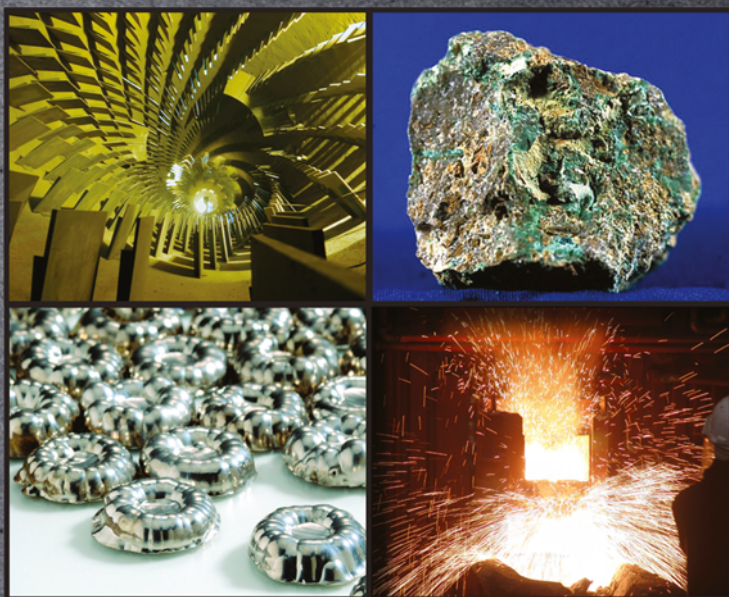


Ni-Co 2013



Edited by:

Thomas Battle

Michael Moats • Violina Cocalia • Harald Oosterhof

Shafiq Alam • Antoine Allanore • Rodney Jones

Nathan Stubina • Corby Anderson • Shijie Wang

Ni-Co 2013

TMS2013

142nd Annual Meeting & Exhibition



Ni-Co 2013

Proceedings of symposium sponsored by
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Metallurgy and Petroleum (CIM)

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Preface

The physical and extractive metallurgy of nickel and cobalt have been a focus of much activity in TMS over the years. For many years, indeed, a Cu-Ni-Co Committee existed in the Extraction and Processing Division, before their efforts were taken over by the Pyrometallurgy and Hydrometallurgy/Electrometallurgy Committees. These committees have conducted extensive programming in Ni-Co metallurgy, including physical metallurgy in cooperation with the High Temperature Alloys Committee and other committees in other divisions of the society. Many of the larger symposia in this area were organized in collaboration with our partners in The Metallurgy and Materials Society of the Canadian Institute of Mining, Metallurgy and Petroleum (MetSoc). TMS-led symposia included Extractive Metallurgy of Ni and Co in 1988, and the International Laterite Ni Symposium in 2004. MetSoc has organized successful symposia on Ni Co in 1997 and 2005.

Soon after the 2005 conference, the two societies decided to collaborate on future programming in this area. The contract we've signed guarantees a series of symposia in coming years, organized by both societies, with the two organizations alternating in the lead. The first of this new sequence was held by MetSoc as the keystone of their Conference of Metallurgists in 2009 in Sudbury, Ontario. The 2013 symposium in San Antonio is the first in the sequence with TMS as the lead organizer.

Following are presentations and papers representing all eight of the sessions organized in this symposium: a four-paper plenary session, one session on Ores and Processing, two sessions each on Pyrometallurgy and Hydrometallurgy, one on Electrometallurgy, and one on Applications and Recycling. We also have a short course on Ni-Co, and a number of exhibitors to support the success of this conference.

Special thanks are due to MetSoc for their assistance and advice, including three members of the organizing committee: Nathan Stubina, Shafiq Alam, and Ron Schonewille. In addition, there is a strong core of TMS organizers representing all aspects of Ni-Co metallurgy: Violina Cocalia, Corby Anderson, Mike Moats, Harald Oosterhof, Phil Mackey, Xingbo Liu, and Shijie Wang, with assistance from long-time members Norbert Piret and Ram Ramachandran. The affiliations of all organizers, as well as logos of the many co-sponsoring organizations, can be found elsewhere in this book's frontmatter.

