Innovative Separation Technologies for High Grade Recycling of Refractory Waste using non destructive technologies

Reporting

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Final Report Summary - REFRASORT (Innovative Separation Technologies for High Grade Recycling of Refractory Waste using non destructive technologies)

Executive Summary:
Refractory products are a vital element in all high-temperature processes. The European refractories industry relies heavily on imports for raw materials, especially for high grade magnesia, bauxite and graphite which are mainly sourced from China. High grade recycling of spent refractories into refractory production is necessary to remain competitive in the current global market, but is only possible when the chemical and mineralogical composition of the spent refractory material meets the given specifications. The main objective of the REFRASORT project is to develop an automated, non-destructive sorting system to separate refractory waste into high purity fractions for high grade recycling.

The first half of the REFRASORT project focused on the development of the individual parts of the system, namely the laser identification (using Laser Induced Breakdown Spectroscopy, short LIBS), mechanical handling and complimentary identification and pretreatment techniques. Prior to starting the technology development, the recycling requirements were well defined.

For the LIBS system, a classification scheme was developed based on measurements carried out on a set of used and freshly produced refractory materials of known composition. The LIBS system employed uses a high pulse energy to ablate surface material prior to analysis, in order to reduce surface contamination effects. The results showed that all desired 8 classes can be identified based on the spectroscopic signals of Mg, Ca, Si, Al, Ti and C.

The mechanical handling system is based on a system of plate conveyors and pneumatical pushing devices. Sorting trials showed that this system is able to identify and separate single bricks with an effectiveness of 95%.

Complementary identification techniques were investigated to overcome the difficulties that LIBS encountered to measure the content of carbon and metallic inclusions. Due to the heterogeneous distribution of these components, they cannot be reliably measured using LIBS. Microwave heating and a portal-type metal detector showed considerable potential for measuring metal and differentiating carbon from non-carbon bricks, but more research is necessary to determine the influence of the matrix material on the detected signal.

In the second half of the project, the individual components were integrated into a functional demonstrator at the site of Orbix. After optimisation in several 2 ton sorting trials, a larger batch of material (30 tonnes)
was sorted during several days of continuous operation. The sorted fractions (magnesia and doloma) were analyzed and found to meet recycling specifications. Validation tests at laboratory scale confirmed that the sorted fractions are suitable for recycling in various refractory applications, of which two were selected for industrial trials. The recycled materials performed equal to or better than the reference in the industrial trials.

An economic and environmental assessment showed that the REFRASORT system could meet the market demand for increasing refractory recycling and create economic benefits for both refractory recyclers and producers while reducing the environmental impacts associated to refractory production at the European and global level. Even with recycled material prices at only 50-60% of virgin materials, the automated sorting of refractories using the REFRASORT system can be a profitable activity, thus providing an economic incentive to refractory recyclers and producers both. A substantial replication potential is possible at the European and global level, for the steel industry as well as all refractory consuming industries.

Project Context and Objectives:
Refractory products are essential for all high temperature processes, such as the production of metals (particularly steel), cement, glass, ceramics and many other materials that are indispensable for the European industry. Refractories are not readily available from nature but are processed from (a mixture of) raw materials, which are themselves derived from (mined) natural resources through a very energy-intensive process.

The performance of refractories is largely influenced by the (quality of) raw materials that serve as input for the production process. Therefore, stringent requirements on the chemical composition of the raw materials are imposed by the refractory producing companies. Unfortunately only a few refractory grade sources are adapted to the needs of the present day industry. China dominates the market for key refractory-grade minerals such as alumina, bauxite, graphite and magnesia, which has led to increased prices and competitive disadvantages for the EU industry [1]. Graphite and magnesite are considered as critical raw materials for the European Union [2]. Bauxite is not considered critical for the EU, but there is a significant supply risk for specifically non-metallurgical grade bauxite, which has higher demands on purity than metallurgical grade [3]. New sources of primary supply are being developed, but these are mostly outside Europe [4].

Recycling of spent refractories could constitute an important new secondary source of refractory raw materials. It is estimated that up to 20% of raw material demand could be met by secondary resources. But although recycling of refractories has increased significantly in Europe in the last decades, it has still far from reached this target. Industrially applied recycling of refractories is mostly limited to magnesia and alumina refractories, although research activities have demonstrated application of recycled refractories for many other refractory types.

The reason for the current low use of recycled refractories in new refractory production is a shortage in high quality recycled material.

