Energy Technology 2011:
Carbon Dioxide and Other Greenhouse Gas Reduction Metallurgy and Waste Heat Recovery
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Energy Technology 2011: Carbon Dioxide and Other Greenhouse Gas Reduction Metallurgy and Waste Heat Recovery

Proceedings of a symposium sponsored by the Energy Committee of the Extraction and Processing Division and the Light Metals Division of TMS (The Minerals, Metals & Materials Society)

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Edited by
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Foreword

This year marks the fourth session of symposiums organized by the Energy Committee, which was initiated in 2007 – 2008. During the first two years, the symposium on minimizing carbon dioxide emissions by chemical reduction of oxides or physical minimization by other methods was called CO2 Reduction Metallurgy. Starting in 2010, symposium shown in these Proceedings is titled Carbon Dioxide & Other Greenhouse Gas Reduction Metallurgy. The revised title fits the efforts going on in addressing the global warming issue from all greenhouse gases including carbon dioxide, water vapor, and other multi-element [more than two] gases which take part in the reflective radiation of heat from the atmosphere and recent developments in waste heat recovery technologies.

Greenhouse gases are produced in a variety of processes and industries, and two of the most significant are electricity production from the burning of fossil fuels such as coal, oil, and natural gas and from extraction of metals that produce greenhouse gases during the reduction process or use energy derived from fossil fuels. In the first session, Electrochemical Reduction Methods – CO2 Use and Other Metal Production, a number of papers will discuss techniques for reducing captured CO2 by producing synthetic fuels and other non greenhouse gas by-products. Besides discussing captured CO2 reduction, several papers will discuss metallurgical processes and advancements that reduce the generation of greenhouse gases. These areas of research could have profound impact on treatment of anthropogenic generated greenhouse gases, particularly in areas such as fossil-fuel based production of electricity and in the iron and aluminum reduction processes.

In the second session, CO2 and Greenhouse Gas (GHG) Reduction In Metal Industries, a wide variety of reduction techniques in metallurgical processes are presented. This includes papers on CO2 and GHG reduction challenges in the Chinese steel and Indian aluminum industries, the use of steelmaking slag and bauxite residue for capturing CO2 and GHG, and the alkali roasting of complex oxides and ilmenites for producing high purity chemicals, rutile, and rare-earth oxides. All of these papers contribute to a growing area of research of reducing CO2 production in metals technologies through a combination of incremental or in some cases, transformative technologies.

While there is extensive coverage in the media on alternative fuels such as biofuels, solar energy, and wind energy; waste heat recovery is just beginning to be discussed by the public. The use of waste heat in the metals, minerals, and materials industry is often more cost effective than projects such as solar or wind without any hidden cost due to the use of rare earths. Waste heat recovery also does not add additional greenhouse gases such as from biofuels. The potential is high within our industry. Waste heat in the form of hot gases, liquids, and solids are estimated to be 20 to 50% of the energy input into the industry.
This is the first year for the Waste Heat Recovery symposium. We see great potential in this area. The papers included in this proceedings discuss the potential sources and use of waste heat in our industry. Both high temperature and low temperature heat recovery is covered. The technology in this field is progressing rapidly from the increasing use of older technologies such as combustion air pre-heating to the newest work in endothermic heat, Organic Rankine Cycle turbines, and thermoelectric generator design. This will be an exciting field to follow.

We acknowledge the effort by the rest of the non-editor - co-organizers - Maria Salazar Villalpando, Malti Goel, Rachel DeLucas, and Xingbo Liu, in collecting papers and presentations for the three sessions of the Energy Technology 2011.

This proceeding title delineates only the 3 sessions run by the energy committee of LMD & EPD and does not include other Energy Related symposiums during the San Diego Annual Meeting TMS – from other divisions – such as Nuclear Energy symposiums, Clean Coal, Hydrogen Based Technologies, Fuel Cells and Materials for Energy Storage, Non-Carbon Materials in Aluminum Production or Sustainable Technologies – each one of which is part of the term Energy Technology.

