DESIGN IMPROVEMENT AND REPAIR OF INTERNAL COMBUSTION CHAMBER STOVES[1]

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Abstract

Paul Wurth has more than sixty years of experience with hot blast stove technology and with the design of internal combustion chamber stoves. The design of these stoves has been permanently improved, considering new operational and environmental requirements as well as new available technologies and experiences. These design improvements lead to stove life times of up to 30 years for the internal combustion chamber stoves. This paper will describe some of these design improvements and will illustrate their implementation in new hot blast stoves but will also describe repair methods for existing stoves.

Key words: Hot stoves; Stress cracking corrosion; Refractory lining; Stoves repair.

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[1] *Technical contribution to the 43rd Ironmaking and Raw Materials Seminar, 12h Brazilian Symposium on Iron Ore and 1st Brazilian Symposium on Agglomeration of Iron Ore, September 1st to 4th, 2013, Belo Horizonte, MG, Brazil*

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1 INTRODUCTION

Paul Wurth has more than sixty years of experience with hot blast stove technology and the design of internal combustion chamber stoves. The design of these stoves is permanently improved, considering new operational and environmental requirements. The new available technologies and experiences from more than 320 internal combustions chamber stoves build so far worldwide have been adopted. These design improvements led to stove life times of up to 30 years for the internal combustion chamber stoves.

This paper will describe some of these design improvements and will illustrate their implementation in new hot blast stoves but will also describe repair methods for existing stoves.

The previous generation of hot blast stoves with internal combustion chambers usually operates satisfactory up to hot blast temperatures of approximately 1,000°C (1,832°F). The design of these older stoves used to differ only slightly from each other until the demand for increased blast furnace operating efficiency forced higher hot blast temperatures.

In order to meet the higher blast temperature requirement, the refractory manufacturers initially recommended improved refractory grades for the hot blast stove. This led to the use of high-alumina and silica bricks.

In regards to the stove lining, little attention was paid to the increased thermal expansion of the bricks and the dimensional changes associated with the improved stove performance. The problems and damages resulting from this negligence were the driving force for the development of a new stove lining concept.

During this time also the external combustion chamber stoves were developed. They have proven for 40 years now to be a good alternative, especially for high capacity or very restricted carbon monoxide emission.

Later, the increased hot blast and dome temperatures caused a new problem, namely the risk of inter-crystalline stress corrosion cracking (SCC) of the stove shell. A thorough analysis of this phenomenon led to the development of a special stove shell protection system.

With the increase in energy prices, the operators and designers of stove plants were challenged to minimize overall energy consumption of the plant. Heat recovery systems and systems for the preheating of combustion air and gas became part of the thermal design of modern stove plants. In addition to energy savings, numerous stove optimizations were implemented. Computer based control programs are now being used to run hot blast stoves, and to accommodate blast furnace operation and performance requirements.

2 DESIGN FEATURES OF PAUL WURTH STOVES

From the beginning of all of this until today, Paul Wurth (formerly Didier and DME) remained a leader in all aspects of stove design and experienced a great deal of opportunities and successes. The key to success was always the technical advantages and reliability of the Paul Wurth stove design based on special design features for these areas where in the past the most problems occurred.

2.1 High Performance Checkers

High performance checkers should feature optimum heat transmission characteristics (heating surface) and heat storage capacity (refractory weight) over a very long service life.

While the refractory weight of the bricks is resulting from other parameters and the material of the bricks, the heating surface can be greatly influenced by the design of the bricks. The size and shape of the holes is one typical parameter to optimize the heating surface.

Small holes and complicated shaped flue gas channels increase the specific heating surface of the bricks and allow the reduction of stove size. However they also influence the pressure loss of the checkerwork and greatly increase the risk of blockages and therefore serious reduction of performance. Paul Wurth has found hexagonal shaped flues (Figure 1) with a minimum diameter of 30 – 35 mm to be the ideal solution for both maximum heating surface and high operational reliability with minimum exposure for clogging.

The flue gasses enter the upper zones of checker bricks with very high temperature allowing high heat transfer rates due to heat transfer by radiation. Therefore, the checkers used in the upper zones of the checker chamber can have smaller flue channels and thicker walls than the checkers installed in the lower zones of the stove. This leads to lower heating surface in favour of higher heat storage capacity in the upper part of the stove checker column. Such optimization allows the reduction of stove size without negative influence of critical hole diameters or complicated hole shapes. The checker bricks used in the lower temperature range have larger flue channels and thinner walls in order to increase the heating surface. Furthermore, such design results in reduced pressure loss but decreased heat storage capacity at the lower parts of the checker column.