The state-of-the-art recycling plant for refractory waste generally includes at least two steps. In a first step the refractory waste is pre-sorted according to the type of refractory. The pre-sorting is generally done
manually, which requires skilled personnel and a-priori knowledge of the vessel type from which the refractories originate. It is well-known that even after this sorting process, different types of refractory materials are often mixed and contaminated with large pieces of iron and slag material [5]. The second step, which consists of further, mostly automated, treatment of the pre-sorted refractory streams is aimed at removing impurities but is not equipped to separate mixtures of refractory materials. This results in output streams that can be recycled in applications such as slag conditioners or road aggregates, but are not pure enough for high value recycling into refractory products.

The main objective of the REFRASORT project is to develop an automated, non-destructive sorting system to separate refractory waste into high purity fractions for high grade recycling.

In particular, the project focused on the most important refractories for the steel industry, which is by far the largest consumer.

The REFRASORT system combines a novel identification technique based on LIBS (Laser induced breakdown spectroscopy) with a mechanical handling system able to deal with large and heavy objects. The basic principle of the LIBS sensor for sorting is shown in Figure 1. With this technique a small amount of material is vaporized by focusing a laser beam on a selected spot on the material and subsequent spectroscopic analysis of the excited material. Because the laser can be employed to analyse material from a greater depth, surface effects e.g. from dust can be minimised. The mechanical sorting system is based on a combination of conveyor belts and pneumatic pushing devices.

To reach the main objective, the following specific objectives were defined:
• O1: Analysis of the separation requirements in relation to the specifications of the end-products and the characteristics of the waste streams;
• O2: Development of a demonstrator LIBS system for inline identification of refractory waste streams with dust issues
• O3: Development of a demonstrator mechanical handling and sorting system for heavy and coarse grained refractory waste streams
• O4: Development of additional identification and treatment techniques (e.g. dust and metal removal) that can be used complementary with LIBS to enhance the quality of the sorted spent refractories
• O5: Integration of identification techniques with mechanical sorting to allow automated separation scalable for high-throughput applications and demonstration of the feasibility of separation of refractories for high-quality valorisation in laboratory, field tests in an industrial recycling plant, performance tests of recycled refractories
• O6: Evaluation of the environmental gain and economic potential of the technology using Life Cycle Assessment approach and by making an assessment of market barriers

References
Project Results:

INTRODUCTION

Within the REFRASORT project, the individual technological components (laser identification, mechanical handling, complementary identification and treatment technologies) were first developed at laboratory scale, supported by the definition of clear boundary conditions such as quality criteria for recycling and economic considerations. Subsequently, the components were integrated into a functional demonstrator which allowed the technology to be evaluated under semi-industrial conditions.

Validation tests were performed by using the sorted fractions to produce new refractories under laboratory and real scale conditions. An economic and environmental assessment was performed to determine the potential of the technology for market introduction and alleviation of environmental impacts.

The REFRASORT system was developed in line with the requirements of the company Orbix, whose final goal is to apply the technology at industrial scale in their facility in Genk. Target throughput of the system was set at 10 t/h, corresponding to an identification rate of 1 brick/s and a belt speed of 0.7 m/s.

In the following sections, the main S&T results are presented per WP.

WP2

The task of WP2 was to support the technology development, by:

- Defining clear targets for the recycled refractories (specifications)
- Creating a solid knowledge base for the consortium partners not familiar with refractories
- Validating the developed process (at laboratory scale) by analyzing the output streams and applying them in the production of new refractories

Table 1 shows the typical composition of the 8 types of refractories that were the focus of the REFRASORT project. These 8 types can be grouped into three main categories based on their chemical composition (magnesia-based, doloma-based and alumina-based) and represent about 90% of the total shaped refractory production. Additionally, they cover the main distinctions that must be made between spent refractories in order to achieve a high recycling potential.

Characterization of both new and spent samples of these materials was performed to generate insight into the changes occurring in refractories after extended, high-temperature operation in a corrosive environment. The analyses that were performed on fresh and spent refractories were also targeted at obtaining information to aid in the technology development. Based on these characterizations, material data sheets were created to serve as boundary conditions for the technology development.

The (chemical) purity of sorted refractories was assessed in support of other work packages to optimize and validate the developed technologies. Furthermore a more detailed characterization using petrographic and mineralogical analysis tools (XRD, optical and scanning electron microscopy) gave insight into the changes occurring in refractories after extended, high-temperature operation in a corrosive environment and showed important features of spent (weathered) refractory bricks with regard to their correct
identification using the REFRASORT system. Contaminants such as dust, metals and slag adhering to the refractory bricks were identified, and this information was used to optimize the detection and sorting of refractory bricks, e.g. to assist in the evaluation of the LIBS identification results and determination of proper pretreatment techniques (laser cleaning depth, dust and metal removal).