Since the Energy issue of the Journal of Metals was scheduled earlier than the Annual Meeting, we decided to move three of the papers to the Journal of Metals, Energy Issue, January 2011. However, these 3 papers will be presented during the Annual Meeting. [a] "Concentrated Solar Power for Producing Liquid Fuels from CO2 and H2O" by Peter G. Loutzenhiser, Anastasia Stamatiou, Daniel Gstoehl, Anton Meier, and Aldo Steinfeld, [b] "CO2 Electrochemical Reduction by Specifically Adsorbed Anions", by Korato Ogura, and Maria D. Salazar-Villalpando and [c] "The Alkali Roasting of Complex Oxide Minerals for High Purity Chemicals – Beyond Le Chatelier into 21st Century" by Animesh Jha. We wish to acknowledge the efforts by Lifeng Zhang, Energy Committee’s JOM advisor in obtaining 3 additional papers for the January 2011 JOM – in subjects on solar silicon recycling and green magnesium – both subjects are part of the efforts in reducing climate change emissions.

Editors:
Neale R. Neelameggham, Ramana Reddy, James Yurko, Cindy Belt, & Mark Jolly
Neale R. Neelameggham is the Technical Development Scientist for US Magnesium LLC. He has 38 years of expertise in magnesium production technology, having been with the plant from its startup company NL magnesium. Dr. Neelameggham’s expertise includes all aspects of the magnesium process, from solar ponds through the cast house including solvent extraction, spray drying, molten salt chlorination, electrolytic cell and furnace designs, lithium ion battery chemicals and by-product chemical processing. In addition, he has an in-depth and detailed knowledge of alloy development as well as all competing technologies of magnesium production, both electrolytic and thermal processes worldwide. Dr. Neelameggham holds 13 patents and has several technical papers to his credit. As a member of TMS, AIChE, and a former member of American Ceramics Society he is well versed in energy engineering, bio-fuels, rare-earth minerals and metal processing and related processes. Dr. Neelameggham has served in the Magnesium Committee of LMD since its inception in 2000, chaired it in 2005, and has been a co-organizer of the Magnesium Symposium since 2004. In 2007 he was made a Permanent Co-organizer for the Magnesium Symposium. He has been a member of the Reactive Metals Committee, Recycling Committee and Programming Committee Representative of LMD. In 2008, LMD and EPD created the Energy Committee following the symposium on CO2 Reduction Metallurgy Symposium initiated by him. Dr. Neelameggham was selected as the inaugural Chair for the Energy Committee with a two-year term. He is also a member of LMD council. Dr. Neelameggham holds a doctorate in extractive metallurgy from the University of Utah.
Cynthia K. Belt previously worked at Superior Industries International and Aleris International in managing their energy programs and is currently consulting within the energy management field. She has published 10 papers in the area of energy management in the metals industry and has co-edited several proceedings in energy and recycling.

Cindy is Chair of the Energy Committee within TMS, member of the TMS/ITP Energy Materials Technical Working Group, a member of the energy committee in AFS, and a member on the Process Heating System Assessment Standard Committee for ASME. Cindy earned her Bachelor of Science, Mechanical Engineering degree from Ohio Northern University with additional graduate work in materials at Case Western Reserve University and Akron University.

Dr. Mark Jolly (PhD, BMet, CEng, CEnv, FIM-MM, FICME), is a Senior Lecturer and Director of Industrial Liaison in the School of Mechanical Engineering at the University of Birmingham, UK. He has run the Castings Centre at the University since 1995. He runs the Process Modelling Group within the school and has been Principal Investigator on more than 15 funded programmes in the last ten years valued at over £5M. He was awarded the University of Birmingham Josiah Mason Award for Business Advancement in 2010 and the Institute of Cast Metals Engineers' Oliver Stubbs award in 2008.

Mark is on the Solidification Committee of TMS and a key reader for Met&Mat Trans B and a previous chair of the board of key readers. He also sits on a number of committees for the UKs Institute of Materials, Minerals and Mining namely, Sustainable Development Committee (Vice Chair), Light Metals Board and Materials Science and Technology Division. He is also on the Institute of Cast Metals Engineers Membership Committee and Education and Training Committee.