Figure 1. High performance checker bricks.

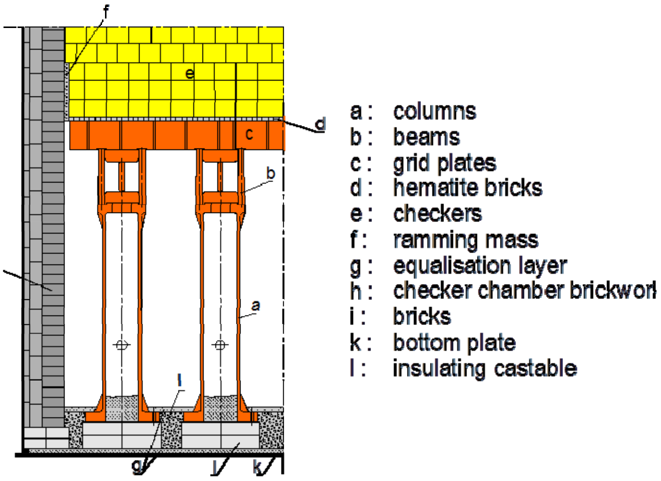

Figure 2. Checker support system adopted by Paul Wurth.

2.2 Checker Support Grid

The main function of the grid is to support the checker bricks during stove operation, when high temperatures occur in the area of the grid. A high design temperature of the grid increases therefore the safety for stove operation. Since high waste gas temperatures also increase the efficiency of heat transfer, they allow the reduction of stove size, while waste gas heat recovery system allow feeding back the higher energy in the waste gas to the stove. The Paul Wurth grid is suitable for short term maximum waste gas temperatures of 450°C (842°F), and of 400°C (752°F) for continuous operations. For special applications, Paul Wurth has developed and successfully applied a high temperature grid, suitable for temperatures of up to 550°C (1,022°F).

The grid material is in direct contact with refractory material, therefore it should have a thermal expansion coefficient as close to the refractory as possible to reduce constant differential movements to a minimum. Since metal has typically much larger thermal expansions than refractory material, the thermal expansion coefficient should be as low as possible for the grid material. The Paul Wurth checker grid is therefore composed of a special cast iron with low thermal expansion. The grid is free standing (Figure 2) without contact to the refractory wall lining to avoid unnecessary differential movement there; the contact surface between grid and checkerwork is protected with separated metal plates for every checker to avoid the constant “grinding” which would occur if checker grid material and checkerwork would be in direct contact.

2.3 Dome Construction

While other elements have a direct influence on stove performance, the dome construction is solely based on the avoidance of hot spots on the steel shell during a maximum service life. Different approaches exist to achieve this requirement; Paul Wurth has developed the refractory design of the spherical dome design so that a long service life can be achieved with simple geometry.

The dome is usually supported by the ring wall. The design of the ring wall aims for a most uniform vertical thermal expansion. This requires detailed calculations that take into account the effects of local temperature variations and different thermal refractory expansion characteristics. The support bricks and transition bricks of the dome have tongues and grooves at their circumference in order to absorb the radial forces (Figure 3). In addition, the radial forces are absorbed by friction due to the vertical load of the dome refractory. This design avoids the reinforcement of the dome refractory through skew back bands.

Depending on the shape and the dimension of the dome in addition to the thermal expansion of the refractories, adequate expansion joints must be provided, even for the support and transition bricks. This is to absorb the horizontal thermal expansion of the ring wall bricks and of the lower part of the dome.

While the spherical design is technically and commercially convincing the spherical design also is the perfect shape for the stove steel shell as a pressure vessel. Especially designs with “sharp edges” in the steel shell are problematic and result in local tension peaks in these areas.

Designs where the dome refractory is not resting on the ring walls is also possible and was successfully applied by Paul Wurth, however it should be noted that in this case the critical areas like the expansion joint between wall and dome lining, the “overlapping areas” of the refractory of wall and dome lining and the shape of the pressure carrying steel shell require special attendance and effort.

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2.4 Division Wall

The division wall is a critical item in internal combustion chamber stoves. It separates the combustion chamber with high flame temperature from the checker chamber which is designed for lower temperatures. The division wall should also prevent the CO contained in the blast furnace gas (BFG) from leaking to the checker grid area. Already traces of diffused, unburned BFG can lead to high emission values of CO in the waste gas which can exceed the environmental requirements.

