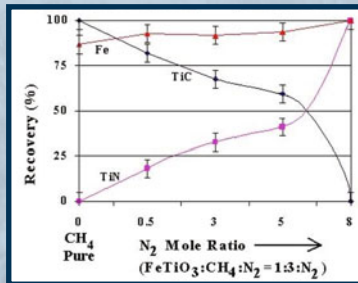# NEW DIRECTIONS IN MINERAL PROCESSING, EXTRACTIVE METALLURGY, RECYCLING AND WASTE MINIMIZATION:

An EPD Symposium in Honor of Patrick R. Taylor

EDITED BY

Ramana G. Reddy

Alexandra Anderson | Corby G. Anderson

Camille Fleuriault | Erik D. Spiller | Mark Strauss

Edgar E. Vidal | Mingming Zhang

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The Minerals, Metals & Materials Series

Ramana G. Reddy · Alexandra Anderson ·
Corby G. Anderson · Camille Fleuriault ·
Erik D. Spiller · Mark Strauss · Edgar E. Vidal ·
Mingming Zhang
Editors

New Directions in Mineral Processing, Extractive Metallurgy, Recycling and Waste Minimization

An EPD Symposium in Honor of
Patrick R. Taylor

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Preface

Professor Patrick R. Taylor is the George S. Ansell Endowed Chair Professor of Chemical Metallurgy and Director of the Kroll Institute for Extractive Metallurgy at the Colorado School of Mines. He is an active member of TMS and has over 45 years of experience in mineral processing, extractive metallurgy, recycling and waste minimization, engineering, research, teaching, and consulting. He has published numerous papers and given invited presentations in over 13 nations and holds 9 patents. He has advised and mentored over 100 graduate students and postdoctoral research associates and served as a consultant for more than 20 companies. Professor Taylor is a Fellow of ASM International and a Distinguished Member (Fellow) of SME. He has received several outstanding awards from several societies and organizations including the Milton E. Wadsworth Award from SME, the EPD Distinguished Lecturer Award, the TMS EPD Distinguished Service Award, and the AIME James Douglas Gold Medal.

To honor Professor Taylor and his vast contributions to extractive metallurgy, The Professor Patrick R. Taylor International symposium titled "New Directions in Mineral Processing, Extractive Metallurgy, Recycling, and Waste Minimization" was held during the TMS 2023 Annual Meeting in San Diego, California, USA, from March 19-23, 2023.

The new concepts and fundamentals, update on reactor design and processes, industrial practices and developments, and environmental issues which influence the selection of metallurgical processes are discussed in the scientific papers published in this proceeding. These issues are discussed relative to new directions in pyrometallurgy, hydrometallurgy, electrometallurgy, mineral processing, metals and e-waste recycling, waste minimization and innovations in metallurgical engineering education and curriculum development.

The editors thank the symposium sponsors Society for Mining, Metallurgy & Exploration (SME), TMS Extraction and Processing Division, and its committees of Pyrometallurgy, Hydrometallurgy and Electrometallurgy, Materials Characterization, Energy, and Recycling and Environmental Technologies. We also thank the authors for providing the invaluable scientific and technical information contained

in this book, and session chairs for their keen interest and support in making the symposium a success.

The lead organizer and editor Professor Ramana Reddy would like to acknowledge the assistance and encouragement of Corby G. Anderson, Colorado School of Mines, Erik D. Spiller, Colorado School of Mines, Edgar E. Vidal, NobelClad, Camille Fleuriault, Eramet Norway, Alexandra E. Anderson, Gopher Resource, Mingming Zhang, Baowu Ouyeel, Christina Meskers, SINTEF, and Mark Strauss, Aqua Metals, Inc., who were very helpful in numerous areas, particularly in soliciting invited papers, organizing sessions, and reviewing and editing the manuscripts.

Finally, we thank TMS Headquarters, particularly Patricia Warren, Kelly Markel, Trudi Dunlap, and James Robinson who made it possible to organize the symposium and publish the papers in the book *New Directions in Mineral Processing, Extractive Metallurgy, Recycling and Waste Minimization: An EPD Symposium in Honor of Patrick R. Taylor*.