Mark graduated from the University of Sheffield in 1978 with a Bachelor of Metallurgy and continued his studies at Cambridge University to obtain a PhD in 1982. He then started worked in industry for 15 years for a number of companies in the UK and abroad before moving back into academia in 1995. He has over 280 publications including 4 in energy. These include: 2 Patents, 2 book chapters, editor of 2 conference proceedings, over 50 invited seminars & lectures and over 100 technical reports for industry.
Dr. Ramana G. Reddy is an ACIPCO Endowed Chair Professor of Metallurgical and Materials Engineering. He served as the Head of the Department of Metallurgical and Materials Engineering and Associate Director of Center for Green Manufacturing at The University of Alabama, Tuscaloosa, Alabama, USA. Professor Reddy has over 29 years of teaching and research experience in the field of chemical and materials engineering, particular in the areas of thermodynamics, materials synthesis, energy materials, fuel cells, ionic liquids and renewable energy. He has published over 336 papers and 23 books, including an undergraduate textbook on thermodynamics. He has also delivered more than 210 invited lectures and research presentations in 25 nations. Dr. Reddy advised and mentored over 52 graduate students. He has received several awards such as the Service Award and the Best Research Paper Award from EPD-TMS. He is the recipient of the TMS Extraction & Processing Distinguished Lecture Award, and the Milton E. Wordsworth Award for Extractive Metallurgy of SME. Dr. Reddy is a Distinguished Member (Fellow) of SME and a Fellow of ASM International.

James A. Yurko is the Process Development Manager of 22Ti LLC, an Elkem Metals subsidiary formed in 2007 to commercialize a titanium extraction process that utilizes molten oxide electrolysis (MOE) technology developed at MIT. Prior to joining 22Ti, he co-founded Electrolytic Research Corporation (ERC) LLC with Prof. Don Sadoway to pursue commercial applications of MOE. In addition, Jim is a Research Affiliate in MIT's Department of Materials Science and Engineering. Before working with 22Ti and ERC, Jim was the R&D team leader and staff metallurgist of BuhlerPrince, Inc. where he was responsible for commercializing the Semi-Solid Rheocasting (SSR) process and various die casting development projects of aluminum, magnesium, and bulk-metallic glass alloys.

Dr. Yurko received a Ph.D. in metallurgy from the Massachusetts Institute of Technology as a National Science Foundation graduate fellow and a B.S.E. in materials science and engineering from the University of Michigan. His graduate research focused on the rheology of semi-solid aluminum alloys under industrially relevant conditions and was a co-inventor of the SSR process. He is currently a member of TMS and ASM, and Jim serves on the University of Michigan Materials Science and Engineering External Advisory Board. In 2010, Dr. Yurko was selected as the TMS EPD Young Leader Professional Development Award winner, given annually to two EPD members under the age of 35.
Energy Technology 2011:
Carbon Dioxide and Other Greenhouse Gas Reduction Metallurgy and Waste Heat Recovery

Waste Heat Recovery

Organizers:
Cynthia K. Belt
Mark Jolly
Xingbo Liu
Rachel DeLucas
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Energy Technology 2011: Carbon Dioxide and Other Greenhouse Gas Reduction Metallurgy and Waste Heat Recovery

Session I

Session Chairs:
Rachel DeLucas
Xingbo Liu
WASTE HEAT UTILIZATION
TO INCREASE ENERGY EFFICIENCY IN THE METALS INDUSTRY

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Keywords: metallurgical, waste heat, heat recovery, boiler, Rankine Cycle, ORC

Abstract

Energy efficiency improvements achieved using heat recovery processes offer benefits to both the business case and environmental impact of metallurgical facilities. Global demand drives the development of lower and lower grade ore bodies. This trend results in higher energy intensity and consequently increased waste heat. Waste heat boilers and Organic Rankine Cycle (ORC) processes are becoming cost competitive methods of utilizing this waste heat.

This study analyzes heat recovery from available sources to produce power using,
- High grade: waste heat boiler and steam turbine generator. This system will produce electricity, and/or process steam.
- Low grade: ORC to produce electricity. The cycle is well adapted to low- moderate temperature heat sources.

Processes used in metallurgical plants, such as hot exhaust streams, cooling and condensers could benefit from application of these systems.

The study demonstrates:
- The energy and cost saving potential of waste heat recovery technologies,
- The environmental benefit.

Introduction

In recent decades, process intensification has resulted in increased productivity from unit operations such as kilns, fluidized bed reactors and smelting furnaces and decreased unit operating costs. In the coming decades, the industry’s challenge will be to continue this trend while at the same time decreasing the consumption of fossil fuels and further reducing the environmental impact of its processes.