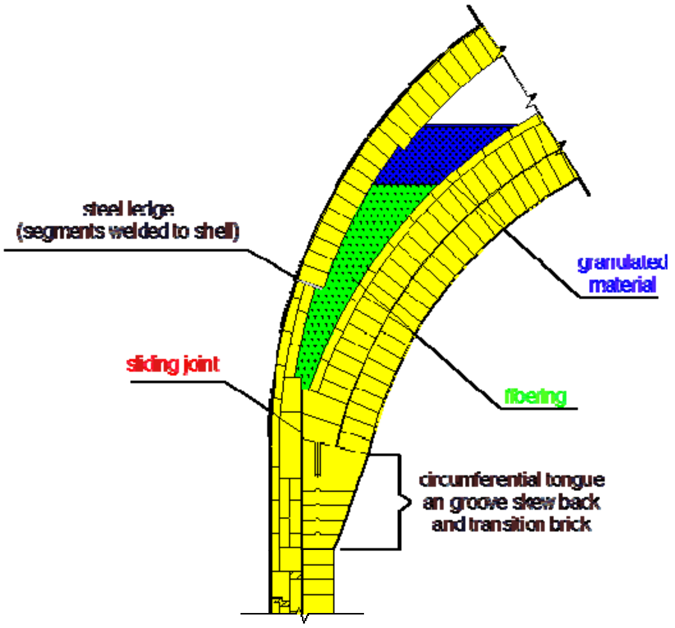

Figure 3. Refractory lining of dome.

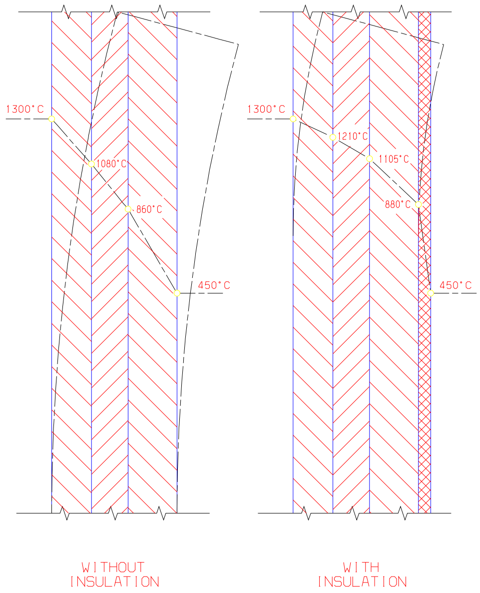

Figure 4. Division walls and measures against “Banana Effect“.

The division wall between the combustion chamber and the checker chamber is exposed to the most critical thermal stresses during operation of a hot blast stove. The face on the combustion chamber side is directly exposed to the high heat impact from the burner flame, whereas the lower part of the division wall that faces the checker chamber is located in the coldest part of the stove. This can cause leaning of the division wall due to different vertical thermal expansions. The optimum division wall construction would consist of numerous walls, which expand independently of each other. Multiple walls would also reduce the temperature gradient across each individual wall. Since this is not possible for construction reasons, other methods for solving the differential expansion need to be found.

The Paul Wurth division wall is typically constructed with three layers of refractory bricks, each utilizing a tongue and groove design on the radial face. Vertical sliding joints between each course allow free vertical expansion of each individual layer. If a metallic burner outside the combustion chamber is used, the lower part of the division wall has an additional refractory wall to protect against flame impingement. In the lower part, where the highest differential expansion occurs an additional wall of insulation is used, which is relatively easy to install.

The principle of the division wall insulation is illustrated in Figure 4. Figure 4 also illustrates the leaning of the division wall (widely known as the Banana Effect) towards the checker chamber as a result of the temperature difference, particularly in the lower part of the stove. The installation of insulation on the cold face of the division wall will reduce the temperature gradient in the division wall bricks which will reduce the leaning to a minimum.

The first stove constructed with this type of division wall insulation was equipped with a large number of thermocouples in the lower division wall. Measurements revealed that most of the temperature gradient had passed from the bricks into the insulation layer.

After the introduction of the division wall insulation, damage due to leaning of that wall has essentially been avoided. The internal combustion chamber design with the division wall has a weak spot on the corners of the combustion chambers. In the past often exceptional disturbances of operation, like explosions etc. led to damages in this area. Therefore these corners have to be supported properly. Paul Wurth has chosen to reinforce the refractory material in this area to solve this problem. While still allowing the required sliding gaps, the Paul Wurth design reinforces the corners enough to avoid any problems in this area since introduction of this design (Figure 5).