Dr. Ramana G. Reddy
Lead Organizer

Contents

About the Honoree

Patrick R. Taylor is a registered professional engineer with over 45 years of experience in mineral processing, extractive metallurgy, recycling, and waste minimization; engineering, research, teaching, and consulting. He grew up in West Denver and served in the US Army in Vietnam. He then attended the Colorado School of Mines (B.S. Mathematics 1974, B.S. Metallurgical Engineering 1974, and Ph.D. Metallurgical Engineering 1978). He began his professional career at the University of Idaho in 1977. He progressed through the various positions and was the Department Head his last five years (1995–2000). He then joined the University of Tennessee where he was head of the Material Science and Engineering Department (2000–2002). In 2002, he accepted the offer to be the George S. Ansell Endowed Chair at the Colorado School of Mines (2002–2022). He directed the Kroll Institute for Extractive Metallurgy. He was part of the team that helped develop the Center for Resource Recovery and Recycling as well as the CSM part of the Critical Materials Institute.

Dr. Taylor has worked or given invited presentations in Canada, Mexico, Peru, Venezuela, Argentina, Chile, Bolivia, Colombia, Brazil, India, England, Turkey, and Egypt. He is experienced and trained in pyrometallurgy, hydrometallurgy, and mineral processing. He has been responsible for lab work, pilot plant work, research, and process development for mineral processing, and extractive metallurgy processes related to a wide variety of metals. He has authored or co-authored numerous papers and presentations and holds nine patents. He

has served as a consultant for more than 20 companies and has been an expert witness. He has directed research for more than 100 graduate students and post-docs. He has taught extractive metallurgy and mineral processing university courses for the past 45 years. He has developed and taught ten short courses to industry. He wrote professional engineering exam questions for 25 years. He is active in many professional organizations including participation in SME (fellow), TMS, ASM (fellow), and MMSA.

In 1982, he was named Outstanding Faculty Member in the College of Mines at the University of Idaho. In 1985, he was the organizing chairman, TMS Fall Meeting for Process and Extractive Metallurgy: Intl. Symposium on the Recycle and Secondary Recovery of Metals. In 1990, he was named Distinguished Faculty Member at the, University of Idaho. In 1994 he received the Research Excellence Award from the University of Idaho. In 1996, he was named Fellow of ASM International. In 2003, he received the Milton E. Wadsworth Award from SME. In 2004, he was the TMS Extraction and Processing Division Luncheon Speaker. In May 2006, he was the CSM Alumni Association MME Graduating Senior Outstanding Faculty Member. In December 2006, he was the CSM Alumni Association MME Graduating Graduate Student Outstanding Faculty Member. In 2006, he was the TMS Extraction and Processing Division Distinguished Lecturer. In 2008, he was a co-organizer and co-editor of the SME 5th International Hydrometallurgy Symposium. In 2008, he was named a Distinguished Member (Fellow) of SME. In 2009, he was a co-organizer and co-editor of the SME Fall meeting, Mineral Processing Plant Design 2009. In 2010, he received the TMS EPD Distinguished Service Award. He received the AIME James Douglas Gold Medal in 2013. In 2017, he was a co-organizer of the symposium "Applications of Process Engineering Principles in Materials Processing, Energy, and Environmental Technologies" TMS. He was elected to the University of Idaho's Academy of Engineers in 2017. He was selected to be interviewed for the AIME Oral Histories program in 2018. Along with his graduate students (Tom Boundy), he received the TMS Light Metals/Extraction and Processing Subject Award—Recycling, 2019. Along with his graduate student (Vivek

Kashyap), he received the Taggart Award for the best paper in mineral processing from SME/MPD in 2021. He received the Industry Involvement award from CSM in 2021. He was named Emeritus Ansell Distinguished Professor of Chemical Metallurgy at CSM in 2022.

Dr. Taylor has been married to his high school sweetheart (Peggy) since 1969. He has two sons (Dylan and Travis) and two granddaughters (Brooke and Morgan).

About the Editors

Ramana G. Reddy is an ACIPCO Endowed 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. He was a visiting professor at the Lawrence Berkeley Laboratory, University of California, Berkeley; Indian Institute of Technology, Bombay; and Argonne National Laboratory, Chicago and Renewable National Energy Laboratory, Golden USA. He was appointed as the University of Alabama Coordinator for the National Space Science and Technology Center (NSSTC) and NASA and served as Council Member for the Alabama State Committee for Department of Defense-EPSCoR programs.

