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# DON'T LET YOUR MONEY GO UP THE CHIMNEY[1]

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## Abstract

Siemens VAI Metals Technologies are dedicated to helping customers reduce costs and to keep their stoves working at peak performance. Stoves are significant consumers of energy and need to be kept in tip-top condition together with the very latest equipment made available to help keep the fuel requirements down. This paper will describe how you can increase the efficiency of your stoves/plant which will lead to lower fuel costs and thus lower emissions. It will describe the various process changes and pieces of equipment available to help achieve this.

**Keywords**: Stoves; Energy; Optimization.

## Resumo

Siemens VAI Metals Technologies é uma empresa que tem como objetivo auxiliar seus clientes a reduzir custos e manter seus regeneradores trabalhando com alta performance. Regeneradores são consumidores significantes de energia e necessitam ser mantido em condições estáveis para que juntamente com as últimas tecnologias em equipamentos possam auxiliá-lo a manter as necessidades de combustível baixa. Este trabalho irá descrever como se aumenta a eficiência dos regeneradores/planta e consequentemente diminui o consumo de combustível e de emissão. Ele irá descrever as várias mudanças de processo e peças disponíveis para ajudar na aquisição destes objetivos.

**Palavras-chave**: Regeneradores; Energia; Otimização.

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## 1INTRODUCTION

Siemens VAI Metals Technologies are dedicated to helping customers reduce costs and to keep their blast furnace stoves working at peak performance. The stoves provide a valuable role in making the blast furnace a high thermal efficiency process. The stoves provide the hot blast which supplies a large portion of the blast furnace heat input. They do this by burning the low heating value blast furnace off gas. However, despite all these benefits, the stoves still consume a large amount of energy. The blast heating process is one of the largest energy consumers in the steel plant and also one of the leading sources for $CO_2$ emissions to the atmosphere.

Stoves need to be kept in good condition and equipped with the very latest equipment to help keep the fuel requirements down. This paper will describe how blast furnace operators can increase the efficiency of their stoves which will lead to lower fuel costs. It will describe the various process changes and pieces of equipment available to help achieve this.

During the 2009 AISTECH Conference, Siemens VAI participated in the Panel Discussion that discussed stove technology to discuss the design change requirements for stove operation in the years after 2020. However, there are a lot of improvements that can be done today with currently available stove technology. This paper tries to summarize these potential opportunities to reduce energy consumption and operating costs.

## 2WASTE HEAT RECOVERY

A large amount of thermal energy leaves through the stove chimney. The typical stove has 18% of the total heat input leaving the stove through the waste gas. A waste heat recovery (WHR) system can recover half of this energy. The WHR process is based on the concept of recovering some of this sensible energy from the stove exhaust stack and to use it to preheat the blast furnace gas and/or combustion air. This energy recovery reduces the heat input required for the stove firing. In addition, the preheating develops a higher flame temperature allowing the amount of gas enrichment to be reduced if the same flame and dome temperature is to be maintained.

