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# Latest results of the slag cleaning reactor for copper recovery and its potential for the PGM industry

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This paper highlights a new invention to improve slag cleaning, which shows great potential especially for the copper and nickel with PGM industry. The fundamental principles are presented together with the latest results of pilot-scale test work, carried out in a Chilean copper smelter.

## Metallurgical principles of conventional slag cleaning furnaces

Metal losses in discard slags as in the copper and PGM industry are the main factor determining overall plant recovery. The metals are present in dissolved form and as matte or metallic inclusions of size from 2 to 1 000 $\mu$m[2–7]. Conventional pyrometallurgical slag cleaning by submerged arc furnaces (see Figure 1) consists of slag heating, reduction of oxides and settling of matte/metal droplets. Slag overheating decreases its viscosity and accelerates reduction reactions[8].

Reduction of magnetite:

$Fe_3O_4 + C \rightarrow 3\,FeO + CO$

decreases the slag viscosity and liberates inclusions. The co-reduction of dissolved copper or nickel in the form of cuprous oxide or nickel oxide is determined by the degree of magnetite reduction. In other words, the removal of dissolved copper or nickel depends on the degree of magnetite reduction.

$Cu_2O + C \rightarrow 2\,Cu + CO$

$Fe_3O_4 + 2\,Cu \leftrightarrow 3\,FeO + Cu_2O$

Figure 1. Conventional AC based slag cleaning furnace (example Mufulira in Zambia)

$NiO + C \rightarrow Ni + CO$

$Fe_3O_4 + Ni \leftrightarrow 3\,FeO + NiO$

Reduction of metal oxides produces metallic inclusions of size from 3 to 50 $\mu$m due to mechanisms of metallic phase nucleation. The particles are too small to settle in reasonable time.

Matte inclusions settling down collect smaller matte and metal inclusions as the effect of their collisions and coalescence. However, gravitational coalescence allows for partial removal of small inclusions and overall metal recovery is usually not satisfactory.

The role of slag motion on the inclusions' coalescence and recovery of nickel and PGMs in an electric furnace as a function of electrode immersion is clearly demonstrated by reported experience in the Polokwane smelter[1].

## Metallurgical principles of the new intensive slag stirring reactor

Coalescence of very small matte or metal inclusions is required to separate them from the slag phase. The developed new concept of slag cleaning combines DC furnace technology with an extra magnetic field for vigorous slag stirring, enhancing mass transfer to the reductant surface, accelerating the rate of reduction, and destabilizing the emulsion of matte or metal inclusions in the slag. Intensive slag stirring increases the probability of collision of inclusions, accelerates their growth and will therefore improve settling[9]. The process is carried out in a patented DC channel furnace, where the liquid metal or matte layer acts as a cathode and the floating coke bed on the slag surface is the anode. In the first zone of the furnace, a superimposed magnetic field induces a Lorentz's force, causing the slag to start an intensive circular motion (hence the name 'slag washing machine'). The next furnace zone does not experience any stirring and is dedicated for smooth settling of the inclusions.

## Overview of past activities regarding the intensive slag stirring reactor

A mathematical model of gravitational coalescence combined with forced slag motion showed the effective removal of copper matte inclusions from the slag. The results of subsequent laboratory pilot-scale tests of continuous slag cleaning showed fast slag reduction and confirmed the improved metal removal from the slag. Simulation and laboratory test results show potential for use in various other non-ferrous industries, like, for example, platinum. It is also possible to use this technique batch-wise.

The settling process has been analysed describing the phenomena taking place in the DC channel-type furnace with an asymmetric magnetic field. The CFD modelling demonstrated the possibilities of intensive slag motion at low magnetic field intensity. The semi-quantitative model combines a previously developed model for gravitational coalescence with the estimated effect of inclusions migration under electric field.

Semi-pilot-scale tests of continuous slag cleaning showed promising results of very fast slag reduction and effective metal recovery.