The U.S. Department of Energy reports that available waste heat sources in industry, which is approximately seven quadrillion BTU (~7,400 PJ/y), exceeds the current production of all renewable power sources combined. In Canada there are about 2,300 PJ/y of available waste heat, with the pulp and paper, metallurgy, chemical/petrochemical and oil refining industries the main players. Natural Resources Canada (NRCan) has estimated that about 25% of that heat could be recoverable using existing technologies, which in turn, represents a reduction of 27 Mt/y of Green House Gas (GHG) emissions, plus considerable water savings due to lower water cooling requirements and less fossil fuel consumption.

The metal and mining industry is adopting sustainable development practices. One cost effective way to achieve this is by using the waste energy that exists in their current processes. Smelting
furnace, coke ovens, ore/calcine pre-heaters, dryers and kilns are all common equipment where large amounts of heat are wasted in the form of exhaust or flue gases to the atmosphere or through cooling systems using either air and/or water.

Recovery of waste heat provides both financial and environmental benefits to process plant operators. The energy that is recovered from these waste heat streams could displace part or all of the energy input needs for a unit operation within a plant and offer a great opportunity to reduce fuel and energy expenses and greenhouse gas emissions. In summary, waste heat recovery improves the energy efficiency of the heating equipment, lowers operating costs and lowers carbon footprint by reducing fossil fuel utilization leading to higher productivity.

Hatch is engaged in innovative techniques for energy recovery that improve overall energy management in the everyday operations of a plant. We systematically identify and quantify waste heat sources, and provide solutions to integrate recovered energy back into the process facility for heat, mechanical work and power generation.

Results include:
- Increased energy efficiency with improved patterns of consumption and reduced energy intensity in industrial processes drawing on secondary sources of heat,
- Replaced and/or reduced the use of other energy sources consequently lowering operational costs,
- Reduced environmental impact and improved sustainable practices.

**Potential Heat Recovery Opportunities**

Depending upon the type of process, waste heat can be rejected at virtually any temperature. There are significant opportunities to recover and utilize some of this waste heat as follows:

1. as part of a process integration scheme, such as preheat incoming primary process streams or secondary streams to recover sensible heat, e.g. pre-heating combustion air, drying of materials, etc.
2. for heat and/or mechanical power production, or
3. for electrical power production.

Quality of heat is one of the key elements to consider when analyzing the potential of the waste heat sources to be used in a heat recovery system. High grade heat refers to the heat source of 600°C and over. Medium grade heat refers to the heat source of 200°C to 600°C. Low grade heat has the temperature range of below 200°C. Generally, the higher the temperature, the greater the potential value for heat recovery.

This study analyzes heat recovery from available sources in different metallurgical processes to produce electrical power as follows:

- **High to medium grade heat**: Using a waste heat boiler and steam turbine system,

For high and medium quality heat sources, the use of a waste heat boiler to recover the waste heat is analyzed. This is generally followed by further gas treatment prior to releasing of flue gas to the atmosphere via stack. High and medium heat sources could be used to produce steam to be used in a steam turbine to produce electricity.

- **Medium to Low grade heat**: Using an Organic Rankine Cycle system.
In the case of low grade heat sources, an Organic Rankine Cycle (ORC) can be used to produce electricity. ORC has been increasingly employed over the last 20 years to produce power from various heat sources such as geothermal and compressor stations. The cycle is well adapted to low and moderate temperature heat sources such as waste heat from exhaust streams, cooling and condensers. An organic fluid, instead of water, is used as a working fluid. At the lower temperature range the organic fluid with its low specific heat of vaporization has advantages over the steam.

Technical Comparison

For some applications, gas composition could be an issue for direct gas recycling. In the metallurgical industry, waste gas streams can have a high dust load and/or has high temperature that can cause abrasion and thermal stresses. Moisture and SO$_2$/SO$_3$ in the hot waste gas stream may condense in the system, causing corrosion or plugging. In these cases, special materials of construction and design techniques may be required to ensure high system availability.

There is various commercially available equipment that can effectively be used to recover heat from waste heat sources depending on the process, flow rate, chemical and mechanical compositions of the stream and heat quality.

Waste heat boiler and steam turbine generator

Waste heat boilers (WHB) are used in many metallurgical facilities to cool off-gases and generate steam. Boiler arrangements can include horizontal or vertical radiation and convection sections, depending on the specific gas characteristics, layout constraints and required outlet temperatures.

The steam produced by the WHB can be used to produce electricity via a steam turbine generator. This system follows the Rankine Cycle principles and it is used for high and medium temperature applications where the working conditions of the operating fluid offer the greatest advantage to the process.