I also wish to acknowledge the co-sponsoring organizations for this symposium: MEI (Minerals Engineering International), GDMB (German Society for Mining, Metallurgy, Resource and Environmental Technology), MMIJ (The Mining and Materials Processing Institute of Japan), SF2M (Societe Francaise de Metallurgie et de Materiaux), SME (Society for Mining, Metallurgy, and Exploration), SAIMM (Southern African Institute of Mining and Metallurgy), High Temperature Materials Committee of the Chinese Society for Metals (CSM), ALTA Metallurgical Services,

ABM (Brazilian Association for Metallurgy, Mining, and Materials), and the Cobalt Development Institute.

We hope you find this proceedings volume a useful review of previous work, summary of the state-of-the-art, and reference for the future.

Thomas Battle, lead organizer

Senior Metallurgist

Midrex Technologies

Pineville, North Carolina

Editors/Organizers

Thomas Battle is currently a Senior Metallurgist at Midrex Technologies in Pineville, North Carolina. He has undergraduate degrees in Materials Engineering and Astronomy from the University of Michigan, a Master's in Metallurgical Engineering from the Colorado School of Mines, and a Doctorate in Materials and Metallurgical Engineering from the University of Michigan. After a time as a Post-Doctoral Research Fellow in the Centre for Numerical Modelling and Process Analysis at Thames Polytechnic, he spent 18 years at various positions with the White Pigments and Mineral Products business at DuPont (now known as DuPont Titanium Technologies). He has spent the last four years as a senior metallurgist at Midrex Technologies, focusing on iron ore pelletizing technology and the direct reduction of iron.



Tom has been active with TMS for more than 20 years, holding a number of volunteer positions, both technical and administrative, mainly for the Extraction and Processing Division. This culminated in a three-year term as chair of the division, and a position on the society's Board of Directors. He is a founding member of the North American Extractive Metallurgy Council.

Michael Moats is an associate professor of Metallurgical Engineering within the Department of Materials Science and Engineering at the Missouri University of Science and Technology. He has published more than 60 papers on various hydro- and electro-metallurgical topics with a particular emphasis on industrial surveys of copper and zinc operations, copper electrowinning and electrorefining and gold leaching. He is a co-author of *The Extractive Metallurgy of Nickel, Cobalt and Platinum Group Metals*. He has been employed in industry, academia, and consulting.



Violina Cocalia holds a Ph.D. in Inorganic Chemistry from the University of Alabama. She has experience in coordination chemistry, solvent extraction, hydrometallurgy, and ionic liquids. She is currently leading the R&D Metal Extraction Products Group at Cytec Industries Inc.



Harald Oosterhof graduated as chemical engineer from the group of Prof. Van Swaaij at Twente University (The Netherlands) in 1994. In the same year, he assumed a position as researcher at Delft University of Technology (The Netherlands) where he worked in the Laboratory for Process Equipment that was headed by Prof. Van Rosmalen. The research that focussed on anti solvent crystallization of well-soluble salts was rewarded with two patents and a dozen publications.



After receiving his Ph.D. in Industrial Crystallization and Precipitation from Delft University in 1999, Harald started working at Umicore, a global materials technology group that is based in Belgium. During his first assignment as Project Leader Hydrometallurgy, he focussed on the refining of cobalt, nickel, and germanium.

Since 2011, Harald has worked as Scientist in the group "Recycling and Extraction" at Umicore's Central R&D department. His main competence areas are:

- Special metals hydrometallurgy (In, Se, Te)
- Recycling and refining of rare earth metals
- Base metals recycling and hydrometallurgy
- Recycling and refining of spent rechargeable batteries (NiMH and Li-ion)

In his current job, Harald is frequently involved in business development of scarce metals recycling and he is heading a team of hydrometallurgical specialists.

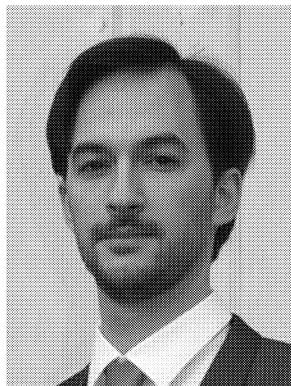
Shafiq Alam is an Associate Professor at Memorial University of Newfoundland, Canada. In 1998, he received his Ph.D. degree in Chemical Engineering from Saga University, Japan. From 1999–2001, he was appointed as a post-doctoral research fellow at the University of British Columbia and the University of Toronto, Canada.



Before joining Memorial University in 2006, he has worked with many different companies, such as, Shell, Process Research ORTECH Inc. (Mississauga, Ontario), Fluor Canada Ltd. (Vancouver), and the National Institute of Advanced Industrial Science and Technology (AIST), Japan. Dr. Alam is highly experienced in the area of extractive metallurgy. He is the lead researcher of the Hydrometallurgy lab at the INCO Innovation Centre (IIC) at Memorial University. He possesses two patents and has over 70 publications in the area of hydrometallurgy.