Additionally, pilot tests (1–2 tph of slag charge) had been carried out at the Anglo American plant in Chagres, Chile and demonstrated the functioning of the process principles. The tests encouraged SMS Demag as well as one of the leading European Cu-producers to proceed with test work with a 2–4 tph pilot plant. The plant is under construction and will be commissioned in 4Q 2008. The aim of the overall project is to install a 100 tph capacity plant, when the good results can be confirmed[10–13].

## General description, design and theory of the intensive DC slag stirring reactor for CU slag

The principle of continuous, electrodynamic slag cleaning in a channel-type DC furnace with perpendicular magnetic field is illustrated in Figure 2.

A floating coke bed on the slag surface, in contact with a graphite electrode serves as the anode. The copper matte layer, in contact with a graphite block, is present as a liquid cathode on the furnace hearth. The position of the electromagnet poles is shown by the white, dotted line. Molten slag flows continuously into the furnace via a launder. The depleted slag is tapped continuously via an overflow at the opposite side of the reactor. Matte is tapped periodically.

The utilization of a DC electric furnace with a superimposed permanent magnetic field for treatment of slag generates a set of complex phenomena. In the left part of the furnace: i) liberation of Joule's heat, ii) reduction of magnetite and co-reduction of cuprous oxides with coke as carbon source, iii) slag electrolysis, iv) intensive stirring of the slag, and v) formation of larger matte/metal droplets by coalescence. In the right side of the furnace, the settling takes place: i) migration of matte inclusions, and ii) settling of metallic copper inclusions enhanced by electrocapillary forces and gravitational coalescence with the enlarged droplets from the first part of the furnace.

The white dotted line that refers to the electromagnet poles is not shown in this figure.

The principles of the new slag cleaning step were jointly developed by SMS Demag and the University of Chile in Santiago/Chile. During the last years, numerous fundamental tests, CFD modelling, and pilot-scale tests have been carried out.

Due to the ability to further reduce the valuable metal content, the unit has internally the nickname 'washing machine'.

During the comprehensive test program, numerous slags from various applications of SAF technology have been investigated such as:

- Copper slag
- Lead and zinc slag
- Waste material
- Ferro alloy slag[13].

## CFD modelling of the intensive slag stirring reactor on the basis of copper

The key question in the concept of electrodynamic slag cleaning is the velocity distribution of the slag phase, induced by the electric and magnetic crossed fields. Modelling has been carried out for a channel furnace of 6 m in length and 1 m in width. Commercial CFD software COMSOL 3.3 has been used for the modelling. The results of modelling are shown in Figure 3.

Distribution of slag and matte velocity in grey scale and flow direction is represented by arrows. The location of the magnet is shown by a white, dotted line. The Lorentz's force is perpendicular to the plane of the vectors of magnetic and electric fields. As a result the force is horizontal under the electrode, forcing the slag to flow in a circular motion. The maximal velocity is about 0.08 m/s, two orders of magnitude higher than slag motion induced by convection without a magnetic field. A relatively weak magnetic field (0.01 tesla ) in combination with a high current density results in intensive slag stirring.

Changing the direction of the magnetic field alters the direction of slag circulation, which is illustrated in Figure 4.