WP3

WP3 started with developing a concept for identification of the eight classes based on measurements on fresh materials (new refractories) (Figure 2). In total, more than 70 spectral lines originating from the elements Mg, Ca, Si, Al, C, Ti, Cr, Fe, Mn and Zr were evaluated. Figure 3 shows that distinction between the three main classes (class A material which is based on MgO, class B containing both MgO and CaO and class C which is produced from mainly SiO2 and Al2O3) is possible based on the intensities of selected spectroscopic features originating from the elements Al, Ca and Mg. The statistical significance of the separation is indicated by the 1-sigma error bars of repeated measurements each taking less than one second – as required for the planned sorting application. The sorting accuracy between these three main classes was calculated to be more than 99%.

After defining the fundamental discrimination of the 3 major classes, the work was continued to identify also the 8 selected sub-classes of refractories used in the steel industry. By adding the elemental lines of Si, C, Ti and Cr, a concept for identification of all 8 classes was developed, with identification correctness above 92%. Due to strongly varying concentration ranges and matrices, it is necessary to use different lines of the same element for different differentiation tasks to adapt the sensitivity. As an example, three different Al-lines and collectives were used for the differentiation of MgO with and without antioxidants, for differentiation between the three Al-based classes and as reference values for the determination of the other main classes.

The LIBS measurements were carried out with tailored laser pulses to enable the bulk material analysis in the presence of a surface contamination layer. These consist of a component to clean the surface and another for the analysis of the underlying material which is applied with a certain delay. Figure 4 illustrates the craters produced by tailored laser pulses in the cover layer of a used brick. With this technique, the penetration of the surface layer could be improved by a factor of ten compared to standard LIBS approaches.

The same spectral specificities which were used for the analysis of fresh refractories were then used for the analysis of spent refractories after adaption to the influences from the material usage. A blind test showed that the three main classes could be differentiated with an overall identification correctness of about 96% (29 out of 30 bricks correctly identified). The sorted magnesia and doloma fractions were then used to prepare new refractories. The results showed that the doloma fraction could replace up to 60% of virgin material without negative effect on the use as backfill or gap filler material.

For the sorted magnesia fraction, however, even one missorted brick resulted in too much CaO for recycling in bricks. These results highlighted the importance of the LIBS thresholds, which were adapted for the later sorting trials. Additionally, since the missorting was hypothesized to be due to a stronger surface contamination, the test demonstrated that the influence of the surface contamination on the measurements was not yet fully eliminated, which triggered research into further enhancements of the ablation of surface contaminations as described further on.
The tests performed in this WP showed that differentiation between the three main classes could be performed with high accuracy using the LIBS system. To differentiate also between the 8 subclasses, accurate measurement of aluminium and carbon content was needed. Mineralogical analysis in WP2 showed, however, that the carbon content in spent brick surfaces can be severely reduced by oxidation in the furnace (Figure 5). Therefore, the analysis by LIBS, which is a surface-near measurement technique, is affected. Research in WP5 therefore looked into complementary identification techniques that could deal with this problem.

WP4
The main aim of WP4 was to develop a prototype mechanical sorting installation for heavy and coarse sized (>60mm) refractory waste, suitable for sensor-based identification and in line with the user requirements of Orbix. The separation method should be compatible with identification by LIBS, but take into account the requirements for complementary identification methods and material pre-treatment (cleaning, metal removal).

The reliable and safe handling of spent refractory bricks requires knowledge about the mechanical behavior of the bricks and the composition of the feed stream. Thus, the composition of the feed in terms of size, shape and material type and the behavior on different surface materials was investigated. For inlining of the spent refractory bricks, a vibratory feeder with a v-shaped inlay and a chain curtain was selected.

For singularisation and separation, pneumatic pushing devices were used that move single bricks out of a line of bricks. Pushing a single brick requires the combination of different movements, all performed by pneumatic cylinders. The motion sequence of pushing a single brick was optimized and is illustrated in Figure 6.

The design for the demonstrator was developed based on the results of the lab tests and is shown in Figure 7. The material is fed to the first conveyor by a vibratory feeder. There the bricks will already be lined up but with undefined distances between the bricks. The position of a brick on the belt is detected by a light barrier. The bricks are pushed from the first plate conveyor into a buffer by an array of four pneumatic pushing devices. From the four buffer places the bricks are released onto a second plate conveyor with a distance of 700 mm so that approximately one brick per second is placed on the plate conveyor. After passing the LIBS-system the bricks are sorted into three different fractions by two pneumatic pushing devices. Two fractions are pushed down from the belt and the third fraction is falling off the end of the belt. Tracking of the bricks between identification and separation is done by observing the movement of the plate conveyor with a rotary encoder on one of its axes with an accuracy of < 1 mm.