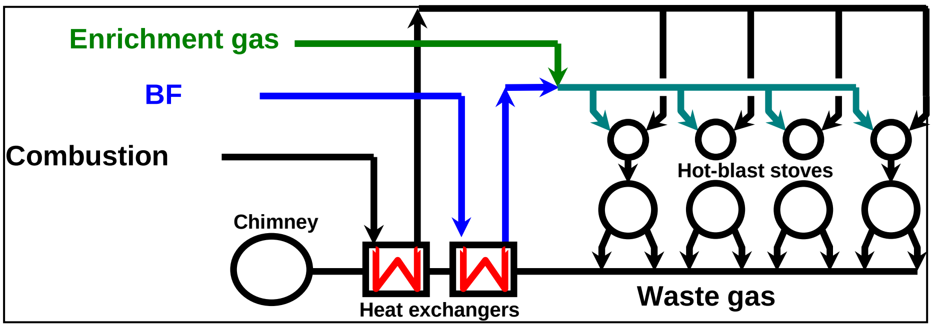

**Figure 1:** Direct Heat Recovery System – Heat Pipe.

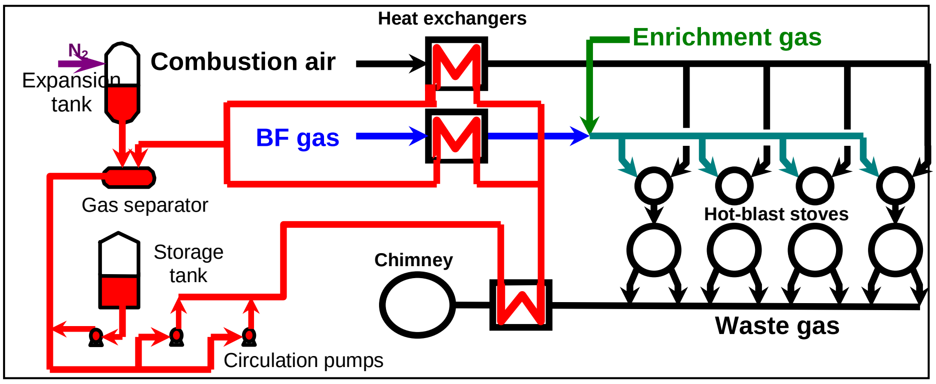

**Figure 2:** Indirect Heat Recovery System – Oil Pipe.

In a recent US installation, a WHR system was designed to preheat the blast furnace gas. Initial stove simulation computer modeling was done to determine the potential benefits from the WHR system. This evaluation involved appropriate iterations to define the stove conditions and required heat exchanger performance. These individual stove results for the two proposed wind rate are shown below:

**Table 1**: 245,700 Nm$^3$/hr Wind Rate

| | **Base** | **WHR Operation** | **Difference** |
|---|---|---|---|
| Natural Gas (Nm$^3$/hr) | 1,672 | 362 | - 1,310 (-78%) |
| BFG (Nm$^3$/hr) | 72,197 | 80,923 | + 8,726 (+12%) |

**Table 2**: 263,400 Nm$^3$/hr Wind Rate

| | **Base** | **WHR Operation** | **Difference** |
|---|---|---|---|
| Natural Gas (Nm$^3$/hr) | 1,770 | 383 | - 1,387 (-78%) |
| BFG (Nm$^3$/hr) | 76,418 | 86,875 | + 10,457 (+14%) |

*Note: These results were for a 200°C BFG preheat temperature.*

Stove model runs confirmed that there would be significant energy savings from the WHR system. The recovered stack heat would reduce the total amount of energy required from the stove firing gases. In addition, the stove burner flame temperature would be increased which allows a significant reduction in the natural gas enrichment rate. The lost heat input from the natural gas reduction is then made up by increasing the firing rate of the lower priced blast furnace gas. It was seen that the total stove energy consumption and product hot blast temperature would be unchanged. The overall external stove energy consumption was decreased by 7% simply due to the energy recouped in the WHR system. However, the amount of energy supplied by the expensive, outside purchased natural gas was reduced by the 78% figure noted previously. The overall projected energy balance is shown below:

**Table 3**: 263,400 Nm$^3$/hr Wind Rate

| | **Base** | **WHR Operation** | **Difference** |
|---|---|---|---|
| Natural Gas (MW) | 34.4 | 7.4 | - 27.0 (-78%) |
| BFG (MW) | 123.6 | 140.5 | + 16.9 (+14%) |
| Recovered Heat (MW) | 0.0 | 10.9 | + 10.9 (NA) |
| Totals | 157.9 | 158.8 | 0.8 (+0.5%) |

*Note: The 0.5% change in total energy change is just basically a round off error.*

The combustion air requirements are lowered because the richer natural gas requires more oxygen per Megawatt provided than the leaner blast furnace gas. The combustion air requirements were projected to decrease by approximately 15% for the 400oF preheat case. This secondary benefit was felt to be significant since the combustion air fans were operating at maximum conditions due to higher pressure requirements from stove checker deterioration. However, no increased hot blast temperature benefits were incorporated into the project justification. In actual operation, the reduced combustion air requirements did allow the hot blast temperature to be increased significantly. The expected WHR system operating benefits were achieved once the system was installed and commissioned. The actual observed results are shown below:

**Table 4**: Results with WHR in operation

| | Base | WHR | |
|---|---|---|---|
| Hot Blast Temperature ($^{o}$C) | 1,108 | 1,154 | |
| Delta Coke Rate (kg/THM) | | | 9.5 |
| Yearly Coke Savings @ 6,000 TPD production (Te) | | | **- 20,805** |
| Average NG Rate (Nm$^3$/hr) | 2,088 | 406 | |
| NG HV (KJ/Nm$^3$) | 38,175 | | |
| NG (GJ/yr) | 698,400 | 135,772 | |
| Delta NG (GJ/yr) | | | **- 562,628** |
| BFG HV (KJ/Nm$^3$) | 3,114 | 3,352 | |
| Average BFG Rate (Nm$^3$/hr) | 136,395 | 132,463 | |
| BFG (GJ/yr) | 3,720,670 | 3,889,580 | |
| Delta BFG (GJ/yr) | | | **+ 168,910** |

