

**Ni-Co 2013**

# TMS2013

## 142<sup>nd</sup> Annual Meeting & Exhibition

*Check out these new proceedings volumes from the TMS2013 Annual Meeting, available from publisher John Wiley & Sons:*

4th International Symposium on  
High-Temperature Metallurgical Processing

Characterization of Minerals, Metals, and Materials 2013

Energy Technology 2013

EPD Congress 2013

Friction Stir Welding and Processing VII

Light Metals 2013

Magnesium Technology 2013

Materials Processing Fundamentals

Ni-Co 2013

REWAS 2013 (CD)

Supplemental Proceedings

To purchase any of these books, visit [www.wiley.com](http://www.wiley.com).

**TMS members: Log in to the Members Only area of [www.tms.org](http://www.tms.org) and learn how to get your discount on these and other books offered by Wiley.**

# Ni-Co 2013

Proceedings of symposium sponsored by  
the TMS Extraction & Processing Division, TMS High  
Temperature Alloys Committee, and the Metallurgy and  
Materials Society of the Canadian Institute of Mining,  
Metallurgy and Petroleum (CIM)

Held during the  
TMS 2013 Annual Meeting & Exhibition  
San Antonio, Texas, USA  
March 3-7, 2013

*Edited by*

**Thomas Battle**

**Michael Moats • Violina Cocalia**

**Harald Oosterhof • Shafiq Alam**

**Antoine Allanore • Rodney Jones**

**Nathan Stubina • Corby Anderson**

**Shijie Wang**



**WILEY**

A John Wiley & Sons, Inc., Publication

**TMS**

**Copyright © 2013 by The Minerals, Metals & Materials Society.  
All rights reserved.**

**Published by John Wiley & Sons, Inc., Hoboken, New Jersey.  
Published simultaneously in Canada.**

---

No part of this publication may be reproduced, stored in a retrieval system, or transmitted in any form or by any means, electronic, mechanical, photocopying, recording, scanning, or otherwise, except as permitted under Section 107 or 108 of the 1976 United States Copyright Act, without either the prior written permission of The Minerals, Metals, & Materials Society, or authorization through payment of the appropriate per-copy fee to the Copyright Clearance Center, Inc., 222 Rosewood Drive, Danvers, MA 01923, (978) 750-8400, fax (978) 750-4470, or on the web at [www.copyright.com](http://www.copyright.com). Requests to the Publisher for permission should be addressed to the Permissions Department, John Wiley & Sons, Inc., 111 River Street, Hoboken, NJ 07030, (201) 748-6011, fax (201) 748-6008, or online at <http://www.wiley.com/go/permission>.

---

**Limit of Liability/Disclaimer of Warranty:** While the publisher and author have used their best efforts in preparing this book, they make no representations or warranties with respect to the accuracy or completeness of the contents of this book and specifically disclaim any implied warranties of merchantability or fitness for a particular purpose. No warranty may be created or extended by sales representatives or written sales materials. The advice and strategies contained herein may not be suitable for your situation. You should consult with a professional where appropriate. Neither the publisher nor author shall be liable for any loss of profit or any other commercial damages, including but not limited to special, incidental, consequential, or other damages.

---

Wiley also publishes books in a variety of electronic formats. Some content that appears in print may not be available in electronic formats. For more information about Wiley products, visit the web site at [www.wiley.com](http://www.wiley.com). For general information on other Wiley products and services or for technical support, please contact the Wiley Customer Care Department within the United States at (800) 762-2974, outside the United States at (317) 572-3993 or fax (317) 572-4002.

---

Cover images are protected under copyright. Image copyrights listed in clockwise order starting with top left. © 2013 Michael Moats, © 2013 Minerals Information Institute, © 2013 Vale, and © 2013 TMS.

---

Library of Congress Cataloging-in-Publication Data is available.

**ISBN 978-1-11860-575-2**

Printed in the United States of America.

