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| Abstract | The purposes of this document, is to describe how we will proceed in experiments that are designed to study the flow behaviour of RFID sensor platforms in silos and in the pellet transportation chain. Experiments will be carried out at LKAB/MEFOS. Variables such as the detection rate and abilities to control the experimental environment will determine the sizes and details of these experiments. The purpose of this document is also to study the readability due to long distances and unknown radio environment, uncertain orientation of transponders, mechanical and electrical interference, and separation due to size and density. Sensor survival in high temperatures is the most challenging part and will be tested in static ovens at LKAB/MEFOS. |

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Content

# 1 Introduction

## 1.1 Traceability in the pellets logistics chain

Traceability and measurement difficulties are two important issues; long lags between a measurement and a laboratory response means that the experimental unit has passed the process step long before results are at hand (Kvarnström & Bergquist, 2012). Low traceability prohibits calculations of when certain disturbances will enter downstream process steps (ibid.), and uncertainties of when and how fast disturbances will influence a downstream process is often hard to establish (Vanhatalo et. al., 2013). Continuous processes that are common in the process industry have special characteristics, for instance the difficulty to determine and maintain virtual borders of a suitable unit that can be followed through the production chain (Kvarnström & Oghazi, 2008).

The main factors affecting the quality of the iron ore pellets are connected to the processing conditions that will vary; conditions will differ from the mine and the ore extraction points, in the plant and through the stresses subjected to the finished product during delivery. However, in the foreseeable future it will not be possible to follow the ore from the mine extraction to the customer’s blast furnaces. This is related to the large volumes of product that is produced and the mixing during processing. The difficulties are also due to that the process changes from at stages being batch wise, such as when the ore is excavated or when the product is shipped on boat or train transports, cutting up the product flow. The processing at the plants is predominantly continuous with products being mixed at various stages, and with counter flows within the plants. The processes thus contain mixing, unknown flow patterns, changes of states from gas to liquids etc., and counter flow that further reduce traceability (Kvarnström & Oghazi, 2008.).

The difficult to separate and trace the product puts restrictions on the production. The storage facilities are limited. When products with qualities unsuitable to some customers are produced it is difficult to sort out these and return or send them to customers less sensitive to such deviations. The reason for this is mainly that the knowledge of the extent of these disturbances is unknown. Moreover, it is difficult to track products for causal analysis when customers have issues with the properties of a certain product shipment. Without good traceability, it is difficult for the producer to direct a specific batch to a specific customer without dedicating a silo or store it on the ground. There is therefore a need to trace and predict the location of a specific product (batch). Today, tracing products can be both complicated (if not im-


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possible) and time consuming. For this purpose, it is valuable to be able to make better predictions of the position of a product, from the plant until it has been delivered to the customer.

A model, which describes the logistic distribution of pellets, is essential to simulate and suggest appropriate actions to maintain a stable product quality. For traceability purposes, the important variables are the time and the position of pellets after production so that the product's properties, which have been selected for a specific customer, can meet certain quality constraints. One method to create online traceability proposed by Kvarnström and Oghazi (2008) includes regular addition of tracers, such as RFID markers that follow the process stream. RFID applications in granular flows have also been demonstrated experimentally (Kvarnström and Vanhatalo, 2010; Bergquist, 2012). An issue that needs to be resolved before research can be implemented in practice includes radio connectivity (Lindgren et al, 2010).

Depending on how often there is a need for using the tracer method, the cost of applying it needs to reflect its intended use. The iron ore product is relatively cheap and if tracers are added often, the cost needs to be considerable low. The method also needs to be robust versus the harsh transport environment that the pellets are exposed to. The tracers must be easily detected, and the tracers must follow the regular product flow without separating from the target batch. Currently, available off-the-shelf RFID transponders do not share the same physical features of a pellet and need to be protected and encased in a casing resembling the pellet properties. The transponder should at the same time make it easily detectable. A transponder pellet (e-pellet) of larger size is detected more easily but risk being separated from the regular pellets flow, due to flow induced segregation. If such segregation could occur, the sensors will not behave the same way as the pellets in the transportation chain. Earlier research has shown that RFID transponders may need to be larger than the pellets themselves to achieve acceptable detection rates (e.g. Kvarnström & Bergquist, 2012). Being able to make transponders with acceptable readability that follow the product along the logistic chain without segregation is thus important.

Currently, the detectability of each sensor depends on its size. With tags of the same size as the iron ore pellet (Ø 10,0-12,5 mm) the detection rate is around 20%. In fact, sensors of the same size of the iron ore pellets are very difficult to detect in a harsh environment: the already weak signal is drowned in the noise from electrical motors and vibrating transport conveyors. This situation could be improved by means of a more efficient signal processing: the currently available readers do not have the data processing capacity to extract data from the noise background and it would be a meaningful development to address this issue within DISIRE.

Up to this point, an increase of the signal to noise ratio has been achieved by increasing the size of the tags (when shortening the reader range is impossible): larger tags, with a diameter of around 20mm, yield detection rates of up to 80%. It will be thus important to show that the novel sensors can be scaled in size and implemented into the flow without the risk of segregation.

A measurable goal of the DISIRE project will be the increasing of the reading rate for the small tags to at least 50%. A second goal will be to investigate and demonstrate how larger tags can be included without segregation from the real pellets.

The main goal of this WP will be the further application of the PAT sensor platform, with the miniaturized tag, that will be able to be fitted with suitable off the shelf sensors that could be utilized for in situ measurements in the production process and logistics flow. Currently, already identified challenges towards delivering this technology are the following ones:

Detection rate of the small RFID tags in a bed of iron ore pellets on a large conveyor belt.

- Encapsulation of sensor based RFID tags to avoid segregation from ordinary iron ore pellets
- Positioning sensor based RFID tags in silos to verify flow model
- Integrate pressure/load force sensing capabilities into a RFID tags

The mixing of the same product but from different production batches in the logistics chain (including storage silos) may affect the properties of the material. The aim of achieving better traceability is to obtain a more evenly distributed production quality through mixing. The strategy to reach the goal is to study the silo's granular material flow and the mixing in the process, thereby creating models to control the mixing from different product batches.

## 1.2 Pellets transportation logistics

LKAB uses two main logistics channels, the south circuit through Luleå and the Gulf of Bothnia and the north circuit through Narvik and the Atlantic. The logistics chain of the finished pellets product can be exemplified through the transport of pellets between the pellets plant in Kiruna through the harbour of Narvik (Figure 1). The transportation chain of the iron ore pellet starts when the refined product is loaded into temporary storage silos at the production site. Each silo normally contains around 10.000 tons of pellets. The pellets are then loaded onto special cargo trains with a capacity of 6.800 tons (68 wagons @ 100 tons each) that transport the pellets to one of the two shipment harbours: Narvik or Luleå (depending on the production site). The final steps in the transportation chain (before the product reaches the customers) are loading the product on cargo ships and the maritime transportation as it is

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being indicated in Figure 1. The loaded amount per ship varies between 70.000 to 140.000 tons.

Figure 1. Pellets loaded at Narvik harbor. Photograph courtesy of LKAB.

The Kiruna-Narvik distribution chain includes three intermediate storage steps, a longer train transport and several shorter transports on conveyors between storages and the longer transports (Figure 2).

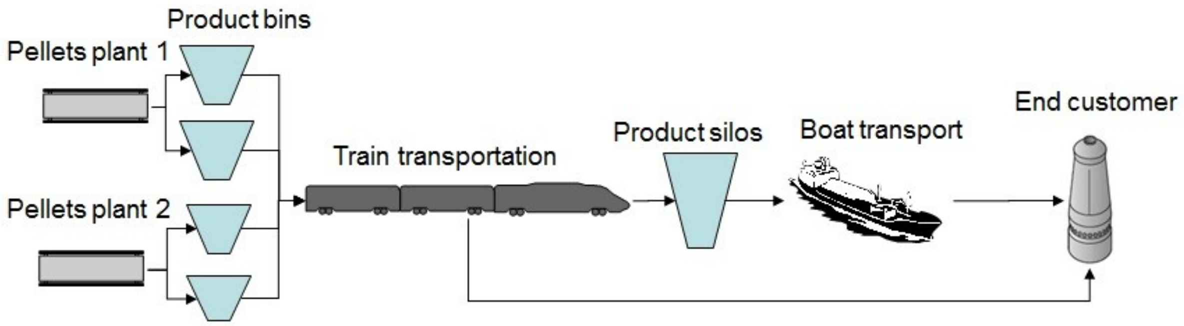


Figure 2. Transportation chain from plant to customer.