The economic evaluation, for a 6,000 TPD production rate, was as follows:

Table 5: Economic results with WHR in operation

| | Annual Cost/Benefit | |
|---|---|---|
| BFG (based on $2.5/ GJ) | + $ 422,275 | (Cost) |
| Coke Savings (based on $440/Te) | - $ 9,154,200 | (Saving) |
| NG (based on $9.00/GJ) | - $ 5,063,652 | (Saving) |
| Total | **- $13,795,577** | **(Saving)** |
| | **- $ 6.30/THM** | |

The project payback based on the installed capital cost was approximately 6 months. If the hot blast temperature increase had not been obtainable, the annual savings would have been about $5,000,000 ($2.28/THM) and the simple payback would have been around 15 months. The project economics for a WHR system will depend on the stove wind rate, hot blast temperature, stove capacity, and pricing for the blast furnace gas and enrichment gas.

## 3 STOVE OXYGEN ENRICHMENT

The flame temperature required to meet the dome temperature set point can be met by using a higher oxygen percentage air instead of using enrichment gas such as coke oven gas or natural gas. Pure oxygen is added to the combustion air to increase the oxygen content above the ambient 21%. Several stove oxygen enrichment (SOE) systems have been installed in the US to utilize this concept. Although the enriched combustion air can allow the required flame temperature to be reached, the total heat input is reduced when the enrichment gas is removed. The additional heat input is made up by firing additional blast furnace gas. The combustion air requirements are reduced significantly as oxygen is used. Each Nm$^3$/hr of oxygen replaces nearly 8.5 Nm$^3$/hr of combustion air. The net impact is that the enrichment gas firing rate decreases, the BFG firing rate increases and the combustion air flow rate decrease significantly. The total flue gas is reduced slightly.

This occurs because the BFG fuel components (CO and $H_2$) actually require less oxygen per unit of energy released than does natural gas.

The economic benefit can be that the enrichment gas savings are larger than the additional cost for the enrichment oxygen and the additional BFG (which is often taken away from use at the boilers or external electricity production). The magnitude of the benefit depends on the oxygen price, the enrichment gas pricing and the actual value of the BFG from the end user. The stove does not see any performance difference as long as the combustion gases are delivered at the same flow rate and temperature. In all cases the enrichment gas (both for natural gas or coke oven gas) is removed and enough oxygen added to the combustion air to maintain the same flame temperature. Then the BFG firing rate is increased, maintaining the same air/fuel ratio, until the total heat input equals the base condition. The total flue gas flow remains relatively constant which results in a constant convective heat transfer coefficient in the stove checkers. The results from one installation illustrate the economic benefits from the SOE technology. The operating values, per stove, for a constant 1250$^o$C hot blast temperature, were as follows:

**Table 6**: Results with Stove Oxygen Enrichment in operation

| | **Natural Gas Base Conditions** | **SOE Operation** | **Delta** |
|---|---|---|---|
| BFG Firing Rate (Nm$^3$/hr) | 99,520 | 148,086 | + 48,566 |
| NG Firing Rate (Nm$^3$/hr) | 3,771 | 0 | - 3,771 |
| Combustion Air Rate (Nm$^3$/hr) | 121,954 | 77,056 | - 44,896 |
| Oxygen Rate (Nm$^3$/hr) | 0 | 5,852 | + 5,852 |
| CA Oxygen Composition (%) | 21.0 | 27.0 | 6.0 |

In both operations, the wind rate was 404,282 Nm$^3$/hr, the dome temperature was maintained at 1400$^o$C and the final stack temperature was 357$^o$C. The stoves were operated in a three stove, cyclic operation with a blast time of 30 minutes and a gas time of 52 minutes. The blast furnace gas (wet) heating value was 3024 KJ/Nm$^3$. The economic evaluation, for a 12,000 TPD production rate, is as follows:

**Table 7**: Economic Results with Stove Oxygen Enrichment in operation

| | **Annual Cost/Benefit** | |
|---|---|---|
| BFG (based on $2.5/ GJ) | + $ 5,574,942 | (Cost) |
| Oxygen (based on $ 0.05/ Nm$^3$) | + $ 4,442,838 | (Saving) |
| NG (based on $9.00/GJ) | - $ 19,672,714 | (Saving) |
| Total | **- $9,654,934** | **(Saving)** |
| | **- $ 2.2/THM** | |

The project simple payback based on the actual installed capital cost was approximately two (2) months. The project economics will depend on the stove wind rate, hot blast temperature, stove capacity, oxygen pricing and costs for the blast furnace gas and enrichment gas. The capital cost included the oxygen supply skids, spargers and local piping tie-ins as well as the changes to the stove firing control system. There was no cost required to increased oxygen production at the supplier's plant or install a larger plant supply line.

