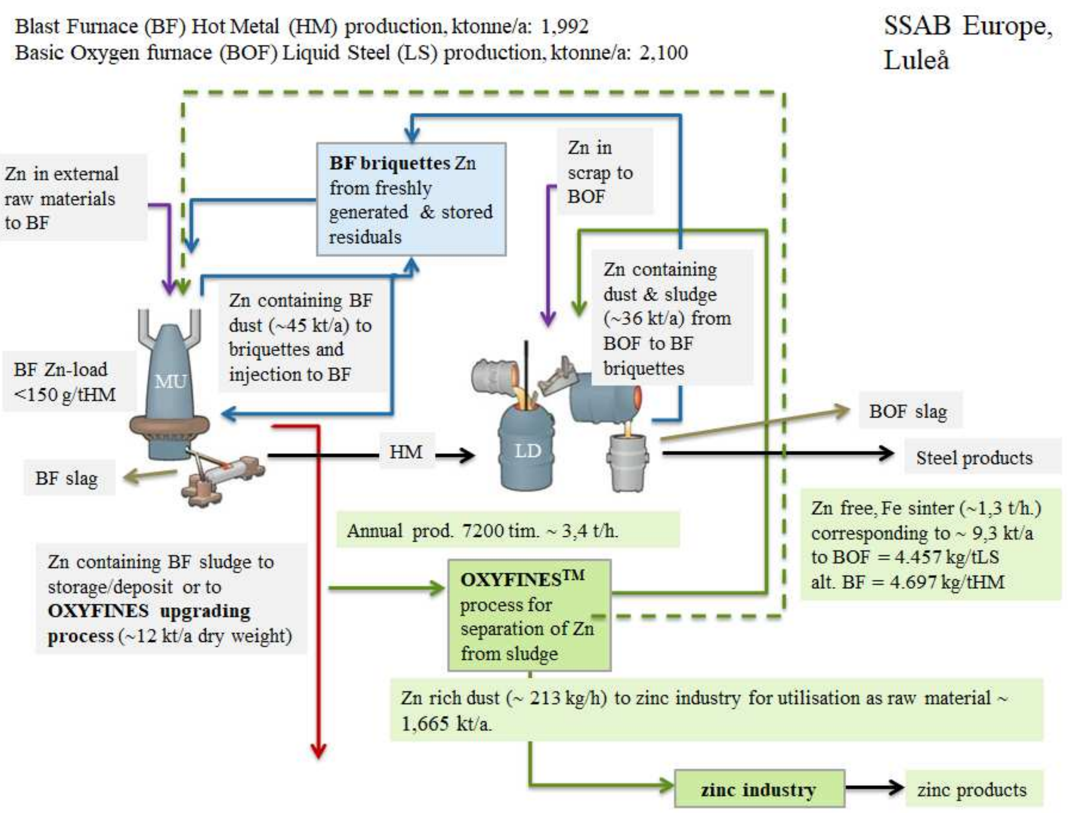


Figure 10. Schematics of the SSAB production system model with the OXYFINES materials and concept included.

Table 12 concludes the analysed scenarios calculated in the system analysis. The outline of the analysed scenarios was:

- BF, BOF and system effects from using the OXYFINES sinter based on the comparison of scenarios to the reference scenario.
- Scenarios 1, 2 and 3 for BF and BOF respectively are the scenarios using the nr. 1, 2 and 3 sinter analyses.
- Regarding BF the analysis is also for investigating the potential effects on the generated blast furnace sludge from increased blast furnace zinc load (up to the set limit of 150 g/tHM) by increased zinc in BF briquettes.

Table 12. List and short description of analysed scenarios of the system analysis.

Scenarios	Description	To BF	To BOF
Reference	Reference scenario according to BF 2019, BOF 2016	**kg/tHM**	**kg/tLS**
BF_1	Sinter product no.1 used in analysis (i.e. the average of 7 batches with less sand included), Zn in sinter **0.072%**	4.70	-
BF_2	Sinter product no. 2 used (i.e. the average of 2 "best batches" regarding separation of Zn and S), Zn in sinter **0.038%**	4.70	-
BF_3	Sinter product no. 3 used in analysis (i.e. the theoretically calculated), Zn in sinter **0.020%**	4.70	-
BF_1a	As scenario BF_1 with increased Zn in briquette to BF Zn load = 150g/tHM	4.70	-
BF_2a	As scenario BF_2 with increased Zn in briquette to BF Zn load = 150g/tHM	4.70	-
BF_3a	As scenario BF_3 with increased Zn in briquette to BF Zn load = 150g/tHM	4.70	-
BOF_1	Sinter product no.1 used in analysis (i.e. the average of 7 batches with less sand included), Zn in sinter **0.072%**	-	4.46
BOF_2	Sinter product no. 2 used (i.e. the average of 2 "best batches" regarding separation of Zn and S), Zn in sinter **0.038%**	-	4.46
BOF_3	Sinter product no. 3 used in analysis (i.e. the theoretically calculated), Zn in sinter **0.020%**	-	4.46

Commercialisation

Proposals on a commercialisation and business plan for a plant on production scale and implementation of the OXYFINES concept at SSAB steel plant were based on results from pilot trials, concept optimisation, cost analysis and sustainability effects.

The proposal on the full-scale plant includes some different layouts of the OXYFINES process unit based on the capacity of the plant from the sludge amounts for treatment per year, moisture content of the sludge for treatment, and variations in the technical requirements thereof, such as reactor design, material handling, burner systems, cooling systems and exhaust gas purification.

The developed plan includes the calculation of consumption figures and the heat balance for the OXYFINES concept regarding using either propane or coke oven gas as energy. The proposal on the design of a full scale OXYFINES process unit layout was prepared based on the technical requirements including tanks, sieves and pumps, reactor, ladles and ladle car, burner and flow train, ducts, filter, fan, chimney and a cyclone.

AGA/Linde made the proposals for the full-scale OXYFINES unit in discussions with equipment constructors. The proposals were based on:

- Cases with different moisture content in sludge before charging into OXYFINES upgrading process.
- Plant variations based on moisture contents, additional handling, and equipment for drying the sludge and its related additions to the plant costs.
- Cases were compared to today's deposit in terms of cost, both regarding handling and investments.

The starting point for the OXYFINES process capacity and calculations for a full-scale plant, was the yearly generated blast furnace sludge amount of 12,000 tonnes sludge dry weight, or 24,000 tonne sludge with a moisture content of 50%.

The sludge in sludge ponds contains ca 50-65 wt.% moisture. The sludge directly from the off-gas purification system contains ca 96 wt.% moisture which based on 12,000 tones dry sludge per year corresponds to 300,000 tones/y wet sludge. Using the sludge directly from the gas purification system requires sedimentation and depending on the case also drying.

The possibility of mixing 6,000 tonne dry weight per year of sludge from the gas purification (96 wt.% moisture) with 6,000 tonne dry weight per year sludge from sludge ponds (55 wt.% moisture) would result in an average 92.6 wt.% moisture in a total sludge amount of 163,333 tonnes per year for treatment.

Sustainability analysis

In relation to the commercialisation activity, the related sustainability aspects on the implementation of the OXYFINES concept were analysed. From RE:Source's sustainability analysis instructions, [16], sustainable development means pursuing a development that meets today's needs, without compromising the ability of future generations to meet their needs. At the same time, a competitive industry is pursued.

Sustainability analysis of projects involves identifying the sustainability potential, potential sustainability risks, and further identifying what needs to be done in the project implementation to optimise potential and minimise risks. The aim with performing the sustainability analysis is to identify environmental and/or sustainability aspects and propose initiatives within projects to secure critical aspects. The analysis was executed as follows:

- Firstly, an object of comparison was identified. The sustainability impact of products or processes, according to the project method or technique, were compared with the sustainability impact of functionally equivalent products/processes that use today's accepted technology. The purpose was to evaluate the potential change if the project is successful and its results are put into practice.

- The next step was to identify the project' significant sustainability aspects in relation to the comparison object in one life cycle perspective, i.e. production of raw materials, manufacture, use as well as recycling and residual handling.
- Finally, management of the significant aspects of sustainability in the project were described.

Results and discussion

Results from pilot trial campaigns

General results from campaigns

In general, the pilot trials demonstrated a very stable OXYFINES process with easily controlled temperature and Vol.% CO in the furnace atmosphere.

The reactor and lining after campaign 1 showed no build-ups or visible wear, Figure 11. After campaign 2, some build-ups were visible at the end part of the reactor and at the off-gas exhaust duct. These were the results mainly from freezing of sinter between the reactor wall and the sandbox in longer batches with more sinter generation. Regarding the build-up at the off-gas exhaust duct this was from zinc condensed on the water cooling which dropped down and started the build-up.

Future reference on the proportions of a full-scale reactor from the trials are a wider reactor in order to concentrate the sinter contact with the sandbox. This, and adjustment of the OXYFINES burner length in the reactor, supports preventing the material from spreading on the lower part of the reactor wall. Further, a sectioned lower part of the reactor would be preferable for easy relining with a planned relining cycle.

The off-gas exit should be placed vertically from the reactor instead of the horizontally placement as in the pilot trials (to fit the existent off-gas duct). Also, installing a cyclone on the off-gas exit could limit this problem. The CO and dust rich off-gas enters the cyclone where coarse dust particles are directly returned into the reactor. Fine particles, zinc fumes, and off-gas exits the cyclone whereby CO are post combusted in the air gap before the water-cooled section of the duct. This would lead to less dust and higher concentration of zinc in the filter dust.

Figure 11. Figure to the left, reactor shaft after campaign 1. The other figures are of the reactor shaft after campaign 2.

A total of 26.7 tonnes of blast furnace sludge was processed during the two pilot trial campaigns during 13 performed batches. Less sludge than expected was recovered in the two campaigns. In campaign 1 this was mainly due to the many stoppages caused by blockage and clogging in the hoses for feeding the sludge to the burner. In campaign 2, the installed sieve and the increased stirring in the container totally prevented any stoppages, Figure 12.

Figure 12. Installation of a sieving table and stirring of blast furnace sludge in a container.

However, a decreased access to sandboxes from three in campaign 1 to only two in campaign 2 limited the number of possible batches per day. Longer batches with more sludge were carried out but then with the result that the generated sinter froze together the oven wall and the sandbox. Figures 13a show the sinter product batch in the sandbox just taken from the reactor, which can be seen in Figure 13b.

(a) (b)

Figure 13. (a) Sinter product batch in sandbox (b) OXYFINES reactor.

The blast furnace sludge moisture content was on average 58% in the two campaigns. The moisture content in the sludge directly from the sludge pond at SSAB was about 50-55%. More water, up to a moisture content of 55-65%, was added in some IBC containers in campaign 1 for handling the stoppages.

Constant stirring of the sludge was required due to the sludge characteristics and that it settles in the bottom of the containers within a few hours. However, stirring separates most of the lumps of compacted material. After sieving and the removal of the stones and gravel, feeding sludge containing higher moisture contents than 50% to the OXYFINES burner, using the hose pump, was considered easy. However, with water contents in the sludge close to 50%, the sludge started to compact during feeding and causing clogging. Therefore, for lower water contents, a more complex feeding system and pump is required.

Generated products from the two pilot campaigns were a sinter of ca 3.9 tonne and a dust, containing most of the zinc from the sludge, corresponding to a total of ca 2.3 tonne, Table 13. Nevertheless, the sinter total weight were ca 6.5 tonnes due to addition of sand from the sandbox which reacted with the sinter product.

Table 13. Processed BF sludge, generated sinter, and dust in campaigns.

Material (tonne)	Campaign 1	Campaign 2	Total
BF sludge	11.420	15.320	26.740
Sinter product	1.488	2.429	3.917
Dust	0.799	1.515	2.314

Figure 14 illustrates the distribution of the 26.7 tonnes recovered blast furnace sludge in the two pilot trial campaigns. The sludge had an average moisture content of 58% i.e. 11.2 tonnes was dry substance) and 15.5 tonnes was moisture. The dry sludge was then distributed into ca 3.9 tonne sinter (calculated without the sand) and 2.3 tonnes of dust. Coal contents of the dry substance was 2.6 tonne (ca 24%) which mostly reacted with some 1.4 tonnes oxygen to CO_2 from reduction reactions. About 1.0 tonne were losses. Losses in campaign 1 was ca 700 kg per 11.4 tonnes (6.1%) of sludge and in campaign 2 about 300 kg per 15.3 tonnes of sludge (1.9%) were lost. Uncertainty in moisture level analysis of the sludge, as well as the sludge handling, with manual sieving and water additives in Campaign 1, are the major explanation for the material losses and this was clearly improved in campaign 2.

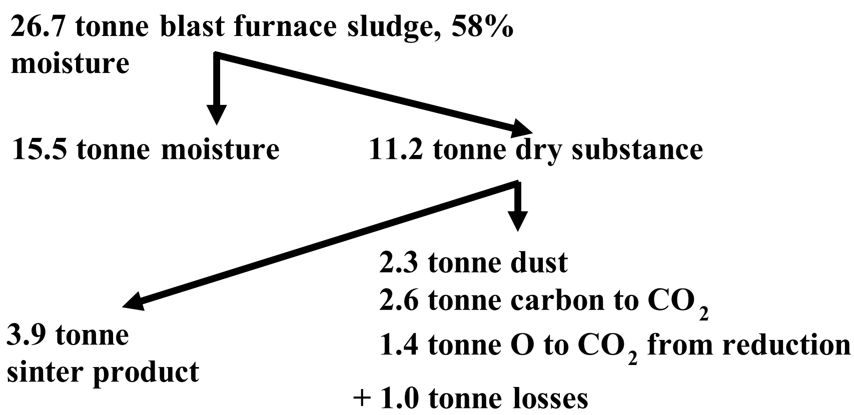


Figure 14. Distribution of the blast furnace sludge from recovery in the OXYFINES pilot trial campaigns.

Results from campaign batches

Table 14 summarises all batches performed during campaign 1 and 2. In campaign 1, (i.e. batches O-002, O-003 and O-006 to O-011) the process settings (i.e. optimal relation of temperature and Vol.% CO in furnace gas analysis) for the zinc separation was evaluated.

The generated sinter product, mostly completely melted, was easily crushed into lumps after cooling with virtually no fines generation, making it a suitable product for handling, and charging to the steelmaking processes. However, for charging larger amounts of the sinter lumps to the blast furnace, it would be recommended to perform strength tests for evaluating the sinter stability in the blast furnace burden.

Table 14. Evaluated process parameters in campaigns (C) 1 and 2.

C	Batch	Index	Feeding rate	H_2O	Lance length	O_2 atom.	Oxygon burner	Temp	CO	Filter flow
No.	No.	No.	kg/min	wt.%	m	Nm^3/min	kW	°C	Vol.%	Nm^3/h
1	O-002	1	14	63	1	0.8	250	1250	5	7500
1	O-003	2	14	62	1	0.8	250	1300	5	7500
1	O-006	3	14	59	1	0.8	250	1250	5	3500
1	O-007	4	14	64	1	0.8	250	1100	1	3500
1	O-008	5	14	68	1	0.8	250	1200	5	3500
1	O-009	6	14	54	1	0.8	250	1250	10	3500
1	O-010	7	14	59	1	0.8	250	1200	10	3500
1	O-011	8	14	55	1	0.8	250	1250	7	3500
2	O-012	9	10	57	1	0.8	0	1270	8	6000
2	O-013	10	8	56	1	0.8	0	1270	8	6000
2	O-014	11	10	56	1	0.6	0	1270	8	6000
2	O-015	12	10	57	1.5	0.8	0	1270	8	6000
2	O-016	13	14	57	1.5	0.8	0	1270	8	6000

The batches results show that the temperature span between non melted and unreacted sinter product (at 1100°C), and completely melted and reacted product (at 1300°C) was very narrow. At 1200°C the sinter product was partially melted and reacted, Figure 15.

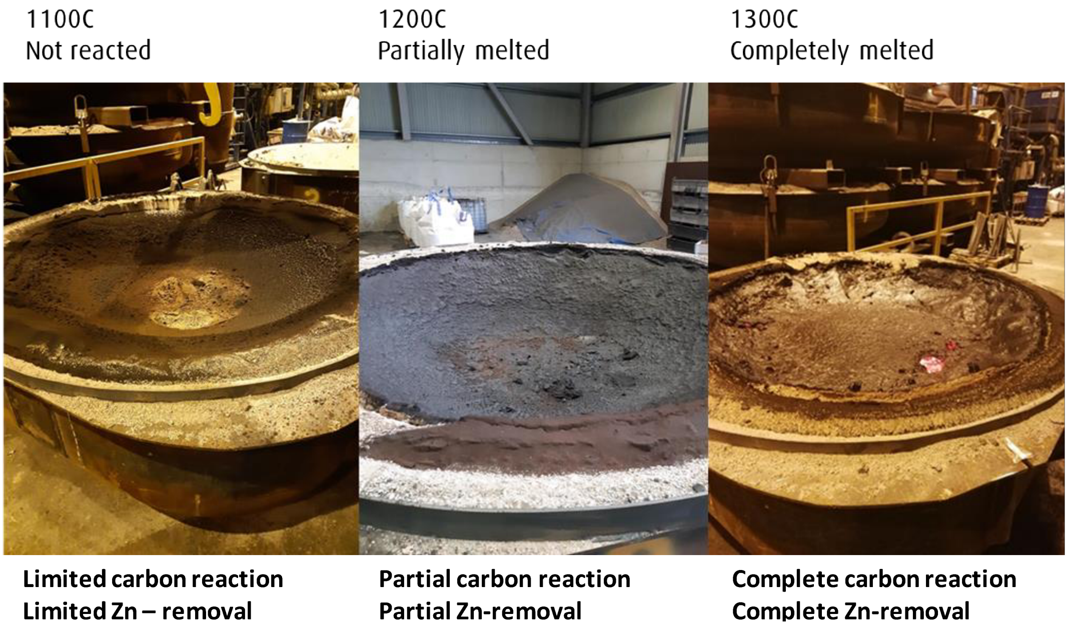


Figure 15. Sinter reacted to different degrees at different process temperatures.

The wt.% iron (Fe) and coal (C) in the sinter product from respective batches are presented in Figure 16. In most batches the main part of coal content from the BF sludge was consumed. The higher coal contents in the sinter product from batch O-007 and batch O-010 is explained by the lower process temperature of 1100 °C respective 1200°C, Table 14. Generally, the iron content in the generated sinter was ca 50 %.

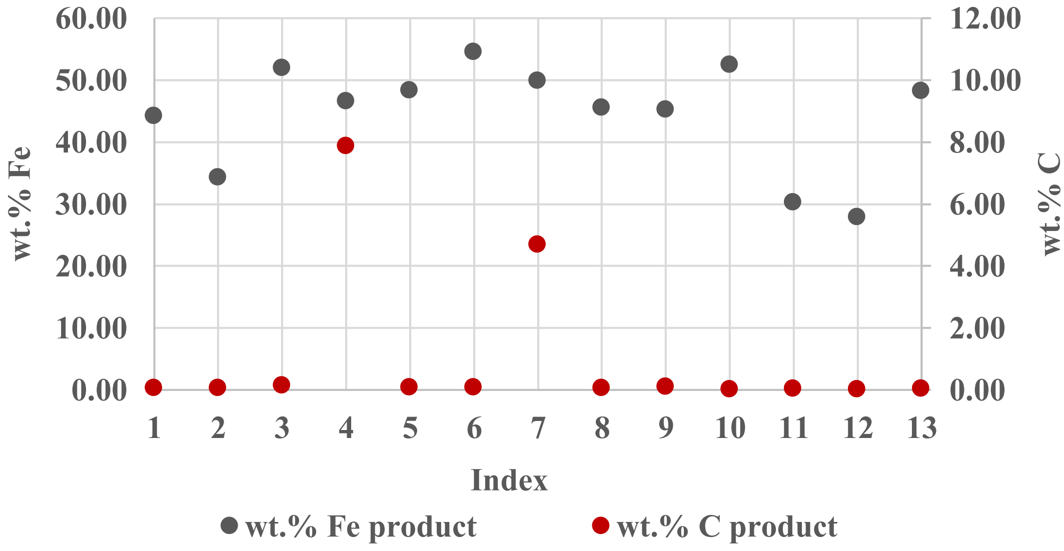


Figure 16. Wt.% iron (Fe) and coal (C) in the sinter product from respective batches during the campaigns.

The dust generation in the campaigns were higher than expected with an average for the batches of 194 kilo per tonne dry sludge, Figure 17. Tests by altered process parameters for decreasing the dust generation, hence increasing the dust zinc concentration, were made in campaign 2 (batches O-012 to O-016), Table 14. The process parameters alterations were made by decreased sludge feeding rate (batches O-012 to O-015), adjustment of the OXYFINES burner length (batches O-015 and O-016) by inserting the burner 0.5 m longer through the furnace lid, and by reduced atomisation oxygen flow (from 0.8 Nm^3/min to 0.6 Nm^3/min in batch O-014).

Moreover, the tests in campaign 2 were on the verification of process stability based on the outcome of temperature and stoichiometry from campaign 1. Another alteration made throughout the whole campaign 2, was that the supporting Oxygon burner only was used in the start sequence and then shut off. This was made to reduce the amount of sinter pressed against the furnace wall and the resulting heat occurring from the angled position of the support burner.

The results from the campaigns show that the major influence on the dust generation was by the filter flow rate, Figure 18. The filter flow was significantly reduced from ca 7500 Nm^3/h to ca 3500 Nm^3/h after the first two batches (index 1 and 2 in Figure 18) in campaign 1, which resulted in the lowest dust generation during the two campaigns. In campaign 2 the filter flow was kept constant at ca 6000 Nm^3/h.

Actions such as increasing the atomisation oxygen flow and the injection length of the OXYFINES burner reduced the dust generation to some extent, whereas sludge feeding rate and moisture content showed very little impact of the dust generation.

To optimise the dust, it is recommended to reduce the filter flow rate, increase atomisation flow rate and to keep the OXYFINES burner inserted closer to the sandbox and thereby further from the gas exit duct.

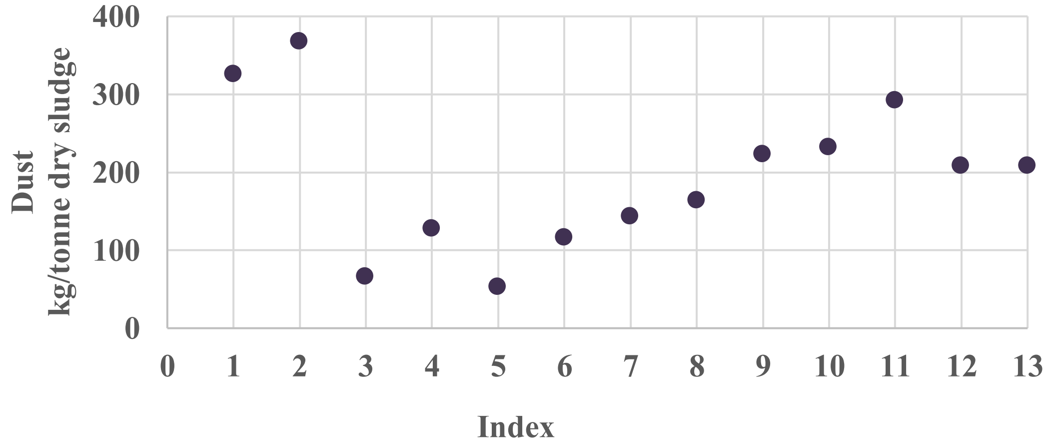


Figure 17. Dust generation in batches in kilo per tonne dry blast furnace sludge.

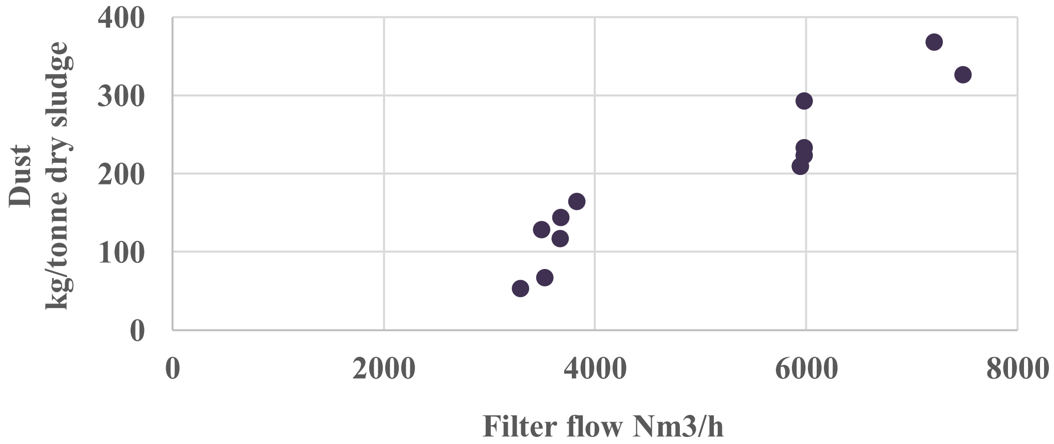


Figure 18. Dust generation in batches in kilo per tonne dry blast furnace sludge at different filter flow rates (Nm^3/h).