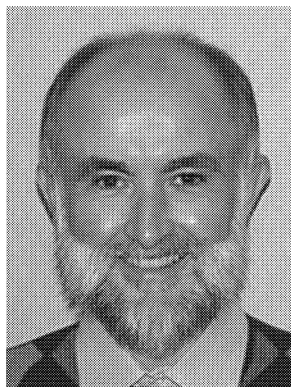
Dr. Alam is a registered professional engineer and has worked on projects with many different mining companies including Xstrata, Phelps Dodge, INCO Ltd. (Vale), and Barrick Gold Corporation. He is an Executive Committee Member of the Hydrometallurgy Section of the Canadian Institute of Mining, Metallurgy and Petroleum (CIM), and is actively involved with the committee in organizing different international conferences, such as, the Conference of Metallurgists (COM) in Canada; Ni-Co Symposium at TMS 2013 in Texas, USA; and the Copper 2013 Conference in Chile.

Antoine Allanore is Assistant Professor of Metallurgy at the Massachusetts Institute of Technology (Cambridge, Massachusetts), in the Department of Materials Science and Engineering where he currently holds the Thomas B. King Chair. He earned a chemical engineering degree from the Ecole Nationale Supérieure des Industries Chimiques de Nancy and a M.Sc. and Ph.D. in chemical engineering from the Institut National Polytechnique de Lorraine. Prior joining MIT, he worked as a research engineer at ArcelorMittal R&D on the development of new electrolytic processes for primary steel production.



Dr. Allanore was a TMS Extraction and Processing Division Young Leader Professional Development Award winner in 2011, and co-recipient of the Vittorio de Nora Prize awarded at TMS 2012.

Rodney Jones has worked in the Pyrometallurgy Division at Mintek since 1985. He holds a B.Sc. (Eng) degree in chemical engineering from the University of the Witwatersrand (Wits) in Johannesburg, a B.A. degree in logic and philosophy from the University of South Africa, and a M.Sc. (Eng) degree in metallurgy from Wits University. He is a registered Professional Engineer, a Fellow and Vice President of the Southern African Institute of Mining and Metallurgy (SAIMM), a Fellow of the South African Institute of Chemical Engineers (SAIChE), and a full member of the Computer Society of South Africa (CSSA). He was a Visiting Professor at the Center for Pyrometallurgy, University of Missouri-Rolla, during July and August 1996, and in 2002 and 2003 also lectured in pyrometallurgy at Murdoch University, Perth, as an Adjunct Associate Professor. The National Research Foundation rated him in 2009 as an "Internationally Acclaimed Researcher." SAIMM awarded him an Honorary Life Fellowship in 2010. Rodney is also a member of the Board of Trustees for OneMine.org.



Nathan Stubina earned a B. Eng in Metallurgical Engineering from McGill University and a Ph.D. in Metallurgy and Materials Science from the University of Toronto. He started working for Falconbridge in 1987 and joined Noranda in 1999. While with those companies he worked at several sites including Sudbury, Norway, Sweden, Belgium and Rouyn-Noranda. Nathan has a mix of plant and R&D working experience.

Nathan joined Barrick Gold in 2005 where he is the Manager of the Barrick Technology Centre. He is a member of the Professional Engineers of Ontario. Nathan is currently VP International for the CIM, is a member of the CIM's Board of Directors, was Chair of the 2009 Conference of Metallurgists (COM) in Sudbury and is a MetSoc Past-President. He is a founding member of NAEMC (North American Extractive Metallurgy Council), is a trustee for the Harold A. Steane Memorial Scholarship, and sits on the board of the Strathcona BIA (Business Improvement Association) for Vancouver's Downtown Eastside. Nathan is the author of over 30 technical papers and patents, and he is a co-editor of the MetSoc commemorative book titled *The Canadian Metallurgical & Materials Landscape (1960 to 2011)*.