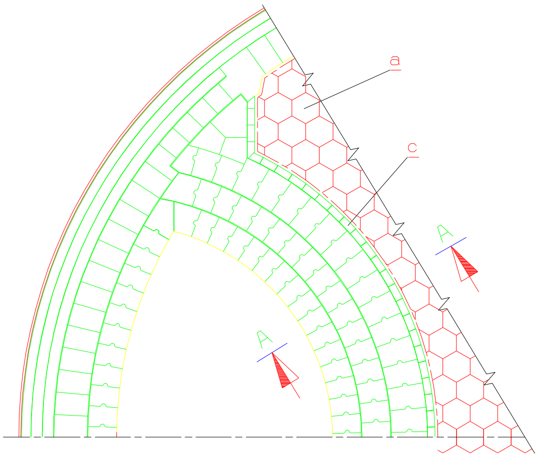

Figure 5. Design of the corners of the combustion chamber.

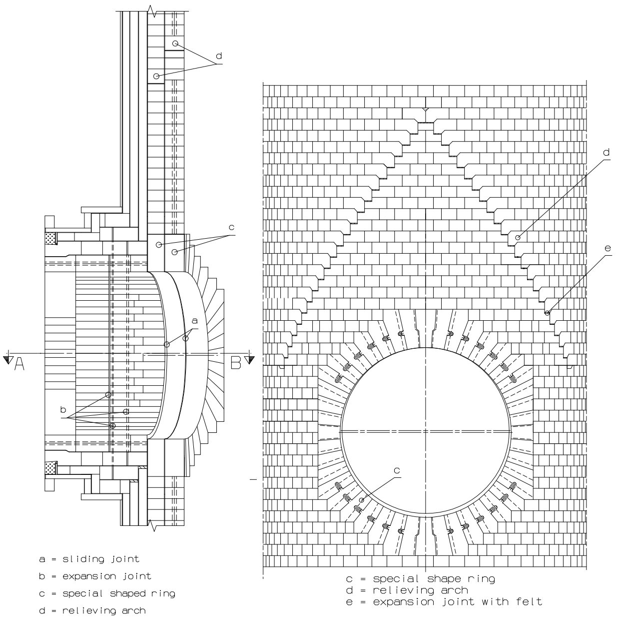

Figure 6. Design of the hot blast outlet with relief arch.

2.5 Hot Blast Outlet

The construction of the hot blast outlet can be seen in Figure 6. The inner shaped ring consists of special bricks that are keyed into the combustion chamber brickwork, so that they cannot move towards the combustion chamber. The outer diameter profile of the shaped ring normally allows the installation of the combustion chamber bricks without cutting.

The combustion chamber brickwork and the openings in the shell brickwork are separated from the ring wall bricks by a sliding joint in order to allow them to expand independently of each other. The opening in the combustion chamber brickwork is similar to the opening in the ring wall brickwork, and is again separated from the stove insulation layers by a sliding joint.

Paul Wurth adopts relief arch which helps unloading the hot blast outlet shapes from the brick dead load above.

2.6 Stove Ceramic Burner

The ceramic burner has the task to achieve complete combustion of air and gas in a large range of operation characteristics and of course a long service life. Since external metallic burners require regular maintenance and always impose larger stress by the direct impingement of the flame and hot gasses on the division wall, DME/M&P developed the maintenance free parallel stream ceramic burner, which was further improved by Paul Wurth. The parallel stream design allows thorough mixing of air and gas over a large range of flow rates and ensures an even load of the combustion chamber beside low emission values.

The brickwork of the burner is self-supporting and is preferably not incorporated into the combustion chamber walls. The burner can easily absorb high temperature fluctuations. The material used for the burner is an andalusite based high alumina refractory with high thermal shock resistance and special sustainability against CO.

Combustion air and gas enter two separate chambers underneath the burner through two separate openings (Figure 7). Gas and air are then directed to a set of parallel slots, thus providing the initial distribution of air and gas across the burner. On top of these slots are refractory courses that provide a very intense mixing of air and gas, a prerequisite for complete combustion.