The Rankine Cycle based on steam usually becomes inefficient for electrical power generation using low grade heat input, usually below 350°C. At these conditions, the steam produced is at low pressures, which is more often used for mechanical drives.

Organic Rankine Cycle (ORC)

Since conventional steam power cycles do not yield cost effective performance to generate power from the recovery of low grade waste heat, the Organic Rankine cycle (ORC) is more often considered.

Organic Rankine Cycle has the same fundamental principle as the conventional Rankine cycle, using heat to convert it into power. However, the substantial difference between the two (2) processes is that ORC uses an organic working fluid as the operating medium such as ammonia, hydrocarbons such as iso-pentane, iso-octane, toluene or silicon oil, etc; instead of water.

The ORC is a closed cycle process of organic fluid connected to a heat exchanger, which acts as a boiler, to recover heat from the available heat sources. ORC has high operational availability, good partial load behavior, quiet operation, allows for unmanned operation with minimum maintenance. ORC is a technologically interesting solution for decentralized applications. It has
demonstrated advantages since it provides low environmental impact, low footprint, low operating and maintenance cost, is suitable for remote operation and low heat grade sources.

The organic fluid allows efficient use of the heat on the available stream sources with temperatures and pressures much closer to conventional heating and refrigeration appliances, (e.g. warm water over 90°C and saturated water steam with low/medium pressure), to produce electricity with different outputs. This characteristic benefits the application of using unused low grade hot streams from waste heat sources in order to produce power.

Applications

Efficient use of all energy resources is becoming more important with regard to both societal and economical considerations. Waste heat sources are plentiful in industrial plants and are often not treated with enough respect as useful and recoverable energy.

When recovering thermal losses from equipment it is vital to ensure that the heat recovery does not impact the availability of the equipment. Even very small impacts in plant availability can negate all benefits of heat recovery. The systems should be designed with back-up systems to ensure that outages of the heat recovery system do not require stoppages to the core process equipment. In general, the design of heat recovery systems is significantly easier during the initial development of the plant rather than as retro-fits to the existing equipment.

During the analysis to implement any heat recovery strategy, there are three key elements to consider:

• Quality, quantity and availability of the heat source. These parameters will define the technology to use to recover the heat and use it as an useful energy source somewhere else in the process.

• Economic impact on the plant, taking into consideration, capital costs, operational costs, including maintenance, additional personnel that might be required as well as the impact on the existing plant.

• Environmental impact, which will take into consideration the footprint of the emissions that, might be avoided by displacing either fossil fuels and/or electricity by using the available heat source. For plants located in developing nations the Clean Development Mechanism (CDM) as part of the Kyoto Protocol might offer additional economic incentives before and during the lifetime of the project.

Heat Losses from Laterite Nickel Production

The smelting of nickel laterites consumes a significant amount of energy, primarily fossil fuel for drying and calcining, and electric power for melting and refining. Waste-gas heat losses are unavoidable in the operation of the nickel process heating equipment such as furnaces, kilns, and dryers. A laterite Nickel Electric Furnace is the main energy consumer and biggest waste heat producer in the process, see Table 1, which refers to a 58,000 tpa ferronickel application.
Different sources of waste heat in a Laterite Nickel process are presented herein.

From Laterite Nickel Process: Waste heat from tapped slag

From laterite nickel production, the majority of the process energy inputs accumulate in the hot slag tapped from the electric furnaces, which accounts for approximately 80% of the total sensible outputs from a furnace. The temperature of slag is approximately 1550 - 1650 °C when it exits the furnace.

In most operations, slag is either allowed to cool in large open slag pits or is granulated using water and the thermal energy of the slag is wasted. In the case of wet granulation, a very low grade heat is produced and has minimal potential for heat recovery and reuse. On the other hand, dry granulation of slag, which is less commonly practised, allows to recycle the slag which can be used as cement aggregate, has attracted considerable interest. Another benefit of dry granulation, which has received less interest to date, is its potential for slag heat recovery.

When the slag is granulated, FeO is oxidised to the more stable form, Fe₂O₃. The heat generated by this exothermic reaction will be added to the total latent heat of the slag and will be considered available for energy recovery. In order to capture the waste heat from slag, a slag handling system, such as a blast granulation, and a boiler is used to produce steam.