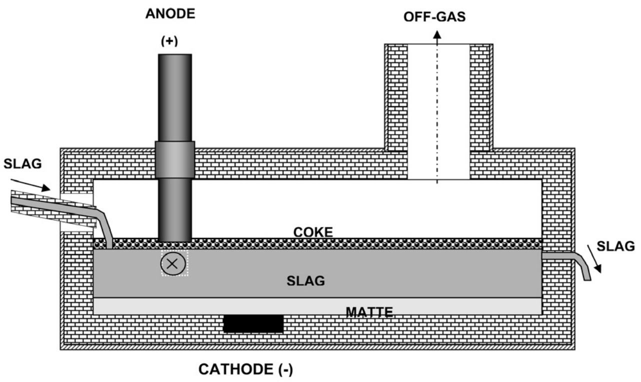


**Figure 2. DC channel furnace with a superimposed magnetic field**

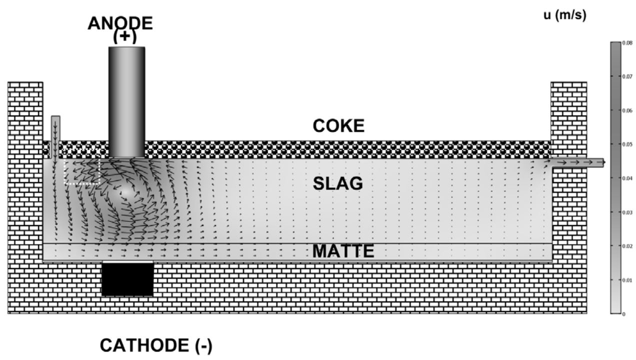


**Figure 3. Slag velocity distribution in the channel furnace ($I$ = 20 kA, $B$ = 0.01 T)**

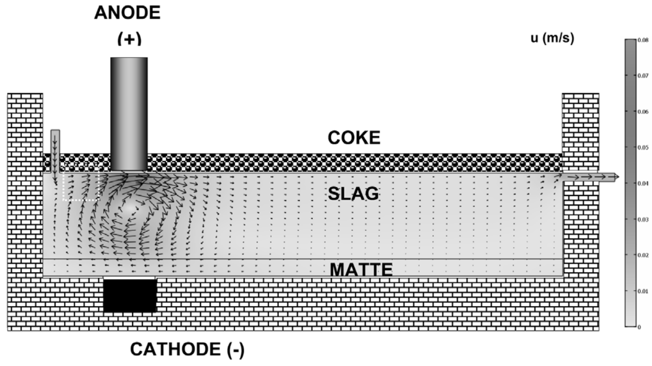


**Figure 4. Slag velocity distribution in the channel furnace ($I$ = 20 kA, $B$ = -0.01 T)**

The slag velocity is similar.

The results of CFD modelling (Figure 3 and 4) for a large furnace show very high slag velocities (up to 0.08 m/s) below the electrode at low magnetic field values (0.01 tesla). The second part of the channel furnace has a uniform slag flow direction towards the overflow (about 4 mm/s), permitting the undisturbed settling of inclusions.

The modelling parameters ($I$ = 20 kA, $U$ = 150 V and slag flowrate 50 t/h) correspond to a unitary energy consumption of about 60 kWh/t and an average slag residence time of 30 min.

The modelling of slag motion in a laboratory scale furnace indicated a similar maximal slag velocity of 0.1 m/s at a current of 250 A and a magnetic field value of 0.1 tesla, due to the influence of the side walls in the narrow channel.

## Semi-pilot tests at UDC in Chile

All research has been carried out and backed up by laboratory tests, to determine process parameters and to have a better understanding of the underlying mechanisms. Results have been demonstrated in a number of presentations over the years, and the Universidade de Chile-SMS Demag AG cooperation will continue to do so in the future.

The DC channel furnace has a hearth of 0.7 m in length, 0.1 m in width and 0.2 m in height and has a structure as shown in Figure 1. An electromagnet was placed at the furnace at the location as shown in Figure 5. The photograph in Figure 5 shows the laboratory furnace during operation[13].

Molten slag flows into the channel furnace. A graphite electrode as anode is in contact with the floating coke bed and a graphite block in the hearth is in contact with the copper matte which acts as a cathode. The current intensity was kept in the range of 200–250 A at a voltage between electrodes of 20–25 V. Some test results are presented in Figure 6.

The copper content decreased from 4.4 to 0.8–1.0% and the magnetite content decreased from 8 to 4–6%. It can be seen that at $t$ = 300 min the power was switched off for about 15 min: the system responded with a rapid increase of copper and magnetite contents in the discard slag[14] due to the continuous feeding principle.