To the present date, more than 120 hot blast stoves have been equipped with this type of ceramic burner. Continuing design optimization for more than 30 years and ever changing operating conditions has resulted in the following characteristics and design standards:

- depending on the layout, the burner can be fired with:
  - mixed (enriched) gases up to 7000 kJ/Nm³ (746.3 Btu/Scf)
  - blast furnace gas only
  - preheated combustion media
  - oxygen enriched combustion air;
- a maximum performance of approximately 60 GJ/m2 h (7 MMBru/Scf h) has been achieved. However, a standard ceramic burner will not continuously be operated with this high heat load;
- the outstanding mixing capabilities of Paul Wurth ceramic burner ensure extremely high energy efficiency and low temperature fluctuations inside the combustion chamber;
- due to the stable acoustic characteristics of Paul Wurth ceramic burner, stove pulsations are unlikely. Nevertheless, a special acoustic study for each stove is part of the Paul Wurth engineering;
- with a factor of excess air of 10% and with good control systems, the CO and NOx emission of the burner is very low. With respect to NOx however the nitrogen containing components of the blast furnace gas have to be taken into account as an additional load which cannot be influenced by the ceramic burner.

Due to these advantages, Paul Wurth always recommends a ceramic burner. On special request, the installation of a metallic burner is possible. To protect the separation wall from the impact of the hot combustion gas, an additional layer of protection bricks and insulation bricks are necessary.

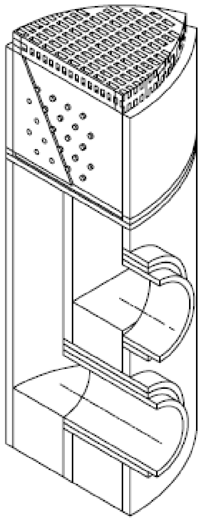

Figure 7. Ceramic Burner with parallel channels.

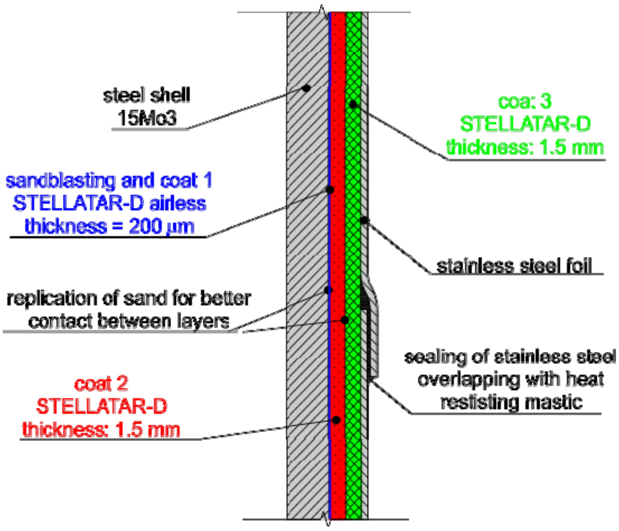

Figure 8. Shell protection system against Stress Corrosion Cracking.

2.7 Stress Corrosion Protection

In the past, stress corrosion cracking (SCC) occurred when unprotected stoves were operated at dome temperatures in excess of 1,300°C (2,372°F) and at high blast pressures. Studies revealed that the formation of nitric oxide from the nitrogen of the air increases exponentially when the temperature is above 1,300°C (2,372°F). As a consequence, aggressive condensates are produced at the stove shell which attack especially in the area of tensile stress concentrations (welds, notches etc.). This leads over time to progressive corrosion damage, continuous crack formation, and ultimately to the failure of the stove as a pressure vessel.

Different approaches exist to address this major problem. All approaches consider eliminating one of the three influencing factors: tension forces, chemical attack and SCC-sensitive material.

The preventative measures start with the thermal layout of the stove. If possible, the heat storage level should be designed in a way that the requested stove performance is achieved with the lowest possible dome temperature. Normally, the temperature differential between the desired controlled hot blast temperature and the dome temperature is approximately 100°C to 150°C (212°F to 302°F).

The heat storage level and the required investment cost can be kept small if the design of the stove permits high waste gas temperatures. This adds to the importance of heat recovery systems, in addition to their advantages associated with energy savings and elimination/reduction of enrichment gases.

The Paul Wurth protection system consists of the following measures:

- tensile stress concentrations in the shell should be kept at a minimum or completely avoided: Design of the steel shell including the dome area, special welding procedures, shot-peening of stress concentration areas is recommended;
- chemicals responsible for the SCC should be separated from the steel shell: coating of the entire internal surface of the stove shell by a specially developed Stellatar-D coating system is recommended (Figure 8);
- the shell should be fabricated from stress corrosion resistant steel: laboratory tests and practical experience have shown that the grade 16Mo3 (ASTM A 204), has both high resistance to corrosion and good welding characteristics.