The distribution chain between Gällivare Malmberget and the harbour in Luleå is very similar to the Kiruna - Narvik distribution chain. The storage capacity in each product bin is between 8.000 - 10.000 tons, in average around 2 trains with a capacity of 6.800 tons leaves for Luleå harbour a day. But with a production capacity of 11.000 - 12.000 tons in each of the pellet plant the amount of trains can be increased if demand and availability of iron ore is high. In Luleå harbour there are three storage silos, each with a capacity of 40.000 tons. The production is ongoing 24 hours a day seven days a week with 3 working shifts a day.

Boat transports are then used before the product reaches the customer. The production process and distribution chain together contain a mixture of continuous and batch flows, and can therefore be categorized as a semi-continuous process. The inflow to the buffer silos at the product plant is continuous, while the remaining flows are batch flows. The batch volumes of pellets, going into or out of the process sections, are determined by the buffer levels and arrival or departures of trains and boats. Every such warehouse and every difference in separating the product into varying sizes makes the need for a good traceability harder to be archived. Traceability in the distribution process is further complicated by the design of some process steps, where the flow induces differences in the residence time of the pellets.

Batches are per definition not part of a continuous process, but it is sometimes convenient to divide a continuous product flow into discrete objects such as batches. The continuous flow of products from the plant is also subdivided into batches due to transportation needs (train cars and boats). In this case, the virtual batches are more interesting since these can be of a defined size throughout the transportation chain, regardless of the product volumes of cars, trains or boats. Such virtual batches may be defined when a marker attrib-

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uted to a certain product production time passing a point in the transportation chain. These virtual batches may then be used to discuss, model or measure how products or disturbances propagate, even for complex flows such as warehouses. Radio Frequency Identification (RFID) offers solutions to trace products. The RFID system consists of a transponder (the marker that carries information, typically a serial number), a reader and a system for data retrieval. The reader consists of an antenna and communication electronics, and the read information is then stored in a server, see Figure 3.

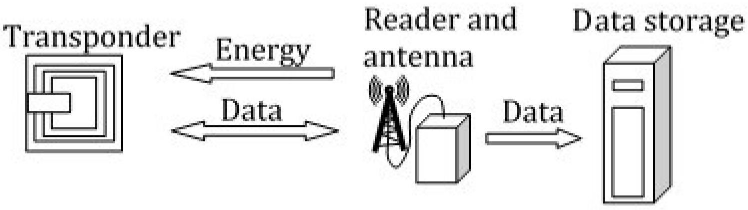


Figure 3. RFID system. Copied with permission from Kvarnström (2010).

Used as a traceability system, the RFID transponders may mark the beginning and end of a virtual batch, and it is thereby possible to create traceability that does not solely have to rely on off-line calculations. Another effect of adding markers is that the spread and mixing behaviour, exhibited between two points of the process, can be estimated accurately. Knowledge of the mixing behaviour makes it possible to calculate dilution effects on disturbances.

Traceability is achieved when the RFID transponders follow the product stream. The traceability can range from perfect, meaning that every iron ore pellets can be picked from somewhere along the transportation chain and it will be possible to identify the exact times and therefore processing conditions that occurred during its production. In the iron ore chain, that would mean marking of every pellet, which is not feasible. Instead, pellets-like objects containing RFID markers (transponders) are added to the flow and by detecting, Figure 4.

Figure 4. Left: 13 mm transponder encased in epoxy/iron ore powder composite. Right: regular iron ore pellets. Photography: Bjarne Bergquist.

Following the RFID pellets, a good view of the throughput times and waiting times of the system can be estimated. The transponders are identified when passing readers along the transportation chain. The readers' reading rate is an important response to detect the passing transponders in the flow. Furthermore, line of sight, disturbances in the reader antenna environment such as other radio emitters, vibrations, electrical conductors such as metal objects affects the reading rate. Finding suitable reading antenna positions in an industrial environment can therefore become a challenge. Studied reader positions include readers encircling conveyors (Figure 5) and placement below conveyors.

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Figure 5. Iron ore conveyor belt running through reader antenna at Luleå Harbor. (Photography courtesy of: Björn Kvarnström.)

The orientation of the transponders when passing the readers is also important. Earlier experiments have used direction sensitive transponder antennas. In an attempt to increase the reading rate, multiple reader antennas have been used in previous research (Figure 6, see also Kvarnström, 2010 and Kvarnström and Bergquist, 2012). The transponder development has progressed and there are currently transponders off-the-shelf that are multi-directional. In this way, the process can be modelled and the model can be regularly calibrated using RFID pellets.

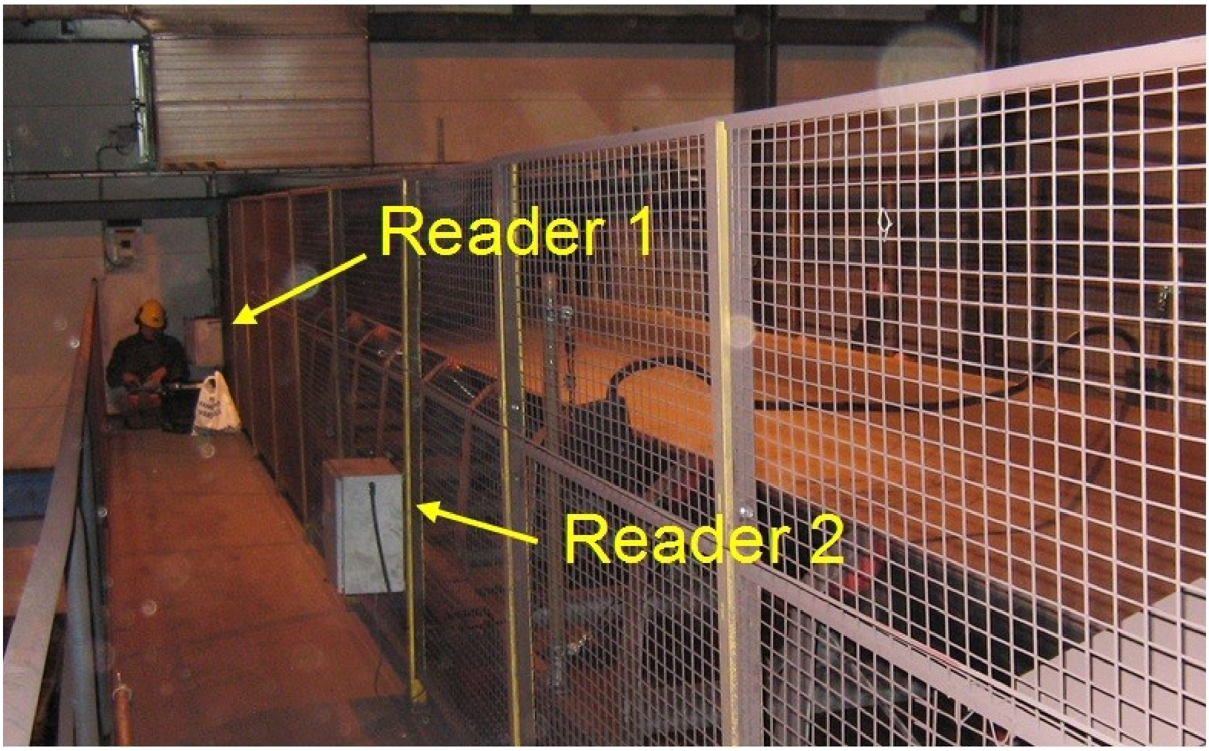


Figure 6. Two readers at the LKAB Kiruna plant. Reader antenna enclosing conveyor belt is seen behind trellis. (Photography courtesy of: Bjarne Bergquist).

The logistics process not only induces traceability difficulties. The stresses subjected to the pellets are believed to be a major cause for pellets breakage before shipping. Currently, it is impossible to measure the acceleration a pellet is subjected to during handling, or the stresses or pressures it is subjected to during storage. Pellets, sometimes called e-pellets, with both communication possibilities and sensors could aid in the design of the logistics chain. In this way, logistics operations could be made aware of where the pellets are subjected to large stresses, how different operation procedures affect stresses or that such high impact process steps could be redesigned. e-pellets carrying pressure sensors or accelerometers, batteries, an internal memory and an RFID transponder could also measure properties in situ within warehouses or during transport, and this information could then be accessed at locations where RFID readers can be installed and the e-pellets can be reached. Such transponders with internal batteries are known as active transponders. Figure 7 shows both various types of off-the-shelf passive transponders as well as an active one.