Another test was carried out to process the discard slag from an electric furnace, containing 0.7% Cu and 5% $Fe_3O_4$. The slag was melted in a crucible placed in an electric furnace and tapped continuously into the channel furnace with a rate of 6 kg/h. The copper content in the treated slag was stable at 0.4% and magnetite content between 2.0–2.5%.

Copper recovery from primary smelter slag consists of the removal of mechanically entrained copper matte and metallic copper inclusions, formed during reduction of dissolved cuprous oxide. After the relatively fast separation of larger matte inclusions the system can be seen as a suspension of liquid matte and liquid metallic copper in liquid slag. Destabilization of the emulsion by intensive slag stirring results in a rapid copper removal because of improved reduction and coalescence of small droplets.

A DC channel furnace with a superimposed permanent magnetic field fulfils the requirements of a continuous process and permits the creation of two zones. First, a reaction zone of intensive slag stirring where fast reduction and coalescence of inclusions take place and secondly a settling zone for phase separation, where inclusions can settle down, aided by electro-capillary forces[15–16].

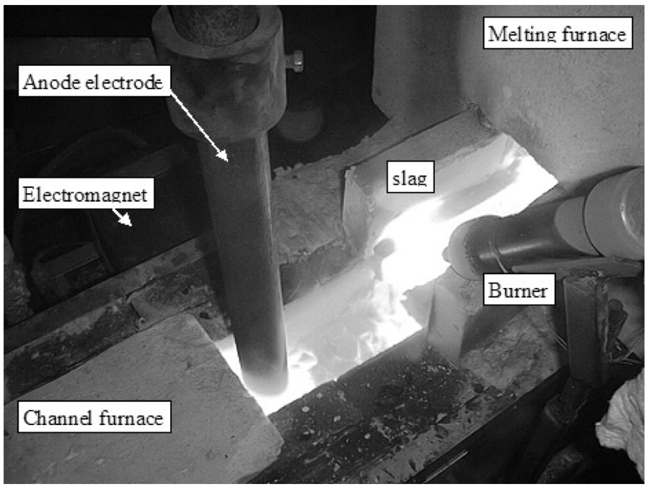


**Figure 5. Photograph of the pilot channel furnace**

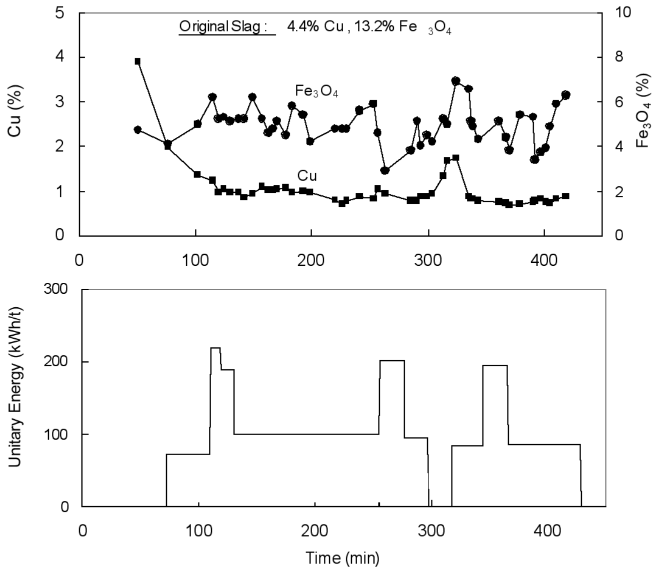


**Figure 6. Copper and magnetite content in outlet slag and unitary energy consumption vs time**

## Pilot plant tests at Chagres in Chile

One major drawback of both pilot test facilities is the limitation in melting capacity. In addition, the pilot plant does not 100% reflect the identical slag characteristics as tapped on industrial site, due to the fact that it needs to be remolten.