Element separation degree

The zinc separation degree in the campaign batches was generally high with the highest achieved separation in batch O-009 of 97%. The results from campaign batches on other analysed elements separation was for the alkali contents an average of some 76% sodium (Na) and 61% potassium (K). For sulphur (S) the average separation was 81% and for phosphorous (P) it was 41%, Table 15.

Table 15. Results on zinc (Zn), alkali (sodium, (Na) and Potassium (K)), sulphur (S) and phosphorous (P) separation degree in batches (%).

Batch (%)	Zn	Na_2O	K_2O	S	P_2O_5
O-002	90	80	55	91	49
O-003	91	70	41	89	43
O-006	31	93	99	94	34
O-007	72	96	96	60	39
O-008	82	97	99	94	36
O-009	97	85	68	72	26
O-010	82	95	93	59	37
O-011	94	80	54	69	32
O-012	89	78	54	91	43
O-013	96	92	91	82	73
O-014	94	61	35	66	20
O-015	93	62	41	75	25
O-016	91	88	84	91	47
Average	93	76	61	81	41

Average Vol.% CO versus average process temperature in OXYFINES reactor for the batches in the campaigns are illustrated in Figure 19. The highest zinc separation in campaign 1 was found in batch O-009 (point in chart indexed 6), Figure 19, with a process temperature of ca 1260 °C and a Vol.% CO of ca 7.

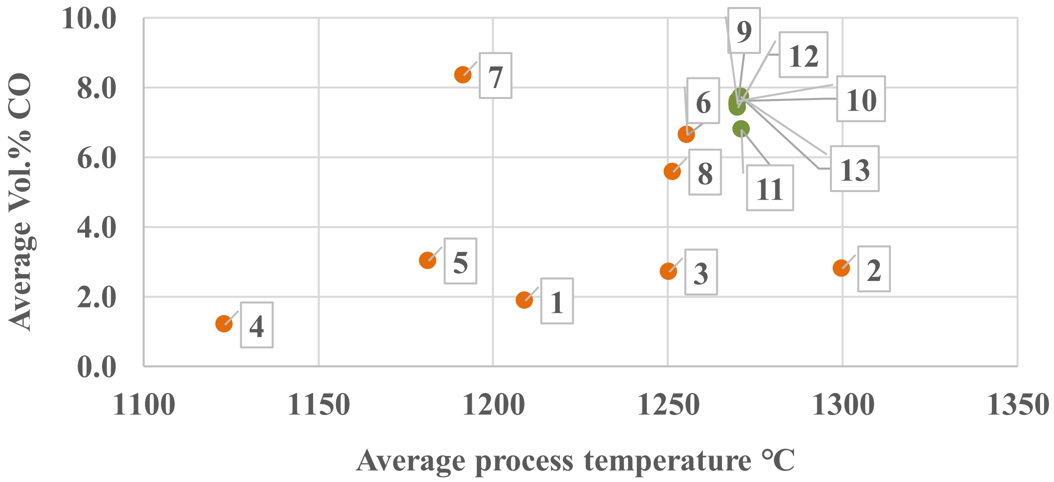


Figure 19. Average Vol.% CO versus average process temperature in OXYFINES reactor (campaign 1, orange colour and campaign 2 green colour). Points in chart are presented with index number for the respective batch.

The average zinc removal from the chemical analysis of campaign 1 was ca 80%. Though, the analysis results of batch O-006 showed unexpected low zinc separation (31%) which may be explained by the sampling of the sinter product. From the overall results of campaign 1, the zinc separation generally was increased with higher process temperature. An ideal CO content was found somewhere around 7 to 8 Vol, Figure 20 and 21. The target temperature and CO for campaign 2 was thereof set to be 8 Vol.% CO and 1270°C. This process setting was during campaign 2 proven successful with an average zinc removal in campaign 2 of ca 93%.

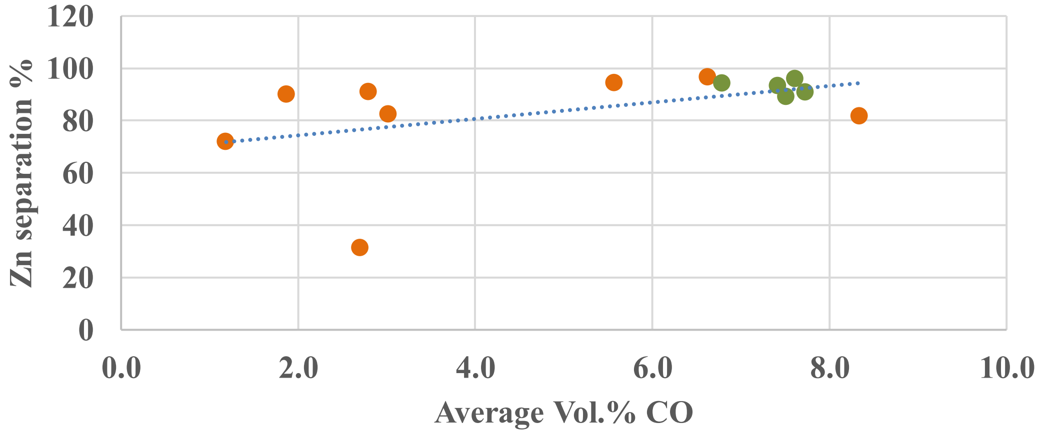


Figure 20. Zinc separation degree (%) at average Vol.% CO in OXYFINES reactor gas analysis (campaign 1, orange colour and campaign 2 green colour).

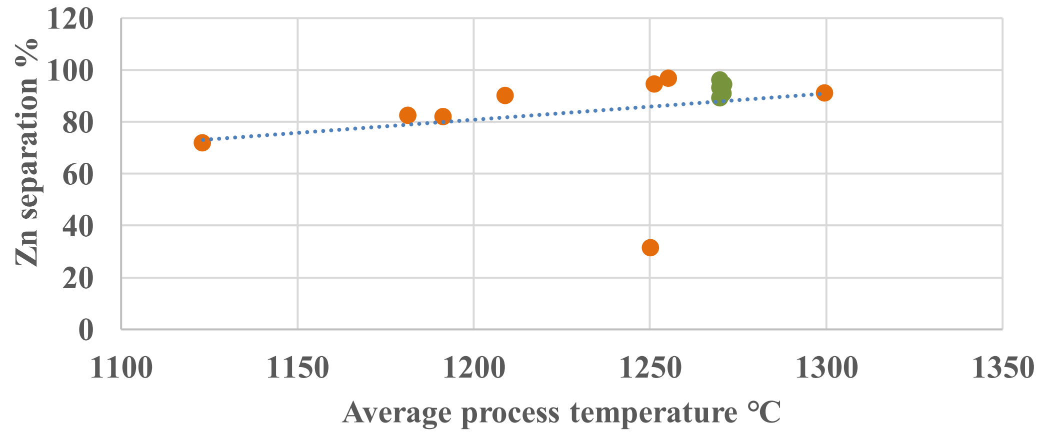


Figure 21. Zinc separation degree (%) at average OXYFINES process temperature (campaign 1, orange colour and campaign 2 green colour).

No obvious trend was found relative to the Vol.% CO for alkali, sulphur nor phosphorous. Nevertheless, lower process temperature seems to increase the alkali (i.e. Na and K) separation, Figures 22 and 23.

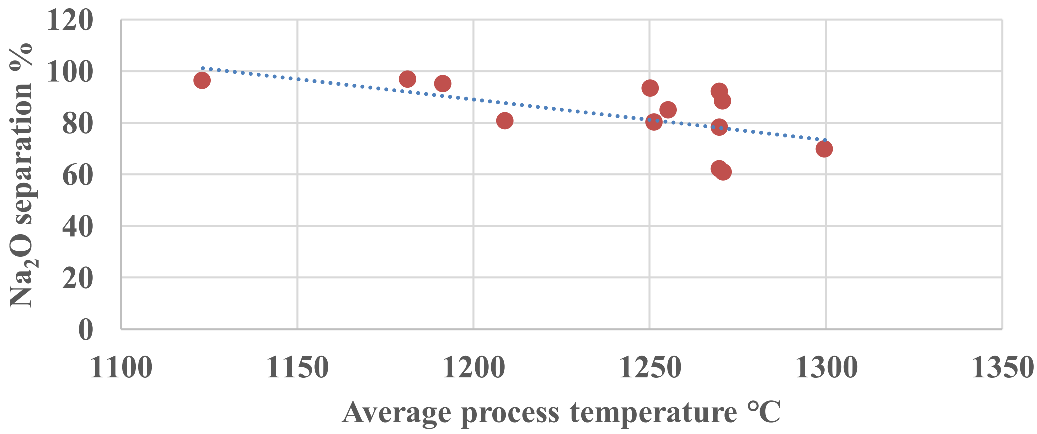


Figure 22. Na_2O separation degree (%) at average OXYFINES process temperature.

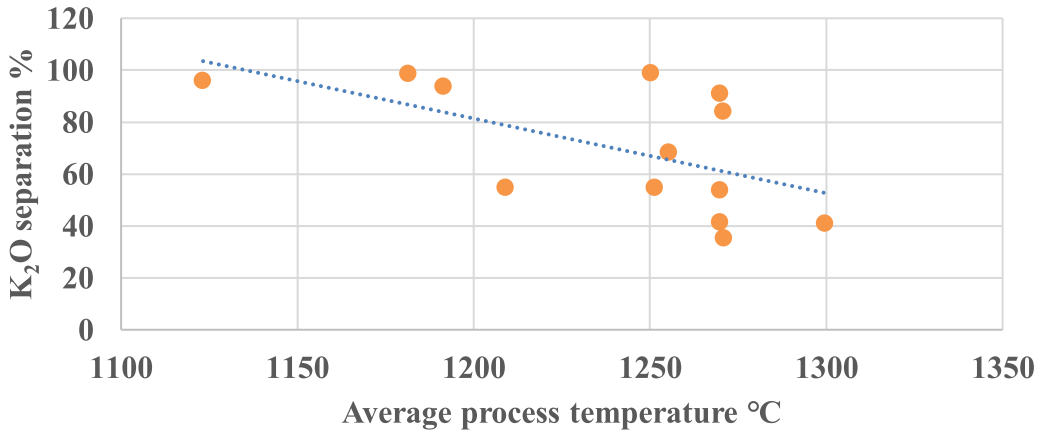


Figure 23. K_2O separation degree (%) at average OXYFINES process temperature.

From the total input of zinc, sulphur, phosphorous and sodium from the blast furnace sludge and sand in sandbox, the main parts of the zinc and sulphur was distributed to the dust, whereas phosphorous is mostly transferred into the sinter. The difference in sulphur is most likely from generated SO_2. The sodium results are uncertain due to the sinter reaction with the alkali rich sand, Table 16.

Table 16. Distribution of zinc (Zn), sulphur (S), phosphorous (P) and sodium (Na) from blast furnace (BF) sludge and sand in sandbox to sinter and to dust (kg).

Distribution	Total Zn (kg)	Diff.	Total S (kg)	Diff.	Total P (kg)	Diff.	Total Na_2O (kg)	Diff.
BF sludge	90.0	-6.5	39.4	21.5	18.7	4.1	15.3	102.5
Sand	0.4		0.6		4.4		127.8	
Sinter product	10.5		7.8		14.1		30.3	
Dust product	86.5		10.6		5.0		10.3	

Chemical analysis of samples from batches in campaigns

The results from chemical analysis of blast furnace sludge and generated sinter and dust is presented in Tables 17 to 21. The analysis of dust in campaign 1, from batch O-003 and O-002, failed to melt in the analysis procedure at SSABs analysis lab, hence no XRF (X-Ray Fluorescence) analyses were made on these samples. Regarding the analysis of the dust from batches O-006 through O-008 these were also difficult to melt whereby their XRF analysis results may be uncertain. Some of the dust samples from campaign 2, batch O-013 and three of the four samples for batch O-012, could not either be analysed by XRF. Sinter samples from batches O-013 and O-014 were additionally difficult to analyse. One sample from batch O-013 were therefore sent to ALS Scandinavia for analysis.

The average content in the blast furnace sludge analysis was for iron (Fe) ca 34%, for zinc (Zn) ca 0.79% and for coal (C) ca 24%, Table 17. In the sinter the average content based on all samples from the two campaigns was for iron ca 44%, for zinc ca 0.18% and for unreacted coal (C) ca 1.42%, Tables 18 and 19. Average iron content in the dust samples from campaigns was ca 43%, and the total average zinc contents in the dust was ca 3.85%. Total unreacted coal content was ca 1.35%, Table 20 and 21. In general, a higher degree of zinc separation and use of the coal content in the sludge was seen in campaign 2, for which the process temperature and Vol.% CO was optimised.

Table 17. Chemical analysis of blast furnace sludge from batches in campaigns, total sludge average and analysis of the sand used in the sandboxes for collecting the sinter product.

Content %	O-003	O-006	O-007	O-009	O-010	O-016	O-014	O-012	Sludge average	Sand
Fe	34.61	34.57	34.56	33.61	34.04	33.75	33.39	32.61	33.76	3.03
CaO	8.61	8.65	8.64	9.37	9.04	9.23	9.70	10.28	9.30	3.10
SiO_2	5.13	5.12	5.19	5.06	5.07	5.18	5.39	5.51	5.24	74.11
MnO	0.24	0.23	0.23	0.24	0.24	0.29	0.34	0.29	0.27	0.05
P_2O_5	0.16	0.16	0.16	0.16	0.16	0.16	0.17	0.18	0.17	0.16
Al_2O_3	2.11	2.12	2.14	2.10	2.10	2.13	2.21	2.25	2.16	14.87
MgO	1.47	1.45	1.46	1.38	1.39	1.41	1.44	1.41	1.43	1.33
Na_2O	0.12	0.13	0.13	0.14	0.12	0.12	0.13	0.17	0.13	4.64
K_2O	0.10	0.09	0.09	0.10	0.08	0.11	0.10	0.14	0.10	3.74
V_2O_5	0.25	0.24	0.24	0.23	0.23	0.23	0.23	0.21	0.23	0.03
TiO_2	0.29	0.29	0.28	0.28	0.28	0.28	0.28	0.27	0.28	0.36
Cr_2O_3	0.03	0.03	0.03	0.03	0.03	0.03	0.03	0.02	0.03	0.09
C_Leco	27.02	24.33	24.35	24.44	24.44	24.32	23.94	23.80	24.47	0.08
S_Leco	0.37	0.30	0.33	0.30	0.28	0.35	0.37	0.38	0.34	0.02
B2	1.68	1.69	1.66	1.85	1.78	1.78	1.80	1.87	1.77	
Zn	0.77	0.75	0.80	0.76	0.63	0.73	0.86	0.94	0.79	0.02

Table 18. Chemical analysis of the sinter product and sinter average from campaign 1.

Content %	O-002	O-003	O-006	O-007	O-007	O-007	O-008	O-009	O-009	O-010	O-010	O-011	Sinter average
Fe	44.25	34.35	51.96	35.66	52.38	52.02	48.38	47.95	61.18	46.32	53.63	45.63	47.81
CaO	10.24	9.82	12.64	8.51	13.40	13.04	13.17	12.72	17.56	13.48	14.23	12.69	12.63
SiO_2	20.88	29.65	7.47	5.11	7.92	7.65	9.81	16.73	9.02	7.10	7.69	19.73	12.40
MnO	0.32	0.27	0.33	0.24	0.37	0.36	0.38	0.37	0.45	0.34	0.37	0.34	0.35
P_2O_5	0.21	0.21	0.23	0.16	0.24	0.24	0.22	0.21	0.28	0.21	0.23	0.22	0.22
Al_2O_3	5.91	8.58	3.11	2.11	3.22	3.12	3.59	5.06	3.72	2.99	3.14	6.05	4.22
MgO	2.16	1.82	2.13	1.46	2.18	2.17	2.12	2.32	2.41	1.88	2.10	2.04	2.07
Na_2O	0.43	0.78	0.20	0.12	0.12	0.11	0.12	0.27	0.10	0.13	0.09	0.36	0.24
K_2O	0.79	1.21	0.03	0.06	0.13	0.12	0.04	0.49	0.14	0.12	0.10	0.65	0.32
V_2O_5	0.31	0.24	0.35	0.25	0.37	0.36	0.33	0.32	0.42	0.32	0.36	0.30	0.33
TiO_2	0.42	0.42	0.43	0.29	0.44	0.43	0.44	0.41	0.50	0.38	0.43	0.43	0.42
Cr_2O_3	0.16	0.10	0.09	0.08	0.07	0.06	0.27	0.28	0.06	0.07	0.07	0.09	0.12
C_Leco	0.06	0.07	0.16	23.36	0.22	0.08	0.08	0.08	0.12	9.29	0.10	0.07	2.81
S_Leco	0.06	0.06	0.03	0.33	0.10	0.10	0.03	0.02	0.35	0.32	0.13	0.17	0.14
B2	0.49	0.33	1.69	1.67	1.69	1.70	1.34	0.76	1.95	1.90	1.85	0.64	1.33
Zn	0.16	0.12	0.81	0.51	0.13	0.20	0.19	0.05	0.04	0.37	0.08	0.07	0.23

Table 19. Chemical analysis of the sinter product and sinter average from campaign 2.

Content %	O-012	O-012	O-013	O-013	O-014	O-014	O-015	O-015	O-016	O-016	Sinter average
Fe	45.33	46.18		52.53	30.29		28.75	27.08	49.07	47.55	40.85
CaO	12.51	17.76		7.39	12.13		10.71	10.42	13.21	12.49	12.08
SiO_2	13.93	10.34		4.95	33.91		32.44	36.31	7.59	15.69	19.40
MnO	0.42	0.39		0.36	0.41		0.32	0.29	0.45	0.43	0.38
P_2O_5	0.20	0.29		0.11	0.26		0.21	0.22	0.20	0.21	0.21
Al_2O_3	6.64	4.66		4.66	8.97		9.39	9.91	7.66	5.89	7.22
MgO	2.18	1.72		2.06	2.10		1.96	1.91	1.96	2.12	2.00
Na_2O	0.26	0.20		0.15	1.05		1.06	1.28	0.13	0.29	0.55
K_2O	0.44	0.08		0.13	1.39		1.36	1.54	0.05	0.42	0.68
V_2O_5	0.23	0.35		0.21	0.24		0.20	0.20	0.27	0.32	0.25
TiO_2	0.36	0.49		0.17	0.47		0.40	0.41	0.40	0.40	0.39
Cr_2O_3	0.34	0.04		0.01	0.05		0.05	0.06	0.05	0.05	0.08
C_Leco	0.11	0.03	0.07	0.00	0.04	0.02	0.05	0.02	0.05	0.04	0.04
S_Leco	0.06	0.01	0.16	0.13	0.18	0.15	0.10	0.11	0.02	0.12	0.10
B2	0.90	1.72		1.49	0.36		0.33	0.29	1.74	0.80	0.95
Zn	0.17	0.54	0.07	0.07	0.08	0.06	0.08	0.05	0.21	0.10	0.14

Table 20. Chemical analysis of the dust product, its average and the exit duct average from campaign 1.

Content %	Exit duct average	O-002	O-003	O-006	O-007	O-008	O-009	O-010	O-011	Dust average
Fe	51.51			39.07	41.47	41.70	46.05	46.97	46.96	43.70
CaO	12.42			10.21	10.13	10.38	11.32	11.58	11.53	10.86
SiO_2	2.65			5.17	5.10	4.77	3.49	3.43	3.30	4.21
MnO	6.67			7.20	6.59	7.01	7.10	7.17	7.27	7.06
P_2O_5	3.26			3.75	3.37	3.56	3.67	3.65	3.75	3.63
Al_2O_3	0.46			0.63	0.58	0.58	0.57	0.56	0.55	0.58
MgO	0.36			0.34	0.33	0.34	0.36	0.37	0.37	0.35
Na_2O	0.22			0.27	0.25	0.26	0.28	0.27	0.28	0.27
K_2O	0.48			1.35	1.41	1.09	0.61	0.56	0.51	0.92
V_2O_5	0.25			1.16	1.02	0.97	0.67	0.6	0.6	0.84
TiO_2	0.13			0.14	0.18	0.21	0.22	0.17	0.19	0.19
Cr_2O_3	0.14			0.16	0.18	0.17	0.09	0.10	0.13	0.14
C_Leco	0.05	3.81	3.16	1.93	2.65	2.73	0.84	1.43	0.59	2.14
S_Leco	0.12	0.70	0.70	0.86	0.76	0.85	0.41	0.39	0.35	0.63
Zn	0.89	2.8	2.7	**5.2**	3.8	4.5	3.6	3.2	3.9	3.71

Table 21. Chemical analysis of the dust product, its average and the exit duct dust from campaign 2.

Content %	Exit duct	O-012	O-012 average	O-013	O-013	O-014	O-014	O-015	O-015	O-016	O-016	O-016	Dust average
Fe	50.65	41.24			37.35	44.11	43.74	45.21	44.18	43.6	44.65	44.66	43.19
CaO	14.18	12.1			10.60	12.63	12.62	12.44	12.71	12.33	12.57	12.57	12.29
SiO_2	7.99	7.22			7.15	7.9	7.91	8.01	7.66	7.81	7.95	8.05	7.74
MnO	0.40	1.06			0.78	0.82	0.83	0.65	0.66	0.55	0.61	0.64	0.73
P_2O_5	0.24	0.23			0.24	0.26	0.26	0.27	0.26	0.27	0.27	0.28	0.26
Al_2O_3	3.23	3.12			3.06	3.38	3.37	3.42	3.3	3.52	3.43	3.48	3.34
MgO	2.09	3.39			3.41	3.03	3.08	2.82	2.65	2.54	2.67	2.76	2.93
Na_2O	0.12	0.63			0.38	0.54	0.59	0.5	0.58	0.57	0.52	0.54	0.54
K_2O	0.02	0.36			0.87	0.28	0.32	0.27	0.41	0.3	0.29	0.27	0.37
V_2O_5	0.34	0.24			0.26	0.29	0.29	0.31	0.27	0.31	0.31	0.32	0.29
TiO_2	0.42	0.31			0.30	0.36	0.36	0.37	0.34	0.37	0.38	0.38	0.35
Cr_2O_3	0.08	0.14			0.09	0.11	0.11	0.1	0.09	0.08	0.09	0.09	0.10
C_Leco	0.14	0.59	0.88	0.63	0.61	0.44	0.44	0.41	0.27	0.50	0.42	0.38	0.56
S_Leco	0.01	0.45	0.48	0.46	0.37	0.36	0.37	0.29	0.35	0.33	0.30	0.31	0.39
Zn	0.16	4.54	4.62	3.81	3.76	3.53	3.5	3.53	4.04	3.93	3.73	3.72	4.00

Chemical analysis for the comparison of oxidation states of blast furnace sludge and one sinter sample is presented in Table 22. The sludge was previously analysed whereas one sample from batch O-016 were sent to YN Nilab AB for analysis. The sample was analysed using titrimetric technique. The results obtained from the analysis show that the sinter iron contents are some 15% as Fe_2O_3, ca 36% as FeO and some 2.5% as elementary Fe and thereof in a more reduced state compared to the sludge.

Table 22. Iron oxidation states in BF sludge and in sinter sample from batch O-016.

	BF sludge	**Batch O-016**
Fe Ox.	**%**	**%**
Fe_{met}	0.53	2.51
Fe^{2+}	3.47	36.15
Fe^{3+}	33.84	14.71
Fe_{tot}	37.84	53.37

Results of industrial tests

The sinter product, Figure 24a and Table 23, was charged to the BOF, Figure 24b, together with the steel scrap, making use of its iron contents (i.e. some 44% of the total sinter amount). The OXYFINES sinter was charged in amounts of 1.2%, 1.6% and 2.4% of the total charge weight calculated on a constant liquid steel weight of 128 tonne per heat. The sinter generated in the pilot campaigns had a basicity B2 (i.e. CaO/SiO_2) of ca 1 which though may lead to an increased use of basic slag formers in the BOF. This is also due to the contents of SiO_2 from the sand inclusions in the sinter. Slag and steel samples from the BOF trials were analysed against reference charges. Evaluated results and analysis of slag and steel showed no negative effects from the input of the sinter product, thus it should be possible to use the sinter product as a raw material in the BOF.

(a) (b)

Figure 24. (a) The sinter product prior to charging in the BOF. (b) The BOF (SSAB Tunnplåt AB in Luleå), photo taken by Stig-Göran Nilsson (Jernkontoret).