WP5
This WP screened different identification techniques to evaluate their potential to complement LIBS in the REFRASORT system. Based on the results of the LIBS detection in WP3, attention was focused on carbon and metal detection. Indeed, WP2 showed that these are not homogenously dispersed in the spent bricks and can therefore pass the LIBS without being detected. Therefore, techniques that analyse the bulk of the material were investigated to identify these components.
Color sorting, X-ray transmission, laser induced fluorescence, X-ray fluorescence, magnetic susceptibility and Terahertz were tested but not selected because they are not adapted to the sorting of waste refractory bricks. Near infrared spectroscopy has the potential to identify doloma bricks but this offers not added value compared to LIBS. Fourier Transform Infrared Spectroscopy could also identify many of the refractory types, but not metal and carbon. Terahertz is not applicable to spent refractory bricks due to their variable dimensions and rough surface.

The most promising techniques for carbon and metal detection were found to be microwave heating and metal detection portals. A summary of the sensor test results is given in Tables 2 and 3.

On artificial samples made of fresh refractories with varying addition of metal, microwave heating showed that carbon containing bricks display a different heating behavior, independently of the metal content (Figure 8). Based on these encouraging results, semi-industrial tests were performed on spent refractories. 3 out of the 4 tested doloma carbon bricks heated up until a temperature clearly higher than the other types of the bricks, but no difference was observed between magnesia and magnesia carbon bricks. Further research is necessary to identify the possible interferences and optimize the measurement method.

Tests with a metal detection portal on artificial mixtures of refractories (with or without carbon) and additional varying amounts of metal showed a clear increase in amplitude with increasing metal content for all materials (Figure 9). However, the absolute value of the amplitudes and the increase with metal content differs between refractory types, indicating a matrix effect. The presence of carbon was not clearly detected.

The next step was testing on spent refractory cylinders which were obtained by drilling of spent bricks. The signal given by the detector was examined in terms of amplitude and phase. The results highlighted that the size of the cylinders has a clear effect on the amplitude, indicating that size has to be taken into account when using metal detection to classify bricks. Doloma bricks can be separated by adapting the sensitivity settings. A distinction between carbon and fired doloma bricks could not be made based on phase alone, however there is potential to make the distinction based on amplitude. Magnesia can be distinguished into fired (no carbon) and tempered (carbon) bricks based on their location in the phase-amplitude plane. Metal content had a disturbing effect on the measurements, possibly due to the equipment specifications.

In conclusion, microwave heating and metal detection show considerable potential for measuring metal and differentiating carbon from non-carbon bricks, but more research is necessary to optimize these techniques and adapt them to the case of the spent refractories. This research should focus on reducing or clarifying the matrix effects, while taking into account size and shape variations. Such follow-up research is necessary for the upscaling planned at Orbix, and the consortium is actively looking for opportunities to continue this research.

Sand blasting was investigated as an alternative pretreatment for carbon detection. It could lead to the removal of the carbon depleted layer and make the brick ready for the LIBS analysis. However, the results showed that a highly abrasive sand should be selected, such as alumina, to remove metal, backfilling or mortar from the bricks. To treat only one face of the bricks, the bricks should already be in line and in the right position for their LIBS analysis; and the addition of a suction device would be necessary to suck up sand dust and refractory dust. Therefore, an additional sensor remains the preferred solution, as this does not require additional manipulation of the bricks and management of the dust.
Based on the results of WP3, WP4 and WP5, i.e. specifications and constraints of the developed methods, a concept was developed for an integrated system for combined evaluation of the technological solutions.

The entire sorting system is shown in Figure 10. In section 1 of the system, the stones are passed by a vibrating chute on the first plate conveyor as a monolayer. The closely spaced stones are detected by a light barrier and pushed in section 2 by four pushers isolated on a second conveyor belt. In this way the stones are lined up on the second conveyor belt. The LIBS-based measuring system is located above the second conveyor (section 3) and is therefore able to measure each stone separately. The measuring system determines the material class of each brick. In section 4, each brick is pushed according to its material class in one of two fractions or falls at the end of the conveyor in a third fraction.

Figure 11 shows schematically the physical integration of the optical system with the transport conveyor. An integrated demonstrator was constructed at the industrial site of Orbix. The whole system is shown in Figure 12 and Figure 13. The singularization unit consists of four individual pushers. They push the refractory bricks from the first conveyor to a waiting position in front of the second conveyor. As soon as the second conveyor has a free place for a brick, the stone is pushed on it. The stone is moved on the second conveyor to the measurement system and pushed at the end of the conveyor, in accordance with the determined class, into the matching fraction. For this purpose, four pushers are used for two fractions. For each fraction two pushers are working independent to reach the required speed. In the case of a very large and heavy brick the two pushers can be operated synchronized with reduced speed.