10 9 8 7 6 5 4 3 2 1



**WILEY**

A John Wiley & Sons, Inc., Publication

**TMS**

# TABLE OF CONTENTS

## Ni-Co 2013

Preface .....	ix
About the Editors .....	xi

### Plenary

Laterites - Still a Frontier of Nickel Process Development .....	3
<i>A. Taylor</i>	
Cobalt ('the Technology Enabler'): CDI Review & Future Challenges .....	25
<i>D. Weight</i>	
The Recycling of Cobalt from Alloy Scrap, Spent Batteries or Catalysts and Metallurgical Residues—An Overview .....	53
<i>C. Ferron</i>	

### Ni Laterite Hydrometallurgy

Acid Leaching of Nickel Laterites with Jarosite Precipitation .....	75
<i>D. White, and J. Gillaspie</i>	
Extraction of Nickel, Cobalt and Iron from Laterite Ores by Mixed Chloride Leach Process .....	97
<i>V. Lakshmanan, R. Sridhar, R. DeLaat, J. Chen, M. Halim, and R. Roy</i>	
Reductive Leaching of Limonitic Laterites Using Ferrous Sulphate .....	107
<i>M. Zuniga, and E. Asselin</i>	
Sulfuric Acid Leaching Characteristics of Ni-Doped Goethite .....	117
<i>G. Li, W. Cai, M. Rao, Q. Zhi, and T. Jiang</i>	
Characteristics of Nickel Laterite Crushed Ore Agglomerates .....	125
<i>A. Janwong, N. Dhawan, T. Vethsodsakda, and M. Moats</i>	

## **Electrometallurgy**

Acid Mist Abatement in Base Metal Electrowinning .....	143
<i>T. Robinson, D. White, and R. Grassi</i>	
Boleo Cobalt Electrowinning Development .....	155
<i>J. Lu, D. Dreisinger, and T. Gluck</i>	
Comparison of Intercell Contact Bars for Electrowinning Plants .....	177
<i>C. Boon, R. Fraser, T. Johnston, and D. Robinson</i>	
High Current Density Electrowinning of Nickel in EMEW <sup>®</sup> Cells .....	191
<i>J. Robinson, I. Ewart, M. Moats, and S. Wang</i>	
<i>Helm Tracker</i> <sup>™</sup> Cathode Current Sensing Technology .....	201
<i>R. Fraser, T. Johnston, J. Yesberg, S. Nolet, and C. Boon</i>	

## **Pyrometallurgy: Solid-State Processing**

Cobalt Recovery through Sulphating Roast of Cu/Co Concentrate of Katanga Mining .....	213
<i>K. Adham</i>	
Experimental Study on Reduction-Magnetic Separation Process of Low-Grade Nickel Laterite Ore .....	221
<i>F. Chen, B. Zhang, W. Li, Q. Wang, and X. Hong</i>	
State of the Art Refractory Corrosion Test Work for the Nonferrous Metals Industry .....	231
<i>D. Gregurek, A. Ressler, V. Reiter, A. Franzkowiak, A. Spanring, B. Drew, and D. Flynn</i>	

## **Ores and Processing**

Mineralogical Characterization of Cobaltic Oxides from the Democratic Republic of Congo .....	243
<i>Y. Vanbrabant, C. Burlet, and P. Louis</i>	
PolyMet Mining Corporation's NorthMet Process Development .....	255
<i>D. Dreisinger, M. Ounpuu, D. Imeson, and N. Verbaan</i>	

Talvivaara Nickel Mine - from a Project to a Mine and Beyond .....269  
*M. Riekkola-Vanhanen, and L. Palmu*

The Sintering Character of Limonitic Nickel Laterite .....279  
*C. Wu, H. Li, Y. Chen, C. Li, and Z. Zhang*

## **Pyrometallurgy: Smelting**

Nickel, Cobalt and Copper Recovery from Sea Nodules by Direct Smelting Process .....291  
*K. Sahu, S. Agarwal, D. Mishra, A. Agrawal, N. Randhawa, K. Godiwalla, and R. Jana*

Alternative Coolants and Cooling System Designs for Safer Freeze Lined Furnace Operation .....299  
*M. Kennedy, P. Nos, M. Bratt, and M. Weaver*