A commercial operation, shown in Figure 1, commissioned in 1981 and operated for about 10 years during the 1980's and early 90's by Fukuyama Steel Works in Japan, utilized blast granulation and a boiler to produce steam, shown in Figure 1. Although the operation was discontinued and dismantled following the return of low fuel prices in the late 80's, it achieved slag rates of up to 80 tonnes per hour. The total heat recovery at Fukuyama Steel Works was reported to be 80% of the total slag thermal energy.

### Table 1. Most relevant heat source in a Laterite Nickel Production.

<table>
<thead>
<tr>
<th>Heat Source</th>
<th>Temperature (°C)</th>
<th>Flow rate</th>
<th>Available Thermal Energy (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Slag</td>
<td>~1600</td>
<td>~140 t/h</td>
<td>98</td>
</tr>
<tr>
<td>Off Gas</td>
<td>~1000</td>
<td>45,000 Nm²/h</td>
<td>20</td>
</tr>
<tr>
<td>Equipment²</td>
<td>~&gt;200</td>
<td></td>
<td>6</td>
</tr>
</tbody>
</table>

Notes: *Temperature of the thermal oil proposed for cooling and heat recovery.
Recovery of the waste heat is considered to give its main advantages if done during dry granulation, which will avoid water usage, further drying of the product and energy recovery as power. A WHB is proposed to recover about 80% of the available heat and the steam produced can be used to produce power for the process using steam turbine generator. The potential power output is about 20MW (see Table 5).

From Laterite Nickel Process: Waste heat from Off Gas \(^1,3\)

In rotary dryers and kilns, air and fuel are mixed and burned to generate heat, and a portion of this heat is transferred to the heating device and its load. When the energy transfer reaches its practical limit, the spent combustion gases are exhausted from the equipment via an off-gas duct. At this point, the exhaust flue gases still holds considerable thermal energy, often more than the energy imparted to the process, up to 80% of the input energy.

Based on Hatch’s previous studies for the nickel laterite processes \(^7\), the general conditions of the off-gas from the processes are presented in Table 2.

<table>
<thead>
<tr>
<th>Systems</th>
<th>Electrical Energy Consumption (MW)</th>
<th>Gas Temperature (°C)</th>
<th>Off-Gas Flow rate (Nm³/h)</th>
<th>Off-Gas Thermal Energy (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Furnace Off Gas</td>
<td>80</td>
<td>1,000</td>
<td>45,000</td>
<td>20</td>
</tr>
<tr>
<td>Kiln Off Gas</td>
<td>95</td>
<td>&lt;250</td>
<td>250,000</td>
<td>23</td>
</tr>
<tr>
<td>Dryer Off Gas</td>
<td>45</td>
<td>&lt;150</td>
<td>50,000</td>
<td>12</td>
</tr>
</tbody>
</table>

Major considerations in the design of off-gas system from the furnace could be,
• Furnace off gas: handling of significant amounts of evolved carbon monoxide gas, there are about 20 MWth available in this stream. This heat could be recovered using a WHB and steam turbine generator to produce power (see Table 5).

• Kiln off gas: kiln off-gas generally has a high percentage of water vapour and some SO₂. This combination points to a low acid dew point and indicates that acid condensation will occur, when certain conditions are met. At the temperature below the acid dew point, acid can condense onto contacted ductwork and equipment, causing corrosion. Due to the lower temperature of this heat source, ORC should be considered to produce power.

From Laterite Nickel Process: Waste heat from equipment

Thermal heat losses can be significant from the major equipment in the processing plants. These losses can be generally grouped into the following categories:

• Losses from the external walls of refractory lined vessels
• Radiation losses from openings, hot exposed parts, etc
• Heat carried by the cold air infiltration into the furnace
• Heat carried by the excess air used in the burners

Typically, the most significant loss is through the refractory lined walls. Steps should always be taken to minimize the losses from radiation and the losses from excess air. Heat loss due to air infiltration can potentially be recovered in the off-gas if it cannot be prevented.

However, when recovering thermal losses from equipment, especially with the retro-fit situation, it is very important to ensure that the heat recovery does not impact the availability of the equipment or process.

Table 3. Typical equipment heat losses in a laterite Nickel process.