Dr. Reddy's teaching and research experience are 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 433 research papers and 26 books, including an undergraduate textbook on thermodynamics. He has also delivered more than 305 invited lectures and research presentations in 26 nations. Dr. Reddy advised and mentored over 115 graduate students and worked with postdoctoral and research associates. He is the recipient of 5 USA patents.

Dr. Reddy is an Associate Editor of several national and international journals. He has received several awards such as the Service Award and the Best Research Paper Awards from several Materials Societies. He is the recipient of the TMS Extraction & Processing Distinguished Lecture Award, the Milton E. Wordsworth Award for Extractive Metallurgy of SME, ATA Award for Excellence in Engineering, and Henry Krumb Lecturer of SME. He is the recipient of the EPD-TMS Science Award, LMD-TMS Energy Committee Energy Paper Award, TMS Distinguished Service Award, Distinguished Alumni Professional Achievement Award (NITW), TMS Educator Award, SEC Faculty Achievement Award, AIME Mineral Industry Education Award, and Burnum Distinguished Faculty Award (University of Alabama, USA). Dr. Reddy was honored with

the Professor Ramana Reddy Honorary symposium on Applications of Process Engineering Principles in Materials Processing, Energy, and Environmental Technologies, TMS.

Dr. Reddy is a Distinguished Member (Fellow) of SME and a Fellow of ASM International.

Alexandra Anderson Ph.D., PMP, is an R&D manager at Gopher Resource, LLC, an environmental solutions company specializing in lead battery recycling. Her work focuses on driving furnace productivity and efficiency initiatives through computational fluid dynamic (CFD) modeling and implementing novel equipment designs. Currently, she is also the principal investigator for a DOE HPC4Manufacturing partnership between Gopher Resource and Oak Ridge National Lab investigating high-fidelity multiphase furnace modeling. Alexandra obtained her B.S. in Mechanical Engineering from Gonzaga University and her M.S. and Ph.D. in Metallurgical and Materials Engineering from the Colorado School of Mines. Her dissertation investigated fluid flow and thermal profiles within secondary lead reverberatory furnaces using CFD techniques. Alexandra is active in The Minerals, Metals & Materials Society (TMS), where she serves as the vice-chair of the Process Technology and Modeling Committee; she was also the recipient of the 2021 TMS Extraction and Processing Division (EPD) Young Leader Award. Her scholarly activities include nine peer-reviewed publications, co-editorships of seven special topics for *JOM*, as well as several podium presentations at national conferences.

Corby G. Anderson is a Licensed Professional Chemical Engineer with over 40 years of global experience in industrial operations, corporate level management, engineering, design, consulting, teaching, research, and professional service. He is a native of Butte, Montana, USA. His career includes positions with Thiokol Chemical Corporation, Key Tronic Corporation, Sunshine Mining and Refining Company, H. A. Simons Ltd., and at CAMP-Montana Tech. He holds a B.Sc. in Chemical Engineering from Montana State University, an M.Sc. from Montana Tech in Metallurgical Engineering, and a Ph.D. from the University of Idaho in Mining

Engineering-Metallurgy. He is a Fellow of both the Institution of Chemical Engineers and of the Institute of Materials, Minerals, and Mining. He has directed or co-directed over 40 graduate students. He shares 16 international patents and 3 new patent applications covering several innovative technologies, 6 of which were successfully reduced to industrial practice. He currently directs the Kroll Institute for Extractive Metallurgy as the Harrison Western Professor as part of both the Mining Engineering Department and the George S. Ansell Department of Metallurgical and Materials Engineering at the Colorado School of Mines. He is also the CSM Director for the Center for Resource Recovery and Recycling. In 2009 he was honored by the Society for Mining, Metallurgy & Exploration with the Milton E. Wadsworth Extractive Metallurgy Award for his contributions in hydrometallurgical research. In 2015 he was awarded the International Precious Metals Institute's Tanaka Distinguished Achievement Award. In 2016 he received the Distinguished Member Award from the Society for Mining, Metallurgy & Exploration, and became a Distinguished Member of the U of Idaho Academy of Engineering. In 2017 he received the EPD Distinguished Lecturer Award from The Minerals, Metals & Materials Society. In 2019 he was named as a Henry Krumb Distinguished SME Lecturer. In 2019 he was also appointed and serves now as a Visiting Faculty within the Minerals Engineering Department of Central South University in China, the largest program of Mineral Processing and Extractive Metallurgy in the world. In both 2016 and in 2021 he received an Outstanding Faculty Award from the Colorado School of Mines. He was also elected in 2021 to the Sigma Xi Scientific Research Honor Society. In 2022 he received the TMS EPD Distinguished Service Award for his career contributions. Finally, in 2022 he and his coauthors received the SME Taggart Award for a notable contribution to the science of mineral processing.