Table 23. Average analysis for the OXYFINES sinter product from pilot trials

Content	(%)
Fe	44.33
CaO	12.69
SiO_2	16.93
MnO	0.37
P_2O_5	0.22
Al_2O_3	5.90
MgO	2.03
Na_2O	0.42
K_2O	0.54
V_2O_5	0.29
TiO_2	0.42
Cr_2O_3	0.10
C_Leco	1.42
S_Leco	0.12
B2	0.81
Zn	0.18

The dust product, Figure 25, generated from the two campaigns was analysed theoretically by Boliden based on its average composition, Table 24. The zinc content in the dust was too low, only up to ca 5% (i.e. ca 6% as ZnO) compared to the required >30% zinc to be regarded as an acceptable raw material in the zinc production process. The other constituents in the dust were comparable to the typical analysis of the iron dust today used in the zinc production. The generated dust was sent to Stena recycling and by them forwarded to Celsa Armeringsstål in Mo i Rana, Norway, a manufacturer of reinforcing steel using Electric Arc Furnace (EAF). The dust from the EAF is sent from Celsa to the zinc industry and by this both the dusts iron as well as its zinc content ended up being of further use in its respective industry.

Figure 25. Dust product in barrels and big bag to be sent off for further use.

Table 24. Average analysis for the OXYFINES dust product from pilot trials.

Content	(%)
Fe	43.45
CaO	11.57
SiO_2	5.98
MnO	3.89
P_2O_5	1.94
Al_2O_3	1.96
MgO	1.64
Na_2O	0.40
K_2O	0.65
V_2O_5	0.56
TiO_2	0.27
Cr_2O_3	0.12
C_Leco	1.35
S_Leco	0.51
Zn	3.85

During the test week with the changed dust briquettes, Figure 26, no negative effects on blast furnace operation were shown. The resulting zinc content in the blast furnace sludge was 1.13% zinc compared to an annual average for 2019 of 0.66%.

Figure 26. Cement-bound dust briquettes.

The results of the blast furnace briquette test were further used for calculations on possibilities for improving the OXYFINES dust zinc contents. These further evaluations were carried out via system analysis to create a comprehensive picture of various opportunities for material recycling in a full-scale implementation of the concept.

Results from system analysis

The results from the system analysis scenarios were compared to the reference system of SSAB Europe, Luleå. The system analysis was made with the focus to describe and compare the use of the OXYFINES sinter product in either blast furnace or basic oxygen furnace. Further the study was intended to investigate the effects on the blast furnace zinc load and the zinc content in the generated sludge to improve the upgrading of the OXYFINES zinc dust for facilitating its further use. From the defined system, the summarised results showed that the optimal metallurgical, environmental, and economic potential was found for the calculations of using the sinter in the basic oxygen furnace. However, the sinter is equally suitable for use in the blast furnace when considering mainly the metallurgical and the economic effects.

Results from system analysis on blast furnace calculations

The system analysis scenarios, of using the OXYFINES sinter as a raw material in the blast furnace, were made with regards to the three different sinter analysis and a charged amount of 4.7 kg sinter per tonne hot metal produced. Further analysis was made by increasing the zinc content in the BF dust briquette up to a zinc load of 150 g per tonne hot metal, Table 25.

Table 25. The analysed scenarios for blast furnace (BF) calculations.

Scenarios	Description	To BF
Reference	Reference scenario according to BF 2019, BOF 2016	**kg/tHM**
BF_1	Sinter product no.1 used in analysis (i.e. the average of 7 batches with less sand included), Zn in sinter **0.072%**	4.70
BF_2	Sinter product no. 2 used (i.e. the average of 2 "best batches" regarding separation of Zn and S), Zn in sinter **0.038%**	4.70
BF_3	Sinter product no. 3 used in analysis (i.e. the theoretically calculated), Zn in sinter **0.020%**	4.70
BF_1a	As scenario BF_1 with increased Zn in briquette to BF Zn load = 150g/tHM	4.70
BF_2a	As scenario BF_2 with increased Zn in briquette to BF Zn load = 150g/tHM	4.70
BF_3a	As scenario BF_3 with increased Zn in briquette to BF Zn load = 150g/tHM	4.70

Figure 27 is the illustrated zinc flow in the steel production system where the flow chart line thickness indicates the percentage of total yearly input and output zinc content for the respective material flow and the major zinc sources of the production system. The major zinc source to the BF is the BF briquettes and to the BOF the zinc is mainly from the steel scrap. Zinc is easily evaporated and thereby it is mostly found in the dust and sludge from the off-gas purification systems and found only in lesser amounts in slag and metal phases. The freshly generated blast furnace sludge with higher zinc content is put in sludge pond deposit, though parts of the old sludge with lower zinc content is used in the BF briquette. The proportion of generated BF dust and BF sludge amounts is ca 80:20 with the respective distribution of zinc of some 20:80.

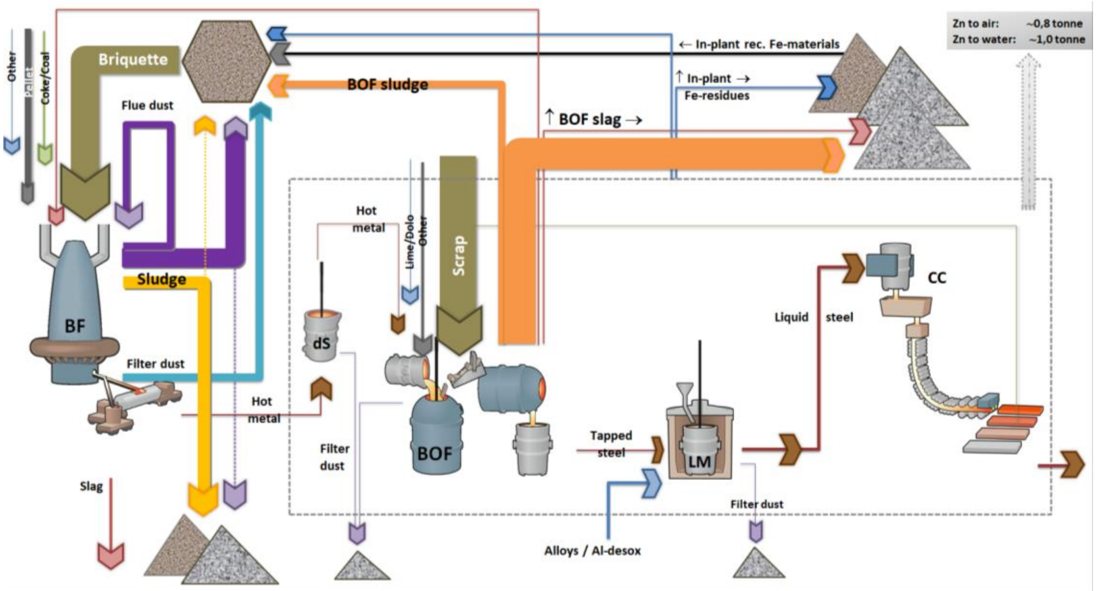


Figure 27. Schematic steel production system zinc flow chart.

System analysis results - zinc flow

The calculations on using the sinter in the blast furnace resulted in a slightly increase in BF zinc load, from 128 g/tHM in reference, to ca 130 g/tHM in the analysed scenarios. By increasing the calculated blast furnace zinc load to the set limit of 150 g/tHM, by increasing the zinc content in the briquettes, in turn increased the zinc content in the BF sludge to ca 1.4%. From the model calculations, using the BF briquette from the BF briquette trials (i.e. scenario: Mod. V1950) in the reference increased the zinc load to 189 g/tHM and thereof the sludge zinc content to some 1.7%, Table 26.

Table 26. Blast furnace (BF) zinc load, zinc content in sinter, briquette, dust and sludge.

Scenario	Ref.	BF_1	BF_2	BF_3	BF_1a	BF_2a	BF_3a	V1950	Mod. V1950
BF zinc load g/tHM	128	133	130	129	150	150	150	181	189
Zinc content %									
OXYFINES sinter	-	0.072	0.038	0.020	0.072	0.038	0.020	-	-
BF briquette	0.086	0.088	0.087	0.087	0.103	0.104	0.105	0.140	0.140
BF dust out	0.250	0.261	0.256	0.253	0.295	0.295	0.295	0.254	0.371
BF sludge out	1.175	1.225	1.201	1.189	1.383	1.382	1.382	1.130	1.742

From the calculations on BF zinc load and generated zinc content in the BF sludge, the resulting zinc content in the dust in a full-scale OXYFINES concept was calculated. For the OXYFINES full-scale concept a dust generation rate of 231 kg/h was assumed (based on 68 kg dust/processed tonne of dry BF sludge), Table 27.

From the reference scenario, with a BF zinc load of 128 g/tHM, and a BF sludge zinc content of 1,127%, this resulted in a zinc concentration in OXYFINES dust of 8.2%. Calculated scenarios with a BF zinc load of 150 g/tHM and 189 g/tHM (i.e. using the briquette from tests with high zinc content) resulted in zinc concentrations in the OXYFINES dust of 9.7% respective 12.2%.

Further, a calculation was made to determine the required zinc content in the BF sludge to achieve 30% zinc in the OXYFINES dust. Based on the defined assumptions for a full-scale concept, the required zinc content was indicated to be 4.29%. With a 97% separation degree of zinc in the OXYFINES process, the calculated zinc content of the sinter product was 0.165%. From BF model calculations, using the OXYFINES sinter with a zinc content of 0.165% zinc in turn resulted in a BF zinc load of 140 g/tHM.

Table 27. Calculation of zinc in dust based on OXYFINES full scale plant.

Bf zinc load	**BF Zn load 127 g/tHM (reference scenario)**	**BF Zn load 150 g/tHM**	**BF Zn load 189 g/tHM (BF briquette Zn 1.4%)**	**Required Zn in BF sludge to reach 30% Zn in OXYFINES dust**
Processed BF sludge, dry wt. (tonne/a)	12,000	12,000	12,000	12,000
Zn in BF sludge (%)	**1.175**	**1.382**	**1.742**	**4.290**
Zn in BF sludge (tonne/a)	**141**	**166**	**209**	**515**
OXYFINES process				
Availability 90% of 8000 (h)	7,200	7,200	7,200	7,200
Sludge feeding rate (tonnes/h)	3.4	3.4	3.4	3.4
Used input coal in sludge (%)	24	24	24	24
dZn (%)	97	97	97	97
OXYFINES products				
<u>Sinter</u>				
Production (tonne/h)	1.3	1.3	1.3	1.3
-”- (tonne/a)	9,360	9,360	9,360	9,360
Zn in sinter (tonne/a)	**4**	**5**	**6**	**15**
Zn in sinter (%)	**0.05**	**0.05**	**0.07**	**0.17**
<u>Dust</u>				
Production (tonne/h)	0.231	0.231	0.231	0.231
-”- (tonne/a)	1,665	1,665	1,665	1,665
Zn in dust (tonne/a)	**137**	**161**	**203**	**499**
Zn in dust (%)	**8.2**	**9.7**	**12.2**	**30.0**

BF scenarios results - effects on charged raw material amounts

The calculated results on charged raw materials from using the sinter product in the blast furnace compared to the reference are mainly a reduced need for iron ore pellet of ca 3 kg/tHM or some 6.6 ktonne/a due to the sinter Fe content. A minor increase in Mn slag use, ca 0.1 kg/tHM, was calculated, due to less input from charged BOF slag. The BOF slag use in the BF was decreased with some 1.6 kg/tHM or about 3.2 ktonne/a to prevent the phosphorous content in the HM exceeding its maximum level of 0.035%. The best scenario compared to the reference, considering the raw material efficiency, was BF_2 using the sinter with the highest Fe and CaO contents, Table 28.

Table 28. BF charged raw materials, kg/tonne hot metal (HM) (italic numbers and *na* = not affected).

Scenario	Ref.	BF_1	BF_2	BF_3	BF_1a	BF_2a	BF_3a	Opt. (BF_2)
Iron ore pellet	1329.58	1326.58	1326.25	1326.60	1326.58	1326.25	1326.60	-3.33
Mn briquette	0.00	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*na*
Scrap mix	33.90	*33.90*	*33.90*	*33.90*	*33.90*	*33.90*	*33.90*	*na*
Limestone	27.58	27.69	27.58	27.79	27.69	27.58	27.79	*na*
Quartzite	0.00	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*0.00*	*na*
BOF slag	21.14	19.78	19.52	19.48	19.78	19.52	19.48	-1.62
Mn carrier	0.42	0.50	0.52	0.53	0.50	0.52	0.53	0.10
OXYFINES sinter	0.00	4.70	4.70	4.70	4.70	4.70	4.70	4.70
BF briquette	99.70	*99.70*	*99.70*	*99.70*	*99.70*	*99.70*	*99.70*	*na*

The charged coal sources raw materials were unaffected. In scenario BF_1, the results show a minor decrease in the coke rate due to some unreacted coal rests in the OXYFINES sinter product, Table 29.

Table 29. BF charged coal sources raw materials, kg/tonne HM.

Scenario	Ref.	BF_1	BF_2	BF_3	BF_1a	BF_2a	BF_3a
Coke	311.51	311.44	311.56	311.52	311.44	311.56	311.52
PCI	135.50	*135.50*	*135.50*	*135.50*	*135.50*	*135.50*	*135.50*
BF dust inj.	6.50	*6.50*	*6.50*	*6.50*	*6.50*	*6.50*	*6.50*

BF scenarios results - effects on hot metal (HM) analysis

The phosphorous (P) content in the HM from the blast furnace were in the calculations kept at its maximum level (0.035%) by using less BOF slag (ca 1.5 kg/tHM). Other element contents such as sulphur in HM were unaffected by the sinter additions, only a minor decrease in vanadium content were calculated because of less BOF slag to the BF. As there was no effect on sulphur content in the HM, consequently HM desulphurisation was unaffected from the use of OXYFINES sinter in the BF, Table 30.

Table 30. Effects on hot metal analysis (%).

Scenario	Ref.	BF_1	BF_2	BF_3	BF_1a	BF_2a	BF_3a
Si	0.411	*0.411*	*0.411*	*0.411*	*0.411*	*0.411*	*0.411*
Mn	0.210	*0.210*	*0.210*	*0.210*	*0.210*	*0.210*	*0.210*
V	0.318	0.315	0.314	0.314	0.315	0.314	0.314
Ti	0.104	*0.104*	*0.104*	*0.104*	*0.104*	*0.104*	*0.104*
P	0.035	*0.035*	*0.035*	*0.035*	*0.035*	*0.035*	*0.035*
S	0.049	*0.049*	*0.049*	*0.049*	*0.049*	*0.049*	*0.049*
Ni	0.034	*0.034*	*0.034*	*0.034*	*0.034*	*0.034*	*0.034*
Cr	0.035	*0.035*	*0.035*	*0.035*	*0.035*	*0.035*	*0.035*

BF scenarios results - effects on BF slag rate and BOF slag recycling

By the calculated sinter product use, a BF slag rate increase by some 0.7 ktonne/a and a BOF slag recycling decrease by some 2% was shown, whereby the BOF slag to storage also somewhat increased. Though, the calculations indicate that sinter use has insignificant effects on BF slag analysis. The best scenario was also in this regard the BF_2, Table 31.

Table 31. Effects on BF slag rate and BOF slag recycling.

Scenario	Ref.	BF_1	BF_2	BF_3	BF_1a	BF_2a	BF_3a	Opt. (BF_2)
BF slag rate (kg/tHM)	166.87	167.35	167.26	167.13	167.35	167.26	167.13	0.39
BF slag generated (ktonne/a)	332.54	333.51	333.31	333.06	333.51	333.31	333.06	0.77
BOF slag to storage (ktonne/a)	138.84	141.66	142.18	142.33	141.66	142.19	142.31	3.34
BOF slag to BF (ktonne/a)	49.06	45.89	45.27	45.18	45.89	45.27	45.18	-3.79
BOF slag to BF (%)	26.11	24.47	24.15	24.10	24.47	24.15	24.10	-1.96

BF scenarios results - effects on CO_2 emissions and energy

A minor increase in CO_2 emissions, Table 32, were calculated in the scenarios of using the sinter in the BF (in total some 0.5 ktonne CO_2 increase per year compared to the reference). Regarding the energy use, Table 33, the total energy required in the process system increased ca 0.2 GWh/a. The best scenario regarding the least increase in CO_2 was scenario BF_2, considering the energy effect, the best scenario was BF_3. These results are an effect of total raw materials charge and by the relative input of coal contents.

Table 32. Difference in CO_2 emission from BF and BOF in scenarios compared to reference.

Scenario	Ref.	BF_1	BF_2	BF_3	BF_1a	BF_2a	BF_3a	Opt. (BF_2)
BF, kg/tonne HM		0.25	0.19	0.23	0.25	0.19	0.23	0.19
BOF, kg/tonne LS		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tot. kg/tonne LS		0.29	0.17	0.25	0.29	0.18	0.25	0.17
BF, ktonne/a		0.60	0.37	0.53	0.61	0.38	0.52	0.37
BOF, ktonne/a		0.00	0.00	0.00	0.00	0.00	0.00	0.00
Tot. kg/tonne HM		0.24	0.19	0.23	0.24	0.19	0.23	0.19
Tot. ktonne/a		0.60	0.37	0.53	0.60	0.38	0.52	0.37
kg HM/kg LS	0.95	0.95	0.95	0.95	0.95	0.95	0.95	

Table 33. Difference in energy use in BF and BOF in scenarios compared to reference.

Scenario	Ref.	BF_1	BF_2	BF_3	BF_1a	BF_2a	BF_3a	Opt. (BF_3)
BF, GWh/a		0.40	0.23	0.17	0.40	0.23	0.17	0.17
BOF, GWh/a		-0.01	-0.01	0.00	-0.01	-0.01	-0.01	0.00
Total, GWh/a		0.39	0.22	0.17	0.39	0.22	0.16	0.17
kg HM/kg LS	0.95	0.95	0.95	0.95	0.95	0.95	0.95	

Results from system analysis on basic oxygen furnace calculations

The system analysis scenarios of using the OXYFINES sinter as a raw material in the basic oxygen furnace were made with regards to the three different sinter analysis and a charged amount of 4.46 kg sinter per tonne liquid steel produced, Table 34.

Table 34. The analysed scenarios for basic oxygen furnace (BOF) calculations.

Scenarios	Description	To BOF
Reference	Reference scenario according to BF 2019, BOF 2016	**kg/tLS**
BOF_1	Sinter product no.1 used in analysis (i.e. the average of 7 batches with less sand included), Zn in sinter **0.072%**	4.46
BOF_2	Sinter product no. 2 used (i.e. the average of 2 “best batches” regarding separation of Zn and S), Zn in sinter **0.038%**	4.46
BOF_3	Sinter product no. 3 used in analysis (i.e. the theoretically calculated), Zn in sinter **0.020%**	4.46

The prerequisites for the calculations of using the sinter as a raw material in the BOF were, depending on heat balance, primarily to reduce the amount of iron ore pellet added.

BOF scenarios results – effects on charged material amounts

The calculated results on charged BOF raw materials from using the OXYFINES sinter product in the BOF, compared to the reference, were mainly from reduced consumption of iron ore pellet, of ca 1.2 kg/tHM or some 2.5 ktonne/a, and reduced HM input to the BOF, of some 1.2 kg/tLS or some 2.5 ktonne/a, due to the sinter Fe content. The use of basic slag formers was somewhat increased by ca 0.5 kg burnt lime/tLS and ca 0.4 kg dolomitic lime/tLS (roughly 1 ktonne/a of each) due to the OXYFINES sinter basicity and the sinter CaO content. The optimal scenario considering the raw material efficiency was BOF_2 due to the highest Fe and CaO content in the sinter no 2, Table 35.

Table 35. BOF charged raw materials, kg/tonne liquid steel (LS) (italic numbers and *na* = not affected).

Scenario	Ref.	BOF_1	BOF_2	BOF_3	Opt. (BOF_2)
Hot metal	898.03	897.01	896.86	896.96	-1.16
Steel scrap	174.51	*174.51*	*174.51*	*174.51*	*na*
Burnt lime	29.57	30.13	30.04	30.03	0.47
Iron ore pellet	7.50	6.46	6.27	6.37	-1.23
OXYFINES sinter	0.00	4.48	4.48	4.48	4.48
FeSi	0.36	*0.36*	*0.36*	*0.36*	*na*
Returned steel	15.89	*15.89*	*15.89*	*15.89*	*na*
Dolomitic lime	24.26	24.71	24.64	24.63	0.39

BOF scenarios results – effects on P & S contents in LS

There was virtually no effect on the liquid steel (LS) quality regarding P and S contents from using the sinter, Table 36.

Table 36. Effects on liquid steel (LS) analysis (%).

Scenario	Ref.	BOF_1	BOF_2	BOF_3
P in LS	0.0082	0.0081	0.0081	0.0081
S in LS	0.0043	0.0045	0.0043	0.0044

BOF scenarios results – effects on slag

By using the sinter, the BOF slag rate increased by some 2.6 kg/tLS or ca 5.6 ktonne/a, Table 37. The sinter effects on BOF slag chemical analysis were insignificant.

Table 37. Effects on BOF slag, slag rates and BOF slag recycling.

Scenario	Ref.	BOF_1	BOF_2	BOF_3	Opt. (BOF_3)
BF slag (ktonne/a)	332.54	332.17	332.11	332.15	-0.39
BOF slag generated (kg/tLS)	89.48	92.49	92.46	92.15	2.67
BOF slag generated (ktonne/a)	187.92	194.22	194.16	193.52	5.60
BOF slag to storage (ktonne/a)	138.85	145.16	145.09	144.45	5.60
BOF slag to BF (ktonne/a)	49.07	49.07	49.07	49.07	*na*
BOF slag to BF (%)	26.11	25.26	25.27	25.35	-0.76

BOF scenarios results - effects on CO_2 emissions and energy

The calculated effects from using the sinter product in the BOF were a decreased total CO_2 emission (in the optimal scenario by some 3.2 ktonne CO_2 decrease/a), Table 38, and decreased energy use in both BF and BOF (total energy decrease ca 3.6 GWh/a), Table 39. This is mainly from the decreased hot metal demand in the BOF.

Table 38. Difference in CO_2 emission from BF and BOF in scenarios compared to reference.

Scenario	Ref.	BOF_1	BOF_2	BOF_3	Opt. (BOF_2)
BF, kg/tHM		0.00	0.00	0.00	na
BOF, kg/tLS		0.38	0.04	0.02	0.04
Total, kg/tLS		-0.95	-1.49	-1.38	-1.49
BF, ktonne/a		-2.81	-3.23	-2.96	-3.23
BOF, ktonne/a		0.80	0.08	0.04	0.08
Total, kg/tHM		0.58	0.25	0.21	0.25
Total, ktonne/a		-2.01	-3.15	-2.92	-3.15
kg HM/kgLS	0.95	0.94	0.94	0.94	0.001

Table 39. Difference in energy in BF and BOF in scenarios compared to reference.

Scenario	Ref.	BOF_1	BOF_2	BOF_3	Opt. (BOF_2)
BF, GWh/a		-2.60	-2.99	-2.74	-2.99
BOF, GWh/a		0.72	-0.57	-0.56	-0.57
Total, GWh/a		-1.88	-3.55	-3.30	-3.55
kg HM/kgLS	0.95	0.94	0.94	0.94	0.001

Cost effects calculations

The summarised positive and negative effects, and thereof the potential cost savings, from using the sinter product in the separate BF and BOF processes, and on the total system analysed, were calculated, Table 40 and 41. From the calculations and by the comparative cost effect against the reference cost, indicating sinter product values were recognised.

Decreased hot metal, iron ore pellet and oxygen use are the main influencing factors on the cost effects in the BOF scenarios. Some cost effects are added from considering the process chain (i.e. BF, deS and BOF) with the summarised effect mainly from the decreased hot metal demand in BOF.

Based on raw material prices and calculated process effects mainly by raw materials quantities, the following approximate values for OXYFINES sinter were calculated:

- Average of 625 SEK/t in BF scenarios (valuation cost effects BF separately)
- Average of 660 SEK/t in BF scenarios (total effects valuation incl. BF, deS, BOF)

The highest sinter value in analysed BF scenarios was 712 SEK/tonne and the lowest value was 588 SEK/tonne.

- Average of 590 SEK/t in BOF scenarios (valuation cost effects BOF separately).
- Average of 598 SEK/t in BOF scenarios (total effects valuation incl. BF, deS, BOF).

The highest sinter value in analysed BOF scenarios was 676 SEK/tonne and the lowest value was 502 SEK/tonne.