There is an additional situation where a SOE system can help improve the stove performance by allowing the hot blast temperature to be increased for old, damaged stoves with excessive pressure drops which limit the hot blast performance. **If** (1) the stoves can not be fully heated during the firing cycle – as apparently indicated by final stack temperatures below the design maximum **and** (2) if the stove firing is limited due to the fact that the combustion air fan can not deliver enough air at the stove pressure drop requirement – as indicated to surging fan and/or high stove pressure drops, **then** stove oxygen enrichment operation can help because it reduces the amount of combustion air required to fire the stove at a given heat input level.

Normally the amount of combustion air is reduced so much in the SOE operation that the heat input rate can be increased by increasing the firing rate (and corresponding air/oxygen) while the total combustion air rate still remains below the base case level. The overall stove pressure drop doesn't increase because the total flue gas volume doesn't increase. The combustion air fan can meet the reduced flow rate requirement at the base static pressure drop requirement as the operating point slides down the fan curve.

At one location, SOE is being considered to reduce operating costs at the current 1010°C hot blast temperature. However, this operation is hampered by damaged stoves that do not allow full firing due to combustion air fan limitations. It was determined that the reduced combustion air requirements with stove oxygen enrichment would allow a firing rate increase resulting in a 1038°C hot blast temperature.

Calculations and stove model runs were made to estimate the benefits of using the stove oxygen enrichment concept to raise the hot blast temperature to 1038°C. The effort was based on increasing the heat input rate to meet the required performance. The approximate operating values are as follows:

**Table 8:** Results with Stove Oxygen Enrichment and temperature of 1038° C

| | Initial Operation | Base SOE Operation | 1038°C HBT Operation | Delta |
|---|---|---|---|---|
| BFG Rate (Nm$^3$/hr) | 88,168 | 97,523 | 100,629 | + 3,106 |
| NG (Nm$^3$/hr) | 821 | 0 | 0 | 0 |
| Comb Air Rate (Nm$^3$/hr) | 79,021 | 70,472 | 72,716 | + 2,244 |
| Oxygen Rate (Nm$^3$/hr) | 0 | 1,465 | 1,510 | +45 |
| CA Oxygen Composition (%) | 21.0 | 22.6 | 22.6 | 0 |

It can be seen that even after the combustion air rate is increased to allow the higher firing rate to achieve the 1038°C hot blast temperature that it is still below the initial combustion air rate which is the current limiting value. The economic evaluation, for a 4,500 TPD production rate, is as follows:

**Table 9**: Economic Results with Stove Oxygen Enrichment and temperature of 1038° C.

| | | Annual Cost/Benefit | |
|---|---|---|---|
| BFG (based on $2.5/ GJ) | | + $ 211,819 | (Cost) |
| Oxygen (based on $ 0.05/ Nm$^3$) | | + $ 19,710 | (Cost) |
| Coke Savings (based on $440/Te) | | - $ 3,613,500 | (Saving) |
| | Total | **- $3,381,971** | **(Saving)** |
| | | **- $ 2.06/THM** | |

The coke savings are based on 5kg/THM for a 28°C HBT increase. The higher hot blast temperature would produce a higher blast furnace tuyere raceway flame temperature which could allow additional fuel injection to be used. No benefit was taken for the additional tuyere injection potential although this is a definite opportunity for large additional savings. Likewise, the lower coke rate could allow the production to be increased if the furnace is charging limited or bosh gas flow limited. These very large production benefits wee also not included in this evaluation.

## 4 COMPARISON BETWEEN WASTE HEAT RECOVERY AND STOVE OXYGEN ENRICHMENT

Both systems lead to reduced operating costs but there are significant trade offs. A WHR system provides the lowest total energy solution as the recovered sensible heat reduces the external heat input requirements. It also reduces the total plant $CO_2$ emissions. However, the installation equipment is substantial resulting in a much higher upfront capital cost. The WHR system also requires much more maintenance with respect to heat exchanger fouling.

The SOE system, similar to the WHR system, provides large economic benefits by reducing the enrichment gas requirements to reach the required dome temperature. However, since there is no recovery of sensible heat from the waste gases, the total external heat input will be higher than that for a WHR system. On the other hand, the SOE system is much simpler requiring much lower installation costs. In addition, there is no outage required to tie the SOE system in. Finally, the SOE system has very minimal maintenance issues.