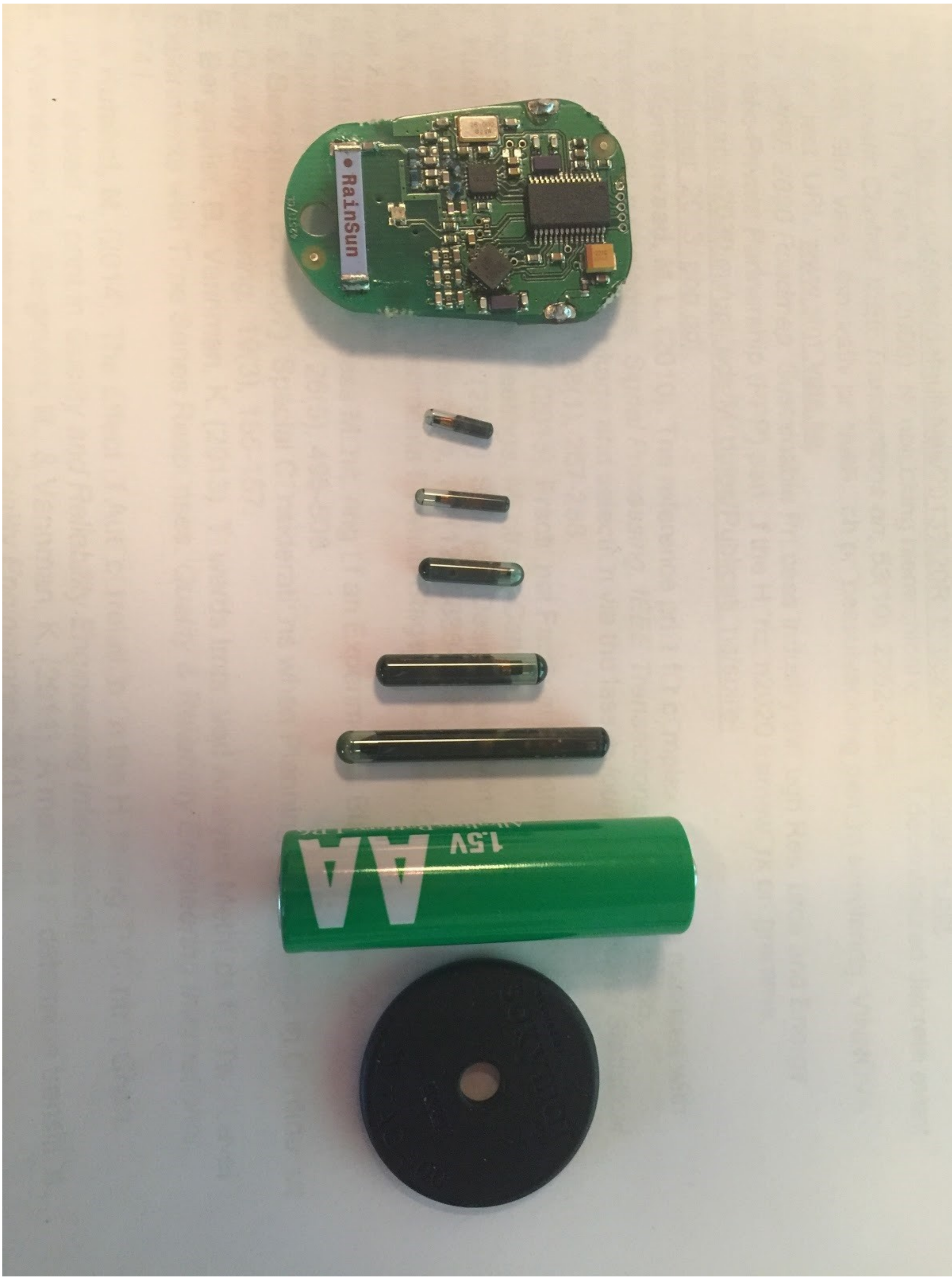


Figure7. Different types of RFID transponders (and AA battery for size comparison). The top transponder is an on shelf active transponder with internal power supply and memory suitable for in-situ tests of positioning or for adding sensors such as accelerometers. Other transponders are passive. (Photography courtesy of: Bjarne Bergquist.)

# 2 Hot iron ore process PAT sensors

Green pellets are ball shaped aggregates of finely ground magnetite and additives, such as binders that undergo a refining thermal process in the so-called Grate[1] Kiln[2]. During the passage through the grate, the initially moist pellets (the moisture content varies between 8.5 and 9.2 %) are dried, heated and oxidized before the sintering[3] phase takes place in the kiln and in the final cooling phase. A schematic representation of a Grate Kiln pelletizing plant is presented in Figure 8.

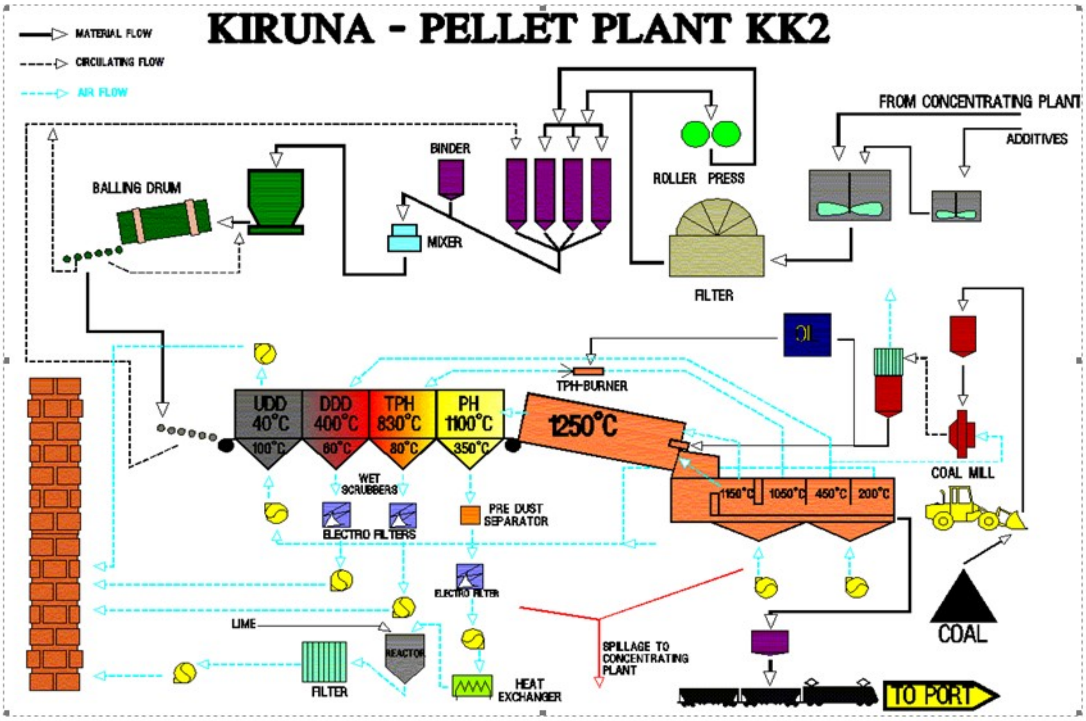


Figure 8: Overview of a pelletizing plant process at LKAB

The first part of the hot process in a pelletizing plant is the grate, which is divided into different zones. The drying takes place in the first two zones of the grate through the forced circulation of hot air. These zones are called UpDraft and DownDraft Drying (UDD and DDD). In the next zone, the pellets on the bed are exposed to the so-called Tempered PreHeat (TPH). The aim is to remove the remaining moisture content and start the oxidation process. The last zone of the grate is the PreHeat zone (PH), where most of the oxidation process takes place. Throughout the Grate the pellets experience widely ranging temperatures that

[1] A **grate** is where a stationary bed of pellets, approximate 20 cm high, is transported and exposed to the process of drying and heating.

[2] A **kiln** is a thermally insulated chamber, a type of oven, that produces temperatures sufficient to complete some process, such as hardening, drying, or chemical changes.

vary between 20°C and 1300 °C. The overall transportation time through the grate can last from 8 to 20 minutes. In the Kiln, the pellets are sintered and the product is refined to meet the customer's quality requirements.

The cooling process (the cooler for short) is divided into four (or five) parts. Here ambient air is circulated to cool down the hot pellets. The air-flow is then recycled in the Kiln and on the Grate and an meaningful aim for DISIRE enabled sensors would be to acquire knowledge on how the gas composition varies throughout the grate through measurements.