Table 40. Difference cost in analysed BF scenarios

BF	Hot metal	Difference cost	OXYFINES sinter	OXYFINES sinter	Valuation BF sep.	Valuation total incl. deS & BOF
Scenario	**ktonne/a**	**MSEK/a**	**kg/tHM**	**ktonne/a**	**SEK/t**	**SEK/t**
Ref.	1,992.83	-	-		*na*	*na*
BF_1	1,992.91	4,229.33	4.7	9.4	619	646
BF_2	1,992.82	4,228.86	4.7	9.4	669	712
BF_3	1,992.88	4,229.62	4.7	9.4	588	622

Table 41. Difference cost in analysed BOF scenarios

BOF	Liquid steel	Difference cost	OXYFINES sinter	OXYFINES sinter	Valuation BOF sep.	Valuation total incl. deS & BF
Scenario	**ktonne/a**	**MSEK/a**	**kg/tLS**	**ktonne/a**	**SEK/t**	**SEK/t**
Ref.	2,100.00	-	-	-	*na*	*na*
BOF_1	2,100.00	5,520.32	4.5	9.4	502	510
BOF_2	2,100.00	5,518.76	4.5	9.4	668	676
BOF_3	2,100.00	5,519.40	4.5	9.4	600	607

Results from commercialisation

The proposals on a commercialisation and business plan for a full-scale OXYFINES concept were prepared as a starting point for the further refinement of the concept. The outline of a full-scale plant is firstly depending on the dewatering possibilities and options. The proposals include the heat and mass balance calculations and a rough cost analysis of the OXYFINES plant based on the different layout cases. The cases depend on amounts of BF sludge for treatment per year, moisture content of the sludge and variations in the technical requirements thereof, such as reactor design, material handling, burner systems, cooling systems, and exhaust gas purification. The OXYFINES cases regarding cost, handling, investments, and outcomes are calculated as indicating results in comparison to today's blast furnace sludge deposit.

The opportunities for a full-scale plant were presented and discussed on a workshop held at SSAB in Luleå on November 27, 2019 titled: *Opportunities for a full-scale plant where zinc-containing dust/sludge is processed with AGA's OXYFINES technology.* At the workshop, results from the project's pilot campaigns as well as the proposals for a plant on production scale were presented.

Case comparison

Three different cases, Figure 28, were defined and calculated depending on different water content in sludge before charging into the OXYFINES process. Decreased water contents in the sludge improves the OXYFINES process efficiency and capacity. However, decreasing the water content in the sludge results in additional handling and equipment for the further drying of the sludge, hence increasing the plant concept related costs. The calculations were made for the total recovery of 12,000 tonnes of dry sludge per year. The calculations were on 6,000 tonnes sludge (dry weight) from the blast furnace gas purification plus 6,000 tonnes sludge (dry weight) from the sludge deposit in sludge ponds. The calculated cases were:

- Case 1, where moisture content in the blast furnace sludge to the OXYFINES process is 50%.
- Case 2, where moisture content in the blast furnace sludge to the OXYFINES process is 35%.
- Case 3, where moisture content in the blast furnace sludge to the OXYFINES process is 10%.

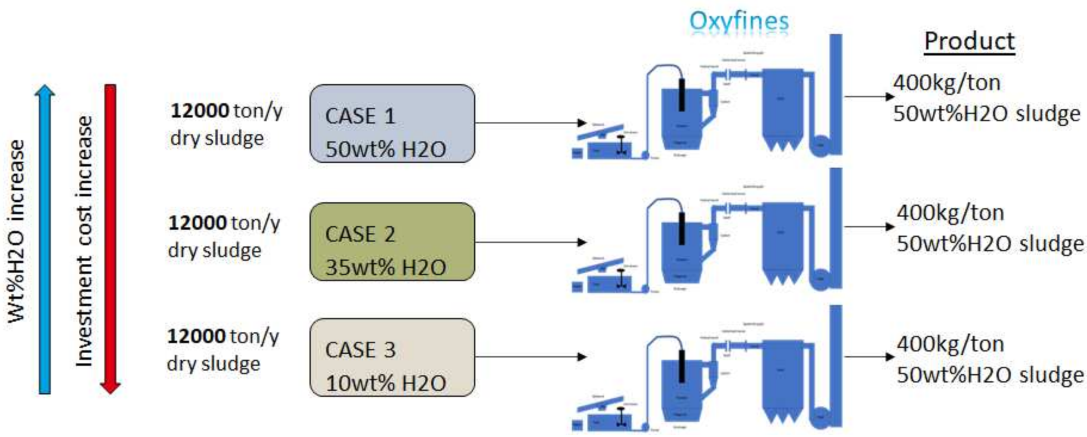


Figure 28. Cases for the full-scale plant calculations and comparisons.

For the comparison with today's sludge deposit, a reference base case (i.e. case 0) for the deposit was defined. Based on the sludge pond deposit capacity of 50,000-70,000 tonne sludge per deposit a new deposit is required every 5-7 years. The investment cost in new sludge deposit is approximately 25 - 50 MSEK for ca 12,000 tonne of sludge generated per year which equals 60,000 tonnes over five years. The calculated related sludge handling cost is estimated to 6 MSEK per year. This resulting in a total cost between 916 SEK/tonne of 50wt.% moisture in sludge and 1,333 SEK/tonne of 50wt.% moisture in sludge.

Mixing 6,000 tonne sludge (dry weight) per year from the gas purification (96wt.% moisture) with 6,000 tonne sludge (dry weight) per year from sludge deposits (55wt.% moisture) results in an average 92.6 wt.% moisture in a total sludge amount of 163,333 tonnes per year for treatment, Figure 29. All the three cases require pre-treatment in sedimentation tank down to 50 wt.% moisture content. However, for further dewatering to a moisture content in the sludge of 35wt.% in case 2, a press filter is required. For the even further dewatering of the sludge, down to a moisture content of 10 wt.%, also drying in a furnace is necessary, Figure 29.

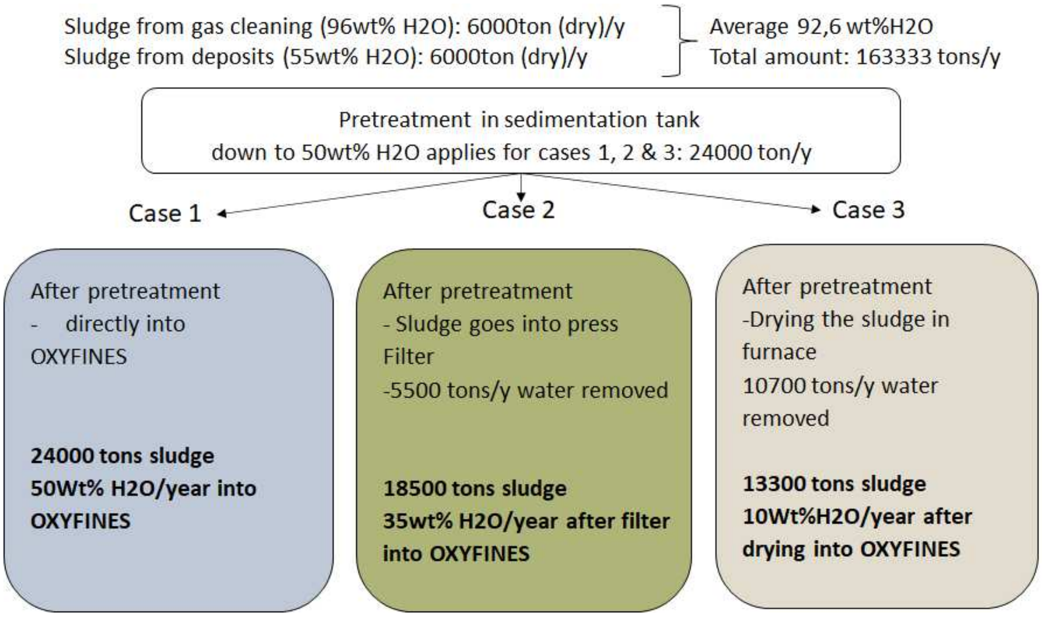


Figure 29. Cases for different moisture in sludge to OXYFINES process.

Basic estimation for a full scale OXYFINES process unit

A rough cost estimation for a full scale OXYFINES process unit, based on a capacity for the recovery of 4 tonne per hour of blast furnace sludge with a moisture content of 50 wt.%, is in the range of 30 – 40 MKR. Prospects and cost for buildings, construction, and media, which has a significant impact on the summarised cost for a total plant description, are not included in this evaluation. Also, scenarios for bringing the sludge to the OXYFINES process unit from sludge pond and from exhaust gas purification system require specification.

Design of the separate full-scale OXYFINES process unit, Figure 30, and its related layout (Appendix 7a – 7i), includes the following estimation of required equipment:

- Reactor
- Ladles x4
- Ladle car
- Burners and flow trains
- Ducts and water-cooled duct
- Cyclone
- Filter, Fan and Chimney
- Tanks, Pumps and Sieves
- Control system and Programming
- Piping, Mechanical, Electrical
- Erection
- Project, Design
- Others and unexpected

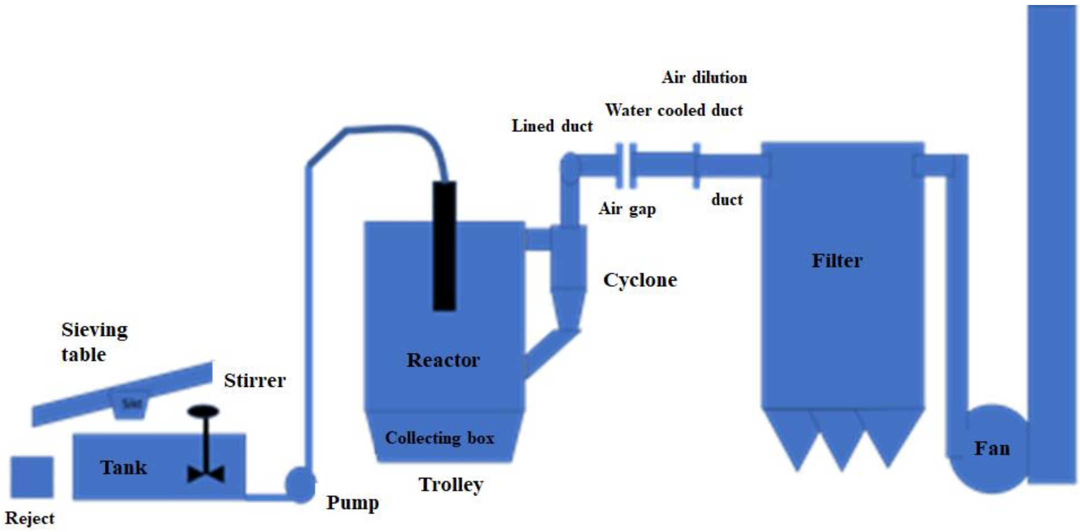


Figure 30. Process lay-out for a full-scale OXYFINES process unit.

Comparative case cost estimations

The calculated costs are indicative costs related to the consumptions, investments, and handling in each of the cases, presented in Table 42. The case comparison to the today's deposit in sludge ponds are made by comparison to costs for a new deposit per tonne of sludge. The costs are calculated in relation to the costs of a new landfill deposit. The cost for a new sludge deposit is in the range of 25 MSEK to 50 MSEK.

OXYFINES process related equipment and a sedimentation tank in case 1, equals the lowest costs per tonne of sludge though entails the highest sludge moisture content to the OXYFINES unit. This is due to the less need for sludge handling and investment for drying. Regarding case 2 and case 3 the costs in relation to the case 0 is increased by the increased dewatering capacity. Considering the case 3, there will be an excess energy in the OXYFINES process which can be used for recirculating the dust and for recovery of other residual materials.

Table 42. Cost calculations for the defined cases.

	CASE 0	CASE 1	CASE 2	CASE 3
Amount of sludge (50wt%)	12000 ton/y	240000 ton/y	24000ton/y	24000ton/y
	CONSUMPTIONS			
LPG (Nm3/ton)	0	28	10	17
O2 (Nm3/ton)	0	222	145	108
LPG Cost (SEK/Nm3)	0	4	4	4
O2 Cost (SEK/Nm3)	0	1,3	1,3	1,3
Tot. Cost (SEK/ton)		**400 SEK/ton**	**228 SEK/ton**	**208 SEK/ton**
	INVESTMENTS			
New Deposit	25-50 MSEK	0	0	0
Sedimentation tank	0	5 MSEK	5 MSEK	5 MSEK
Oxyfines	0	35 MSEK	40 MSEK	40 MSEK
Press Filter	0	0	10 MSEK	0
Drying furnace	0	0	0	15 MSEK
Tot. investment Cost	25-50 MSEK	40 MSEK	55 MSEK	60 MSEK
Tot. Investment cost(SEK/ton)	**417-833 SEK/ton**	**333 SEK/ton**	**458 SEK/ton**	**500 SEK/ton**
	HANDLING			
Handling cost	6 MSEK/y	8 MSEK/y	10 MSEK/y	12 MSEK/y
Tot. handling cost(SEK/ton)	**500 SEK/ton**	**333 SEK/ton**	**416 SEK/ton**	**500 SEK/ton**
Product value	0 SEK/ton	400 SEK/ton	400 SEK/ton	400 SEK/ton
Total cost per ton	**917-1333 SEK/ton**	**667 SEK/ton**	**703 SEK/ton**	**808 SEK/ton**
Savings compared to Case0		**249-666 SEK/ton**	**213-629 SEK/ton**	**108-525 SEK/ton**
				530 kW

Calculated heat and mass balance

Calculation examples are made for using propane or coke oven gas in the OXYFINES concept for a full-scale plant, Tables 43 to 46. The calculations are based on results in pilot campaigns (i.e. actual results) and further calculated with reduced leakage air, with 60% and 50% moisture content in sludge, and for an upscaling to a full-scale plant with moisture levels of 50%, 35% and 10%.

Due to the lower energy value in coke oven gas compared to propane, the required amount is higher. However, using coke oven gas will decrease the CO_2 emissions from the process, and a cost saving can be foreseen as well.

If the sludge fed to the OXYFINES process is drier, i.e. 10% moisture content, there will be an excess energy that can be utilised for recirculating the generated dust for accumulating the zinc content up to at least 30%. Otherwise the excess energy could be utilised for the enhanced treatment of other iron-rich and zinc-containing, but low-coal materials (e.g. mill scale).

Table 43. Mass balance using propane for energy in the OXYFINES process.

	Actual results	**Reduced leak air**	**Reduced water**	**Scaled 4 ton/h**	**Scaled 35 wt.%**	**Scaled 10 wt.%**
Propane flow Nm^3/h	68	52	41	111	41	6
Oxygen flow Nm^3/h	237	286	258	886	578	430
Propane for drying Nm^3/h						60
Propane Nm^3/ton sludge	**76**	**58**	**45**	**28**	**10**	**17**
Oxygen Nm^3/ton sludge	**264**	**318**	**287**	**222**	**145**	**108**
Feeding rate kg/min	15	15	15	67	52	38
wt.% H_2O	60	60	50	50	35	10
wt.% dry sludge	40	40	50	50	65	90
Process temp	1270	1270	1270	1270	1270	1270
CO Vol.% dry off-gas	8	8	8	8	8	8
Leak Air Nm_3/min	5.8	1.0	1.0	4.0	4.0	4.0
Off-gas from reactor						
H_2O Nm^3/min	14.41	13.94	11.30	46.44	23.03	2.95
H_2 Nm^3/min	1.40	0.78	0.78	2.74	2.36	2.18
CO Nm^3/min	1.12	0.62	0.63	2.19	1.89	1.74
CO_2 Nm^3/min	4.89	4.57	4.61	17.61	14.46	13.00
O_2 Nm^3/min	0.00	0.00	0.00	0.00	0.00	0.00
SO_2 Nm^3/min	0.01	0.01	0.02	0.08	0.08	0.08
N_2 Nm^3/min	6.57	1.80	1.80	4.80	4.80	4.80
Off-gas dry tot Nm^3/min	13.99	7.78	7.84	27.42	23.58	21.80
Off-gas wet tot Nm^3/min	28.41	21.73	19.13	73.85	46.61	24.75
Off-gas wet tot m^3/min (1270 °C)	161	123	108	417	263	140
Off-gas wet tot m^3/s (1270 °C)	2.7	2.0	1.8	7.0	4.4	2.3
Reactor volume m^3	12	12	12	46	29	16
Residence time s	4.4	5.8	6.6	6.6	6.6	6.6

Table 44. Mass balance using coke oven gas for energy in the OXYFINES process.

	Actual results	**Reduced leak air**	**Reduced water**	**Scaled 4 ton/h**	**Scaled 35wt.%**	**Scaled 10 wt.%**
Coke oven gas flow Nm^3/h	329	251	196	535	196	6
Oxygen flow Nm^3/h	235	285	257	883	577	409
Coke oven gas for drying Nm^3/h						288
Coke oven gas Nm^3/ton sludge	**365**	**279**	**217**	**134**	**49**	**74**
Oxygen Nm^3/ton sludge	**262**	**317**	**285**	**221**	**144**	**102**
Feeding rate kg/min	15	15	15	67	52	38
wt.%H_2O	60	60	50	50	35	10
wt.% dry sludge	40	40	50	50	65	90
Process temp	1270	1270	1270	1270	1270	1270
CO Vol.% dry off-gas	8	8	8	8	8	8
Leak Air Nm^3/min	5.8	1.0	1.0	4.0	4.0	4.0
Off-gas from reactor						
H_2O Nm^3/min	16.51	15.55	12.54	49.86	24.29	2.70
H_2 Nm^3/min	1.26	0.67	0.70	2.51	2.27	2.15
CO Nm^3/min	1.01	0.54	0.56	2.01	1.82	1.72
CO_2 Nm^3/min	3.72	3.67	3.91	15.71	13.76	12.76
O_2 Nm^3/min	0.00	0.00	0.00	0.00	0.00	0.00
SO_2 Nm^3/min	0.01	0.01	0.02	0.08	0.08	0.08
N_2 Nm^3/min	6.57	1.80	1.80	4.80	4.80	4.80
Off-gas dry tot Nm^3/min	13	7	7	25	23	22
Off-gas wet tot Nm^3/min	2 9	22	20	75	47	24
Off-gas wet tot m^3/min (1270 °C)	164	126	110	424	266	137
Off-gas wet tot m^3/s (1270 °C)	2.7	2.1	1.8	7.1	4.4	2.3
Reactor volume m^3	12	12	12	45	29	15
Residence time s	4.3	5.6	6.4	6.4	6.4	6.4

Table 45. Heat balance using propane for energy in the OXYFINES process.

	Actual results	Reduced leak air	Reduced water	Scaled 4 ton/h	Scaled 35wt.%	Scaled 10 wt.%
Heat Balance						
Combustion of C to CO_2	556	660	857	3957	4061	4144
Combustion of propane kW	1736	1326	1034	2823	1034	152
Combustion of S top SO_2 kW	6	6	8	34	34	35
Sum input kW	2297	1993	1899	6814	5129	4331
Vaporisation of water kW	339	339	283	1262	686	143
Heating of ash kW	106	106	132	591	597	604
Melting of ash kW	100	100	125	560	565	571
Formation of CaO kW	29	29	36	163	164	166
Formation of H_2 kW	252	140	141	493	424	392
Reduction of iron oxides kW	4	4	5	20	20	21
Heat losses from lances kW	301	301	301	301	301	301
Heat losses from reactor kW	147	147	147	588	588	588
Heat losses from off gas kW	1019	826	728	2835	1784	948
Sum output kW	2297	1992	1898	6814	5130	3734
Excess power kW						596
Extra dry BF sludge mix kg/min						12

Table 46. Heat balance using coke oven gas for energy in the OXYFINES process.

	Actual results	Reduced leak air	Reduced water	Scaled 4 ton/h	Scaled 35wt.%	Scaled 10 wt.%
Heat Balance						
Combustion of C to CO_2	791	791	989	4419	4458	4511
Combustion of propane kW	1705	1304	1014	2775	1017	31
Combustion of S top SO_2 kW	6	6	8	34	34	35
Sum input kW	2502	2101	2011	7228	5510	4577
Vaporisation of water kW	339	339	283	1262	686	143
Heating of ash kW	106	106	132	591	597	604
Melting of ash kW	100	100	125	560	565	571
Formation of CaO kW	29	29	36	163	164	166
Formation of H2 kW	226	120	126	451	409	387
Reduction of iron oxides kW	4	4	5	20	20	21
Heat losses from lances kW	301	301	301	301	301	301
Heat losses from reactor kW	147	147	147	588	588	588
Heat losses from off gas kW	1038	840	789	2867	1796	925
Sum output kW	2502	2100	2012	7226	5509	4069
Excess power kW						508
Extra dry BF sludge mix kg/min						10
Product kg/min	5	5	6	26	26	37

Results from sustainability analysis

The sustainability analysis was performed by comparing the implementation of the OXYFINES concept to the today's handling of the blast furnace sludge. This means that the sustainability impact of the recovery of the BF sludge via the OXYFINES processes was compared with the sustainability impact of depositing the BF sludge in sludge ponds. The effects are from avoiding landfill in sludge ponds by applying OXYFINES technique for upgrading the sludge to useful products i.e. an iron-rich sinter product and a zinc-rich dust for use in zinc production.

The significant sustainability aspects in relation to the object of comparison was evaluated in a life cycle perspective in relation to production of raw materials, the process, utilisation of the products from the process as well as recycling and residues handling, Table 47. In Table 49, the management of the significant aspects of sustainability is described.

Table 47. Sustainability analysis aspects in a life cycle perspective.

	Raw material	Process	Utilisation	Recycling & residues handling
Environmental sustainability	Improvement by implementation of the OXYFINES concept from reduced need of virgin raw materials (i.e. primarily iron ore, secondarily coke and lime products).	Increased energy requirements and emissions through the utilisation of the coal contents in the sludge and propane or coke oven gas for energy in the hot process (1270 °C).	Enhanced resource efficiency and reduced emissions (Zn via leachate from deposits to the environment) and, depending on the process for utilisation of the sinter product, also reduced CO_2, energy and raw materials (primarily iron ore pellets, but also limestone and coke). The use of the zinc dust would provide the zinc industry a raw material source.	Clearly improved via reduced landfill and no new landfill sludge ponds.
Work environment & health	-	Some increased risk with the implemented new process (CO gas and hot process).	-	Reduced handling of landfills, no new sludge ponds.
Human rights	-	-	-	-
Equality & diversity	-	-	-	-

In general, the project results show the impact potential on sustainability mainly by improved material efficiency from implementing the OXYFINES process. The improvements are from recovery of the BF sludge and thereby making useful products which reduces the need of virgin raw materials. Raw material savings potential is from the use of OXYFINES products in BF, BOF and in the Fuming process. From the system analysis calculations, using 1 tonne of sinter decreases the iron ore pellet use with some 0.7 tonne in the BF and some 0.3 tonne in the BOF. In the BOF also a decreased use of HM of some 0.3 tonne is estimated. Provided a zinc content of 30% in the dust, this would result in an annual amount of zinc of 500 tonne to the zinc industry based on the full-scale calculations of processing 12 ktonne dry BF sludge. The decreased material amounts to landfill and thereof no new sludge ponds improves the overall sustainability.

The separate OXYFINES unit process results in increased energy use and CO_2 emissions through the utilisation of the BF sludge's coal content and the use of propane or coke oven gas for energy in the hot process. Improvements can be made e.g. by optimising the moisture content in the BF sludge prior to feeding, optimising the process efficiency, and using coke oven gas alternatively natural gas or hydrogen as energy source for the process. Utilising heat in cooling water used for the OXYFINES process, and the hot exhaust gases, e.g. for drying material (sludge) would further benefit the sustainable aspects of the concept.

The risks of increased energy use and emissions by implementing the OXYFINES process are however outweighed by the overall positive effects in a life cycle perspective. Based on the calculated heat and mass balance at different moisture levels in the BF sludge, the resulting CO_2 emissions from OXYFINES processing (i.e. from propane, and coal in BF sludge) is at best 1.1 tonnes of CO_2 per tonne of product, Table 48.

Assuming a CO_2 generation of 1.7 to 2 tonnes per tonne of hot metal produced, including CO_2 from production of iron ore pellets, this would result in some 2.5 to 2.8 tonnes of CO_2 per tonne of iron raw material. Replacing one tonne of this iron raw material with one tonne of OXYFINES sinter thereby results in a reduction in CO_2 of at best 1.4 tonnes. By using the sinter product in the BOF, the CO_2 emissions are reduced by ca 0.3 tonnes per used tonne of sinter whereof a total reduction in CO_2 would be at best ca 1.7 tonne.

From this perspective, if charging the OXYFINES sinter, generated from a total of 24,000 tonnes BF sludge per year (i.e. 50% moisture) to the BOF, this would correspond to a total annual reduced CO_2 emission by about 12,200 tonnes.

Considering a BF sludge of 10% moisture content, there would in addition be an excess energy that could be utilised for an enhanced treatment of other iron-rich and zinc-containing, but low-coal materials, thereby further improving the CO_2 perspective.

Table 48. Calculated CO_2 from OXYFINES process and from sinter use in iron and steel production based on moisture content in the BF sludge.

Moisture content in BF sludge for OXYFINES processing (%)	**50%**	**35%**	**10%**
CO_2 from OXYFINES process (tonne/tonne sinter product)	1.5	1.2	1.1
CO_2 reduction by replacing iron raw material (tonne/tonne sinter product)	1.0	1.3	1.4
Total CO_2 reduction (tonne/tonne sinter product in BOF)	1.3	1.6	1.7

Table 49. Description of how the sustainability aspects will be handled.