With the demonstrator system which has been implemented, it was possible to carry out measuring runs and sorting trials with material directly available from the production of Orbix. This allowed a better adaption of the optical measurement system to the industrial material than had been possible on lab scale before. Sorting trials with about one ton of spent material were carried out starting in December 2015. The fractions resulting from the sorting trials were subsequently characterised by laboratory analyses as part of WP2.

Several sorting trials were conducted, each with more than 500 kg of material. In the first trial, visual inspection showed that the fractions were not well sorted. After further revisions of the instrument settings, the input material was sorted well into the three main classes, according to visual inspection. The sorted fractions were sent to the laboratory for characterisation. In one sorting experiment the Al-based fraction was sorted as a separate fraction, in a second sorting run with adapted classification settings, and examined in the laboratory.

In order to further improve the sorting results and to evaluate the sorting of all eight subclasses, further tests were carried out on pre-sorted bricks from other sources, since not all types were available in the input stream of Orbix. However, these bricks were found to have a thick and tightly adherent layer of non-representative material. This layer reduces on the one hand the intensity of the laser-induced plasma and on the other hand increases the differences between measurements on one class of refractory bricks. These effects reduce the sorting accuracy.

To be able to investigate the reduction of the significance of the LIBS measurements, thirty bricks of each of the classes were passed through the REFRASORT system, measured by the LIBS system and the data
evaluated offline. To evaluate the influence of the surface layer, the bricks were cleaned by sandblasting on one side. These bricks were then passed several times through the system and measured by the LIBS module.

The results showed that by sand blasting, the mean amplitude of the spectral intensity on one refractory class could be increased by about 20%. At the same time the standard deviation in the evaluation of individual measurements could be reduced by about 30%. In total the signal-to-noise ratio was significantly improved. Therefore, this method is estimated to provide a significant improvement also in industrial scale, if heavily contaminated material occurs in the recycling process.

As described above, the surface contamination or alteration of spent refractories remains a critical issue for the laser-based material characterisation. As it is required to measure the composition of the material underneath such surface regions a laser is employed which emits bursts of laser pulses instead of individual pulses. These bursts consist of a series of individual pulses from which the first ones are used for material ablation only, whereas the analytical spectrum evaluation is taken only at the end of the burst. It had been shown in WP3 that this concept strongly reduces the influence of the surface contamination on the measurements. The LIBS system is using an optical scanner to steer the laser beam and move the measurement position also in the direction of material transport. While one piece is moving underneath the optical system at the conveying speed of 0.7 m/s it is possible to irradiate up to 10 measurement spots. The spots can be distributed over the surface area in order to achieve a lateral averaging of the inhomogeneous material, but it is also possible to irradiate a single spot by several laser bursts in order to improve the local surface cleaning effect. Since the conveyor moves by 47 mm between two laser bursts, which are emitted at a rate of 15 Hz, the laser is steered at high precision of better than 0.1 mm to hit the same spot again. Due to a limited precision of the conveyor movement it is recommended to adapt the conveyor system for an industrial installation.

The robustness of the demonstrator to industrial conditions was also investigated during the on-site operation. The construction of the LIBS analyser appeared to avoid a large dust contamination of the optical window, which was one risk of the operation in this environment. The dust generation by the laser ablation is not very high, however a dust protection and extraction should be considered for an industrial scale system since the dust load of the ambient air can be high.

In addition the onsite trials at almost outside temperature conditions demonstrated the importance for an industrial system of a fully controlled temperature regulation to heat or cool down the system at any ambient temperature.

It was decided within the course of WP6 that the performance of the system and thereby its perspectives for exploitation would be enhanced with an improved spectrometer for the LIBS unit.

During the test runs on-site further investigations of the characteristics of the LIBS spectra showed effects on the profile of the detected spectral lines. As mentioned above the laser system generates laser bursts where the first pulses are used to clean the surface while the last pulse is used to analyzed the sample. This procedure results not only in the necessary surface cleaning but also has an influence onto the detected plasma emission by the detection of a “ghost-signal” originating from the cleaning process. The standard Toshiba CCD detectors used in the spectrometer provide a limited read-out efficiency, which results in an left-over of created charges for the next read-out. This appears as an attenuated spectrum
from the surface material which is added to the desired spectrum from the bulk material. As an appropriate alternative detector a Hamamatsu CCD array was identified. With this detector type an improved spectrometer concept was set up in the lab and tested under different conditions before it was provided for the REFRASORT demonstrator.