With respect to the involvement in DISIRE the aim is to measure the temperature and gas composition on the grate of the pelletizing plants. The novel sensor technology shall be able to measure temperature in the pelletizing plant’s preheating oven (the grate). The sensor will travel inside the bed of pellets through the oven and continuously report the temperature via radio signals to a reader-equipment.

The high temperatures will be a challenge for the sensor that will have to be insulated with state of the art materials in order to keep the electronics working over the entire measurement cycle. The reader antenna will need to be endowed with a milder form of heat insulation as well. It should be noticed that there are additional challenges in transmitting radio signals within the grate, since airborne particles and gases will absorb part of the signal's power. In the case that the radio communication would not be able to be established, a proper reading infrastructure in the cooler parts of the process might also be investigated in DISIRE.

The identified challenges towards working implementations are:

- Encapsulate the sensor to withstand temperatures up to 1200°C for up to 20 minutes
- Wireless transmission of data through that encapsulation
- The size of the sensor must not impact the gas flow
- Measure the oxygen content in process's gasses

## 2.1 Hot process integration strategy

The PAT sensors will report their data to a reader located nearby. This reader will store all sensor data locally or in a remote database, while the data should be accessed through TCP/IP. No further integration is planned at this stage. First high temperature measurements can be tested and verified in static laboratory ovens at MEFOS to avoid disturbing the production process at LKAB. A detailed integration strategy will be analysed in the future

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of the project with respect to the corresponding deliverables, from this as well as from other work packages.

## 2.2 Description of the physical process

From a control perspective, the physical process has two inputs:

1. grate-temperature: the temperature on the grate
    1. Admissible values for this temperature are in the range 0°C to 1200°C.
2. grate-gas-composition:
    1. Admissible values for the oxygen content are from 0% to 100% (ambient air has on average 21% oxygen content)

## 2.3 Mathematical models

Empirical models for the temperature dependent thermal conductivity of suitable types of thermal insulation will be developed as required for simulating the thermal conductivity of encapsulations used for enhancing the temperature range of PAT sensors. The material flow model in WP5 could also extended to include information from this process in order to improve the customer order to delivery chain.

## 2.4 Simulation tools

At the current stage of the project, one possible solution to the problem of building sensors that survive high temperatures is to create a shell of a highly insulating material and fill this shell with a material that absorbs the energy transmitted through the insulation through phase change, high specific heat and/or evaporation. As part of the work towards a PAT sensor that survives high temperatures, a Matlab/Comsol hybrid tool will be developed for optimizing the ratio between the amount of insulation and the amount of heat absorbing material. This tool may be extended to supporting multiple materials of both types.

## 2.5 Control oriented models

The grate process as well as the logic chain will generate knowledge useful for off-line or open loop control purposes. The LKAB processes are not expected to be controlled in closed-loop within the duration of the DISIRE project.

## 2.6 Control system

The grate control system is proprietary to LKAB and no additional information will be provided.

## 2.7 Measurement and Sensor systems

The measurements and sensor systems of the grate process include temperature and oxygen content gauges, such as thermocouples and lambda sensors; these allow for a better understanding of the chemical environment and the heat distribution within the process.

The novel in situ sensor technology will be able to report data, while it is transported through the Grate (online PAT). By giving each sample a time-stamp and by knowing the transport conveyor speed, this will make it possible to estimate the temperature and oxygen content at various positions inside the oven. The conveyor speed is very slow and the sampling speed is only relevant in terms of optimising the radio data channel. From LKAB's perspective, a sampling rate of about 1 Hz (or less) could be enough. In general within the DISIRE project we expect that the novel sensors will be able to measure temperatures with an absolute error of 1-3% (depending on thermocouple type).

The reader will be connected to a database over GPRS. The sensors cannot be accessed directly, only via the reader. Further developments to this system could be to devise a sensor technology that can measure the combustion parameters and to support positioning measurements via 3D inductive coils.

## 2.8 Hot process actuation

The grate process is currently open-loop and operator controlled, and the expected actuation is a better control of the grate environment including atmosphere flow, atmosphere oxygen content and temperature profiles along the grate and at different depths of the grate’s pellets bed.”

## 2.9 Hot process data analytics

The analytics of the data stemming from the grate process includes regular experimental analysis to calibrate the readings obtained from the grate bed oxygen and temperature sensors, and to compare readings performed externally, in fan channels, furnace chamber mounted sensors and so on.

## 2.10 Evaluation platform in Tube furnace Pot-furnace Grate Kiln plant

To ensure that the sensor is working in the desired temperature range and can measure the gas compositions wanted, it is important to test it in steps. The first step will be to run multiple tests in LKAB's tube furnace. Within the furnace it would be possible to run trials while controlling the environment's temperature and gas composition.

The tube furnace is a Carbolite STF 15/450 with a maximal temperature of 1500°C and 5,5kW maximal effect. The furnace is controlled by a Eurotherm 3508P1 PID-temperature regulator with RS232 interface. The regulator can store a program with a maximum of 20 segments in which one has to be of the type "End". The rate of heating up should not exceed 5 K/min, above 1000°C it can be increased slightly (up to 7,5 K/min). A faster increase or cooling can cause damage to the tube. The heating is done by six SiC spiral rods. Both the heating element and thermocouples are placed outside the tube. The temperature inside the tube therefore deviates slightly from the temperature on the display if the furnace is not calibrated. For the same reason the sample is not affected by the IR radiation from the heating elements. The furnace can be connected to a gas supply and allows experiments in different (not corrosive) gases. The only way to communicate with the sensors is through a reader. This reader will access and poll data from the sensor with radio signals over a distance of 10-50 meters.

This long reading distance must be achieved when monitoring hot processes where the reader equipment cannot sustain the harsh conditions. The reader will, at periodic intervals, scan for all the sensors in its vicinity and collect their data. For each successful poll, it will store the tag's id-number, sensor data, link quality, battery status and a time-stamp. Furthermore, the reader will store all the sensor data until the operator erases it. During the evaluation period (i.e., during the project time) all the data from all readers will be transported over GPRS to a database that will be made available to all partners through a web-interface over the Internet. The sensors will be destroyed and eventually burned up at the end of each test. The reader’s antenna should survive several test phases but will need to be dismounted between test campaigns. Since each sensor can be used only once, they will be produced in small volume in a serial manufacturing fashion.

It should be noticed that, when integrated into the real factory environment, the data will be directly accessible at the reader through IP on Ethernet or WiFi. This could be possible already at the project phase but usually the test site owner does not allow access through their Intranet.

## 2.11 Evaluation cases

Sensor survival in high temperatures is the most challenging part and will be tested in static ovens at LKAB or MEFOS. The temperature of the electronic components inside the encapsulation cannot rise above 100°C while the surrounding temperature will reach above 1000°C.

The sensors will continuously report both inside and outside temperature to let the end-user monitor the sensors performance. Notice that the radio environment inside the grate oven will have to be examined in parallel to the tests and most likely on the real site.

## 2.12 Final industrial demonstration

The sensors will be finally tested / demonstrated in one of LKAB's pellet plants with a Grate / Kiln process. The real data from the process will have to be scrambled due to privacy concerns connected with the use of proprietary IPs.

The sensor data will be provided unscrambled to project partners along with reference data from existing sensors. The available sensor data will be sensor id, timestamps, temperature and oxygen readings. The database will have export functions for .csv formatted files. Finally, the Database with the above listed data will remain and be accessible throughout the project period. No other process data regarding the grate will be disclosed.

## 2.13 DISIRE Technological Contribution

The expected major contributions from the project will be: a) the DISIRE based in situ sensors for temperature and gas decomposition measurements, and b) DISIRE based On Line PAT, with potential extensions in influencing the overall IPC in simulation and hardware in the loop trials.

# 3 Pellets transportation chain

## 3.1 Experiment setup, granular flow test rig

Important traceability data include volumes in storage facilities, type of storage facilities, storage and transportation mixing and flow behaviour. The volumes can be studied by blueprints. However, the flow behaviour needs to be determined experimentally since current theoretical models are too coarse and since that large storage volumes are suspected to be inactive, meaning that these volumes are stagnant. A laboratory 2-D test rig useful for simulating specific silo model flow have been designed, Figure 9.

### 3.1.1 Experimental plan 2-D test rig

The dimension of the test rig is 1000 x 1000 x 50 mm, Figure 9. It contains a bottom throttle facilitating experiments with both symmetric flow with centre opening and asymmetric flow with openings at the sides. Glass walls facilitate studies of the flow pattern.