Another option to avoid the chemical attack would be external insulation of the steel shell in order to keep the shell temperature above 180°C (356°F), i.e. above the dew point of the aggressive chemicals. However this approach requires constant attention in case of changes of the shell temperatures and regular maintenance.

Since the introduction of this system in 1980, DIDIER/ DME/ Paul Wurth's Stellatar-D protected stoves have not yet shown stress corrosion damage.

3 REPAIR METHODS DEVELOPED BY PAUL WURTH

3.1 Cold Repair

The cold repair is the classic repair method for hot blast stoves. The stove is cooled down and repairs on the refractory lining and the steel shell can be carried out. Even if this repair method requires taking the stove out of operation and longer repair time it is still the most common repair method and sometimes even the only alternative for repairs in certain high temperature areas. The larger scale stove relining during cold repairs were further developed by Paul Wurth, in order to provide methods for design improvement to allow overcoming as much weak spots in older stove plant designs as possible.

Modern ceramic burners with low emission values can be incorporated in most stoves. The position of the hot blast outlet, gas and air nozzles and surrounding wall lining are incorporated in the design of the new state of the art ceramic burner.

The hot blast outlet is often a weak spot of old stove designs. Here a local replacement of the nozzle refractory lining and steel shell is often chosen to increase the amount of insulation material, replace unreliable fibre or block insulation by high performance insulation bricks and incorporate a sophisticated and reliable expansion design to this area.

During cold repairs even the replacement of a complete dome is possible. Often "flat arch" designs cause problems, hot spots and regular outtakes in hot blast stoves of older design. In order to modernise this area there are two approaches. The steel shell can be cut and both the steel shell and refractory lining can be adapted to a modern spherical design. But often even the replacement of the steel shell can be completely avoided! In this case the refractory design is carried out with a spherical dome while keeping steel shell, refractory wall lining and checker bricks without modification! This leads to a reliable new dome design with minimum investment cost and short relining durations.

Beside the replacement of checker bricks and checker support grid also other methods are available to increase the performance of the stoves itself with minimum cost and under tight relining schedules. In combination with a replacement of the dome the stove height often can be modified to allow the installation of additional checker bricks. In order to verify this, the old checker bricks and checker support system is completely recalculated for the new loads and temperatures. New high performance checkers are installed on top of the existing checker bricks, with special transition bricks for the interface between old and new checker bricks. The grid is reinforced by additional columns for the new refractory weight.

3.2 Hot Repair

Typically only emergency repairs are carried out in hot condition of the stoves. Mortar injection is used in order to stop back flowing of hot gasses to the steel shell, gouging and welding or welding of patches is used as temporary repair for damages of the steel shell. Also for these repairs new approaches were developed. Modern mortar injection methods during operation allow direct monitoring of the development of the steel shell temperature or tailor made steel shell bandages allow at least a reliable operation to the next scheduled shutdown. However the main subject addressed here as hot repair are repairs of the refractory lining in the lower combustion chamber area in a hot condition of the stoves, this can include repairing one of the following areas:

- hot blast outlet, including the installation of relief arches if not available in the old design;
- ceramic burner;
- the division walls or in general any damages in the combustion chamber.

Often the long cooling down and heating up periods of a hot blast stoves make even small refractory repairs very time consuming and expensive. The idea of the hot repair concept with a heat shield is to allow access to the ceramic burners, lower combustion chamber and hot blast outlet area while avoiding the cooling down of the complete stove. In order to allow the repair, the stove is separated and isolated from the blast furnace during a normal, short maintenance shutdown (Typically one day). All openings of the stove are sealed and the furnace can be continued to be operated with the remaining stoves.

Depending on the exact extend of the repair a heat shield is inserted, via the hot blast outlet in case of ceramic burner or through the mechanical burner opening. The heat shield seals off the working space from the rest of the stove. It allows the local cooling down of the working area below the heat shield, while the rest of the stove remains in hot condition. Figure 9 illustrates the concept of hot repair.

The heat shield is of a foldable design and is driven into the combustion chamber on air cooled rails. When in the combustion chamber the shield is unfolded from outside and raised above the hot blast outlet. Also the heat shield itself is air cooled and works both as isolation and insulation for the stove dome area and as protection against any falling bricks from above. When the heat shield is raised to its final position, the area below the shield is ventilated by fans and thereby cooled down to acceptable working conditions. Due to the small volume of refractory in this area, the repair work can start in a couple of days after the heat shield is in position.