Camille Fleuriault is senior project manager at Eramet Norway AS in Sauda, Norway. Her work focuses on identifying and enabling zero carbon strategies for the production of manganese alloys. She previously worked on developing innovative and environmentally friendly recycling processes for the secondary metals industry. She holds a B.S. in Geological Engineering and an M.Eng. in Mineral Engineering from the National School of Geological Engineering in Nancy, France, and a M.Sc. in Metallurgical Engineering from Colorado School of Mines, USA. She is chair of the TMS Pyrometallurgy Committee and a former *JOM* advisor for the same committee.

Erik D. Spiller has more than 45 years of experience managing research, process development, technology, engineering, sales, and operations in the minerals industries. For the past 30 years he combined that successful career with a second career in academia lecturing and conducting research at the Colorado School of Mines. He contributes technical expertise in processing from mineral liberation (comminution) through separations using various physico-chemical techniques based on particle attributes such as size, magnetic susceptibility, specific gravity, surface chemistry (flotation), conductivity, leaching, and liquid/solid separation. He received the AIME-SME prestigious Richards Award in 2009 and was a SME Fellow Member in 2018.

Mark Strauss is passionate about creating and implementing extractive metallurgical innovations to advance decarbonized and electrified clean energy technology, waste minimization, and critical materials independence. As a post-doctoral fellow at Idaho National Laboratory, he developed innovative recycling strategies to separate and purify lithium batteries into saleable lithium, copper, manganese cobalt, and nickel products. His research experience involves the primary and secondary production of critical materials using pyro-electro-hydrometallurgical techniques. His undergraduate research involved by-product recovery of rare earths from copper leach solutions at the University of Arizona. His master's and Ph.D. research investigated hydrometallurgical strategies for recycling fluorescent lights at the Colorado School of Mines and Worcester Polytechnic

Institute. He is currently developing and implementing electro-hydrometallurgical and pyrometallurgical innovations to optimize lithium-ion battery recycling at Aqua Metals.

Edgar E. Vidal holds a doctorate in Metallurgy-Mining Engineering and Bachelor's and Master's degrees in Materials Engineering. For the last four years he has been responsible for NobelClad's strategy in developing new composite metal products, applications, and markets. Prior to NobelClad, for ten years Dr. Vidal developed beryllium-related materials and processes at Materion (former Brush Wellman) and became Global Director of Sales, Marketing and Business Development. He holds four patents with an additional two pending. Dr. Vidal has over 50 publications in diverse areas of materials, from mineral processing to nuclear applications. He continues to be involved in academia as an Affiliate Faculty at Colorado School of Mines.

Mingming Zhang is currently a principal consultant at Wood Mackenzie. He has more than 20 years of experience in the field of mining, mineral processing, smelting and refining, and materials engineering. Before joining Wood Mackenzie, Dr. Zhang held lead engineer position at ArcelorMittal Global R&D in East Chicago, Indiana. He obtained his Ph.D. in Metallurgical Engineering from The University of Alabama and his master's degree in Mineral Processing from the General Research Institute for Non-ferrous Metals in China. Prior to joining ArcelorMittal, he worked with Nucor Steel in Tuscaloosa, Alabama where he was a metallurgical engineer leading the development of models for simulating slab solidification and secondary cooling process. Dr. Zhang has conducted a number of research projects involving mineral beneficiation, thermodynamics and kinetics of metallurgical reactions, electrochemical processing of light metals, metal recycling, and energy-efficient and environmentally cleaner technologies. He has published more than 50 peer-reviewed research papers and he is the recipient of several U.S. patents. Dr. Zhang also serves as editor and reviewer for a number of prestigious journals including *Metallurgical and Materials Transactions A and B*, *JOM*, *Journal of Phase Equilibria and Diffusion*, and

Mineral Processing and Extractive Metallurgy Review. Dr. Zhang has made more than 30 research presentations at national and international conferences including more than 10 keynote presentations. He was the recipient of the 2015 TMS Young Leaders Professional Development Award. He has served as conference/symposium organizer and technical committee chair in several international professional organizations including The Minerals, Metals &Materials Society (TMS), the Association for Iron & Steel Technology (AIST), and the Society for Mining Metallurgy & Exploration (SME).