Figure 9. 2-D test rig with transparent walls, allowing monitoring flow patterns depend on shape and size on silo. (Design and photography: Stefan Englund)

The purpose of using a 2-D laboratory scale model is to predict product flow behaviour in industrial scale warehouses. The test rig will also facilitate planning of experiments in larger scale, reducing cost, time and also increasing safety.

### 3.1.2 Laboratory test granulates

The shape, surface properties, density and cost needs consideration when choosing bulk granulates for the laboratory tests. Considered materials include iron pellets, metal, plastic or beans, seeds and other on shelf available alternatives. Since the experimental rig is miniaturized, the size of the bulk material should likely be smaller than the iron ore pellets and have similar shape and surface features to replicate true flow behaviour. A size of 3-5 mm was considered appropriate (if scales were to be maintained, the granular material would need to be less than 1 mm, but this was considered impractical for experimental reasons). Iron ore pellets was the preferable material to be used but that material needed to be custom made, this option was excluded due to costs. Plastic balls were disregarded because of their smooth, low friction surface. Instead peas and beans were selected. Peas have a comparable shape and surface features and were obtainable for free, courtesy of Lantmännen, an agricultural supplier that could see the importance of the tests on their area of expertise. The beans could in turn simulate larger RFID pellets due to their oblong shape. This would then simulate the possible segregation behaviour of such larger size RFID pellets, see also Figure 10.

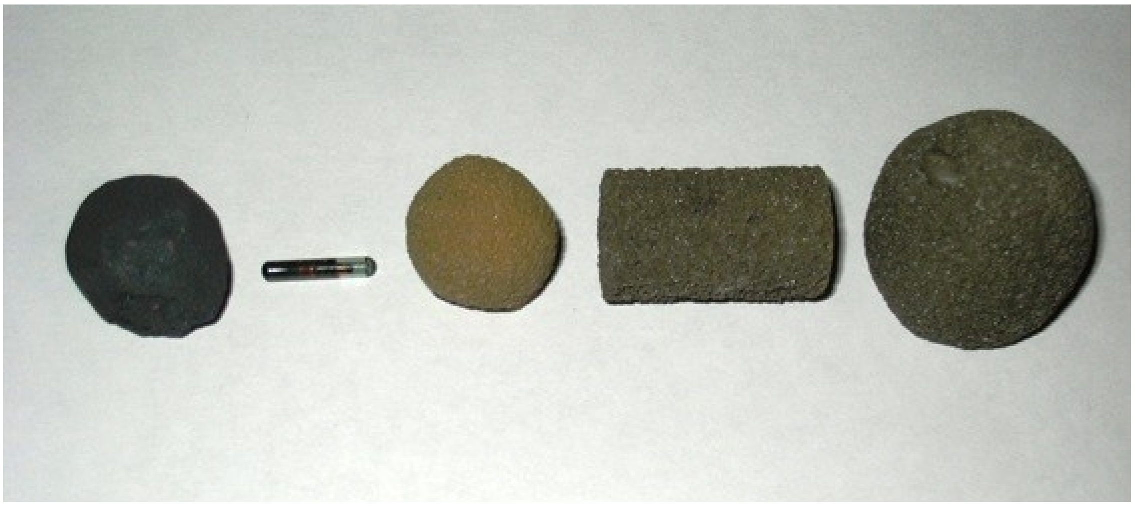

Figure 10. RFID transponder casings used previously (Kvarnström, Bergquist et al. 2011). The 22 mm sized glass tube transponders embedded in a cylindrical shape casing containing dolomite and polyester composite with a shape of 13 by 30 mm showed reasonable good detectability during previous experiments and can be seen in the picture among other shapes. (Photography courtesy of: Björn Kvarnström).

The bean shape does in the laboratory experiments simulate downsized cylindrical shaped transponders used in previous research (Kvarnström, Bergquist et al. 2011) and has similar density and surface properties as the peas. All beans were painted to aid visual detection easier, Figure 11.

Figure 11. Beans (red) and peas. The colouring is used for flow pattern detection during the experiments. (Photography Stefan Englund)

### 3.1.3 Test plan for the experimental test rig

The test rig was designed for three major purposes:

1. The first purpose of the rig was to evaluate different flow patterns for different silo types that are currently used in Malmberget plant - Luleå harbor (Gulf of Bothnia) supply chain. A hypothesis is that the flow pattern will be important for the design of the off-line supply chain traceability model.
2. The second purpose was to evaluate measureable segregation tendencies in the material flow. Presence of segregation will need to be countered by the transponder designs, such as design of the casing density, shape or surface features.
3. The third purpose was to analyse mixing behaviour in the silos, for tracking purposes.

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#### 3.1.3.1 Experimental design of the test rig EBF simulation

Today, the blast furnace steelmaking process is the primary source of the world's steel production. The blast furnace can be characterized as a high temperature countercurrent reactor for reduction and smelting of iron ore into hot metal (Geerdes et al., 2000). Coke and coal are used to reduce iron oxide, normally in form of sinter and/or pellets, into liquid iron.

In 1997 LKAB inaugurated a pilot scale blast furnace. Although the experimental cost per run and risks associated with performing experiments are great even in pilot scale, they are substantially lower than they would have been in full scale operation. The EBF is specifically designed for experimental purposes and has many possibilities for measurement during operation. An outline of the EBF, examples of measurement possibilities, and some specifications of the furnace are presented in Figure 12.

The general customer demands on iron ore pellets are that their blast furnaces may be run efficiently and effectively with few disturbances and that the resulting iron is of a high grade.

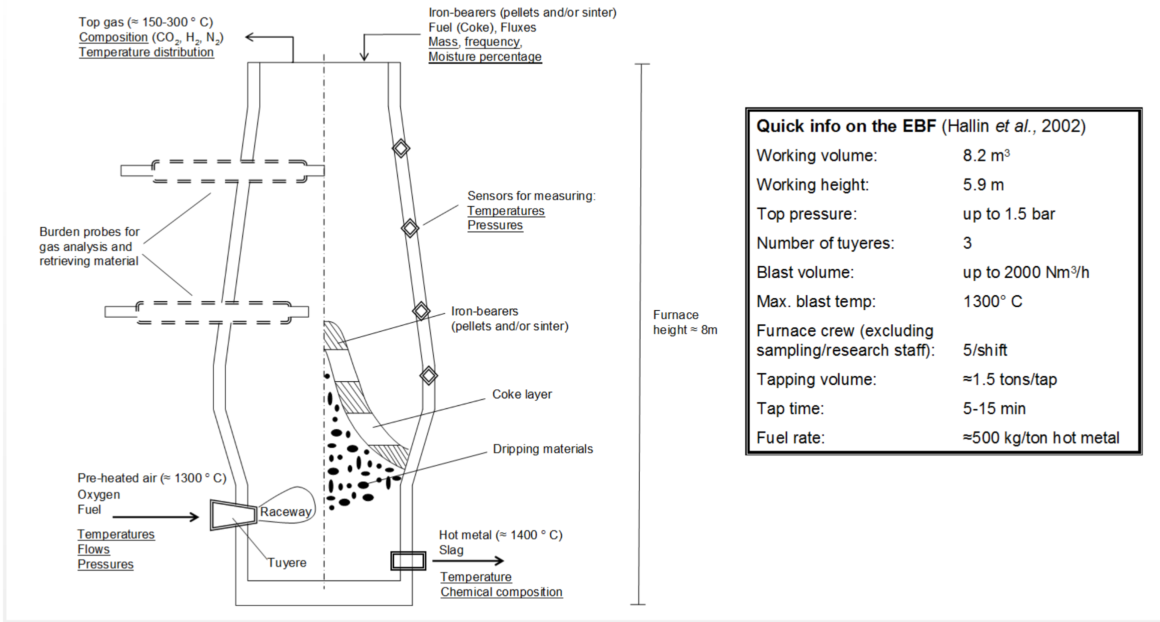


Figure 12. Outline of the Experimental Blast Furnace process (Vanhatalo & Bergquist 2007).

Four bins are used for feeding the blast furnace with pellet during EBF experimental campaigns. One of these bins may be used for RFID and active sensor evaluation. Flow pattern analyses in the 2-D-silo are performed before the pilot scale experiments to evaluate segregation tendencies and silo design-mixing behaviour. The analyses will aid the planning of the

EBF traceability experiment. Such results include insights into how to place transponders and antennas in the bin at the EBF test facility.

The experiments in the experimental test rig have been filmed to evaluate flow patterns and how individual beans behave compared to the bulk in general. Some bulk material was coloured black to enhance contrast and to visualise flow patterns, and beans were coloured red Figure 13.