## 5 LEVEL 2 AUTOMATION

Level 2 Control Systems have bee around for some time but recent enhancements have focused on providing a much more stable and safe operation. These systems have the capability to detect faulty measurements and make set point corrections to optimize the stove heating process. The new systems also focus on maximizing the hot blast temperature while minimizing energy usage and operating costs. Level 2 systems try to simulate and control the entire stove operation. This includes the following areas:

- Hydraulic System (controlling all stove changing, valve movement, etc.)
- The Combustion Air System including preheating
- The Stove Oxygen Enrichment System
- The Blast Furnace Gas System including preheating
- The entire Stove Firing Combustion Control including the blast furnace gas enrichment, dome temperature control, waste gas oxygen level control, etc.)
- The Blast Oxygen Enrichment System
- The Blast Steam Injection Control System

As this paper focuses on the stove energy efficiency, we will focus on the Stove firing Combustion control portion of the Level 2 Automation System. The overall aim is to maximize stove efficiency and minimize energy consumption while providing the desired hot blast temperature. Thermal models are used to determine the required heat input and flame temperature requirements. In particular, the models determine the minimum dome temperature required to develop the required hot blast temperature; this allows the amount of expensive enrichment gas to be minimized. The models also monitor the energy input and output trends to fine tune the stove operation to protect from over or under heating.

The modern Level 2 control system combines short term direct control and longer self-tuning control as illustrated below.

- Rapid control is used to correct the firing rate with respect to maintaining the proper stoichiometric ratios, heat input rates, dome temperature, stack temperature, waste gas oxygen, etc. This control also reduces the $CO_2$ emissions and maximizes stove efficiency.

- An intermediate feedback control system allows measurement errors to be determined which allows accurate firing corrections to be made
- Longer term trends are monitored to optimize the stove efficiency performance and corrections made when the overall heat storage is trending high or low.

The Self Learning Behavior allows the model to identify measurement errors and make corrections. It even allows the stoves to be controlled if an instrument is lost by incorporating and evaluating all the other pertinent stove operation information.

The stove firing and efficiency control systems are developed to not only optimize based on the lowest total energy usage but also the lowest operating cost by incorporating actual plant fuel pricing. This latter function generally allows enrichment gas usage to be minimized.

The system can also bring the operation back to the desired set points even as the heat duty driving factors (wind rate, hot blast temperature set point) are changed or the firing interrupted.

## 6 UPGRADES TO EXISTING CONTROL SYSTEMS

Stove energy efficiency can also be improved without implementing a new Level 2 Automation System by modifying existing control systems. Many current systems provide stove firing control routines to “automatically” control the blast furnace gas, enrichment gas and combustion air flow rates to meet heat input, dome temperature and enrichment gas set points. However, these set points often require significant operator input. This leaves the stove operation at the mercy of the operator’s experience and know how to monitor and adjust these key set points. It also often leads to erratic operating concepts from operator to operator resulting in unstable operations, higher energy consumption and a higher cost overall operation. In particular, it has been found often that opportunities to garner large savings by reducing dome temperature and enrichment gas usage are missed when the stove is operating below its maximum design point.

Relatively simple modifications to existing control systems can be made to improve this situation. For one facility, the control system is being modified to assist the operators to develop the heat input, dome temperature and enrichment gas set points to take the operator discretion out of the picture. This will allow them to develop a consistent, steady operation while minimizing enrichment gas usage. At this particular site, it will also allow them to make large enrichment gas savings because the current wind rate and hot blast temperatures are significantly below the stove design capability which will allow significantly lower dome temperature operation.

With the modified control system, which is basically a spreadsheet based on stove modeling results that is added to the control screen, the operator inputs the basic requirements such as the hot blast temperature, wind rate, blast furnace gas heating value and cold blast temperature. The spreadsheet then calculates all the firing set points for the operator to utilize.

The spreadsheet allows the operator to choose from two operating philosophies:

- Philosophy 1 where the stove heat storage is maximized (maximum dome and stack temperatures) to fully heat the stove. This option provides the longest blast cycles. When the stove heat input demand decreases (lower wind rate and/or hot blast temperature), the blast cycles can be extended.
- Philosophy 2 where a minimum blast cycle time is set and the heat input adjusted to meet the operating demands. This concept always maximizes the

final stack temperature but utilizes the lowest dome temperature that will meet the hot blast temperature requirements. This option always produces the lowest enrichment gas usage. When the stove heat input demand decreases, the dome temperature and enrichment gas is reduced while maintaining the short blast cycle.