Corby Anderson has over 33 years of global experience in industrial operations, management, engineering, design, consulting, teaching, research, and professional service. His career includes positions with Morton Thiokol, Key Tronic Corporation, Sunshine Mining and Refining Company, H. A Simons Ltd., and Montana Tech. He holds a B.Sc. in Chemical Engineering and an M.Sc. and Ph.D. in Metallurgical Engineering. He is a Fellow of the Institution of Chemical Engineers and the Institute of Materials, Minerals and Mining. He currently serves as the Harrison Western Professor in the Kroll Institute for Extractive Metallurgy as part of the George S. Ansell Department of Metallurgical and Materials Engineering at the Colorado School of Mines. In 2009 he was honored by SME with the Milton E. Wadsworth Extractive Metallurgy Award for his contributions in hydrometallurgical research.



Shijie Wang received his B.Sc. in Mineral Processing from China and his Masters and Ph.D. in Metallurgical Engineering from the University of Nevada at Reno. Dr. Wang has experience working at the Beijing General Research Institute for Non-Ferrous Metals, ASARCO Inc., and Phelps Dodge Corporation. He is currently Principal Advisor at Rio Tinto Kennecott Utah Copper. Dr. Wang has been active in extractive metallurgy and has experience in metallurgical process development and existing operation optimization as well as troubleshooting. He is copper and precious metals refining subject matter expert.



Dr. Wang has been a TMS member since 1991 and is currently Chair of the Hydrometallurgy and Electrometallurgy Committee of TMS.

Ni-Co 2013

Plenary

Session Chair

Thomas Battle

LATERITES – STILL A FRONTIER OF NICKEL PROCESS DEVELOPMENT

By

Alan Taylor
ALTA Metallurgical Services

Presented by

Alan Taylor
alantaylor@altamet.com.au

INTRODUCTION

- Nickel production has been historically based on sulphide resources & high grade saprolitic laterites.
- Based on currently known resources, future production will increasingly have to come from low grade limonitic & saprolitic laterites with <1.5% Ni.
- Commercially applied processes for low grade laterites are:
 - Caron Process: reduction roast – ammonia leach)
 - PAL (or HPAL) Process: high pressure sulphuric acid leaching
 - EPAL Process: enhanced pressure acid leaching

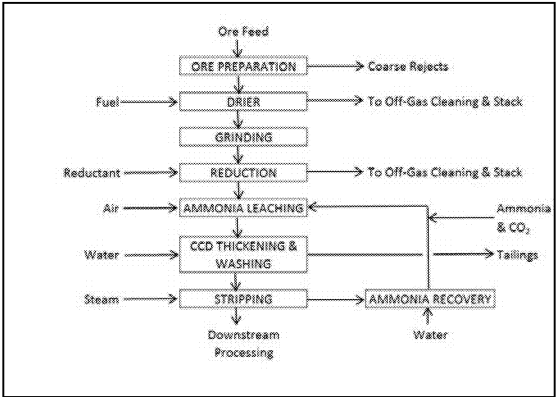
INTRODUCTION

Note: There is a also single known application of ferronickel smelting operated by LARCO, Greece. However, ferronickel smelting is generally considered to be uneconomic for low grade laterites.

CARON PROCESS

- It is not a new process and was first proposed by Professor Caron, Delft Univ. Netherlands, in the 1920s.
- It was pioneered commercially by Freeport at Nicaro, Cuba, in 1944, then taken over by the Cuban Government in 1960. It is still in operation.
- A further five plants were constructed in the 1970s-1990s, one of which was closed (Nonoc in the Philippines) and one never completed (Los Camariocas in Cuba).

TYPICAL CARON FLOWSHEET



CURRENT CARON INSTALLATIONS

Plant	Start-up Date	Builder	Location
Nicaro	1944	Freeport	Cuba
Yabulu	1974	Freeport	Qld, Australia
Tocantins	1982	Votorantim	Brazil
Punta Gorda	1986	Cuban-Russian	Cuba

YABULU OPERATION, AUSTRALIA



ISSUES WITH CARON FLOWSHEET

- It has a high energy consumption for the initial ore drying step.
- Nickel recovery is only moderately high.
- Cobalt recovery is relatively low.
- It is generally limited to limonite and mixed ores with >35% Fe.
- Recovery falls off with saprolite ores.
- It is sensitive to mineral composition and requires careful mining and blending.