<table>
<thead>
<tr>
<th>Equipment</th>
<th>Electrical Energy Consumption (MW)</th>
<th>Heat Loss, Thermal Energy (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dryer</td>
<td>45</td>
<td>1.5</td>
</tr>
<tr>
<td>Kiln</td>
<td>95</td>
<td>6.5</td>
</tr>
<tr>
<td>Furnace</td>
<td>80</td>
<td>≥ 6.0</td>
</tr>
</tbody>
</table>

From Table 3, heat losses from the dryer and kiln feeding a typical 80 MW furnace can be 1.5 MW and 6.5 MW respectively. The thermal losses from these pieces of equipment occur in the form of natural convection and radiation through naturally cooled steel shells. Unfortunately the recovery of this energy is difficult due to its low grade quality and its diffusion over a large surface area. The equipment, with the current technology, is insulated as much as possible with low conductivity refractory to reduce these losses.

Heat losses from electric furnaces are generally, through the roof and sidewalls. This energy is a typically steady thermal source and is often captured as low grade heat in furnace cooling water and could be recovered at higher temperatures using a thermal oil heat exchanger. Hot thermal oil would then power an ORC to generate electricity at between 12 and 15% thermal efficiency.

Available heat captured from a furnace cooling system also presents a potential heat recovery case. While water is the most common cooling fluid, there are many precedents where thermal fluids have been used where ambient temperatures are very cold and therefore require special fluids to prevent freezing.
The flow of heat through the wall begins in the molten slag bath (1450 °C) where convective heat transfer between the bulk temperature of the bath and the frozen face of the refractory wall. Thermal energy is transmitted via conduction through the wall and into furnace cooling elements which are required to remove the intense process heat flux. Finally, the heat is transferred into the bulk cooling fluid; water or thermal fluid, through convection at the surface of the cooling passages.

If water is used, water would exit the system with a temperature of 50 – 60 °C. This heat will be lost in the cooling water tower. However, if thermal fluid, such as thermal oil, is used instead of water, the exiting bulk temperature of the thermal oil could be as high as 200 °C, which then could be used to generate electricity in ORC. This application could reduce the plant’s overall water requirement and water treatment while producing power from waste heat (See Table 6).

**Heat Losses from Aluminum Production**

Aluminum is produced from alumina by an electrolytic process that uses large quantities of electrical energy to separate aluminum from oxygen in the alumina.

Aluminum smelting from alumina is relatively intensive in electricity demand and much of the energy going into a smelter is lost as heat. In order to smelt alumina into aluminum, alumina is dissolved in a fluorine bath, and electrically reduced to aluminum using a carbon-based anode.

Sources of waste heat from aluminum production and related processes could be as follows:

- Off gas from smelter, low grade heat (<200 °C)
- Casting process, metal plate at 230 °C
- Off gas from anode baking process, low grade heat (<200 °C)
- Off Gas from Cast House, high grade heat (>1000°C)

The heat recovery considered in the case study is from the off gas from the Cast House. The energy content of the exhaust gas can be recovered in using a waste heat boiler to produce steam for a steam turbine generator (See Table 5).

**Gold Calcine Process**

Hatch performed a study of waste heat recovery from a gold roaster process. Roasting is used as a pre-treatment process to free the gold, and to convert base metals, such as zinc, iron, lead, and copper, to their respective oxides so that they can be easily removed into a slag during subsequent smelting process.

Each roaster at this process site generates between 17,000 and 20,000 m³/h of off gas at temperatures between 480 - 590°C. The gas is cooled through the scrubber system and reheated to approximately 340°C for NOx reduction before being exhausted to the atmosphere. In addition to heat within the roaster off-gas system, there is a considerable amount of energy contained in the roasted calcine, approximately 370 t/h at 550°C, which is currently quenched after discharge. These heat sources are summarized in Table 4 below.
Table 4. Most relevant heat sources in a Gold Roaster Process.

<table>
<thead>
<tr>
<th>Heat source</th>
<th>Temperature °C</th>
<th>Available Thermal Energy (MW)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Roaster off Gas</td>
<td>480</td>
<td>4.4</td>
</tr>
<tr>
<td>Stack Gases</td>
<td>360</td>
<td>5.2</td>
</tr>
<tr>
<td>Calcine Product</td>
<td>550</td>
<td>100</td>
</tr>
</tbody>
</table>

Even though the main sources of waste heat at a roaster area of a gold process operation are located in the roaster off-gas and stack gases, the biggest single heat source is the calcine product, which is about 50 MW thermal energy available per roaster. There are two (2) roasters in the case study implying a total of 100MW of heat usually wasted. Therefore, for the purpose of this study, only the heat available in the calcine product will be presented as a potential case to recover available heat and produce electricity.