Outotec's Ausmelt Top Submerged Lance (TSL) Technology for the Nickel Industry .....315  
*R. Andrews, R. Matusewicz, L. Aspola, and S. Hughes*

Processing of PGM Containing Ni/Cu Bulk Concentrates in a Sustainable Way by Outotec Direct Nickel Flash Smelting Process .....325  
*S. Jyrkonen, K. Haavanlammi, M. Luomala, J. Karonen, and P. Suikkanen*

Nickel-Chromium-Boron Alloys Production by Aluminothermic Processes ...335  
*O. Yilmaz, M. Alkan, and O. Yücel*

## **Applications & Recycling**

Numerical Simulation of Temperature Field in Directional Solidification of Turbine Blade by Liquid Metal Cooling Method .....343  
*N. Tang, Q. Xu, and B. Liu*

Influence of Thermomechanical Treatment on Structure and Properties of a Cobalt Based Superalloy .....353  
*P. Sarkar, S. Prasad, M. Chatterjee, and M. Rao*

Effect of Processing Conditions on Structure, Properties and Performance of a Nickel Base Cast Superalloy for High Temperature Applications .....357  
*M. Chatterjee, A. Kishore, P. Sarkar, and M. Rao*

Development of Nickel Boron Alloys for Brazing Materials .....	365
<i>K. Tasyürek, M. Alkan, and O. Yücel</i>	

## **Ni and Co Hydrometallurgy**

Continuous Co-Precipitation Behaviour and Stability of Arsenic(V) from Fe(II,III)-Al(III)-Ni(II) Sulphate Effluent Solutions.....	371
<i>C. Doerfelt, and G. Demopoulos</i>	

Hydrochloric Acid Regeneration via Calcium Sulfate Crystallization for Non-Ferrous Chloride Leaching Processes.....	379
<i>T. Feldmann, and G. Demopoulos</i>	

Hydrometallurgical Nickel Laterite Processing: A Review of Current SX Flowsheets and Industry Trends .....	391
<i>A. Fischmann, S. Wiggett, T. Bednarski, V. Cocalia, and C. Bourget</i>	

Studies on Refining Cobalt Salt Solution by Extraction Chromatography to Prepare High Purity Cobalt.....	405
<i>C. Song, Z. Li, L. Shuling, C. Zhenping, and W. Lijun</i>	

The Starved Acid Leaching Technology (SALT) for Recovery of Nickel and Cobalt from Saprolites and Caron Plant Residues .....	413
<i>D. Dreisinger, and J. Clucas</i>	

Selective Production of Co and Ni Powders Through Hydrothermal Reduction of Leach Solutions of a Synthetic Matte Containing Cu-Ni-Co-Fe-S.....	425
<i>D. Mishra, K. Park, K. Sahu, A. Agrawal, and C. Nam</i>	

Author Index.....	435
-------------------	-----

Subject Index .....	437
---------------------	-----



## 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**  
*Edited by: Thomas Battle, Michael Moats, Violina Cocalia, Harald Oosterhof, Shafiq Alam,  
Antoine Allanore, Rodney Jones, Nathan Stubina, Corby Anderson, and Shijie Wang  
TMS (The Minerals, Metals & Materials Society), 2013*

# 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

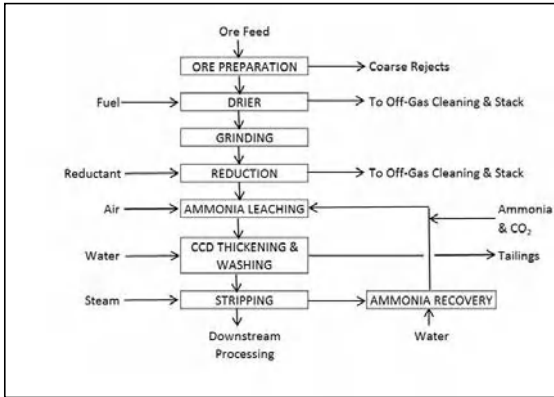
## **INTRODUCTION**

Note: There is also a 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.