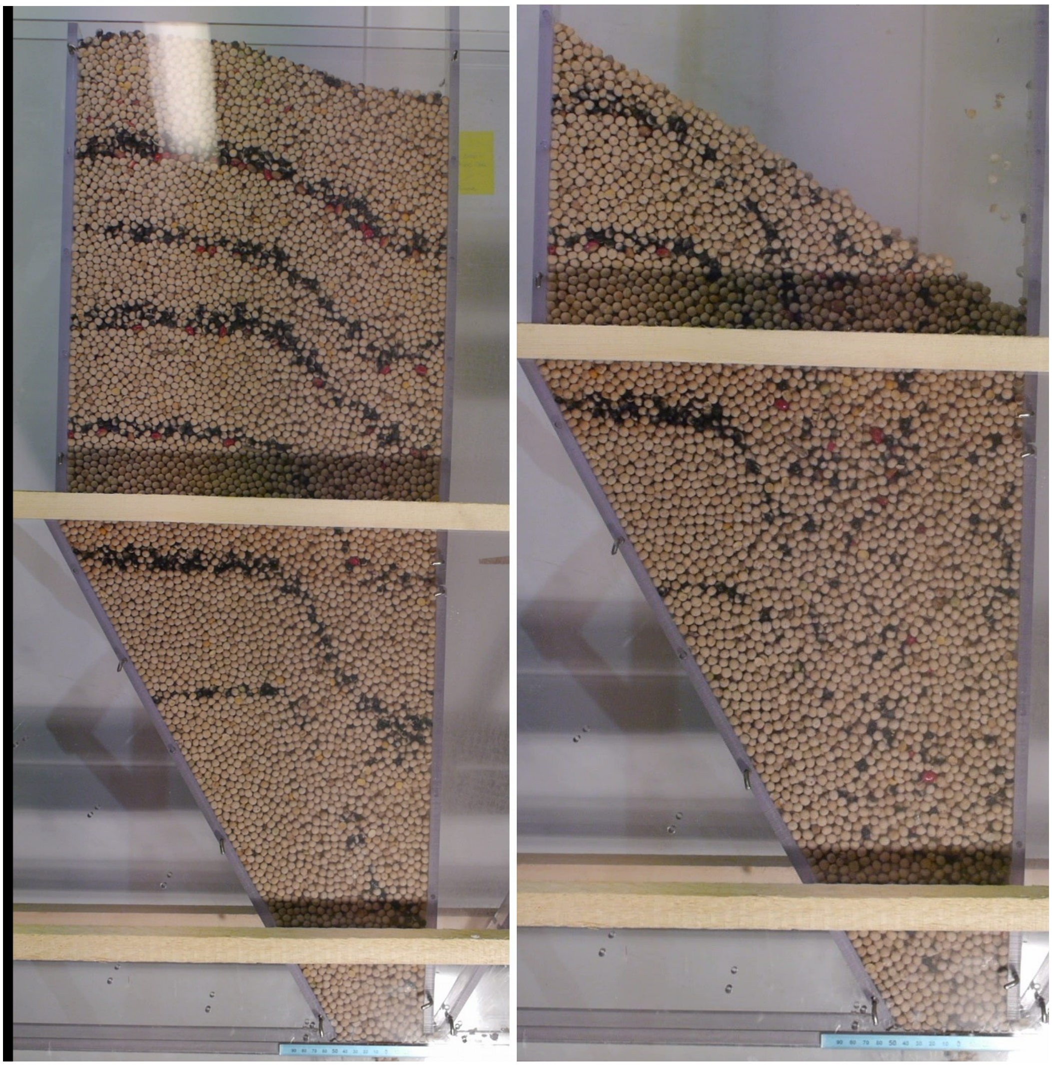

Figure 13. An experiment simulating a storage bin used at LKAB's Experimental blast furnace. Analyses of flow pattern will help verifying if the transponders exit the bin in an expected way to detect differences between experiments and the bin related to flow pattern or segregation.

The analyses regarding segregation, is ongoing. One notable result is that even when the bins or silos have steep bottoms (60 degrees from horizontal) there are still static volumes, which is seen in Figure 12 as the horizontal black lines. The velocity of the material is increasing from the static areas and highest above the bottom exhaust hole. The angle of re-

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pose is constant and the top layer peas have the highest velocity of all the peas along this angle. Forthcoming analyzes will establish velocity profile, mixing and segregation behaviour.

#### 3.1.3.2 Test plan of storage silo

Luleå harbour hosts three full size storage silos with an approximate capacity of 40,000 ton and one of 10,000 ton capacity for storage of special products. The latter of these is also a possible location for a semi-scale silo experiment. The storage silos are the last storage before pellets is loaded on the ships. Knowing the flow pattern and mixing rate in these silos is therefore important for the traceability model. Generally, only one product is shipped through the Luleå harbour. The sole product type is to be advantageous as this will eliminate some complexity.  However, many issues need to be solved before the experiment. The possibility of performing an experiment using the special product silo is currently evaluated by LKAB and LTU.

#### 3.1.3.3 Laboratory flow tests simulating the storage silo

The 2-D test rig was adapted to simulate the conditions at the special product storage facility, Figure 13.

Figure 14. Laboratory granular flow test rig. Shown is a test simulating bottom centre exhaust using peas. Black beads are painted peas used for amplifying flow patterns.
*(Photography courtesy of: Rickard Garvare and Stefan Englund)*

### 3.1.4 Experiments and results so far

The experiments are ongoing and will continue. Preliminary results and conclusions include observation from the 2-D-test rig experiments intended to simulate the EBF pellets bin and the storage silo in Luleå harbour.

### 3.1.5 Observations from EBF bin simulation tests

The bin in the test is approximately 500 mm wide and 1000 mm high with a bottom angle of 60 degrees from horizontal. The opening on this experiment was 20mm.

The angle of repose depends on the material; once it is set it will remain constant until the bin is empty. A zone with no material flow is created at constant angle, The flow zone will remain nearly stationary, except at the angle of repose close to the surface, see Figure 14 below.

Approximately half of the volume of the bottom layer of material leaves the bin without being mixed before the top layer starts to mixed with the above layers. The flow in the flowing zone demarcated by the green line and the vertical silo wall resembles laminar flow, where mixing of levels on top of each other are mixed sequentially. All levels of the material in the bin are mixing once the the top level reach the outlet, and the mixing stops in reverse order, with the top layer being the first layer to completely leave the bin. The last material leaving the bin is the remainder of the bottom layer.


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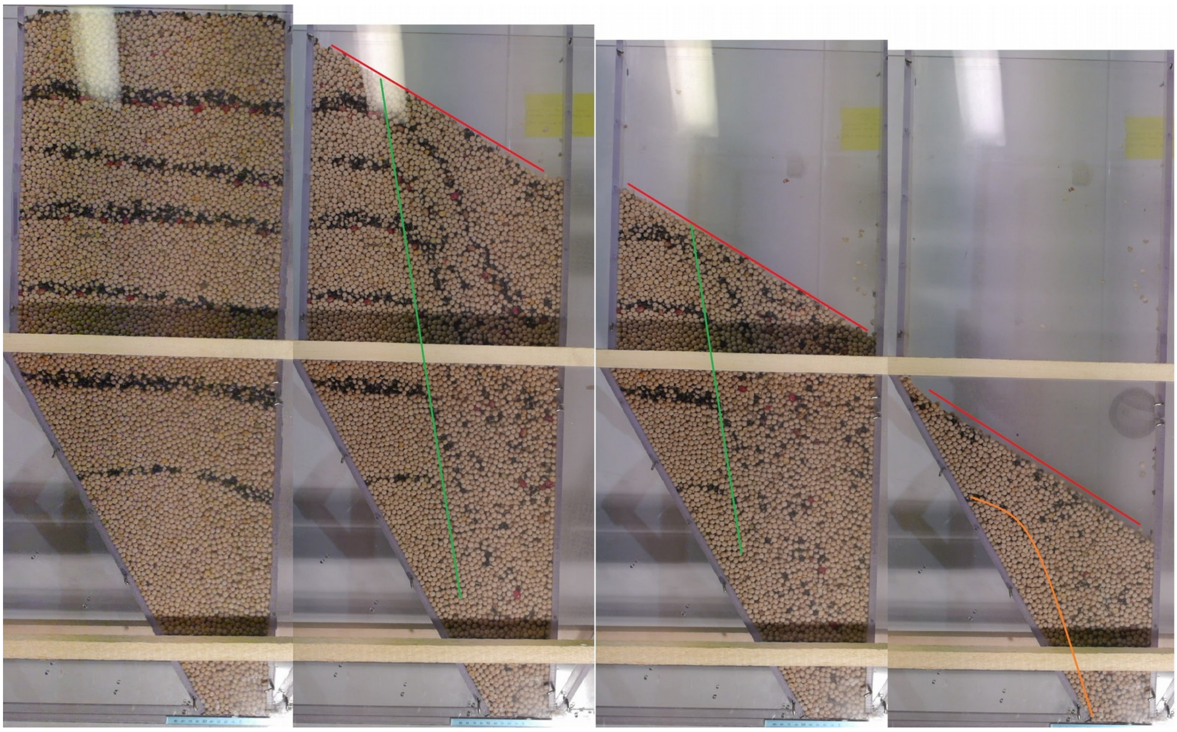

Figure 15. Sequence pictures from EBF bin simulation experiment. Rapid granular flow at angle of repose is marked in red. Start of mixing zone marked with green and remaining material of the first layer marked with orange. (Photography courtesy of: Rickard Garvare and Stefan Englund)

Segregation analyses and more detailed flow pattern analyses are yet to be made. However an observation is that no deviation from the flow line is noticed. Another observation is that some of the observed beans had a slightly lower velocity than the peas. These observations need further research.