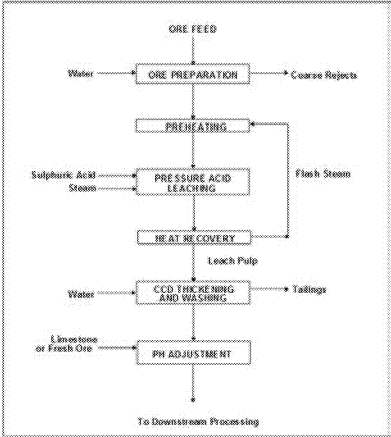
PAL PROCESS

- The process is also not new. The first plant was commissioned by Freeport at Moa Bay, Cuba, in 1959. It was also taken over by the Cuban Government in 1960 and remains in operation today.
- The next major action was not until the development of the AMAX and Nical Processes in the 1970s and 1980s for the Prony Project in New Caledonia and the Gasquet Project in Northern California respectively. Neither reached commercialization due mainly to low nickel price.
- In fact there were no further commercial PAL operations till the 1990s when 3 plants were built in Western Australia, namely Bulong, Cawse & Murrin Murrin (Bulong & Cawse are now closed).

PAL PROCESS

- Since then, 5 PAL plants (not including the Ravensthorpe EPAL plant) have been constructed and are either operating or in commissioning; a further two are under construction.
- The main driving forces for the PAL projects include:
 - Increased nickel demand and higher price
 - Availability of numerous low grade laterite deposits
 - Higher energy efficiency and higher nickel and cobalt recoveries than the Caron Process
 - Longevity of the Moa Bay operation.
 - Successful commercial application of horizontal autoclaves and related facilities for pressure leaching of other ores such as gold and zinc.

TYPICAL PAL FLOWSHEET



**CURRENT PAL INSTALLATIONS
(EXCLUDING RAVENSTHORPE EPAL PLANT)**

Plant	Country	Nickel (t/y)	Status
Moa Bay	Cuba	33,000	Operating
Murrin Murrin	Australia	40,000	Operating
Coral Bay	Philippines	20,000	Operating
Goro	New Caledonia	60,000	Operating
Ambatovy	Madagascar	60,000	Commissioning
Ramu	PNG	31,000	Commissioning
Taganito	Philippines	30,000	Construction
Gordes	Turkey	10,000	Construction

MURRIN MURRIN OPERATION, AUSTRALIA



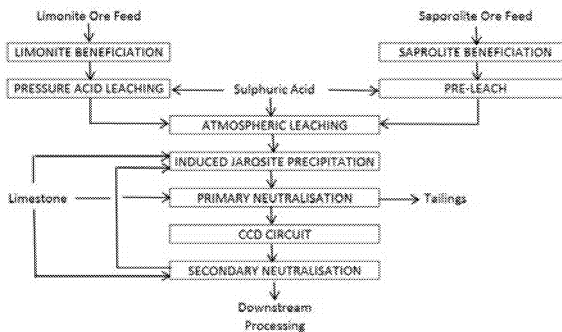
ISSUES WITH PAL PROCESS

- The capital cost is high.
- It has a high acid consumption for saprolitic ores with high magnesium content.
- The process conditions are highly corrosive.
- The maintenance cost is relatively high.
- Autoclave descaling and maintenance involves significant plant downtime.
- Sophisticated control/safety systems are needed.
- Downstream processing is complex.
- There has been a lengthy ramp-up time for the majority of projects.

EPAL PROCESS

- It was developed by BHP Billiton and installed at Ravensthorpe, Western Australia. Commissioning commenced in late 2007, and operation was suspended in early 2009, attributed to a fall in nickel price.
- It was acquired by First Quantum in Dec. 2009 and restarted after modifications, with commercial production achieved in late 2011.
- Limonite ore is treated by PAL and saprolite ore by atmospheric tank leaching.

EPAL PROCESS FLOWSHEET (Ref: Ravensthorpe Presentation at ALTA 2005)



ISSUES WITH EPAL PROCESS

- It retains the disadvantages of PAL for the limonite ore portion of the flowsheet.
- It is relatively complex, with two different leach processes.

DEVELOPING PROCESSES USING SULPURIC ACID

- Pressure acid leaching (PAL) combined with atmospheric pressure agitated tank leaching (AL).
- Stand-alone atmospheric pressure agitated leaching tank (AL).
- Heap leaching (HL)