	Sustainability aspect	**Description of how the project will handle the sustainability aspect**
Positive sustainability aspects	Improved environmental sustainability regarding raw materials from reduced need for virgin raw materials by using the OXYFINES products from implementing the OXYFINES concept and recovering the BF sludge.	Included in the project's goal fulfilments in the long term. Raw material savings potential is from the use of OXYFINES products in BF, BOF and in the Fuming process. Using 1 tonne sinter decreases the iron ore pellet use with some 0.7 tonne in the BF and some 0.3 tonne in the BOF. In the BOF also a decreased use of HM of some 0.3 tonne is calculated. Provided a zinc content of 30% in the dust this would result in an annual amount of zinc of 500 tonne to the zinc industry based on the full-scale calculations of processing 12 ktonne BF sludge (dry weight).
	Environmental sustainability with respect to the OXYFINES concept provides a potential overall improved resource efficiency by considering material use, emissions, and energy.	Included in the project's goal fulfilments in the long term. Energy and CO_2 calculations shows potential decreases. Using 1 tonne of sinter in the BOF potentially decreases the CO_2 emissions in the overall production system and value chain with some 12.5 ktonne per year also decreasing the energy use.
	Overall, reduced handling of landfills, no new sludge ponds.	Included in the project's goal fulfilments in the long term. No land space required for the further construction of sludge ponds. Less handling is required due to no new sludge ponds.
	Clearly improved environmental sustainability from recovery of the BF sludge via reduced landfill and no new sludge ponds is required.	Included in the project's goal fulfilments in the long term. Decreased material to deposits. No zinc emissions from leachate to surroundings from new sludge ponds.
Risks	Environmental sustainability with respect to the manufacturing process (here the OXYFINES process), results in increased energy consumption and emissions through the utilisation of the BF sludge's coal content, and the use of propane alternatively coke oven gas for energy in the hot process (approx. 1270 °C).	The risks of increased energy consumption and emissions by the OXYFINES process are outweighed by the overall positive sustainability effects in a life cycle perspective. Calculations of the heat and mass balance scenarios, producing 1 tonne of OXYFINES product result in a CO_2 emission of some 1.1 tonne at best. Improvements can be made e.g. by optimising the moisture content in the BF sludge prior to feeding, optimising the process efficiency, and using coke oven gas alternatively natural gas or hydrogen as energy source for the process. Utilising heat in cooling water used for the OXYFINES process, and the hot exhaust gases, e.g., for drying material (sludge) would further benefit the sustainable aspects of the concept.
	Some increased risk regarding personnel with additional process (CO gas and hot process).	When implementing the OXYFINES process, safety regulations according to the standards applies in the daily work.

Conclusions, utilisation, and the next step

Conclusions from the project work

OXYFINES pilot and industrial trials

- The OXYFINES technique is by the project results proven to be suitable for the upgrading of blast furnace sludge. The trials demonstrated a very stable OXYFINES process with easily controlled temperature and Vol.% CO in the furnace atmosphere. (Identified optimal temperature of 1270°C and ca 7-8% Vol.% CO).
- The technique is a refining process, not just a transformation, whereof it should preferably be used for materials that requires both refining and transformation, such as removal of zinc from blast furnace sludge. In the process a refined sinter product, with virtually no zinc, suitable for use as a raw material in as well BF and BOF, and a dry zinc containing dust, was generated. The industrial trials of using the sinter in BOF showed no negative effects on the steel quality. From the trials it is presumed that the iron content of the sinter was credited in the BOF process.
- Compared to the previous trials, in this OXYFINES pilot trials, the processing was made at lower temperatures generating a sinter product (instead of the earlier higher temperatures, generating a melt), which can be seen as a new development. Trials were performed by batch operation instead of continuous tapping through taphole. This resulted in lower consumptions and minimal refractory ware. The process is sized against the amounts of material to be processed and the removal of undesired elements sets the process temperature and stoichiometry. A zinc separation degree up to 97% and alkali separation of some 75% Na and 60% K was demonstrated in performed pilot trials.
- The requirements of the dust products zinc concentration, to be used as a raw material in zinc production, was not met in the pilot trials (up to ca 5% as elemental Zn, or ca 6% as ZnO compared to the required >30% Zn). This can, for further work, be managed by less leak air to the off-gas flow, lowering the off-gas filter flow (significant effects on dust amounts were seen by reducing the flow from 7500 Nm^3/h to 3500 Nm^3/h). Also, the required zinc concentration in the dust can be met by higher zinc concentration in the blast furnace sludge or by recirculating the generated dust in the OXYFINES process. One other possibility of improvement is to install a refractory lined cyclone on the off-gas exit of the reactor.
- The full-scale reactor design should be wider, hence focusing the material to the center of the sandbox. This, and adjustment of the OXYFINES burner length in the reactor, prevents the material from spreading on the lower part of the reactor wall. Further, a sectioned lower part of the reactor would be preferable for easy relining with a planned relining cycle. The off-gas exit should be placed vertically from the reactor instead of the horizontally placement in the pilot trials.

- The sand in the sandboxes used for gathering the sinter product reacted with the sinter and thereby added to its contents. As the sand contained alkali this affected the alkali concentration in the sinter. In a full-scale plant, this could be improved by using a material, with a higher melting point compared to the sinter material and with less influence on undesired elements. This could be e.g. crushed converter refractory, some sintered product, or some injection mould. Other options are using water-cooled copper plate or casted iron.

- Compared to other pyro metallurgical techniques, the OXYFINES technique is relatively simple, cost-effective, less space-consuming and adjustable to the material amounts for treatment. Further the technique does not require pre-treatment of the sludge, such as drying and agglomeration, prior to its recovery. Compared to other options such as landfill, the technique will significantly reduce the requirements of costly landfills in sludge ponds, as well as the handling of sludge ponds and the landfill related occupation of space, as no new landfill will be required. In addition, the valuable contents in the sinter product will benefit the steel production system by improved material efficiency and reducing the use of virgin raw materials (mainly iron ore pellets).

System analysis

Based on the calculated scenarios, the following conclusions can be drawn:

- In general the calculated effects from using OXYFINES sinter as a raw material in the basic oxygen steel production were, that important elements, from a steel quality perspective, i.e. S and P, are virtually unaffected by using the 4.46 kg sinter per tonne of liquid steel. Raw material savings from the calculations are mainly a decreased hot metal demand of some 2.4 ktonne per year (by this also decreasing blast furnace raw material use) and a decreased iron ore pellet use of ca 2.6 ktonne per year. However, an increased requirement of basic slag formers of some 1.8 ktonne per year were also calculated, and this is due to the low basicity of the sinter. Positive total effects on CO_2 emission (in the optimal scenario by some 3.2 ktonne CO_2 decrease annually) and on the energy use in the system (total energy decrease ca 3.6 GWh annually) are calculated for the sinter use in BOF. This is mainly from the decreased hot metal demand in the BOF.

- Calculated effects from using 4.70 kg OXYFINES sinter per tonne hot metal as a raw material in the blast furnace is mainly raw material savings in the form of decreased iron ore pellets demand of some 6.6 ktonne per year. The P content is slightly increased by the sinter additions and in the calculations adjusted by a slightly less BOF slag recirculation of ca 1.5 kg per tonne hot metal.

- The cost calculations result in relatively similar value of using the sinter in the blast furnace or in the basic oxygen furnace (ca 550 - 700 SEK/t), with somewhat higher calculated value in the blast furnace.

- From restrictions set for the calculations and the effect on the full-scale OXYFINES dust zinc concentrations, some 4.3% zinc is required in the BF sludge to achieve a concentration of 30% zinc. New BF process measures are proposed concerning the sequential collection of a sludge with elevated zinc content, thus obtaining a sludge with lesser zinc in between the sequences. However, the possibilities of generating a BF sludge with such increase in zinc content has yet not been tested.

Commercialisation

- The OXYFINES concept depends on the moisture content of the BF sludge to the process. The solution with the lowest costs per tonne of sludge is the case of feeding sludge with 50wt.% moisture to the OXYFINES process. This is due to the less need for sludge handling and investments for drying. Heat and mass balance calculations present the potential of either using propane or coke oven gas as the energy source. From the calculations it is shown that feeding a drier sludge provides possibilities for using excess energy for recirculating the dust for zinc accumulation and for recovery of other iron-rich and zinc-containing, but low-coal materials.
- Prospects and cost for buildings, construction, and media, which has a significant impact on the summarised cost for a total plant description, are not included in the performed valuation. Scenarios for bringing the sludge from the sludge pond and from the exhaust gas purification system to the OXYFINES process unit require additional specifications.
- The most important aspect of the OXYFINES concept outcome is the potential for improved material efficiency.

Sustainability analysis

- Impact potential on sustainability are mainly from the improved material efficiency by implementing the OXYFINES process. The improvements are from the recovery of BF sludge, making products to be used in BF, BOF and e.g. the Fuming process, thereby reducing the need for virgin raw materials. The decreased material amounts to landfill and thereof no new sludge ponds improves the overall sustainability.
- The risks of increased energy use and emissions by implementing the OXYFINES process are outweighed by the overall positive sustainability effects in a life cycle perspective. In view of a holistic perspective, the positive effects on CO_2 emissions and energy use in the steel production system and in the production of raw materials should also be taken into account.

Utilisation of project results

The project aimed to develop solutions that support the objectives within RE: Source, which includes successful application of solutions for sustainable resource and waste management and thereby increased competitiveness for Swedish industry. Significantly increased material recycling with reduced storage/landfill can be achieved by separating zinc from blast furnace sludge via the OXYFINES technology and implementing a concept for maximised recycling through collaboration between different industry branches. Depending on the design and capacity of the process, it would be possible to recover also historically stored or deposited amounts of zinc-containing sludge (about 900,000 tonnes of blast furnace sludge, based on ore-based steel mills in Sweden).

Pilot trials were performed demonstrating and optimising OXYFINES technology and thereby creating the necessary knowledge of process parameters and performance to generate recyclable products. The holistic recycling concept has been evaluated through system analyses. Based on the pilot and industrial trials and the system analysis results, the project's sustainability and commercialisation proposals were carried out.

The primary stakeholders for the project are Swedish ore-based steel mills within SSAB Europe with SSAB Merox working to optimise SSAB's by-product, scrap and waste management, AGA/Linde, developer of the OXYFINES technology, and the base metal industry via Boliden Mineral. For commercialisation, a design and business plan as well as knowledge of process capacity and degree of utilisation are presented from the results obtained. The system analysis includes material and energy efficiency, environmental effects and economic potential, and the analysis was intended to contribute to increased knowledge by indicating effects in process system and hence possible recycling scenarios.

Other target groups for technology and concept development are other metallurgical industries, primarily in Sweden and in the Nordic countries, but also in Europe as well as globally. Previous tests with the OXYFINES technology have been successfully carried out on a variety of dry and wet fine particulate materials. By disseminating the results of this project, the target groups gain increased knowledge for future investigations and applications of both technology and dust/sludge reprocessing concepts.

Publication in scientific technical journals and participation in an international conference is planned to disseminate information about the technology, project results and the potential for increased material recycling, in order to contribute to increased opportunities and progress in the field. The main target groups for the project results will be:

- Primary, Swedish, and Nordic ore-based steel mills for the recycling of zinc-rich dust/sludge who are notified of project results through meetings, collaboration, reports, networks, and scientific publication.
- Other steel and ferro alloying industries, both within Europe and globally, for reprocessing/recycling of dust and sludge who are notified the result of the project mainly through scientific publication.
- External recycling companies for reprocessing/recycling of dust and sludge who are notified of the result of the project mainly through scientific publication.
- Researchers at research institutes and universities who are notified of the project results through scientific publication such as journal and conference.

By testing and validating the potential of OXYFINES technology and presenting an optimised recycling concept with synergy effects between industrial sectors, further opportunities for increased recycling are created. For the Swedish steel industry, the implementation of the OXYFINES technology and the concept would represent a major step towards the "zero waste" vision. For the developer of the technology (AGA/Linde), the project results and an implementation of the technology in the steel industry would help to demonstrate its potential for further applications and commercialisation. By extension, the results of the project can be used for the application of technology and concepts in other ore-based steel mills, but also in other industrial sectors for dust/sludge recycling. Based on an annual global production volume of hot metal of about 1.2 billion tonnes (according to the World Steel Association, statistics for 2016), 30 million tonnes of blast furnace dust and sludge are generated annually. An implementation of the OXYFINES technology contributes to increased opportunities to return valuable elements to their proper value chain, which contributes to increased sustainability and an adaptation to circular economy.

Further work

A continued work is required for the implementation of a full-scale OXYFINES concept. Based on the results obtained from this project, the following is proposed:

- The possibilities to generate a useful dust product is essential for the concept. Thereby, further work is important to establish the means to enable the requirements of the dust zinc concentration for a full-scale implementation of the OXYFINES concept.

- Analyses of using the OXYFINES process for recovery also of other residual materials and material mixes, e.g. using zinc-containing, low coal, materials when feeding drier sludge, need to be performed. Furthermore, studies should be conducted on how a recirculation of the dust in the OXYFINES process should be made in order to achieve the desired > 30% zinc in the dust product. For this, refined calculations are essential, including the impact on media based on the numbers of circulations required.

- Further pilot trials are recommended to determine how a dust recirculation should be carried out, for filter flow adjustments, and for improved possibilities by installing a hot cyclone. Supplementary tests for making burner and process adjustments such as altered input for drier material, e.g. burner configuration and material feeding options with higher complexity. Additional tests should be on the OXYFINES process media, using coke oven gas instead of the propane or also investigating possibilities of using natural gas or even hydrogen. In new pilot trials, sufficient material volumes could be produced for extended industrial tests and comparability with iron ore pellets in the BF and BOF processes. The proper dimensions of the reactor need to be adapted for the desired material feeding rate. In further trials it is essential to also measure the generation of SO_2 and NOx. Based on the conclusions of this work and by these complementing investigations and specified trials, a complete illustration of the optimal concept should be outlined.

- A new project is in the application phase where the intention is, among other things, to investigate possibilities for increasing the zinc concentration in the BF sludge to the OXYFINES process by a fractional extraction of a more zinc-rich sludge directly from the BF exhaust gas purification system.

- Effects on CO_2 emissions should be investigated and optimised based on a developed overall picture of a concept for implementation. This should result in a description of the total effect from a life cycle perspective.
- The proposal on a commercialisation and business plan for an OXYFINES concept is to be considered a basis for the continued work for a full-scale plant. SSAB needs to make their own calculations and prospects by refined figures, creating an overall picture. The calculations need to be based on decisions for specified cases on sludge handling and dewatering, planning of media for energy (e.g. coke oven gas or propane), design, placement, and construction of the plant.

List of publications

Article 1, “OXYFINES TECHNIQUE FOR UPGRADING ZINC CONTAINING BLAST FURNACE SLUDGE – Part 1: Pilot trials”, is to be submitted to the peer-reviewed journal *Metals* for the Special Issue *"Sustainable Steel Industry: Energy and Resource Efficiency, Low-Emissions and Carbon-Lean Production"*.

Article 2, “OXYFINES TECHNIQUE FOR UPGRADING ZINC CONTAINING BLAST FURNACE SLUDGE – Part 2: System analysis”, is to be submitted to the peer-reviewed journal *Metals* for the Special Issue *"Sustainable Steel Industry: Energy and Resource Efficiency, Low-Emissions and Carbon-Lean Production"*.

Project communications

The possibilities for a full-scale OXYFINES plant were presented and discussed at a workshop held at SSAB in Luleå on November 27, 2019 titled: *Opportunities for a full-scale plant where zinc-containing dust/sludge is processed with AGA's OXYFINES technology.* At the workshop, project results and proposals for a plant on a production scale were presented.

Activities such as the pilot trials and the workshop were presented and published via LinkedIn as well as via several news dissemination:

Date	**Publication**
28-aug	SR P4 Norrbotten
29-aug	Metaller och gruvor
02-sep	Ny Teknik
02-sep	MSN Nyheter
04-sep	Affärer i Norr
04-sep	Papernet
04-sep	Process Nordic
04-sep	Recycling
03-dec	Energigas

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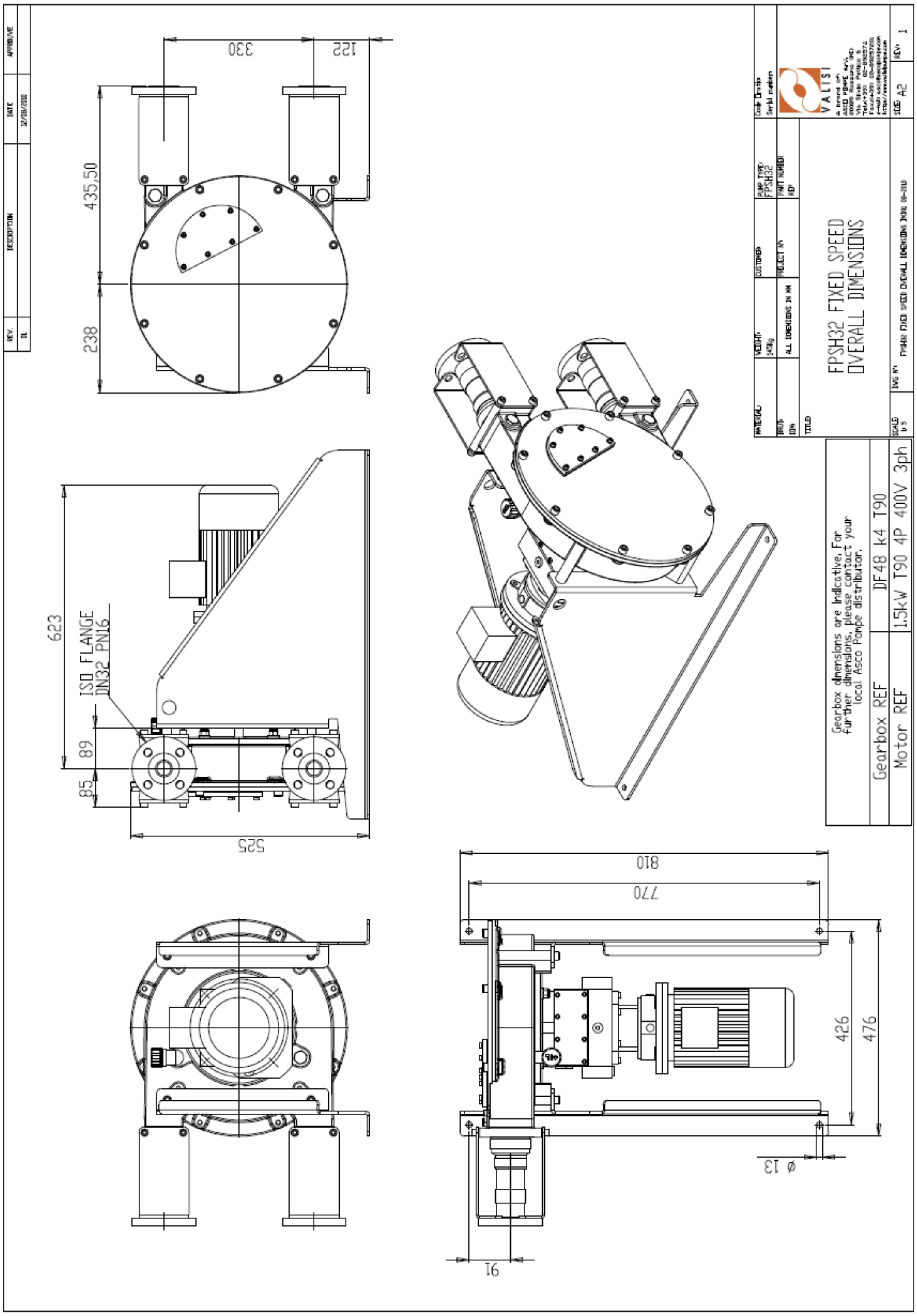
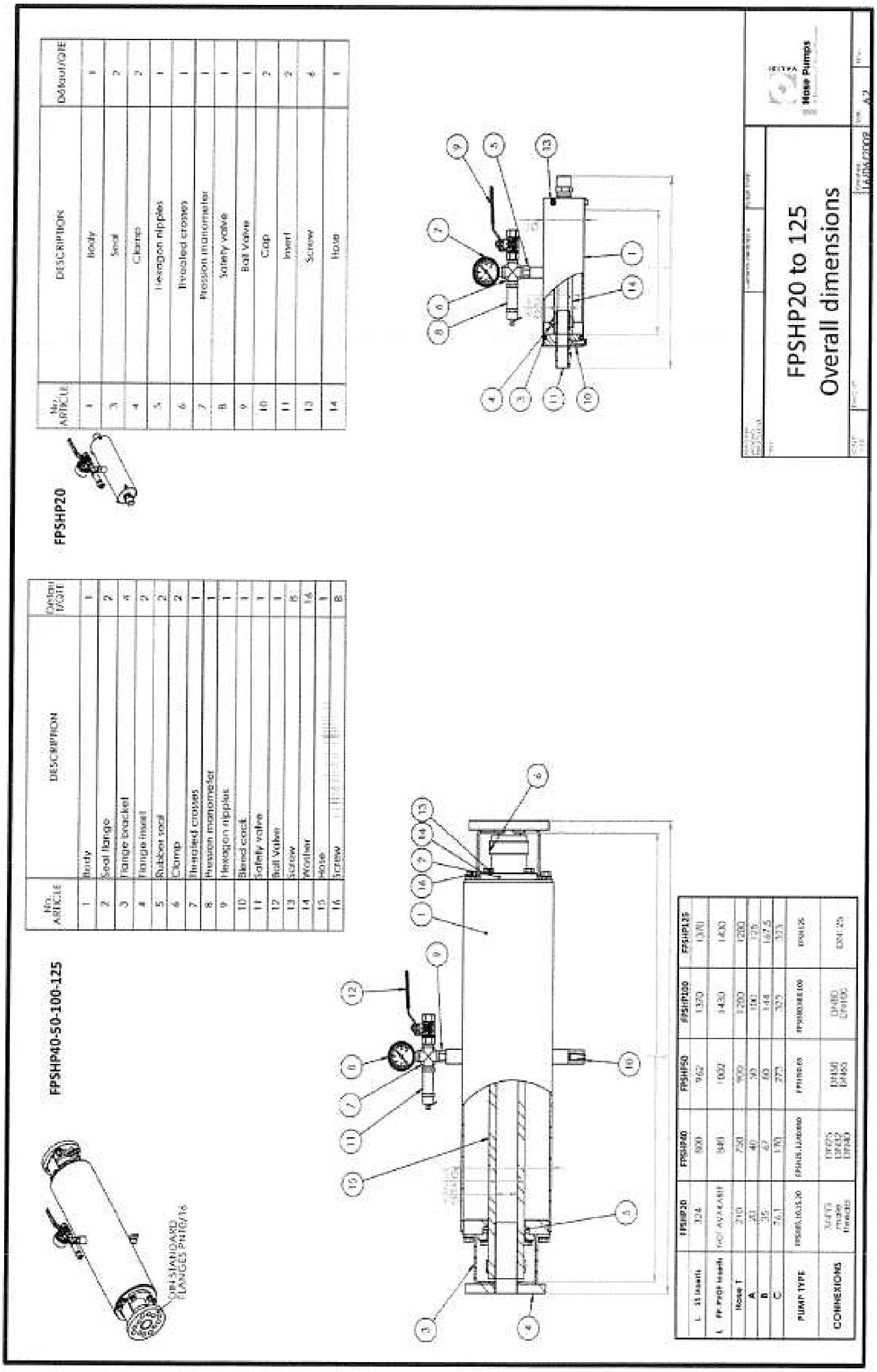
Appendix

Appendix 1a - Hose pump for pilot set-up (FPSH 32)