#### 3.1.5.1 Observations from storage silo simulation tests

The bin in the test is approximately 1000 mm wide and 1000 mm high with a flat bottom. The opening on this experiment was 40 mm.

An angle of repose is formed on the top surface, and this angle will depend on the granular material properties. Once the angle is set it will remain constant until the bin is empty. A tunnel shaped zone without material flow is created. The tunnel shape will break towards the surface and will, as flow continues, appear more cone shaped. The top angle of this cone will increase until it equals the angle of repose. At that time, no more material will flow out of the silo, see Figure 15.

In this experimental setup a small amount of the volume of the bottom layer leaves the bin before the material in this layer is starting to mix with material from the above layers. A tunnel of flow is soon created. In this tunnel, mainly the top layer is leaving the silo with limited mixing of the lower layers. When the surface enters the below laying layer, these layers will start mixing. As the surface is lowered and the silo is emptied, this process is repeated for layers below until the top surface has sunk and reaches the outlet. Much material will remain in the silo until it is emptied in some other way.

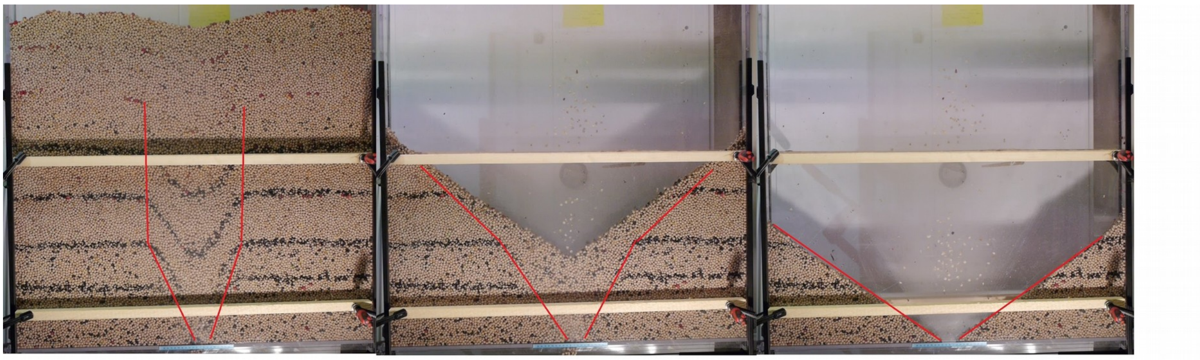

Figure 16. Sequence pictures from silo simulation experiment. Tunnel and cone marked in red. Mixing of material is in this flow small except closer to the surface illustrated by the tunnel open up to a cone shape. This means that once the top layer reach the outlet, the material from the surface will leave the silo. Other material remains more or less static until the surface reaches it. (Photography courtesy of: Rickard Garvare and Stefan Englund)

## 3.2 Experiment on Granular Flow on industrial level

The purpose of the half scale tests planned in the LKAB EBF facility in Luleå and in the harbour in Luleå is to verify the results from the 2-D silo experiments and to develop a robust technology before going to full scale tests.

### 3.2.1 Test plan for experiment in the bins at the LKAB EBF facility

The LKAB EBF facility is a good environment for testing on pilot scale and plans are to perform experiments on one of the product bins when the blast furnace is running other experiments. The purpose of this experiment is to evaluate the sensor technology both active and passive transponder and to evaluate mixing and segregation behaviour. We hope to confirm the flow, mixing and segregation we have obtained in the laboratory tests; thus validating the laboratory equipment and methodology for further use for warehouses where experiments are not practically feasible.

- The pellet bin at the EBF is normally empty since the EBF is only run during experimental campaigns. The empty represents a unique possibility to install antennas is that we can place transponders and sensors where we prefer, something that will not be possible on tests on industrial level. The experiment is intended to accomplish three things:

- By placing transponders at predetermined positions in the pellets volume of the bin and studying the sequence by which the sensors exit the bin, it is possible to confirm or reject similarities with behaviour seen in the 2-D test rig.
- By using transponders of size 12 mm and accompanied casings, and placing these next to 22 mm transponders and casings, differences in flow behavior can be measured as these exit the bin. .
- By using active sensors and antennas within the bin, it may be possible to detect the flow directions of particular transponders, thus enabling validation of flow of these transponders that need to be markedly larger than the pellets (egg-shaped 50 mm casings). .

#### 3.2.1.1 Active sensor technology

The position of the PAT at the time of data acquisition is not only of interest for the hot side process. As mentioned in D3.1, one solution for accurately determining the position of a sensor within a process can be through measurements of the propagation delay of radio signals between the sensor and a number of fixed reference nodes.

It is desirable to use as wide bandwidth as possible to minimize the influence of reflected waves bouncing off objects in the environment around the sensor. Reflecting waves makes it harder to separate the direct signal from indirect signals with small differences in path length: Choice of wrong signal renders the positioning calculation to be wrong. On the other hand, wide bandwidths have traditionally corresponded to high operating frequencies to keep the fractional bandwidth small. However, recent developments in RF circuits and standards have enabled so-called ultra-wideband (UWB) positioning based wide bandwidth transmission at moderate frequencies. If the same technology as the one intended to be used in hot process is applicable to the cold process is to be investigated.

In the hot process the intention is to investigate if IEEE 802.15.4-2011 based solutions can be applied to position measurements in industrial processes. The basis for this work will be the Decawave DW1000 chipset (http://www.decawave.com/products/dw1000 ) that uses 1 GHz bandwidth channels in the 3.5-6.5 GHz frequency band to achieve better than 10 cm positioning accuracy.

Another technology available for position determination, is the use of low frequency magnetic

Field ”beacons”. The beacons technique is based on measurement of the strength of the received magnetic in a transponder. One commercial use of the technology is to determine the position of wireless car keys to allow start of vehicle (http://www.atmel.com/Images/article optimizing passive keyless entry.). Another application is found in the tracking of elderly, disoriented people inside buildings. In these applications the target is not three dimensional positioning, but instead to determine if the transponder is in the vicinity of a single beacon, or, in between two. This is something that might be applicable in a silo environment. For more specific description see D3.1

#### 3.2.1.2 Risk factors

In the outlet of the EBF storage bin is a vibrator feeding the pellets on to a conveyor. The best places to locate antennas for the purpose of detecting sequence, is close to the outlet of the bin. However the oscillations from the vibrator might make detection difficult or even impossible. Placing the antennas further away, if possible, might reduce the probability to make proper conclusions from the test with the RFID transponders.

A risk with the active transponders is related the location of the antennas inside the bins. Sins the bin is narrow, only height positioning may be possible. However, since the starting location will be known, the exit sequence can be compared with the RFID transponders, if they can be detected.

### 3.2.2 Test plan for full scale experiment in special product silo at Luleå Harbour

The suggested trial is intended as an almost full scale experiment, also with the purpose of verifying the result we get in the test rig and EBF experiments and to develop a robust platform for the RFID technology. To have a robust technology is important before attempting a full scale test on the supply chain between LKAB’s facility in Malmberget and the harbour in Luleå. The technology that we intend to use is both passive and active sensors. With these we intend to show that;

- The technology we intend to use is robust enough to be used in full scale in an industrial environment. The passive RFID technology must be able to detect at least 50% of the transponders released into the system.