WP7

The objective of WP7 was to construct a demonstrator at the Orbix plant, using the concept developed in WP6. The demonstrator was designed as an independent stand alone unit. The layout of the REFRASORT demonstrator is designed to sort 1 stone per second (corresponding on average to 10 t/h). The demonstrator is built in a modular design (Figure 13) to allow it to be easily disassembled and transported. The modules are the following: the vibrating feeder (1) for inlining the stones, the transfer plate conveyor (2) for spacing the stones, the pushers (3) for transferring and sorting the bricks; the return station (4) to take over the stones from the transfer pushers on to the sorting plate belt, the LIBS station (5) to analyse the bricks and form the connecting link to the sorting plate conveyor and, the drive station (6), the push the identified stones into separate containers. The stations 4, 5 and 6 together form the sorting plate conveyor.

The modules are interconnected to transfer information to each other. This system allows all the components of the demonstrator to be synchronised. The position of the bricks, their type and the place where they have to be pushed are transmitted between the LIBS system and the mechanical part of the demonstrator.

A risk assessment was realised to determine the exhaustive list of potential hazards and the solutions to be implemented. Structural solutions were implemented through the design of the mechanical handling installation and of the LIBS system. In addition, the area was arranged in a way to suppress any risk of exposure to the laser light for people outside the test area. Moreover, specific personal protective equipment (PPE) was used for the operators of the demonstrator, especially laser safety glasses. For general safety, an emergency stop circuit was installed. For an industrial plant, adaptations should be made to improve the design of the feeding and the sorting operations. The electrical control could also be improved by creating a two-levels access and by adding a data logger. For safety regarding the laser radiation, a zig-zag housing blocking the scattered and reflected radiation could be used to offer a higher structural protection.

After the smaller sorting trials described above, a 30 tons trial was performed on site in March 2016. The spent refractories were taken from the streams treated by Orbix. As the pilot installation comprises 3 outgoing streams, it was decided to first separate magnesia and doloma from the rest. The remaining fraction was then sorted to separate the aluminium based bricks. During the 30 tons trial, the throughput was between 0.5 and 1 brick/s. The wear of the equipment was found to be very low. The expected life duration of such a robust mechanical equipment is 10 years as well as for the LIBS system. As a result of the aim to reach a high purity and of a delay of data transmission between the LIBS system and the controller of the pushers, the efficiency of the system was limited: around 26% of the doloma and magnesia bricks were directed towards the residual fraction (off the belt).

Chemical analysis of the sorted fractions confirmed the high purity of the magnesia and doloma based
fractions coming from the first step. The chemical and mineralogical composition was found to meet the requirements for recycling as ramming and gunning mix (magnesia), and backfill and levelling (doloma). Based on availability, for each material a real scale validation test was performed in a working EAF vessel. For the magnesia fraction, application as a gunning mix was selected, whereby virgin magnesia was completely substituted by the recycled material. Laboratory trials, performed before the industrial application, showed a good workability. On site observations during the application in the EAF vessel confirmed that the gunning mix performed equal to or better than the reference product, with a much lower rebound, good sticking to the walls and a very regular surface. By application of the gunning mix, the lifetime of the vessel could be extended by 8%.

The doloma fraction was used as backfill in an EAF, again with full substitution of virgin doloma material. The installation of the trial material was better than the standard product of the steel plant, with a very low dust generation which is very important parameter because of worker health and safety.

In conclusion, the recycled refractory materials were easily applied in both applications with no significant differences from the reference materials. This shows that the composition of the recycled material was in accordance with the technical specifications needed for such applications, and thus that the 30 tons sorting trial resulted in sorted fractions that meet recycling specifications.

The trials highlighted improvements to be applied for an industrial installation. To enhance the tracking of the bricks and allow a more accurate analysis to be performed, a conveyor with a smooth and continuous movement without vibrations should be chosen. An extraction system should be used to clean the measuring station from the dust generated by the laser ablation and ambient dust. A robust system should be used to provide a temperature control over the range of temperatures measured on an industrial site. Finally, in case of heavily contaminated material, the selected degree of laser cleaning could be insufficient and it is advised to clean the bricks by a stronger impact like sand blasting.

WP8

In WP8, an economic and environmental assessment was performed to establish the potential of the new technology for market introduction and alleviations of environmental impacts.