The chemical composition of the heat source limits its potential heat recovery and allows for about 60% potential recovery leaving some heat in the off gas to prevent acid condensation. Based on the temperature and flow rate of the process, a fluid bed heat exchanger, similar to a WHB, is proposed to recover the heat and produce steam to drive a steam turbine generator, following the Rankine Cycle principles. The results in Table 5 show that about 19MW of electrical power could be produced by using the proper heat recovery strategy.

Platinum Group Metal (PGM) smelting

Platinum group metal (PGM) is a family of six grayish to silver-white metals with close chemical and physical affinities; platinum (Pt), iridium (Ir), and osmium (Os), palladium (Pd), rhodium (Rh) and ruthenium (Ru). The PGMs have very high melting points, and are chemically inert to a wide variety of substances (even at very high temperatures), and resist corrosion. They also have excellent catalytic properties. Operation processes for PGM consist of concentration (milling, flotation and drying), smelter operation and refineries, Base Metals Refinery (BMR) and Precious Metals Refinery (PMR).

Each processing step is designed to increase the grade (concentration) of the valuable components of the original ore, by reducing the bulk of the products. The mined ore undergoes comminution, and a gravity concentrate is extracted. The sulphides are concentrated by flotation. The flotation concentrates undergo smelting and converting, to produce a PGM-containing nickel-copper matte. The matte is treated hydrometallurgically to separate the base metals from the precious metals. Finally, the PGM concentrate is refined to separate the individual precious metals into their pure forms.

The main energy losses are heat in the cooling system, losses directly from the furnace and heat lost by the furnace off gas.

Even though, waste heat availability is likely variable on an hourly, daily and weekly basis, waste heat available from the cooling system of the converting process could be a candidate for waste heat recovery application.

Converting process is an exothermic process that produces a high temperature off-gas of approximately 1200 °C. This gas is currently cooled directly in a water-cooled uptake and then by evaporative spray cooling and quenching. High temperature and pressure cooling water (250 °C and 50 bars) from this cooling system is a result from the process and is generally flashed and quenched before drained.
This cooling water presents a good waste heat source, which could be recovered to produce electricity using an ORC system.

**Results**

The following results summarize the findings from various case studies completed by Hatch to different global clients. It should be noted that the purpose of the study was to present a comparison between current operating scenarios and potential to utilize the available heat sources to produce electricity only. It is recommended that each opportunity be analyzed on a case by case basis to determine which recovery strategy will be more suited for each plant, for their unique operational scenarios.

**Assumptions**

To provide a common basis for comparison the following are the assumptions used for the studies.

- Fossil fuel displaced is Natural Gas, in the case of any other fossil fuel utilized a proper analysis should be performed and the CO₂ emissions avoided will vary.
- Cost of electricity at $0.09/kWh,
- Recovery of available heat 70%, due to losses from equipment, transportation, limitations to remove heat from main process, etc. Any improvement in the recovery process will benefit the final output.
- Efficiency of each cycle was assumed at standard ranges: Rankine Cycle: 32%, Organic Rankine Cycle: 8%.

**Table 5: Potential results: Application of a Rankine Cycle to recover heat to produce electrical power.**

<table>
<thead>
<tr>
<th></th>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NICKEL (Laterite process)</td>
<td>58,000</td>
<td>Slag</td>
<td>1650</td>
<td>353</td>
<td>250</td>
<td>22</td>
<td>69,379</td>
<td>14</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Furnace Off Gas</td>
<td>1000</td>
<td>40</td>
<td>28</td>
<td>2</td>
<td>7,849</td>
<td>2</td>
</tr>
<tr>
<td>ALUMINIUM</td>
<td>1,000,000</td>
<td>Cast House</td>
<td>1000</td>
<td>28</td>
<td>20</td>
<td>9</td>
<td>32,918</td>
<td>6</td>
</tr>
<tr>
<td>GOLD</td>
<td>60</td>
<td>Calunor*</td>
<td>550</td>
<td>364</td>
<td>216</td>
<td>19</td>
<td>60,549</td>
<td>12</td>
</tr>
</tbody>
</table>

Notes: * Only 60% of the heat available could be effectively recovered due to chemical composition.