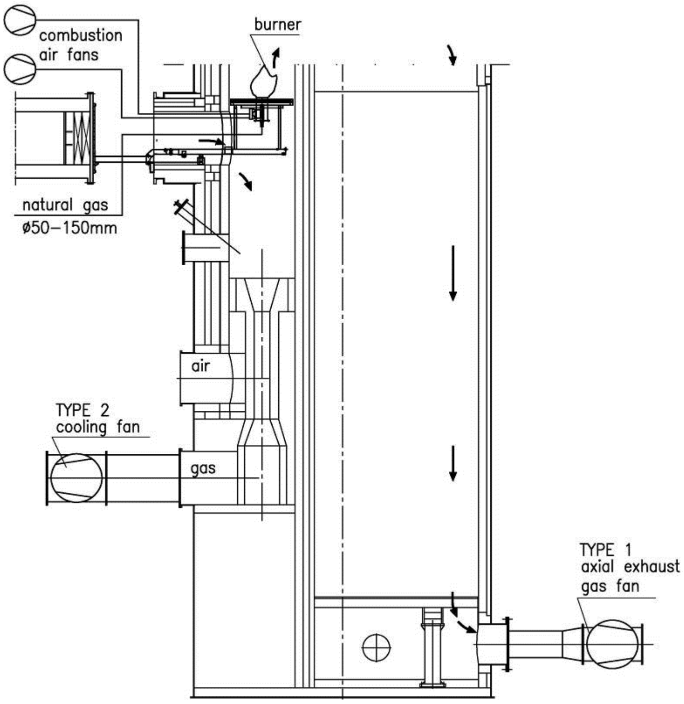

Figure 9. Concept of hot repair.

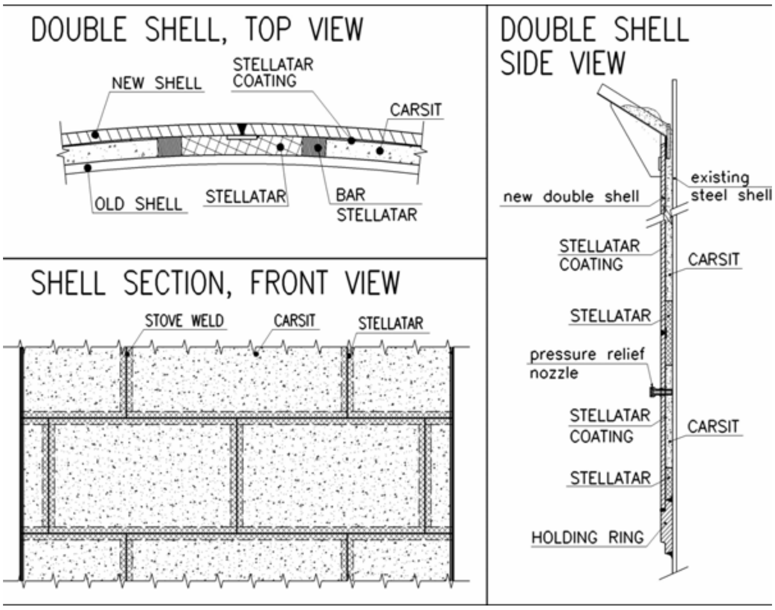

Figure 10. Illustration of double shell repair.

Depending on the extent of the repair, temperature maintenance can be included in the working cycles of the repair. Using a pot burner mounted in the heat shield regular heating up of the dome is possible to keep the dome temperature above 800°C. By this the duration of the repair can be outspread, so that also larger repairs like the complete rebuild of new ceramic burners are possible and were already carried out by Paul Wurth under the heat shield.

After the completion of the repair another short shutdown is used for the reconnection of the stove.

Safety is the key topic during hot repair. The personnel for the repair should be experienced with hot works and undergoes various special trainings for the repair itself. Part of this training is for example the repeated simulation of the installation of the heat shield in a 1:1scale mock-up of the stove combustion chamber. Special safety concepts are developed with the refractory installation companies carrying out the work, the plant operation team and the Paul Wurth experts with their experience on the many hot repairs carried out till the present date.

3.3 Double Shell Repair

A lot of the hot stoves built back in the 70th and 80th did not address the problem of Stress Cracking Corrosion (SCC). Most of those stoves are suffering now from SCC, some of them in very urgent conditions. There were some attempts to control the problem by welding of the cracks or patching the cracks area with new steel plates. Nevertheless, all those counter measures did not represent a long term and reliable solution as it merely transfers the problem to the adjacent zones of the new welding. It’s worth to mention that SCC typically occurs in the heat influenced zones along the welding seams, due to the thermal stresses concentrated in this area.