The economic viability of the new separation technology was evaluated by a cost-benefit analysis (LCC) under different scenario’s. A sensitivity analysis was performed to gain insight into the most important parameters that determine the economic viability. For this analysis, parameters such as throughput, composition of the input, sorting effectivity and market value were varied. The Net Present Value (NPV), Internal Rate of Return (IRR), and (Discounted) Payback Period (DPBP and PBP) were calculated for the different scenarios. The process was shown to remain profitable even under unfavourable conditions such as lack of a gatefee and value of the output fractions strongly reduced below the current market prices for recycled refractories. Even though the system is economically viable without a gate fee, the disposal cost does form an important incentive to change from the state-of-art process.

The environmental impacts associated with the infrastructure and the process of automated sorting of refractory material were assessed with the life cycle assessment (LCA) method in accordance with ISO 14040 and ISO 14044. For the REFRASORT project a consequential approach was selected, meaning that only the environmental effects resulting from a change in the sorting process are taken into account.
The environmental profiles indicate that the most important factor to reduce the total environmental impact is the increased recycling of refractory materials (Figure 14). An important positive effect on Urban land occupation is also reached by the reduction of the landfilled waste. For the sorting process itself, the highest impact is caused by the energy consumption and the industrial machines. To determine the impact of variations in the input stream, the environmental footprint of the different refractory classes was compared. This shows that bauxite has the highest impact, and therefore the highest improvement potential. Nevertheless, all refractory types have a positive environmental impact, signifying that environmental gains can be achieved by avoiding the primary production through recycling.

A market study was also performed that discusses the current size and potential of the market for recycled refractories, including a description of the main players (potential competitors). The state-of-art in refractory processing for recycling consists of two steps: a manual sorting step to separate different refractory types followed by a more automated purification process to remove impurities such as metals and slags. REFRASORT aims to improve the first step, by replacing the manual sorting with an automated process.

Particular attention was therefore given in the market study to other automated sorting installations. Only one other installation has been reported recently which also operated on a LIBS-based identification but requires continuous manual handling and pre-treatment [6]. Thus, it does not reach the same degree of automated sorting as was achieved in REFRASORT.

In conclusion, the main advances of REFRASORT compared to the state-of-art are that:

- A wider range of refractories can be sorted
- Surface treatment is automated, the full potential of the laser is used
- Bricks can be measured at any position on the belt, no manual positioning needed
- The REFRASORT system will be made available on the market
- A higher throughput can be achieved

Furthermore, the REFRASORT system has a significant potential for replication on the European and global market, in the steel industry but also (after further R&D) in other industries that consume refractories (Table 4).

Finally, a SWOT analysis was performed on the recycling of refractories as refractory raw materials. The REFRASORT process has the potential to alleviate or even overcome many of the barriers that were identified. A very important barrier that is felt within the industry is the cost competitiveness compared to virgin raw materials – due to the (real or perceived) higher risk associated with using secondary materials, refractory producers are only willing to apply recycled material if there is a cost benefit. As demonstrated in the economic analysis, the REFRASORT process can be economically viable even at strongly reduced market value of the recycled material, indicating a win-win for both refractory recyclers and producers. Automation of the process can also allow pooling of streams, thereby creating further benefits of scale and a more stable supply.

CONCLUSION S&T
In conclusion, the REFRASORT project developed an automated sorting system using a laser-based identification system that can sort spent refractories into fractions that meet the specifications for recycling. A functioning demonstrator was constructed at the site of Orbix, and shown to be fully functional during several sorting trials that treated up to 30 tonnes of material. The sorted fraction were used in real scale applications, and found to meet all recycling specifications. The system has significant technical advantages compared to the state-of-art, and has the potential to be economically viable while significantly reducing the environmental impacts associated with refractory raw materials.

Nevertheless, some issues require further investigation. The detection of metal and C, and the accurate determination of Al-content must be improved to allow the correct identification of all 8 selected types. This follow-up research will be performed in parallel to the planned upscaling at Orbix.

References

Potential Impact:
1. POTENTIAL IMPACT

Europe is highly dependent on import of key refractory-grade minerals such as alumina, bauxite, graphite and magnesia, particularly from China. This import dependence has led to increased prices and competitive disadvantages for the EU industry. Recycled refractories could form an important resource, provided that sufficient high quality secondary materials are available.

The outcome of the REFRASORT project is a LIBS-based automated sorting system that is able to identify and separate up to 8 types of refractories into high purity fractions that meet the requirements for high value recycling in refractory production. During the project, the new technology was demonstrated at the industrial facility of Orbix. Further upscaling to a sorting system for routine industrial operation is planned to take place at the Orbix plant within the next two years, in cooperation with all technological and research partners. The system will also be made available on the market.

The REFRASORT system has considerable technical advanced compared to the state-of-art in refractory recycling, where the sorting into different types is still done manually. Manual sorting requires skilled personnel with a-priori knowledge of the material origins, and even then still results in frequent errors and low purity output streams. With the REFRASORT system, a wider range of refractories can be sorted without prior knowledge and without manual positioning due to the automated surface treatment with LIBS.