No matter which philosophy is selected, the spreadsheet model always compares the enrichment gas rate and the overall total fuel cost for both philosophies to point the operator to the lowest cost option.

The spreadsheet model also provides a correction function that allows the operator to easily make timely set point corrections when actual measurements are known to be incorrect.

The operator picks the operating philosophy, the required performance (wind rate, hot blast temperature, etc), and the plant fuel costs. The spreadsheet model then provides the key set points. These set points can then be entered into the base control system.

The model also calculates the annual fuel cost for both philosophies. In this case it shows that Philosophy 2 will have a $1,700,000 lower annual operating cost than Philosophy 1. This information provides a strong incentive to the operator to select the lower cost operation scheme.

Finally, when there are measurement errors, it can be difficult for the operator to determine the magnitude of the error and then make calculations to adjust his set point selection. If the operator inputs the actual measured values, the spreadsheet can compare it to the expected value in a steady state operation and develops a correction factor. The spreadsheet model then provides a “correction” set point to allow the operator to input an actual set point to get the theoretical value the model recommends.

The spreadsheet model also produces some charts showing the required operating values for the two philosophies

The screen will show in simple graphical form the difference between the two philosophies for the current operation range. It also provides the operator with a sense of the process variable change required when a process step change, e.g. a move to a different hot blast temperature, is being planned. The main driving force for these figures are to show the operator the lowest cost operation and encourage him into operating in that fashion.

## 7 OPTIMIZE STOVE REPAIRS AND REBUILDS

In addition to optimizing operation of existing stoves, another very important item is to get the best return on any repair or replacement. Alternatives with relatively small differences in upfront capital costs can have tremendous long term differences in operating performance, energy consumption, blast furnace coke rate and other impacts and $CO_2$ emissions. In one recent effort, a client was looking at a situation where one stove needed to be rebuilt and the other three stoves needed significant repairs but it was believed that full rebuilds were not needed. It was hoped that full rebuilds on the three remaining stoves could be delayed for 8, 10 and 13 years. From an upfront capital consideration only, this was a much lower cost option than performing four complete rebuilds at the current time. However, knowing that the hot blast temperature could be increased with a complete stove rebuild using higher efficiency checker design, it was decided to do an evaluation that included not only the capital cost but the impact on the blast furnace coke rate and overall economics.

As shown below, the blast furnace process benefits of all the options were developed. Likewise, the capital cost estimates for each option was developed.

**Table 10**:.Cost Saving for situation 1, 2, 3 and 4

| Option | Description | Hot Blast Temp. ℃ | Coke Savings (kg/THM) | Coke Savings ($/yr) |
|---|---|---|---|---|
| **Base Case** | 1 New Stove, 3 Repaired | 1066 | N/A | N/A |
| **1** | 2 New, 2 Stoves Repaired | 1093 | 5.0 | 2,463,750 |
| **2** | 3 New, 1 Stove Repaired | 1121 | 10.0 | 4,927,500 |
| **3** | 3 New Only | 1093 | 5.0 | 2,463,750 |
| **4** | 4 New Only | 1150 | 15.0 | 7,391,250 |

**Table 11**: Capital cost for repair

| **No.1 Stove** | **Repair** | **Rebuild** |
|---|---|---|
| Shell & Installation | N/A | 7,086,368 |
| Refractories | N/A | 3,742,560 |
| **Total** | **N/A** | **10,828,928** |
| **No.2 Stove** | | |
| Shell & Installation | 2,772,898 | 7,086,368 |
| Refractories | 1,778,933 | 3,742,560 |
| **Total** | **4,551,831** | **10,828,928** |
| **No.3 Stove** | | |
| Shell & Installation | 2,671,654 | 7,086,368 |
| Refractories | 1,778,933 | 3,742,560 |
| **Total** | **4,450,587** | **10,828,928** |
| **No.4 Stove** | | |
| Shell & Installation | 1,473,219 | 7,086,368 |
| Refractories | 299,108 | 3,742,560 |
| **Total** | **1,772,327** | **10,828,928** |

Using the capital and process impacts, a time value of money evaluation was done. The results are summarized below.