- The active sensors will hopefully give a graphical picture of the material flow that can confirm the result in the previous experiments. And also get a level of the expected physical impact that the iron pellets are exposed of in the supply chain.
- The physical way a pellet travels through a silo is longer than can be achieved in the experimental 2-D-silo. In the experiment we hope that any segregation tendencies will be more easily detected than in the 2-D-experiments. Since the analyses regarding segregation still is in progress we can still not tell if this is an significant factor or not. Regardless of our findings we hope that an experiment of this size will confirm any result we find in the smaller experiments. The result is important since the detectability of the transponders we intend to use increases significantly with size.

#### 3.2.2.1 Technical challenges

The use of RFID in the mining environment presents many challenges. These include readability due to long distances and unknown radio environment, uncertain orientation of transponders, mechanical and electrical interference, and separation due to size and density.

The work performed in DISIRE on these matters link to work performed in the ePellet project, which was done by LTU in cooperation with LKAB. More details related to this work can be found in D3.1 which contains what were achieved in the frame of the ePellet project, as these to a high degree will affect the work and decisions taken in DISIRE.

Tests were performed in Luleå harbour during early 2015. The tests were conducted at the location shown in Figure 17, the belt going up to “siktfickan” using a 3.D magnetic probe (Figure 18).

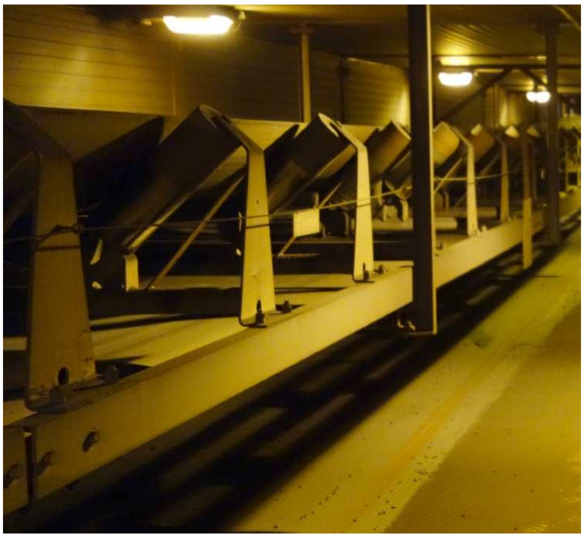

Figure 17: The conveyor belt where the measurements were performed.

*More details regarding the result of this test can be found in D3.1. Although two RFID-antennas were installed at the belt the results presented in D3.1 only presents results from the antenna surrounding the conveyor belt due to experimental difficulties and anunfavourably low signal level from the former. (Photograph courtesy of: Johan Borg, LTU)*

The following measurements were performed:

- Magnetic field strength at 10 positions along the length of the conveyor belt.
- Magnetic field strength at 9 positions over the belt, in the approximate volume where pellets can be expected.
- Responses from both large and small RFID transponders were recorded using the digital sampler for 9 positions (only the large transponders) within the volume where pellets can be expected. The response was detected in terms of the cross-correlation between the known response and the measured complex ratio between coil voltage and excitation (to suppress some of the noise in the excitation signal).
- Ambient magnetic field strength in the 50 kHz-30 MHz band and ambient electromagnetic field strength in the 800 MHz-6 GHz band. These measurements were performed both with the conveyor belt stationary and with the belt running without pellets.
- Modulation of the received signal due to motion of magnetic material or the antenna. This test was performed with the belt stationary, and in motion both with and without pellets.

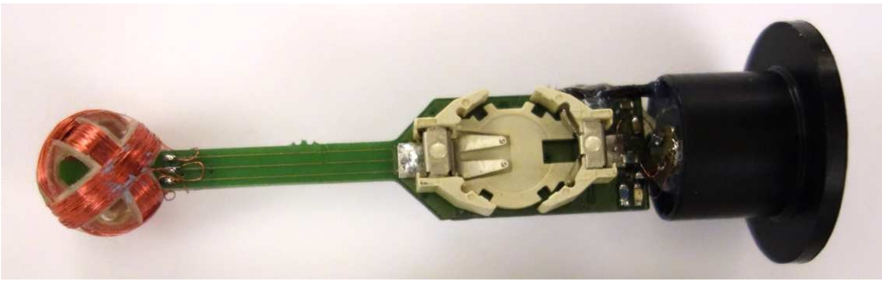

Figure 18: The 3-dimensional magnetic field probe used for measuring the magnetic field in the vicinity of the RFID antenna. (Photograph courtesy of: Johan Borg, LTU)

#### 3.2.2.2 Risk factors

Since we still cannot say if an experiment on this facility can be performed, the risk factors include the costs for the test, if the facility can be used in the way intended for the experiments, if the silo can be used using pellets without risking storage of special products, how and where equipment can be installed and the presence of LTU personal during loading and draining of the silo.

# 4 Use of empirical data

Simulation models will be implemented during the project. The plan is to devise the empirically validated flow models as well as probabilistic models of the flow distribution based on data obtained from experiments.

## 4.1 Simulation tools

The corresponding simulation tools will be based on the mathematical models with empirical origins generated from the experiments. The simulation tools will aim at facilitating the prognosis of virtual batches so that different product qualities can be traced and positioned in product warehouses along the transportation chain. This task is non-trivial since the continuous product flow at the plant is made discrete by intermittent use of conveyor systems, by collecting the product into iron ore freight trains and freight boats.

## 4.2 Control oriented models

The logistic chain as well as the grate process will generate knowledge useful for offline or open loop control purposes. The LKAB processes are not expected to be controlled in closed loop during the development of the DISIRE project. However, this knowledge will be of paramount importance either for laboratory evaluations with hardware in the loop test bends or for full simulation test cases.

## 4.3 Control system

The existing control systems for the LKAB processes are open-loop. Human operators perform control decisions based on the simulation of the position of virtual product batches in the transportation chain.

## 4.4 Measurement and Sensor systems

The goal of the project is that a simulation model should be calibrated using full-scale tests in the production environment. The measurements and sensor systems for the product transportation chain are limited to positioning; that is to measure time and location of virtual batches. These tests should be preceded by laboratory studies using, e.g., granular material of different sizes to study the segregation aspects.

## 4.5 Actuation

No additional information on how the system is actuated will be provided, since the actuation of the transportation chain is operator controlled and the operator will have better knowledge of the position of virtual batches so that the product quality shipped to customers could be improved. Moreover, this WP will focus in the evaluation of the novel embedded in the flow PAT sensors, on traceability and in situ measurements of the flow behaviour in the aforementioned processes.

## 4.6 Data Analytics

The data analytics of the product transportation chain will be developed based on statistical models of the mixing and distribution of the pellets along the transportation chain (i.e., inside the silos, on the cargo trains and ships). The currently performed data analytics are performed off-line using statistical software such as the R programming language. Further investigations in the current Data Analytics and for enabling the online PAT analysis will be performed in WP4.

## 4.7 Evaluation platforms

During evaluations the only way for sensors to communicate back information will be through a reader. The reader will detect and activate a sensor travelling on a conveyor belt, when it passes through or over the reader antenna. During this passage the sensor's unique serial number is read out. The reader-tag uses inductive coupling and reading in only possible while the sensor is energized for a very short period, while it passes in the centre of an antenna. Sensors will be battery powered and may transfer additional measurement data through radio signals when triggered by the inductive reader.

The reader will store all sensory data until an operator erases it. During the evaluation period (i.e., the project time) all data from all readers will be transferred over GPRS to a database. This database will only be available to the peers of WP6 since the data has no relevance to other partners before it has been processed further and compared with the flow models.

Notice that when the novel sensors will be integrated into the real factory environment, the data will be directly accessible at the reader through IP on Ethernet or WiFi. This could be possible already during the project's phase but usually the test site owner does not allow access through their Intranet.


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## 4.8 Final industrial demonstration

In the final demonstration, a batch of sensors will be dropped in one of LKAB's plants (Kiruna or Malmberget). Readers will be placed at least in the harbours of Narvik or Luleå and possibly at additional reading stations at the plants (before the pellet is loaded on the trains). When the sensors pass the readers their ID and timestamp will be collected and verified later using existing flow models (the timestamp and tag's ID will be compared with the registered data of same tag when it was manually dropped). A reader will be placed typically aside a transport belt conveyor with antennas around and below the belt. The flow of the iron ore pellets and the sensors with embedded tags will pass through one antenna and above the other antenna. This 2-antenna system will increase the detection rate since the small coil inside the sensor can perform poorly depending on its orientation with respect to the reader's antenna.

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