Encouraged by the good results as shown above, SMS Demag decided, together with the Universidade de Chile and Anglo American, to install a 1 tph demonstration plant at the Chagres plant of Anglo American in Chile. The layout was based on the results of the lab-scale tests and the support with CFD modelling. The construction of the mobile equipment was finished in 2006 and five test series have been carried out between 2006 and 2007.

The unit was placed in the casting bay of the primary smelter and converter complex at Chagres. Figures 7 and 8 illustrate the setup of the plant.

The 1.5 tons of slag were charged to the test unit by means of a manual tiltable ladle (as shown in Figures 9 and 10). The flow rate of the charge was measured by a load cell. During the test series, 1–2 ladles were charged into the unit. Numerous samples have been taken at the slag inlet, inside the smelter (by a steel rod), and at the slag overflow. The tapped matte was also analysed.

The slag was charged into the unit; after approximately 10 minutes the unit was filled up and the overflow of slag started. After a holding time, the next ladle was charged into the test unit.

In all five test series it was observed that the unit is easy to control and to handle. The noise and dust/fume emissions of the test plant were very limited.

The quick analysis via microprobe gave already the indication that the copper content could be reduced significantly. The following photo (Figure 11) shows the cross section of the slag at the inlet and outlet of the test unit.

A typical test sequence and the main metallurgical results are illustrated in Figure 12.

The chemical analysis confirmed that the initial copper content of 1.6% in the slag was reduced to below 0.7%. In addition, the magnetite content decreased from 14% to 8%.

In general, it can be stated that the test results confirmed the previously carried out results of the CFD modelling and the lab scale tests at the Universidade de Chile.

The obtained test results exceeded the expectations of SMS Demag despite the fact that the transformer capacity of the unit was too low and the used equipment was not reliable, leading to several unfavourable test conditions. The slag temperature level of all test series was much too low, leading to a high slag viscosity as well as to built-ups in the reactor. The consequence was a too small reaction volume leading to a short residence time. The more astonishing are the already achieved 'slag cleaning level'. This clearly shows that the full potential of the technology is still unknown.