**Table 12** Cash Expenditures

| | | **5 Years** | **10 Years** | **15 Years** | **20 Years** |
|---|---|---|---|---|---|
| Base Case | 1 New Stove, 3 Repaired | 21,603,673 | 52,453,267 | 69,790,730 | 69,790,730 |
| 1 | 2 New, 2 Stoves Repaired | 13,063,086 | 12,856,963 | 10,441,358 | -13,591,269 |
| 2 | 3 New, 1 Stove Repaired | 7,570,182 | -24,900,982 | -47,069,654 | -95,134,909 |
| 3 | 3 New Only | 19,142,319 | 2,906,738 | -16,846,330 | -40,878,957 |
| 4 | 4 New Only | 3,282,318 | -45,424,427 | -104,683,630 | -176,781,511 |

**Table 13**: Present Value based on 8% Rate of Return

| | | **5 Years** | **10 Years** | **15 Years** | **20 Years** |
|---|---|---|---|---|---|
| Base Case | 1 New Stove, 3 Repaired | 21,603,673 | 30,035,272 | 43,410,221 | 43,410,221 |
| 1 | 2 New, 2 Stoves Repaired | 15,815,491 | 14,469,651 | 13,582,265 | 7,568,808 |
| 2 | 3 New, 1 Stove Repaired | 13,074,990 | -4,466,171 | -12,615,892 | -24,642,806 |
| 3 | 3 New Only | 21,894,724 | 13,124,143 | 5,861,808 | -151,649 |
| 4 | 4 New Only | 11,539,531 | -14,772,212 | -36,559,217 | -54,599,587 |

The evaluation showed that the total cash flow (cash expenditures) was significantly much better when the stoves were rebuilt due to the higher hot blast temperatures and resulting lower coke rates. Likewise, the net present value on the capital expenditures for this alternative is much better. The large cost savings were gathered early in the time period and continued through the entire period. This alternative also has a business continuity benefit in that the long term operation will be based on new rebuilt stoves. This effort matches that seen in several other evaluations and highlights the importance of looking at the total capital and operating costs when making a stove rebuild study rather than looking at capital costs only.

## 8 DEVELOPMENT OF FLAMELESS STOVE TECHNOLOGY

Siemens VAI has begun development work with Linde to develop a new concept in stove operation. The concept grew out of the growing trend of utilizing Oxy-Fuel combustion in the steel plant to utilize stack gas recycling and high velocity lancing to reduce fuel consumption and $CO_2$ generation. In the Flameless Stove application, pure oxygen is used for combustion. A portion of the stack gas is recycled to the combustion chamber. This recycle gas tempers the flame temperature and also brings sensible heat back to the combustion process. The net impact is a reduction in the amount of enrichment gas required to meet flame temperature requirements. This recycle gas also decreases the nitrogen content significantly with a corresponding increase in $CO_2$ which makes carbon capture much more feasible. The actual stove operation and performance is kept the same with the combustion gas flame temperature and flow rate / heat input matching the base operation. The stove heat transfer is actually improved because the higher $CO_2$ concentration gas has a higher radiative heat transfer coefficient. This is a key environmental advantage as the blast furnace stoves produce 20-25% of the total plant $CO_2$ emissions to the atmosphere. The following table illustrates the impact of $CO_2$ concentration on the radiative and overall heat transfer coefficient.

**Table 14**: Radiative and overall heat transfer coefficient impact with $CO_2$ concentration

| Stove Gas Temperature (℃) | 1371 | 1316 | 1260 |
|---|---|---|---|
| Base $CO_2$ Concentration = 36% | | | |
| $h_{convetive}$ (W/mK) | 0.474 | 0.477 | 0.480 |
| $h_{radiative}$ (W/mK) | 0.067 | 0.062 | 0.058 |
| $h_{total}$ (W/mK) | 0.541 | 0.539 | 0.538 |
| Base $CO_2$ Concentration = 56% | | | |
| $h_{convetive}$ (W/mK) | 0.525 | 0.532 | 0.538 |
| $h_{radiative}$ (W/mK) | 0.084 | 0.080 | 0.074 |
| $h_{total}$ (W/mK) | 0.609 | 0.612 | 0.612 |
| **Improvement** | **12.6%** | **13.4%** | **13.7%** |

It can be seen that the higher $CO_2$ flue gas in the Flameless Stove concept leads to a higher heat transfer coefficient. This higher heat transfer coefficient allows for increased heat storage in the upper sections of the checkers which leads to a higher hot blast temperature for a given dome and stack temperature as well as a higher overall stove thermal efficiency.

The net impact on a sample US blast furnace operation is shown below. These results are based on US economic factors but the principles can be extrapolated to any operation.