In many cases the SCC is very severe in such a way that it compromises the safe operation of the stoves. In such situation, the stove shell has to be replaced by new one. In many cases the refractory lining has to be also replaced even though it is in good conditions. Such repair requires taking the stove under consideration out of operation for long time. During the repair campaign, the hot blast temperature will be reduced and the consumption of the coke will increase reflecting on higher operational costs.

Paul Wurth addressed the problem of SCC long time ago. Paul Wurth applies the so called “double shell repair” or “double skinning” for affected stoves during normal operation without any reduction of the blast capacity or additional operational costs.

The double shell repair can be applied partially to specific area of the stove shell like, dome, combustion chamber (for stoves with external combustion chamber), or hot blast outlet but can be also applied to the complete stoves shell. Such flexibility allows reliable repair with the investment reduced to the absolute necessary. The new shell will be attached to the old one in area free of any cracks; normally bellow the SCC affected zones. A gap will be kept between the two shells by casted bars made out of the resin material Stellatar-D. The inner surface of the new shell will be also coated by Stellatar-D primer.

The gap between the two shells is filled with a special DRY backfilling mix characterised by high thermal conductivity (see Figure 10). Such high thermal conductivity is essential to keep the temperature difference between the two shells to the possible minimum to avoid thermal stresses. The word DRY cannot be over emphasised, using regular castables with water contents will provide a source for water vapour building up pressure between the two shells. The old shell is primary designed for internal pressure; excessive pressure from outside (in the gap between the two shells) can deform the shell a push the refractory lining out of position.

The cracks of SCC are typically very thin in the beginning and only allow slow equalisation of pressure over time. During the fast pressurisation and the pressure release cycles of the stove this could result in a pressure building up between the two shells, which could lead to the same effect as evaporating liquids described above. To solve this problem a connection between the inside of the stove and the space between old and new shell needs to be installed. A perforation of the old shell would lead to regular flow of gas through the refractory lining which could stimulate the formation of hot spots, the unnecessary release of aggressive substances onto the new shell and would be unreliable in case the refractory lining would block the drilled holes. Therefore an external pressure equalisation system is connected to the stove in the area of the checker support grid and to each segment of the new shell. The pressure inside and outside of the old shell are hereby always kept in balance, the old shell is hereby no pressure vessel anymore. The formation of SCC is stopped at the old shell, but even entering chemical substances are not able to attack the new, pressure bearing shell due to the complete SCC protective system installed.

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The double shell repair has been applied to nearly 50 stoves affected by SCC. The double shell repair can be applied either to the complete shell or in local areas of stoves such as the dome, combustion chamber or even on hot blast main. Especially the installation during operation and the avoidance of a demolition and rebuild for a long time made the Paul Wurth double shell repair both a technical and commercial success.

3.4 Surveillance and Evaluations

Often damages in refractory lining can be identified by simple means of inspection and evaluations. Paul Wurth have been contracted to inspect and evaluate the conditions of the stoves in general. The inspection covers different areas of the stove like ceramic burner, combustion chamber, dome and checker support system. A thorough inspection and evaluation study will include:

- Endoscope in the combustion chamber and dome to check for any refractory damages
- Thermography investigation to identify any hot spots and effectiveness of refaractory lining
- Ultrasonic tests to check the thickness of the steel shell or to identify cracks
- Thermodynamic analysis to look for possible operational optimization

Additionally, pressure losses measurements and waste gas analyses under controlled operation conditions of the ceramic burners do often allow an assessment of the burner or checker bricks performance. Repairs can so be scheduled more precisely and even regular surveillance of the development of critical plant units is possible.

The final results of such study allow the development of repair concepts and planning for service extension of the stove plant. Furthermore, Paul Wurth has a great experience in solving problems related to stoves pulsation and acoustic resonance.

The expertise of Paul Wurth can be employed, to develop an optimal operation mode for the stove plant, to meet special environmental limits or to cut operational costs

5 CONCLUSION

As it was discussed, Paul Wurth has been improving the design of the hot blast stoves over the past years. The applied design features aim to mitigate the common problems associated with internal combustion chamber stoves. Furthermore, Paul Wurth applied different kinds of repair methods like Hot Repair and Double Shell Repair to damaged stoves (those repair methods were exclusively developed and applied by Paul Wurth). The situation at each stove is different and Paul Wurth always tailor the repair method based on professional analysis for the clients requirements.