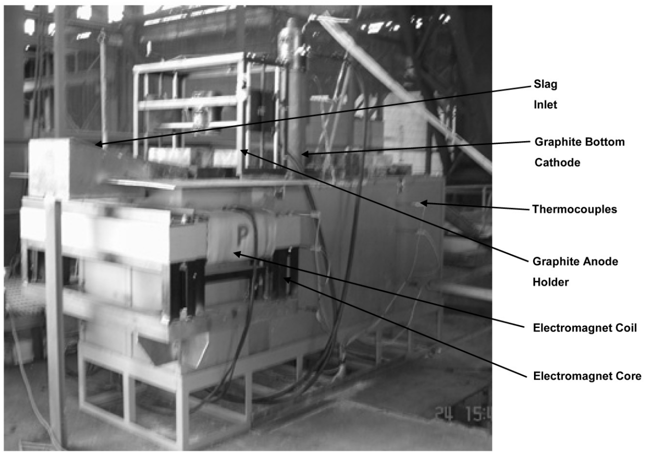


**Figure 7. New pilot plant for testing various slags as installed at Chagres in Chile**

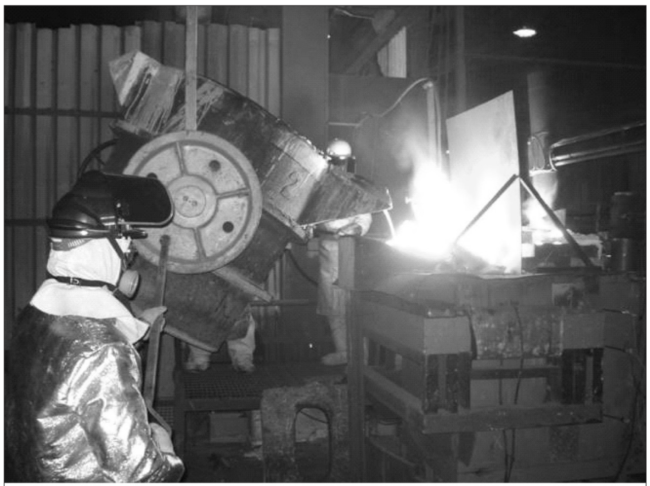

**Figure 9. New pilot plant for testing various slags as installed at Chagres in Chile**

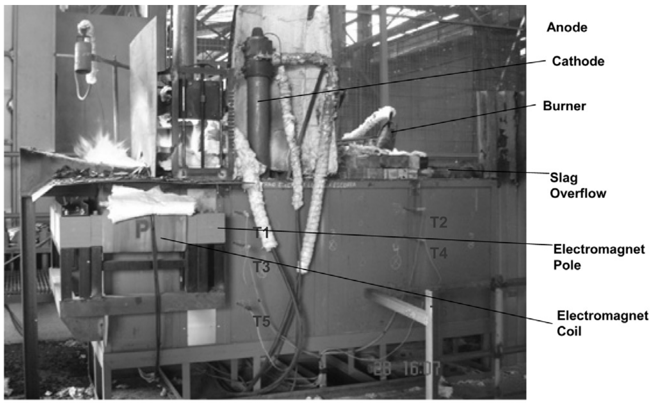


**Figure 8. New pilot plant for testing various slags as installed at Chagres in Chile**

**Figure 10. New pilot plant for testing various slags as installed at Chagres in Chile**

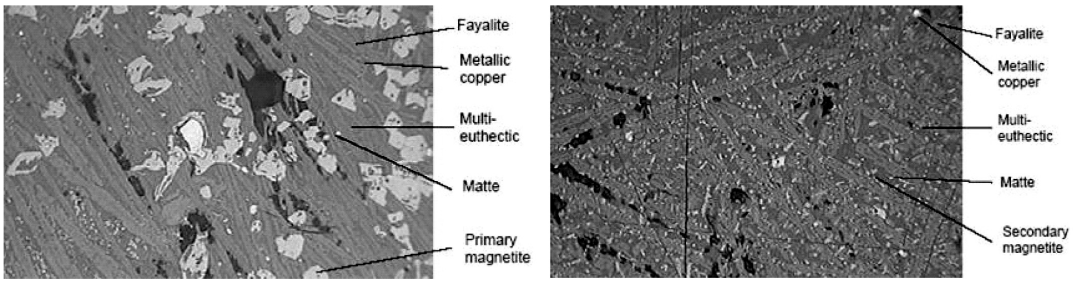


**Figure 11. Microphotographs of the inlet and outlet slag samples**

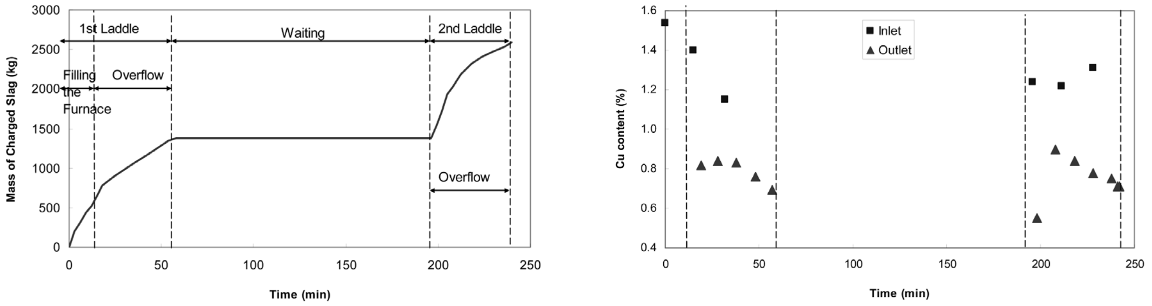


**Figure 12. Slag charging and and content of Cu and $Fe_3O_4$ in slags**

## New test plant in Europe under execution on the basis on copper

The experience gained from the tests in Chile established the basis of a newly projected pilot plant in Europe. The test unit will have a capacity of up to 4 tph and will be equipped with a larger transformer. In addition, the unit has several more features, allowing a more flexible test phase in order to evaluate the full potential of this process principle. It is planned to commission the test unit within the 4Q of 2008.