**Table 15**: BF operation with flameless stove technology

| | | Base Natural Gas Enrichment | Base Waste Heat Recovery | Flameless Stove Technology |
|---|---|---|---|---|
| **Firing** | | | | |
| BFG | $Nm^3/hr$ | 83,673 | 97,109 | 126,049 |
| BFG Temp. | ℃ | 38 | 188 | 222 |
| Natural Gas | $Nm^3/hr$ | 4,908 | 2,723 | 550 |
| Combustion Air | $Nm^3/hr$ | 116,060 | 105,160 | 0 |
| Oxygen | $Nm^3/hr$ | 0 | 0 | 19,649 |
| **Recycle Gas** | | | | |
| Flow | $Nm^3/hr$ | 0 | 0 | 49,596 |
| Preheat Temp. | ℃ | N/A | N/A | 191 |
| **Stove Flue Gas** | | | | |
| Flow | $Nm^3/hr$ | 194,097 | 192,251 | 173,050 |
| $CO_2$ | % | 31.27 | 35.54 | 66.62 |
| $N_2$ | % | 56.61 | 53.42 | 24.13 |
| $H_2$ | % | 11.12 | 10.04 | 8.25 |
| **Stack Gas to Atmosphere** | | | | |
| Flow | $Nm^3/hr$ | 194,097 | 192,251 | 123,454 |
| **Stove Operating Parameters** | | | | |
| Hot Blast Temp. | ℃ | 1,253 | 1,256 | 1,267 |
| Dome Temp. | ℃ | 1,385 | 1,393 | 1,392 |
| Final Stack Temp. | ℃ | 398 | 399 | 401 |
| Stove Efficiency | % | 78.78 | 85.31 | 83.26 |

The Flameless Stove Technology was compared to a base operation and that same operation utilizing stack gas heat recovery. It can be seen that the Flameless Stove Technology option has the lowest natural gas enrichment requirement (nearly 90% which is much greater than the 55% reduction obtainable with a waste heat recovery system). In addition, the higher heat transfer coefficient with the $CO_2$ enriched stove flue gas produces a slightly higher hot blast temperature which provides additional blast furnace coke rate savings.

The economic impact for this example is shown below. It can be seen that the Flameless Stove technology concept can lead to significant reductions in the gas enrichment. These savings are much larger than the cost of the oxygen used in the process.

**Table 16**: Economic impact of BF operation with flameless stove technology

| | Annual Cost (US$) | | |
|---|---|---|---|
| | Base Natural Gas Enrichment | Base Waste Heat Recovery | Flameless Stove Technology |
| BFG (1) | 9,703,428 | 11,261,575 | 14,617,655 |
| Natural Gas (1) | 34,137,425 | 18,937,876 | 3,827,869 |
| Oxygen (2) | 0 | 0 | 11,933,885 |
| Coke Savings (3) | 0 | -867,240 | -4,047,120 |
| Total | 43,840,853 | 29,332,211 | 26,332,289 |
| Delta | N/A | -14,508,642 | -17,508,564 |

*Notes: 1 – BFG 3055 KJ/*$Nm^3$*, value $2.50/GJ; 2 – NG 38,175 KJ/*$Nm^3$*, cost $12.00/GJ; 3 – Oxygen cost $0.04/*$Nm^3$*; 4 – 0.2kg/THM coke savings per ℃, 12,000 TPD pro duction, and coke cost $330/Te*

It must be noted that actual benefits for any particular stove operation will depend on the specific process conditions and the site specific economics. 0There is another significant aspect from a $CO_2$ / greenhouse gas perspective. One major alternative being developed to reduce blast furnace $CO_2$ emissions, with the blast furnace being by far the largest steel plant $CO_2$ emitter, is to use processes to recycle the BF top gas through the blast furnace in an Oxy-Fuel concept. This type of a process has a very complicated flow sheet which needs very complex control strategies. In addition, it greatly adds to the blast furnace operating cost. In contrast, the Flameless Stove Technology requires a much simpler process modification to the stove only, will have a much lower capital cost and need a much simpler control strategy. In this case the blast furnace operating cost is reduced and the savings can be used to fund any subsequent $CO_2$ capture operation. Form an operational risk standpoint, any upset in the Flameless Stove operation can be handled by a quick return to “normal” stove operation compared to a serious blast furnace impact with other alternatives.

## 9 CONCLUSION

Much can be done currently to optimize stove performance with respect to stove performance, energy consumption, emissions and the overall blast furnace economic and environmental performance. Much of this benefit can be achieved by maximizing the performance of the existing stoves without erecting new stoves. There are various economic benefits, capital implications and operating practice trade offs for each of the items discussed in this paper. The potential benefits are also dependent on the operation, stove capabilities, plant energy balances and other economic impacts. A thorough study of these options, including stove modelling, is required to determine the optimum solution for each location.