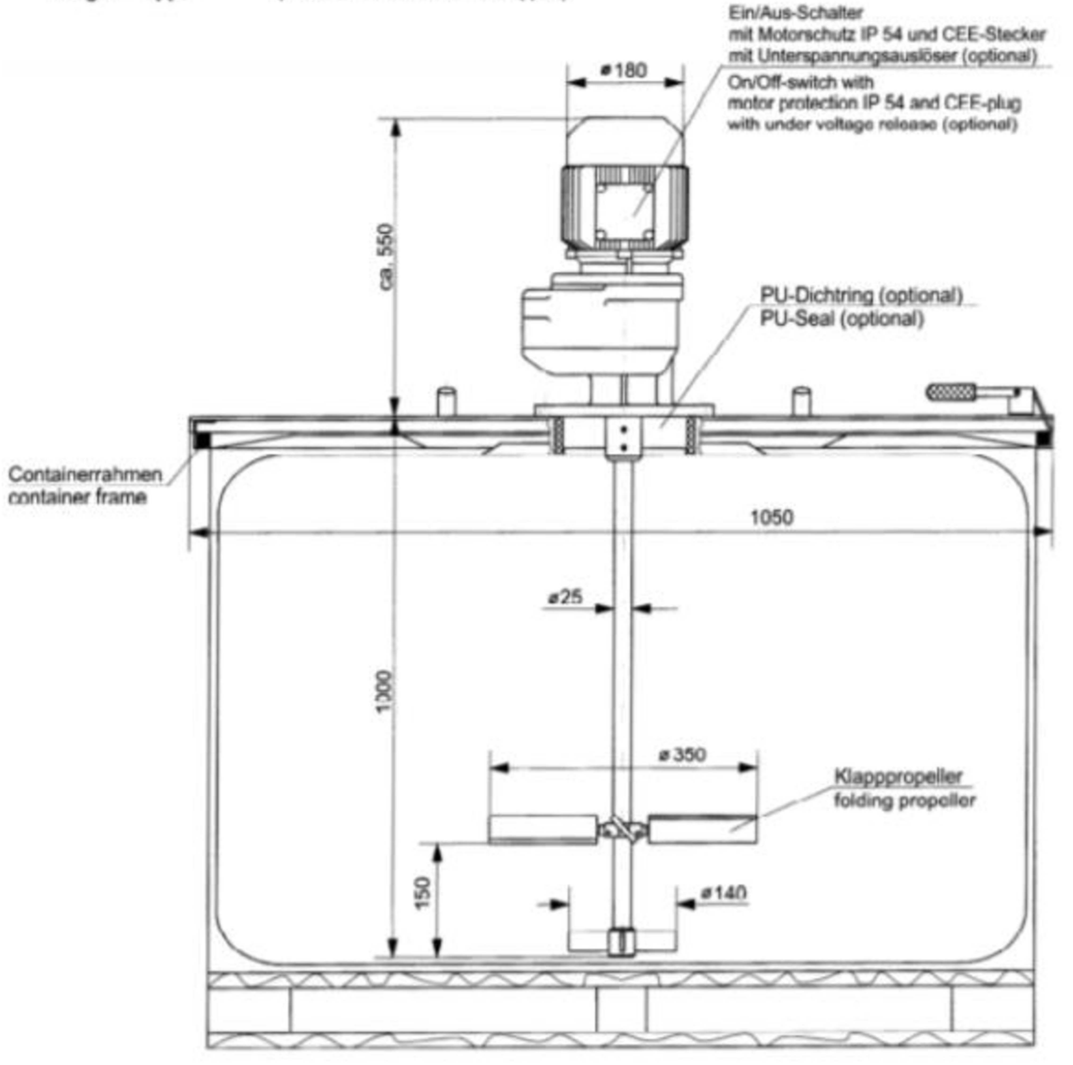
Appendix 1b – Pulsation damper for pilot set-up



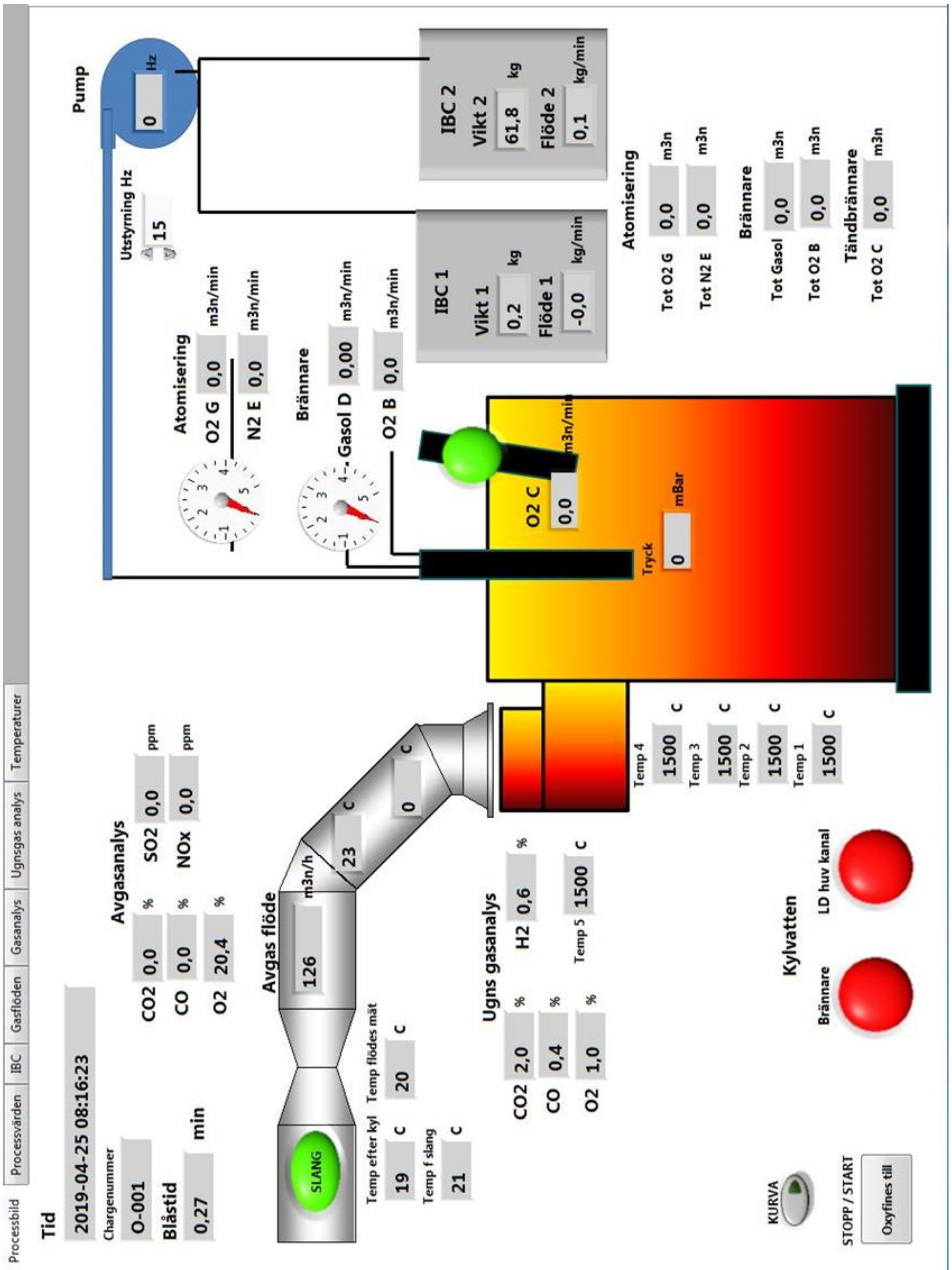
Appendix 1c – Mixer (CR 300) for pilot set-up

Geräte-Typ: CR300 / 1,5

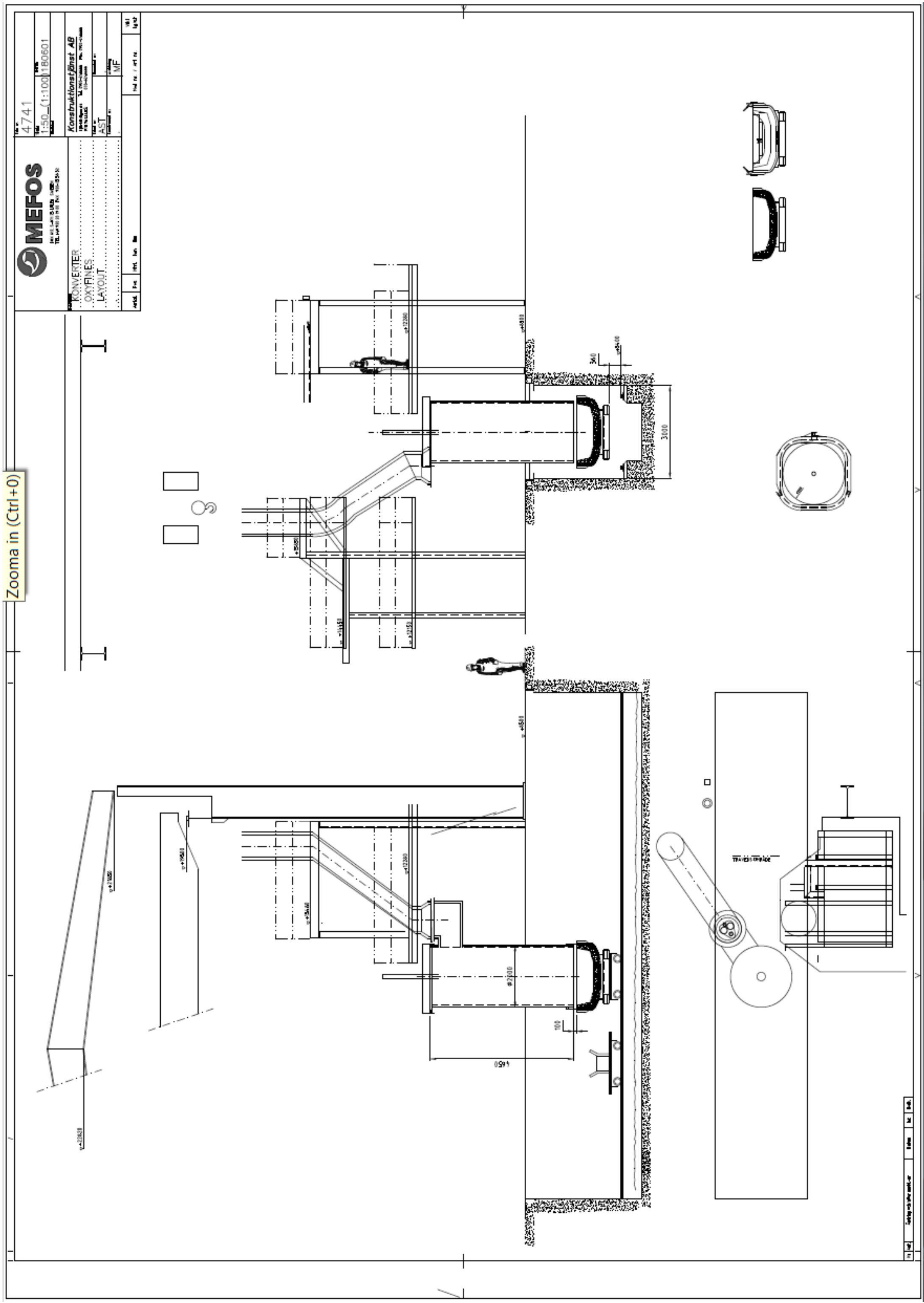
Antriebsleistung Motor output	KW	1,5
Rührerdrehzahl Agitator speed	1/min	300
Werkstoff: Welle/Rührorgane Material: Shaft/Mixing elements		1.4571
Gewicht ca. Weight appr.	Kg	40 (mit Containertraverse / incl. Support)



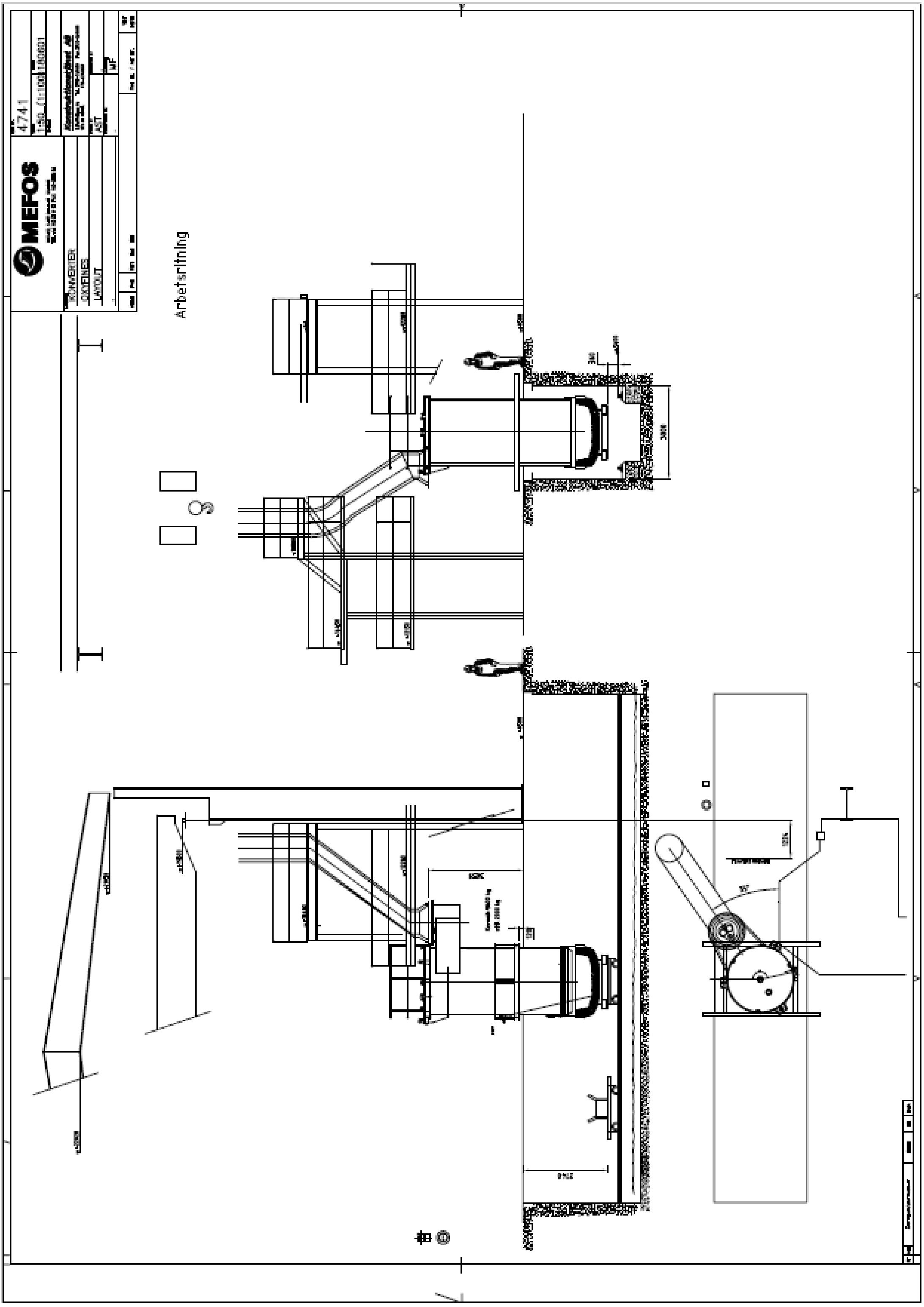
Appendix 2 – LabVIEW for process monitoring and logging of operational data



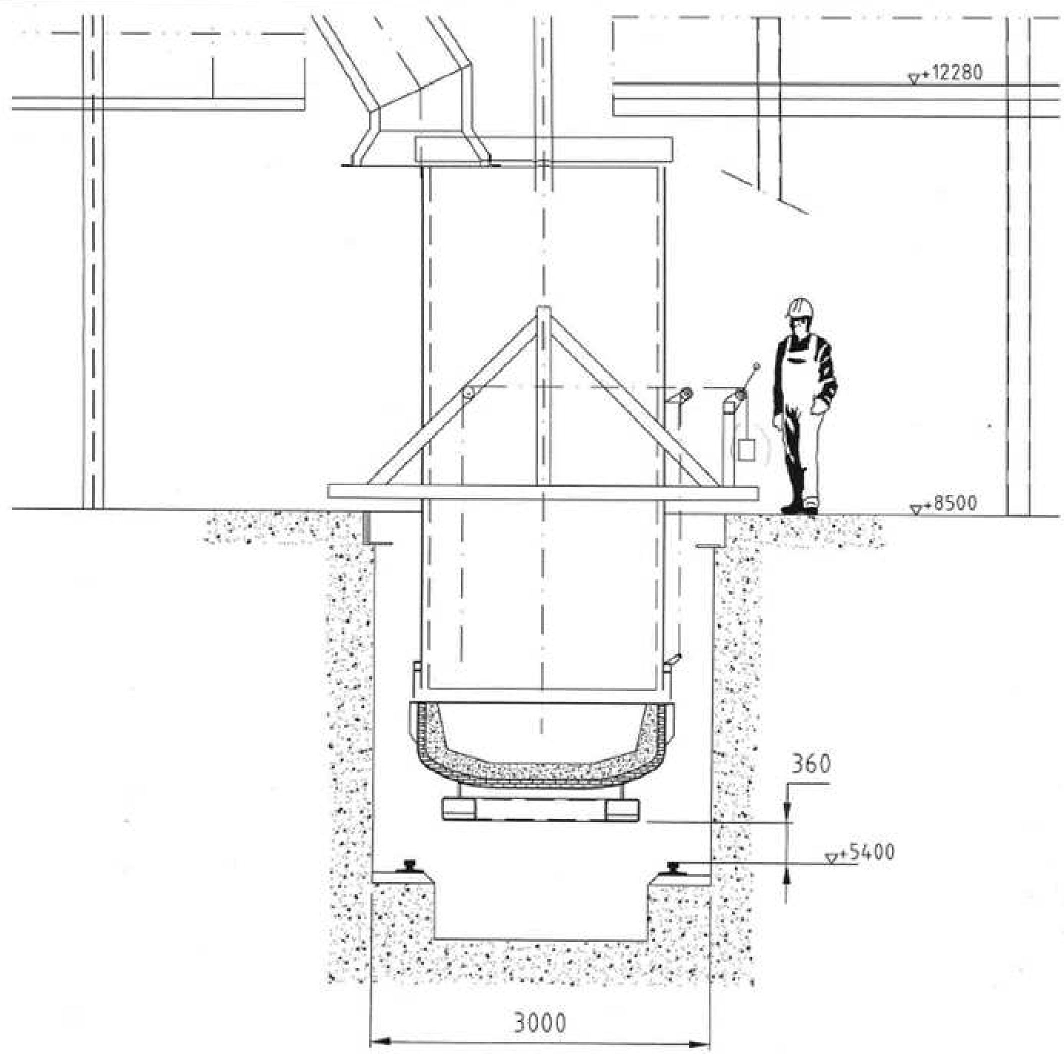
Appendix 3a – Layout of pilot reactor dimensions and placement

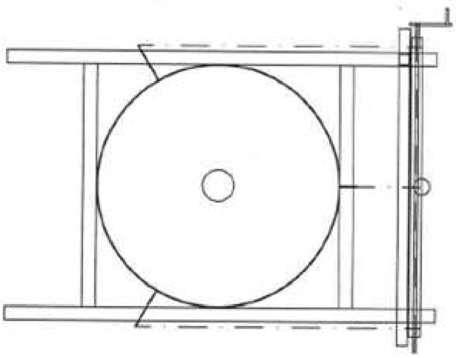


Appendix 3b – Layout of pilot reactor dimensions and customising to the exhaust channel

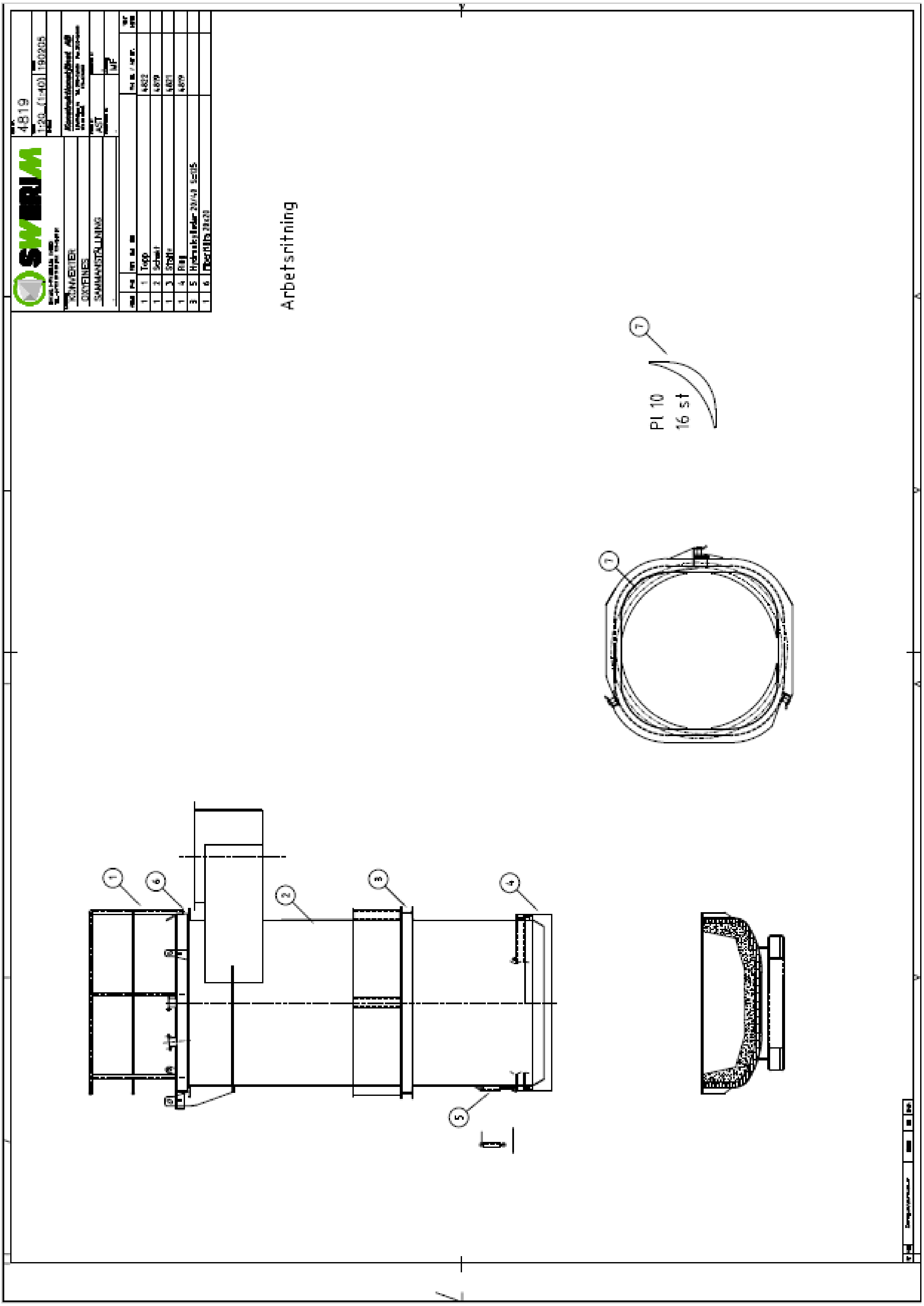


Appendix 3c – Layout of pilot reactor dimensions, lifting device for sandbox exchange