## Industrial plant set-up on the basis on copper

SMS Demag is already in the planning phase to implement this technology at industrial scale. Capacities of up to 150 tph are possible. Figure 13 shows a cross section of an in-dustrial unit. The basic engineering has been carried out in order to determine the capital costs for such a unit[17].

The up-scaling risks should be moderate for such a new technology for the following reasons:

- Larger units minimize the energy losses and prevents build-ups/accretion in the unit
- Charging and tapping is easier
- Ladle handling is easier
- Industrial standard components are easier to integrate into the system.

Potential critical aspects are the unknown refractory wear in the stirring zone of the reactor. In general, pilot tests units do not allow long-term refractory wear predictions.

## Economical aspects

The economics of this unit are for some applications outstanding. Taking the example of conventional plant utilizing submerged arc furnace for copper slag cleaning and taking the current copper price of approximately 8 000 US$ per ton of copper and a copper production of approx. 200 000 tpy, such a unit might have an amortization period of less than 1 year.

Additionally, SMS Demag is in talks with numerous other companies in the copper and PGM industry to install the first industrial scale plant. The return of investment period of less than half a year is encouraging[18].

## Transfer of the results to the PGM-related industry

The recovery of copper inclusion had been demonstrated successfully. Currently talks are held with the platinum and palladium-producing industry especially in Africa. SMS Demag sees great potential for this technology in this field. A recovery of >50% of the lost PGM-containing matte as inclusions at a unitary electric energy consumption of 50–70 kWh/t of slag might be feasible, according to the test work[19].

SMS Demag sees good potentials for the new technology in existing platinum production lines, where conventional electric slag cleaning furnaces and various primary smelters (such as Ausmelt furnaces—as applied at Anglo Platinum in South Africa) are in use. The process principles are the same and good additional recovery rates are expected. A comparable test set-up can be also installed in South Africa.

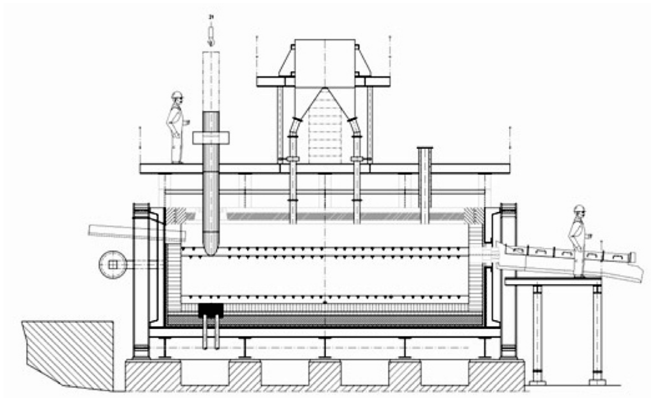

**Figure 13. Large scale 75 tph DC-based slag cleaning step**

## Conclusions and outlook

Our recent innovations focus on the additional recovery of valuable metals out of liquid slag. The developed intensive slag stirring reactor 'washing machine' will become a very attractive solution especially for the PGM and non-ferrous industry worldwide. The advantages of the reactor are obvious:

- High recovery of valuable metals
- Extremely low investment due to simple principle and high intensity
- No control of the electrode necessary leads to easy operation
- Minimum of graphite anode consumption due to coke layer principle
- Possibility of bypass option will not affect daily operation and minimizes project risks
- Small compact unit will fit in almost all downstream locations of primary smelting unit
- Amortization period of less than a year possible.

In a few months, tests will be carried out at two pilot plants in South America and Europe. When the excellent results are confirmed in the pilot plant, SMS Demag will start to market the technology in 2009.

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