The market introduction of such an automated system for refractory sorting has the potential to overcome a number of barriers currently hindering the high value recycling of spent refractories. One of the most important barriers to overcome is the cost competitiveness compared to virgin materials, especially given the (real and perceived) higher risks associated with using recycled materials. The economic analysis clearly showed that even with recycled material prices at only 50-60% of virgin materials, the automated sorting of refractories using the REFRASORT system can be a profitable activity, thus providing an
economic incentive to refractory recyclers and producers both. A substantial replication potential is possible at the European and global level, for the steel industry as well as all refractory consuming industries.

Another major challenge is the shortage of high quality recycled materials that meet recycling specifications. By enabling the automated sorting of refractories into high quality recycled fractions, REFRASORT will greatly enhance the proportion of spent refractories that can be reintroduced into the production process. This will significantly increase the available stock of recycled refractories, thereby decreasing primary raw material consumption and import dependency while simultaneously reducing the amount of refractory waste generated. It is estimated that the REFRASORT technology, when applied across Europe, can increase recycled material input from the current 5% up to 20% of refractory raw material demand. This corresponds to more than 700 kton of quality raw materials, representing a value of more than 350 million Euros each year in the EU-27 (based on 2012 raw material prices of refractory bauxite and magnesia).

As the production of virgin raw materials, such as firing of magnesite (MgCO3) to produce magnesia (MgO), is very energy intensive increased recycling of refractories also has a significant positive impact on energy consumption and the resulting greenhouse gas emissions, as was shown in the LCA analysis. An important positive effect on urban land occupation is also reached by the reduction of the landfilled waste. In this way, the REFRASORT project will contribute significantly to the transition towards a green and circular economy with more sustainable consumption patterns.

Increased recycling will also reduce the cost for raw materials and make the production of refractory material in Europe more competitive and resource efficient. The technology will open up new opportunities for the recycling industry as well as technology providers and research institutes. Adaptation of the technology to other production industries can further increase the impact.

2. MAIN DISSEMINATION ACTIVITIES AND EXPLOITATION OF RESULTS

A project website (www.refrasort.eu) was established at the start of the project and continuously updated. A project video was made and, after official release during the REFRASORT demo-day, placed on the website for further dissemination.

The results of the project are communicated to the general audience through the flyer, the public part of the project website and other channels such as VITO’s annual report. Additionally, the results were presented to the scientific community, stakeholders and potential clients at 14 relevant dissemination events, including scientific conferences in the field of

- Refractories (UNITECR 2015, 59th International Colloquium on Refractories)
- Mineral processing (Balkan Mineral Processing Congress, XXVIII International Mineral Processing Congress)
- Sensor based sorting (7th Sensor-Based Sorting & Control 2016)
- Analytical chemistry (CETAS 9th International Conference on Progress in Analytical Chemistry & Materials Characterisation in the Steel and Metals Industries)
Abstracts and papers of these dissemination activities have been made available on the project website under the Downloads-section. The papers that were published in conference proceedings with ISBN-number have also been deposited in Zenodo, with reference to REFRASORT, to ensure open access. Further dissemination activities are foreseen in the near future, such as publications for peer reviewed journals (in preparation) and presentation of REFRASORT at the Mineral Recycling Forum (March 2017) and UNITECR 2017.

A demo-day was organized on 21 September 2016 at the premises of Orbix in Genk. The demo-day was attended by more than 30 representatives from industry, universities and research institutes. Participants were introduced to the project and its results by way of presentations given by the consortium members. Afterwards, they were given the opportunity to visit the installation and see it in action. Feedback from the attendants was very positive.

A dedicated section was created on the project website with pictures of the event, and the presentations were made available online.

Policy-related results were communicated to policy makers through their involvement in the follow-up committee (FC). A policy brief was prepared which includes recommendations to stimulate high value refractory recycling.

Exploitation of the results will take place in first instance by further development and upscaling of the technology at the site of Orbix. Orbix intends to start these works in 2017, with the involvement of all consortium partners. A industrial installation should be operational by the end of 2018. Simultaneously, the partners will continue research to optimize the technology and solve the remaining challenges, such as metal and C detection. The consortium is actively exploring options for such follow-up research.

Additionally, further exploitation of the results is envisaged by replication of the technology at other production sites. This will in first instance be focused on recycling of refractories from the steel industry, but as research continues also other applications may be targeted. The REFRASORT demonstrator will remain available to the consortium for proof-of-concept testing, to facilitate the replication step.

List of Websites:
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Related documents

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