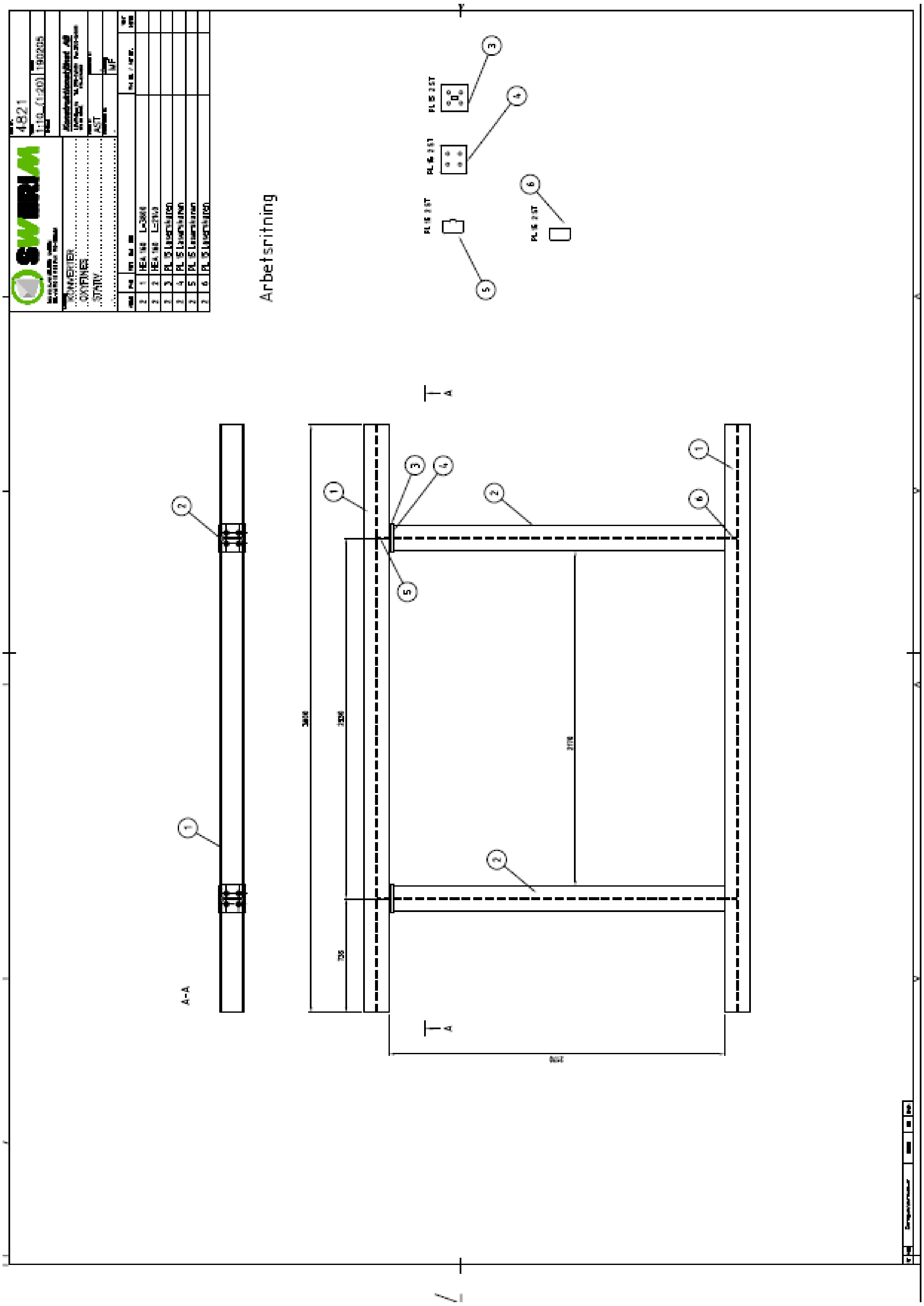




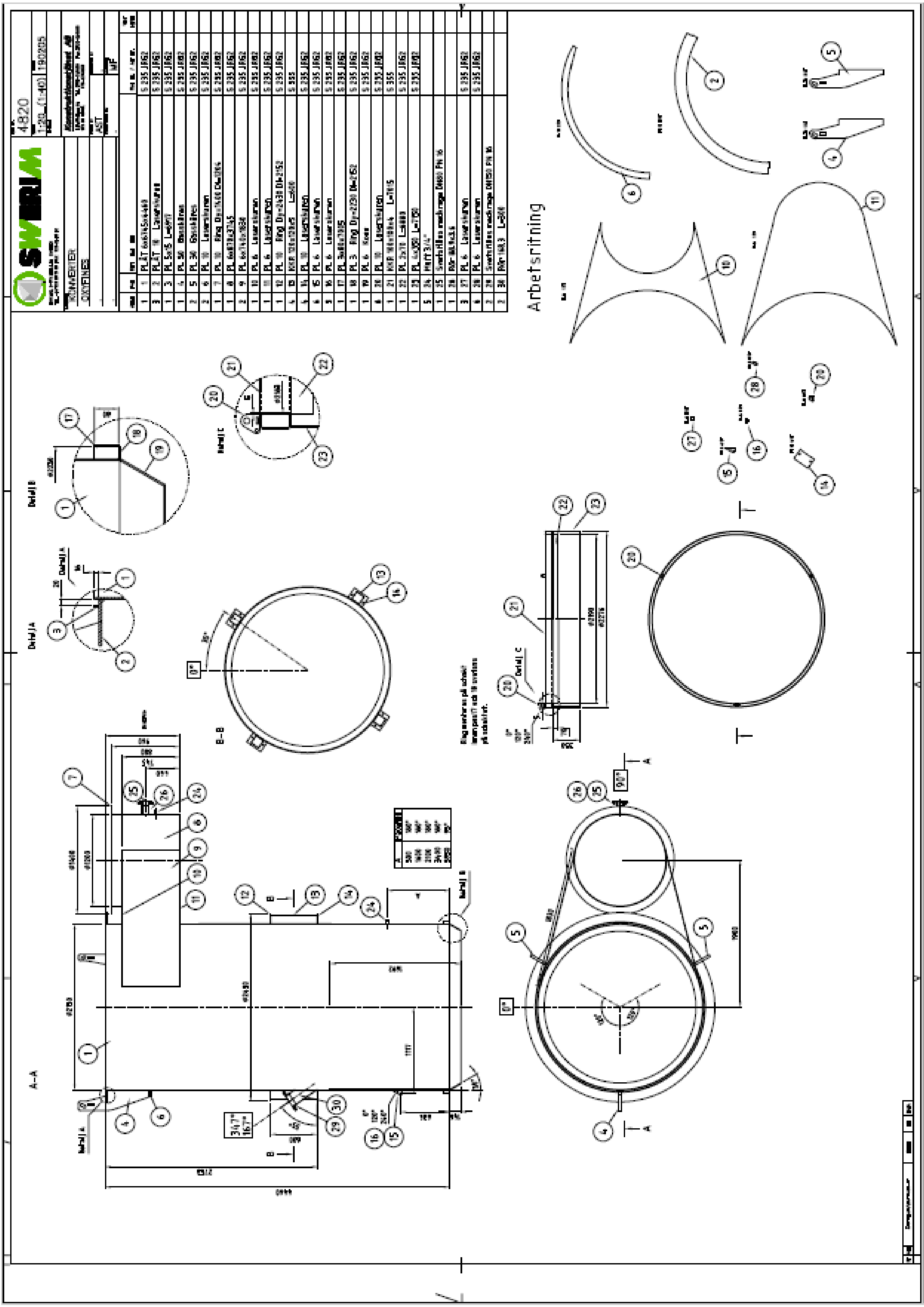
Appendix 3d – Layout of pilot reactor dimensions, sizing of reactor edge to sandbox



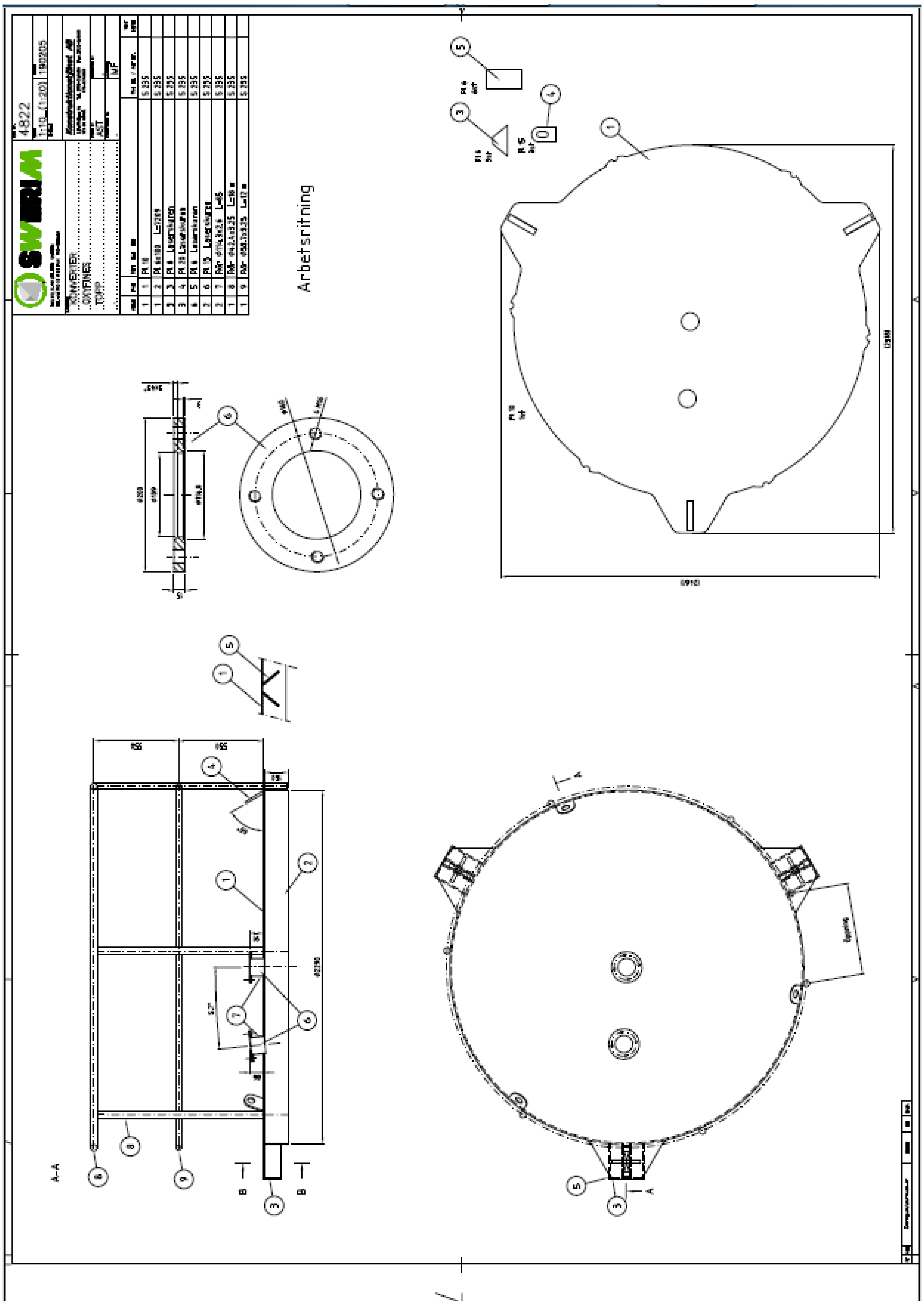
Appendix 3e – Layout of lifting device for sandbox exchange



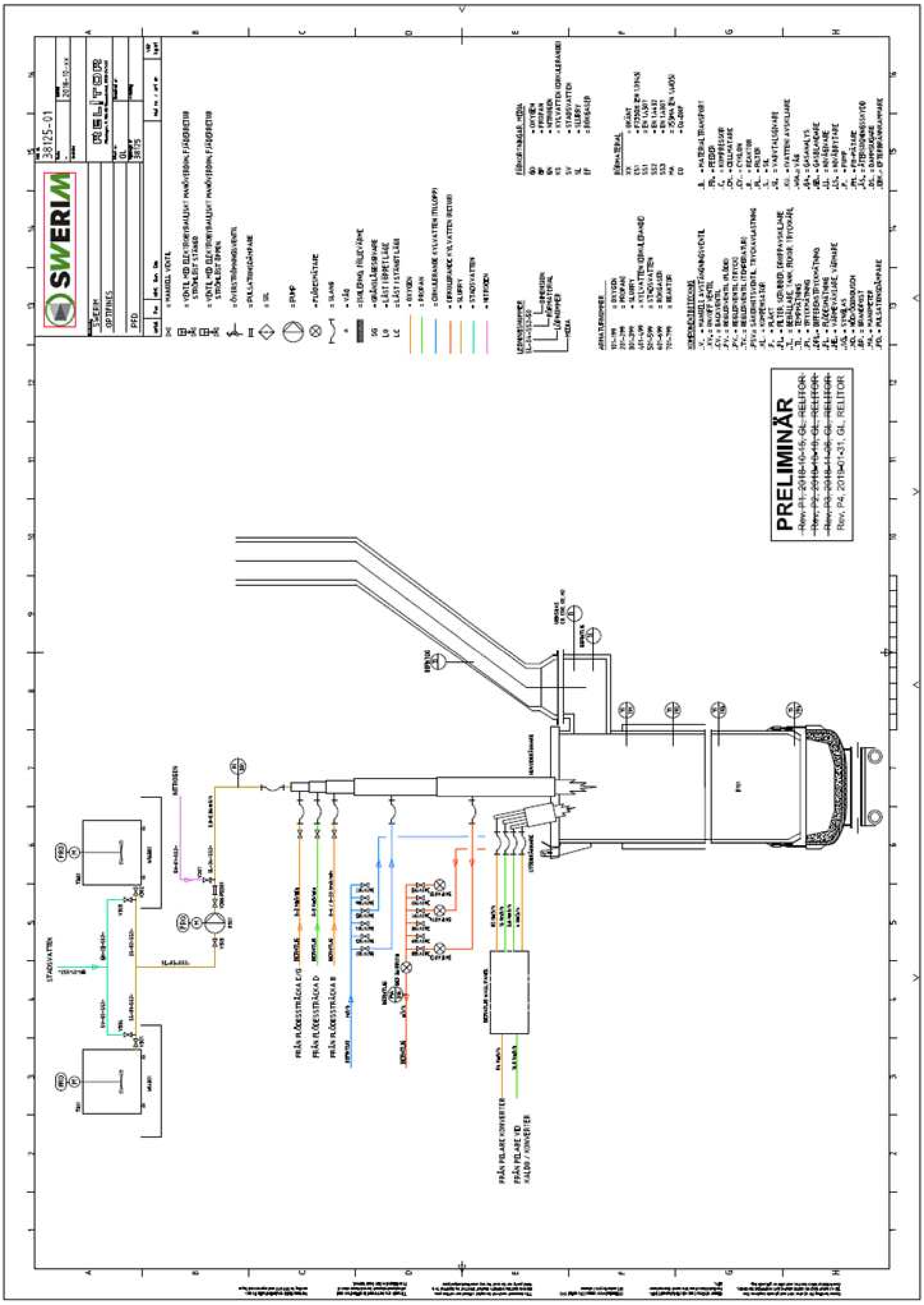
Appendix 3f – Layout of pilot reactor dimensions, exhaust duct



Appendix 3g – Layout of pilot reactor dimensions, reactor lid



Appendix 4 – Flow chart for the pilot set-up



Appendix 5 – Castable lining material for pilot reactor and lid

GOTHIA 98 CS

Product Description : Gothia 98CS is a cement free, high alumina castable (2 part System)

Typical Applications : Various applications where fasting dry-outs are required.

Maximum Service Temperature	… 1750°C
Bond Type	… Chemical
Storage Life	… 12 Months In Normal Storage Conditions
Installation Method	… Vibration Casting
Dry material required per Cubic Metre	… 3150
Liquid Addition(%) 2 part system	… 6.7-8.3 by weight

Bulk Density

Dried @ 110°C	3000	Kg/m^3

Cold Crushing Strength

Dried @ 110°C	60	N/mm^2
Fired @ 1600°C	90	N/mm^2

Permanent Linear Change

Fired @ 1600°C	-0.3	%

Chemical Analysis (Dry)

Al_2O_3	97.5	%
SiO_2	2.0	%
Fe_2O_3	0.03	%

Manufactured at:
LKAB Minerals Ltd.
Flixborough Industrial Estate
Flixborough, DN15 8SF
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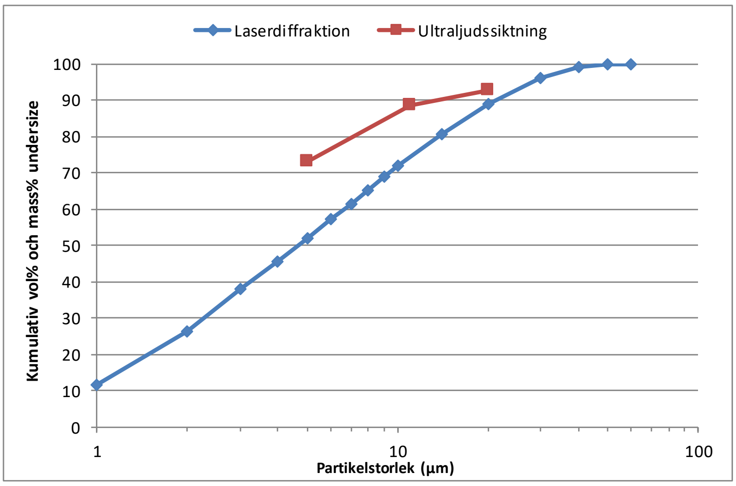
RE: SOURCE

Med stöd från: VINNOVA Energimyndigheten FORMAS STRATEGISKA INNOVATIONS-PROGRAM

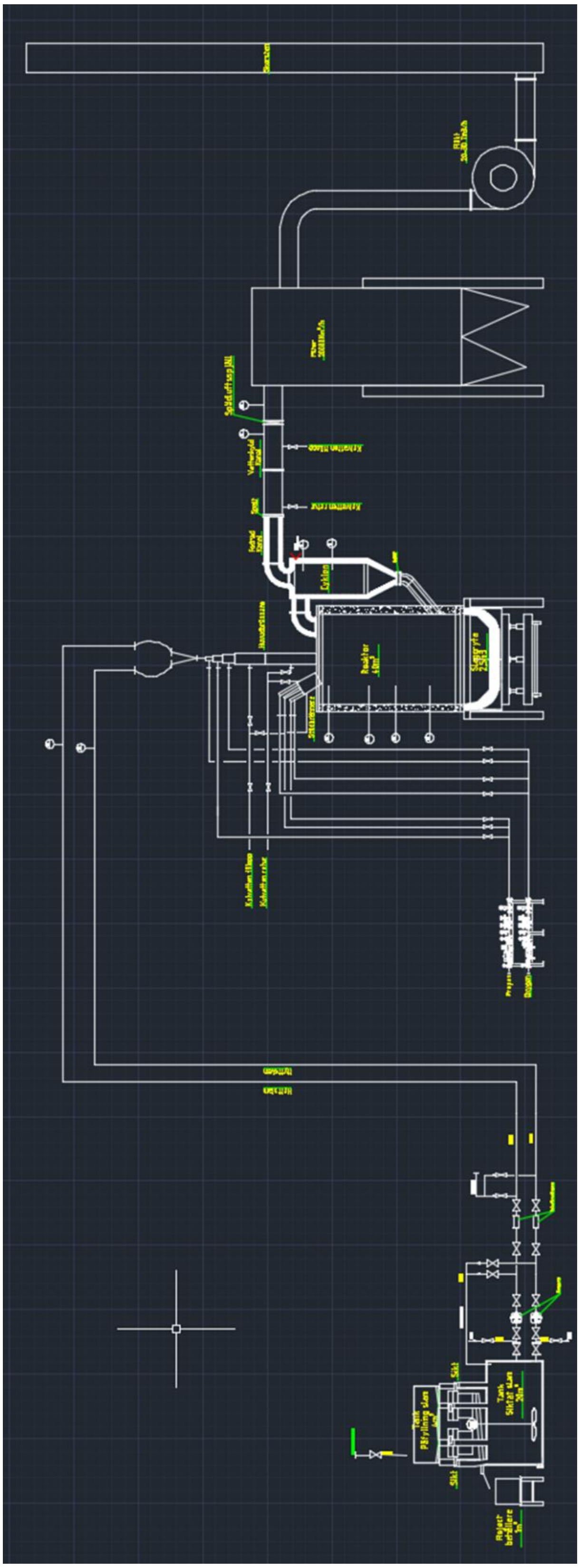
Appendix 6 – Size distribution of particles in BF sludge



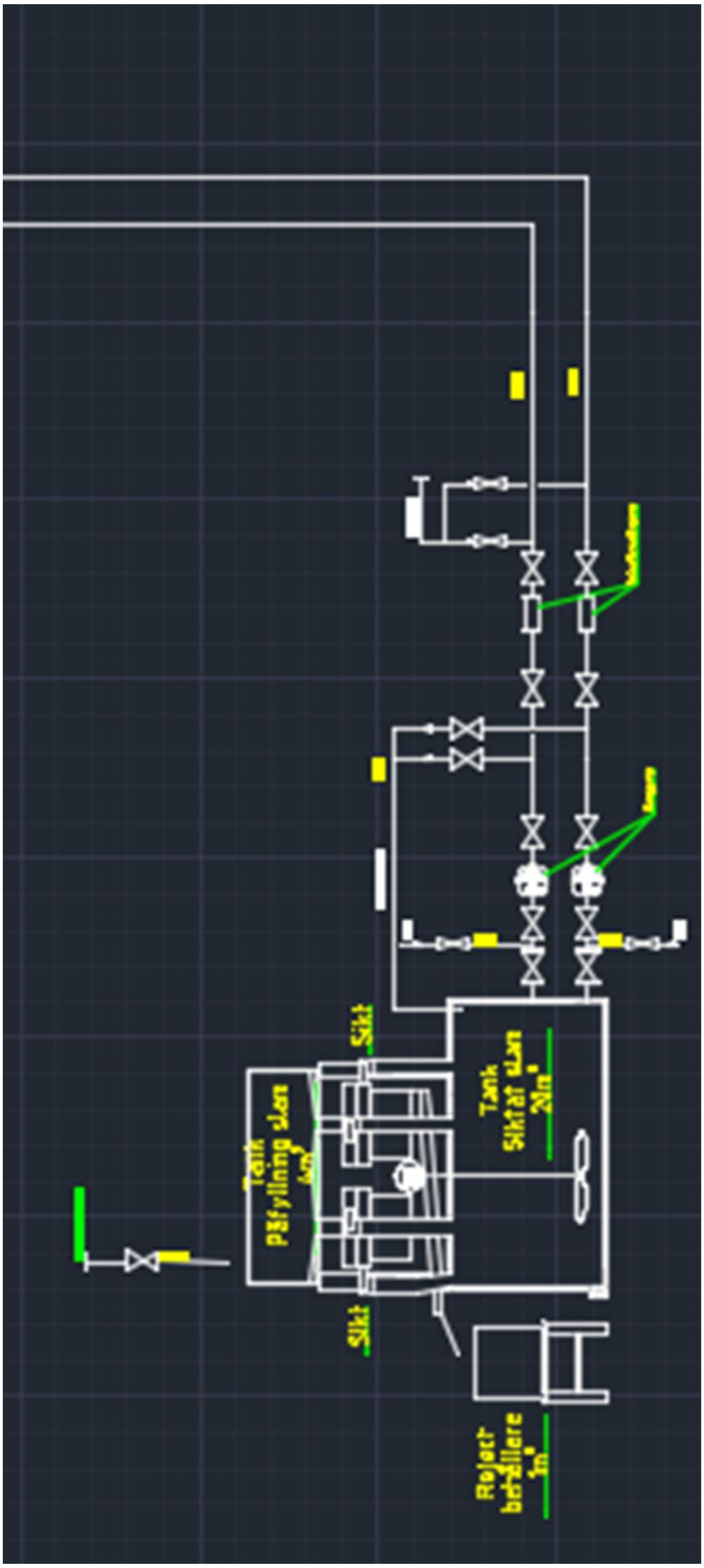
Laser diffraction	
Partikelstorlek (µm)	Kum. Vol% undersize
1	11.8
2	26.4
3	38.2
4	45.5
5	51.9
6	57.4
7	61.6
8	65.2
9	68.8
10	72.1
14	80.8
20	89.0
30	96.1
40	99.0
50	99.9
60	100.0

Ultraljudssiktning					
Tom bytta (g)	Bytta med torrt slam (g)	Torrt slam (g)	Fraktion	Partikelstorlek (µm)	Kum. Mass% undersize
521.13	521.55	0.42	<5µm	5	73.3
566.06	566.68	0.62	<5µm	11	88.8
447.5	449.5	2	<5µm	20	92.6
567.53	569.46	1.93	<5µm		
566.35	569.07	2.72	<5µm		
521.43	523.87	2.44	<5µm		
529.44	530.79	1.35	<5µm		
564.12	568.23	4.11	<5µm		
390.6	393.53	2.93	<5µm		
449.23	451.05	1.82	<5µm		
528.55	530.33	1.78	<5µm		
424.83	425.52	0.69	<5µm		
316.06	317.7	1.64	<5µm		
409.65	411	1.35	<5µm		
447.58	458.42	10.84	<5µm		
567.41	579.03	11.62	<5µm		
521.1	525.7	4.6	<5µm		
528.59	529.86	1.27	<5µm		
566.01	577.66	11.65	<5µm		
529.23	530.59	1.36	<5µm		
449.28	457.16	7.88	<5µm		
529.13	535.55	6.42	<5µm		
316.08	322.9	6.82	<5µm		
409.56	411.7	2.14	<5µm		
528.66	536.9	8.24	<5µm		
390.59	393.3	2.71	<5µm		
423.98	426.2	2.22	<5µm		
564	568.01	4.01	<5µm		
241.06	246.34	5.28	>20µm		
241.17	246.76	5.59	>20µm		
567.55	570.07	2.52	5-11 µm		
566.27	568.65	2.38	5-11 µm		
449.45	460.53	11.08	5-11 µm		
529.4	530.53	1.13	5-11 µm		
287.74	293.36	5.62	11-20µm		
564.12	569.73	5.61	5-11µm		