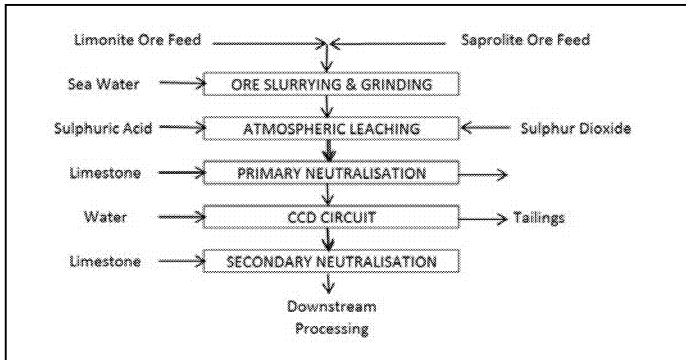
PAL COMBINED WITH AL

- These combine PAL for limonite with AL for saprolite in a parallel circuit and/or use saprolite to neutralize the residual acid from PAL.
- Objectives include:
 - treating the whole orebody
 - reducing the net acid consumption for saprolite
 - eliminating or reducing the limestone needed to neutralize residual acid from limonite PAL
 - reducing capital cost.
- It has been piloted by a number of companies as far back as AMAX and Nical in the 1970s, but not yet commercialized with the exception of EPAL.

STAND-ALONE AL

- Stand-alone AL has also been tested by a number of organizations. A recent example is Eramet who have adopted AL for the Weda Bay Project in Indonesia.
- The advantage of stand-alone AL is the absence of a PAL circuit which should translate into capital cost savings, reduced down time and lower maintenance costs.
- However, this may be offset by increased sulphuric acid consumption.
- Higher acid consumptions lead to higher iron and other impurities to downstream processing.

PROPOSED WEDA BAY FLOWSHEET (Ref: Eramet Paper at ALTA 2012)



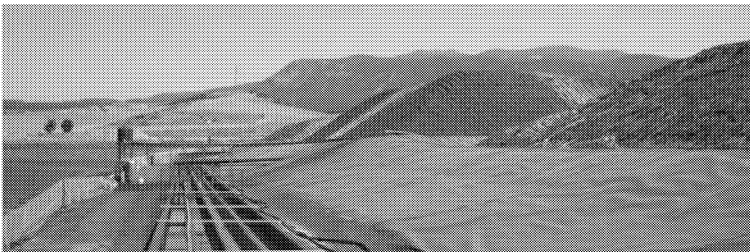
ISSUES WITH AL

- It generally has a high acid consumption, especially for saprolite ore, leading to higher operating cost which offsets the saving in capital cost versus PAL.
- It produces high levels of iron and other impurities in the leach solution which makes downstream processing more challenging.
- It is generally less effective for leaching limonite ore and sulphur dioxide injection may be needed to achieve high cobalt extraction.
- It typically operates close to 100C so that expensive materials of construction are needed.

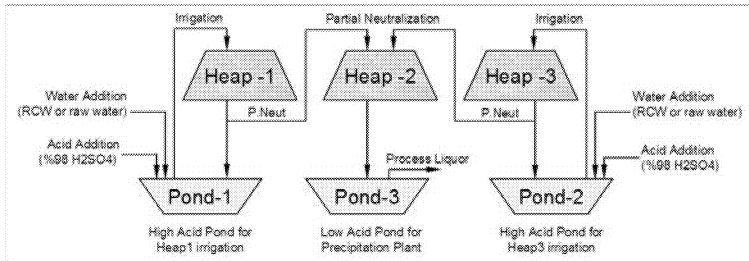
HEAP LEACHING

- Development work has been carried out by numerous organizations since the 1990's, but no stand-alone commercial operation has yet been established.
- A commercial satellite operation treating grinding circuit scats was established in 2007 by Minara at Murrin Murrin in Western Australia. Fresh ore treatment was also successfully demonstrated, but is not currently practiced as it is said to be more profitable to send ore through the existing PAL circuit.
- A stand-alone HL demonstration plant was operated by European Nickel at Caldag in Turkey, in 2004; but the project was held up by permitting issues. It was sold in 2011 and is now owned by VTG Nikel of Turkey who are aiming for commercial operation.

CALDAG HL DEMONSTRATION PLANT (Ref: European Nickel Paper at ALTA 2006)



CALDAG DEMONSTRATION PLANT HL FLOWSHEET (Ref: European Nickel Paper at ALTA 2006)



ISSUES WITH HL

- Laterites frequently have a high fines content and agglomeration with a polymer is typically required.
- Heap stability is a problem, especially in high rainfall locations. High rainfall can also cause breakdown of agglomerates and cause dilution of the leach solution.
- It generally has a high acid consumption, especially for saprolite ore, leading to higher operating cost which offsets the saving in capital cost versus PAL.
- It typically produces higher levels of iron and other impurities in the leach solution than PAL, which makes downstream processing more difficult.