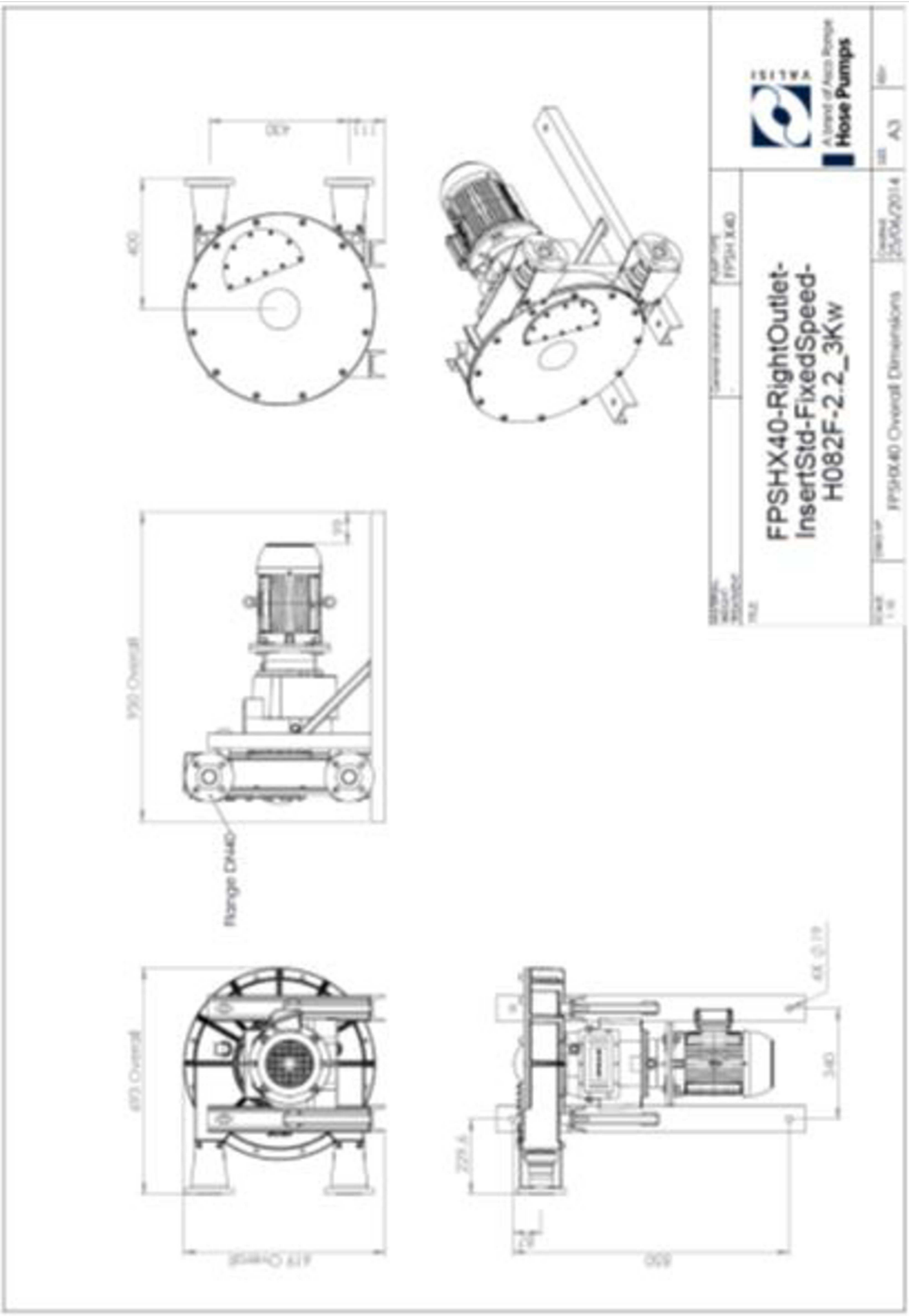
Appendix 7a – Layout of the OXYFINES process unit



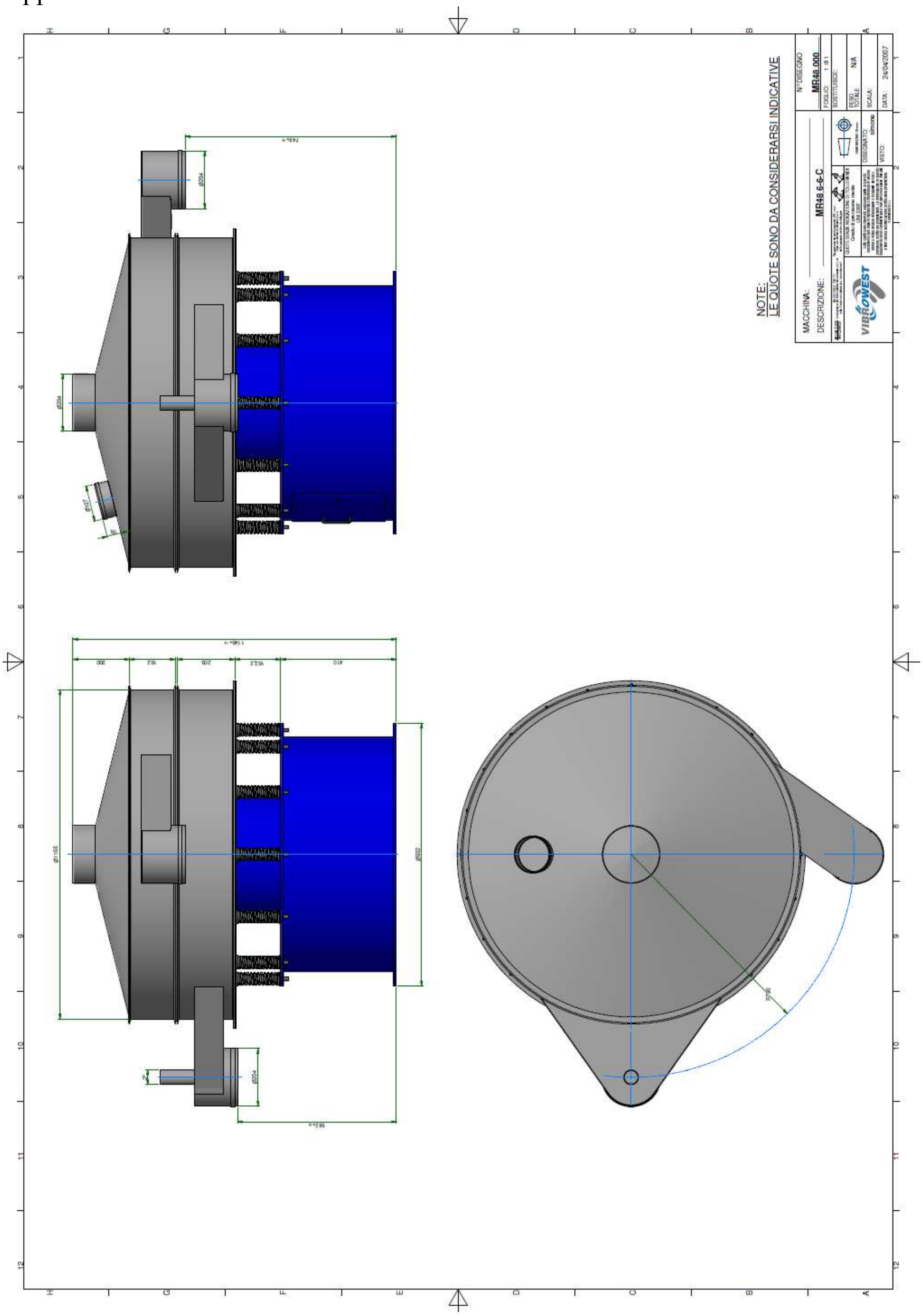
Appendix 7b – Layout of the OXYFINES process unit, tanks, screeners and pumps



Appendix 7c – Pump

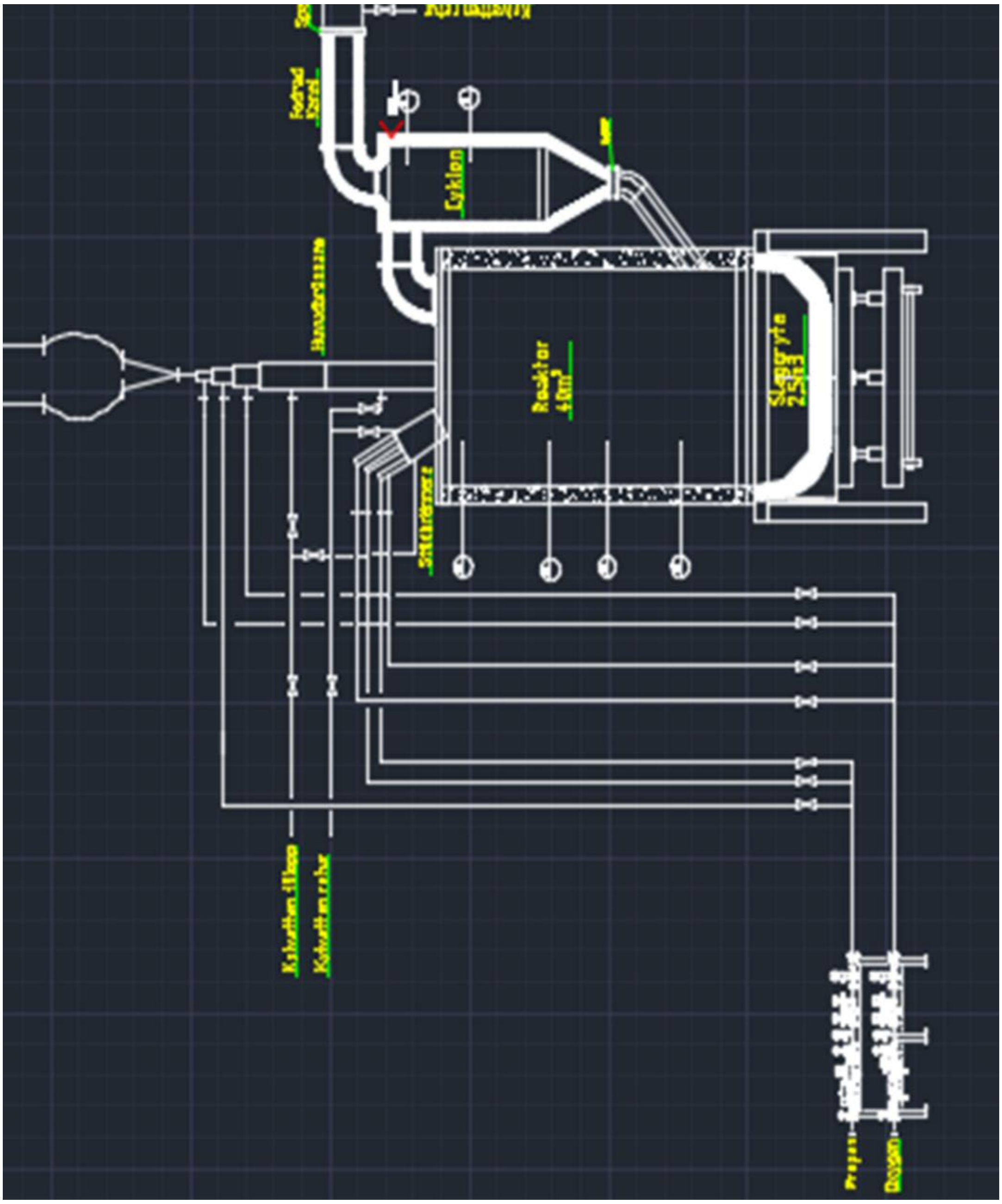


Appendix 7d – Sieve



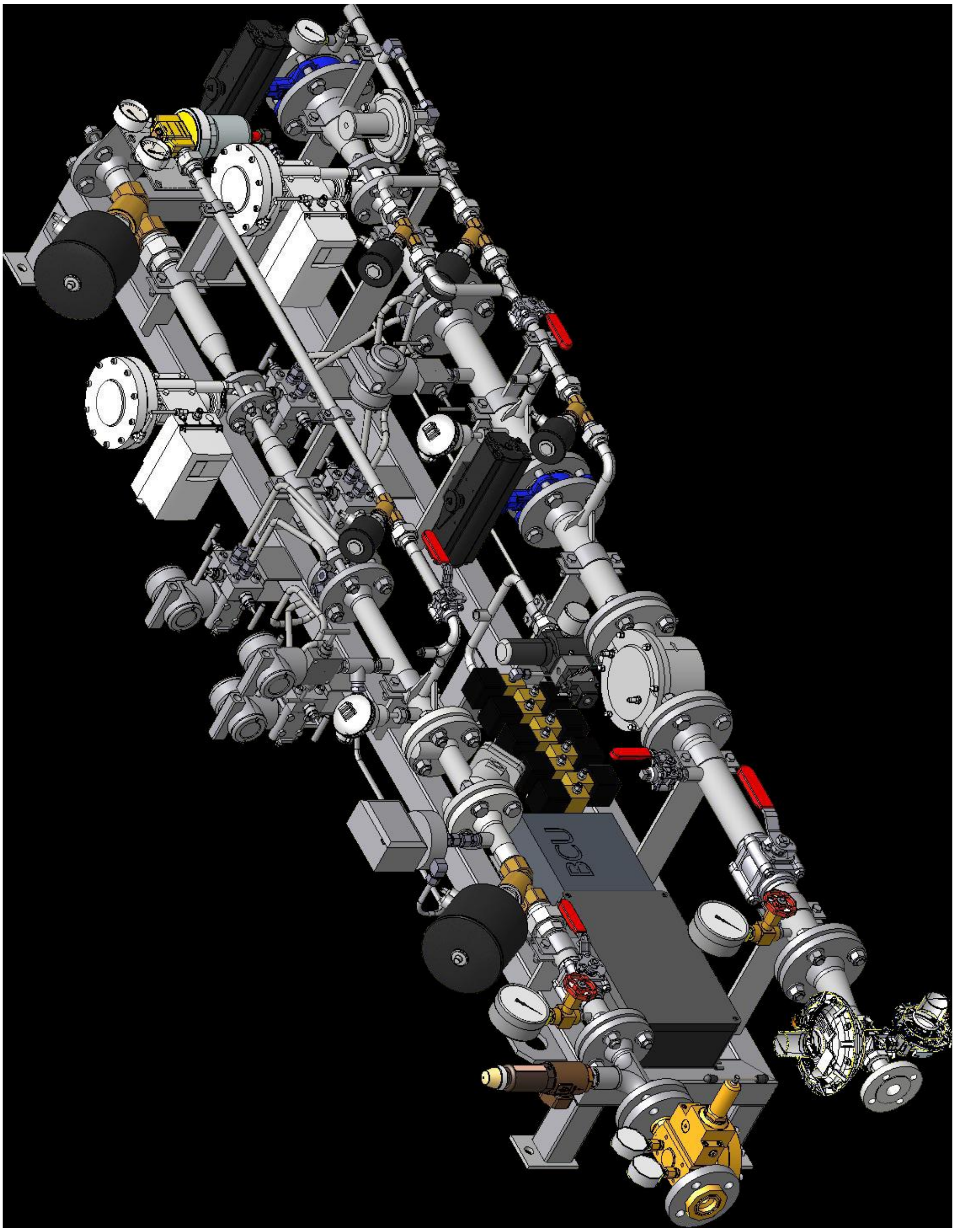
Med stöd från:
STRATEGISKA INNOVATIONS-PROGRAM

Appendix 7e – Layout of OXYFINES reactor, ladles, and ladle car

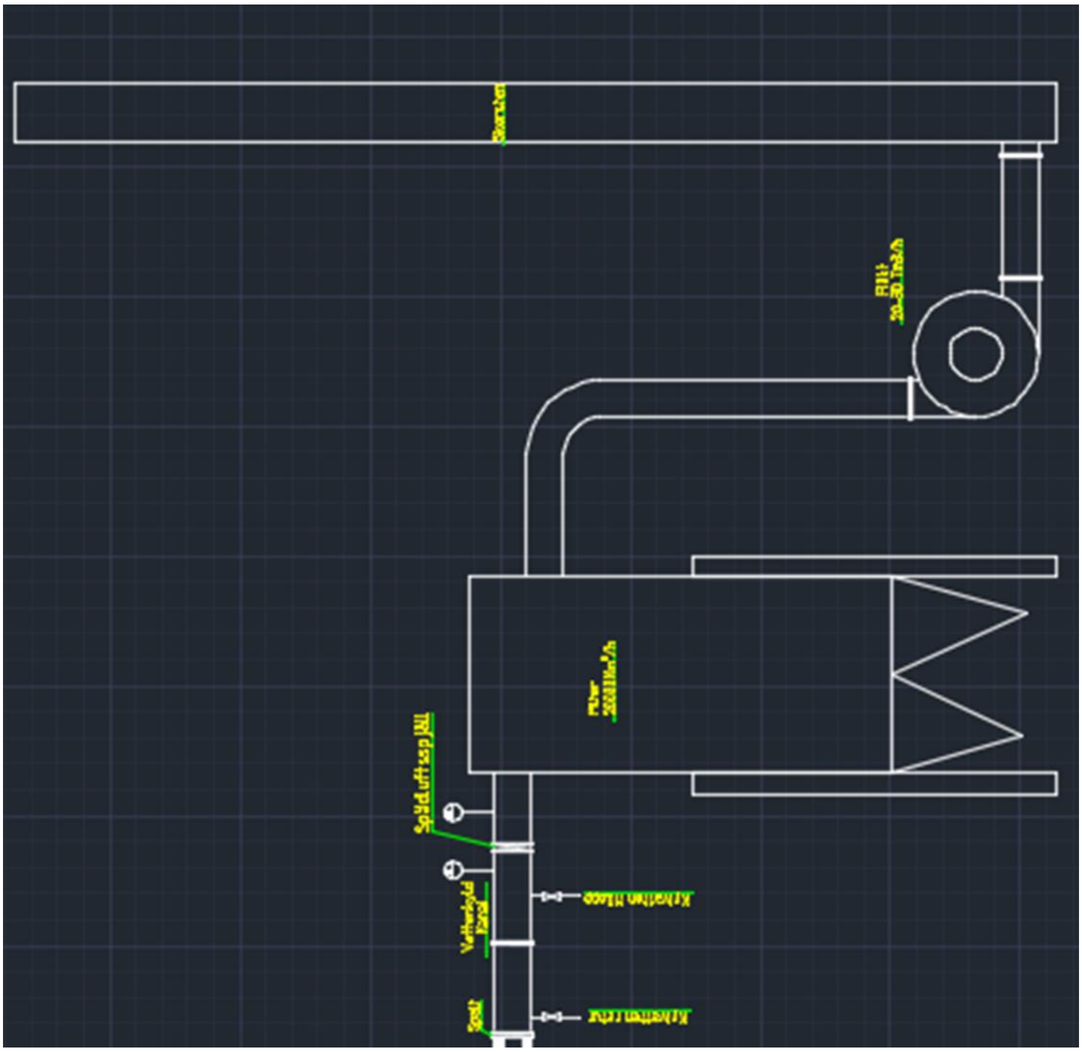


Appendix 7f – Burners

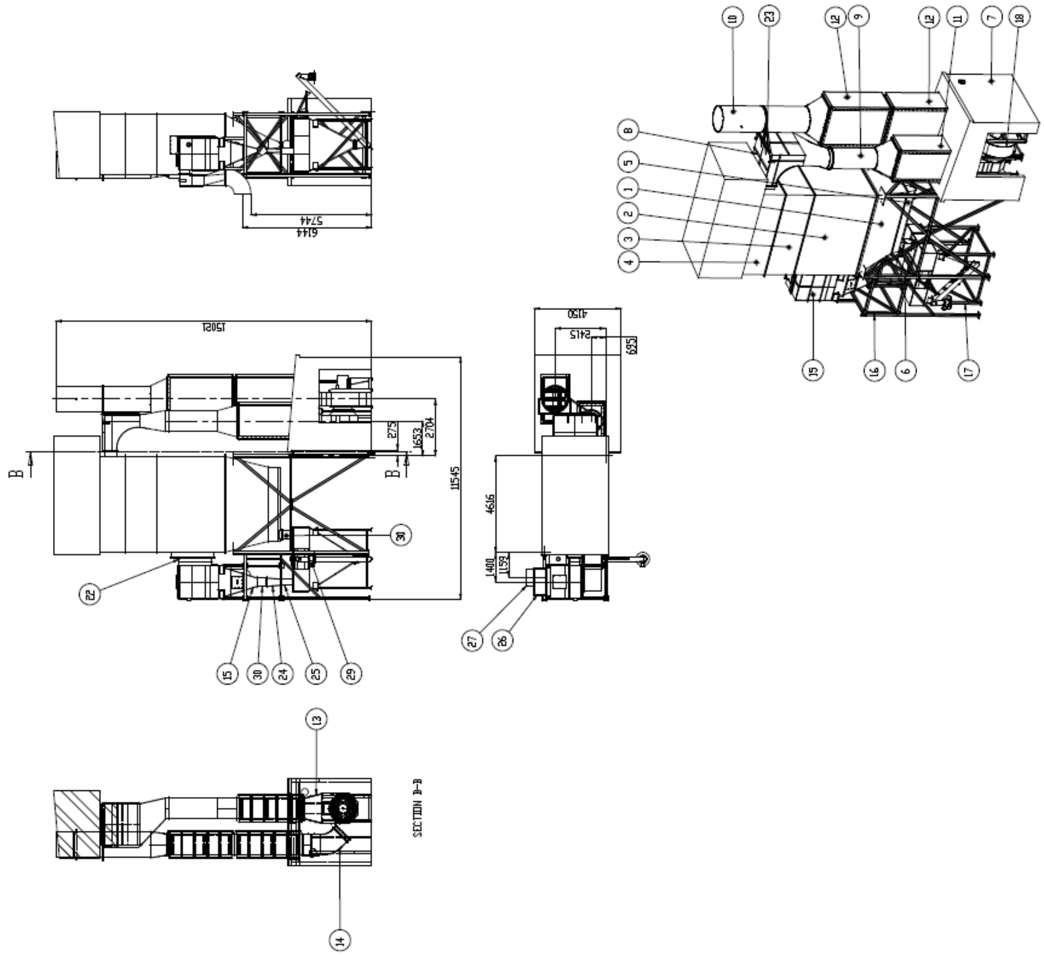
Appendix 7g – Burners flow train



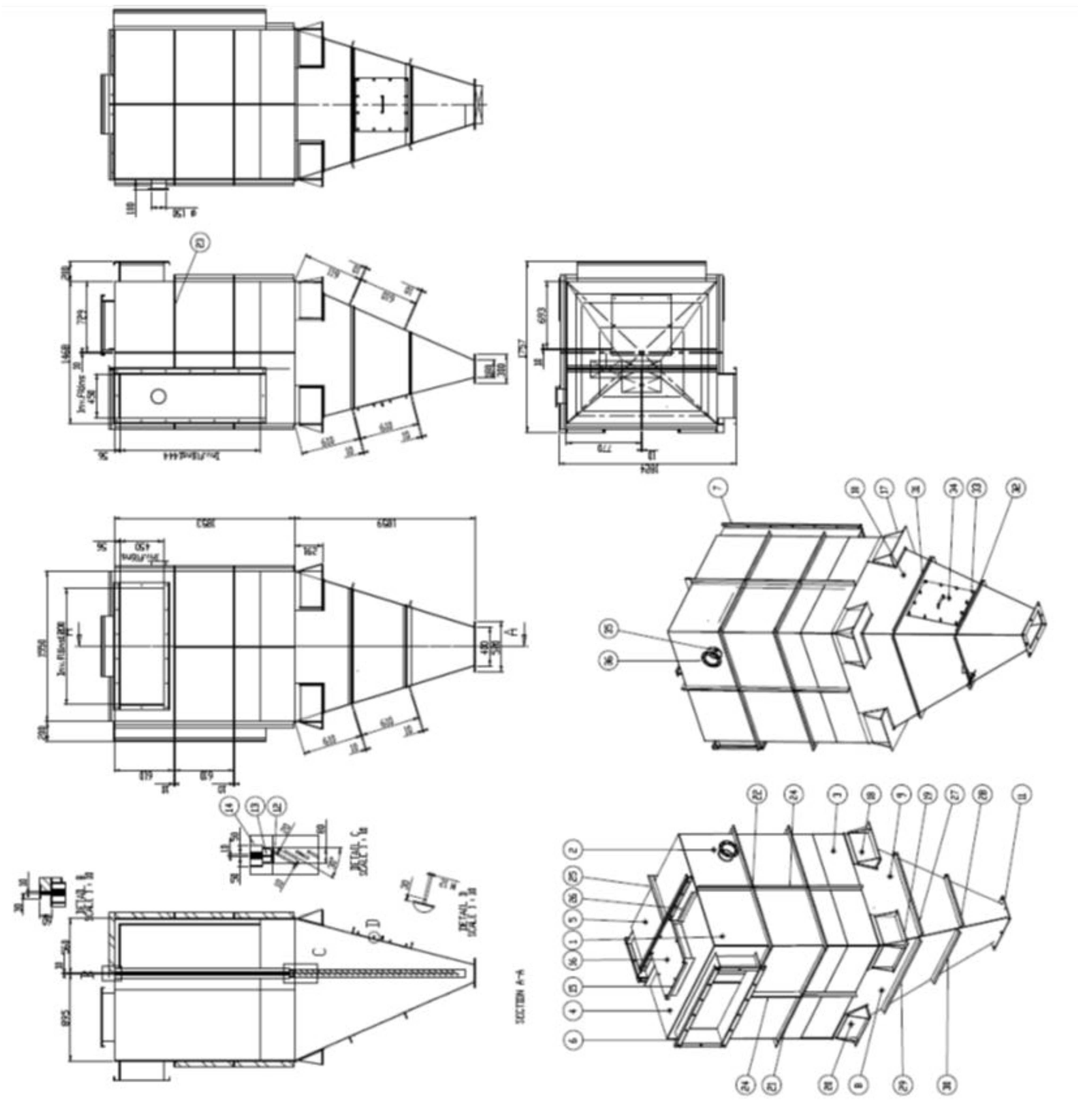
Appendix 7h – Ducts, filter, fan, and chimney



Appendix 7h continued – Ducts, filter, fan, and chimney



Appendix 7h continued – Ducts, filter, fan, and chimney



Appendix 7i – Cyclone