Development of Ironmaking Technology by the Direct Gaseous Reduction of Iron Concentrate

Hong Yong Sohn

Abstract Considering the two most important issues the ironmaking industry faces today, i.e. energy consumption and greenhouse gas emissions, it would be advantageous to utilize the concentrate-size raw materials directly without pelletizing or sintering, especially without the use of coke. This plenary lecture describes two such processes developed at the University of Utah. One is the Flash Ironmaking Technology (FIT), and the other is a moving-bed process for continuous ironmaking with gaseous reduction of iron ore concentrate (MBIT). These technologies are designed to produce iron directly from iron concentrate without requiring pelletization/sintering and cokemaking. They take advantage of the high reactivity of the concentrate particles and will significantly reduce energy consumption and carbon dioxide emissions compared with the current processes. The process of the development from the conception of the idea, to kinetic feasibility establishment, and to the operation of a prototype facility will be discussed.

Keywords Flash ironmaking technology (FIT) · Moving-bed ironmaking · Carbon dioxide · Concentrate · Hydrogen · Magnetite · Natural gas · Pilot plant · Reformerless · Energy consumption · Sohn's law

Introduction

Primary steel is produced from iron oxide minerals through the integrated production using blast furnace (BF), combined with subsequent refining steps such as basic oxygen furnace (BOF), or by direct reduction (DR) process, combined with subsequent steelmaking steps such as electric arc furnace (EAF) treatment. Steel is also made from scraps through the EAF steelmaking process.

The integrated steelmaking process involves many steps, emits a great deal of carbon dioxide, and requires a large amount of energy compared with steelmaking

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from scraps. However, integrated steelmaking will remain the major steel producing route for a long time. This is because most steel products last for decades, before they become scrap and there are insufficient amounts of scrap to meet the rapidly increasing demand for steel.

Raw materials preparation consumes much energy and emits a large amount of CO_2 gas. The U.S. emitted 55 MMT CO_2 from iron and steel production in 2014 [1]. Pelletizing, sintering, and cokemaking processes emit ~20% of the total CO_2 in the BF-BOF route and the BF contributes ~70%.

According to the above discussion, the two most critical issues that the steel industry currently faces are energy consumption and greenhouse gas emissions. Large amounts of energy are consumed in the sintering/pelletizing steps and cokemaking, which are also responsible for much carbon dioxide emissions. Up to ~70% of iron production in the U.S. currently depends on magnetite concentrate produced from the low-grade taconite ore. Further, there is a trend to upgrade even reasonably high-grade iron ores up front to remove bulk of impurities before reduction. This required grinding the ores to concentrate-size particles.

It would then be advantageous to utilize the concentrate-size raw materials directly without pelletizing or sintering, especially without the use of coke. This plenary lecture describes two such processes developed at the University of Utah. One is the Flash Ironmaking Technology (FIT) [2–8], and the other is a moving-bed process for continuous ironmaking with gaseous reduction of iron ore concentrate (MBIT) [9].

Flash Ironmaking Technology (FIT)

The Flash Ironmaking Technology (FIT) is based on the reduction of iron oxide concentrates by gas in a flash reactor. This technology utilizes hydrogen or natural gas as a fuel as well as reducing agent. The development of FIT started from the kinetic feasibility determination to the laboratory flash furnace work and finally the tests in a pilot plant. Process simulation and economic analysis on the new process were also performed.

A sketch of the Flash Ironmaking process is shown in Fig. 1. A gaseous fuel is partially oxidized with industrial oxygen to generate a reducing gas at 1600–1900 K. Iron ore concentrate is fed from the top, and the reduced iron product can be collected as a solid powder or as a molten bath for direct steelmaking.

Natural gas is plentiful in the U.S. and could easily supply potential ironmaking based on the FIT. Hydrogen would be cleaner once the hydrogen economy is developed.

The development of the FIT started with the establishment of sufficient kinetic feasibility, considering the fact that there are only a few seconds of residence time available in a typical flash reactor. Upon the establishment of the kinetic feasibility, a laboratory flash reactor was tested, which was followed by a pilot-scale reactor test program.
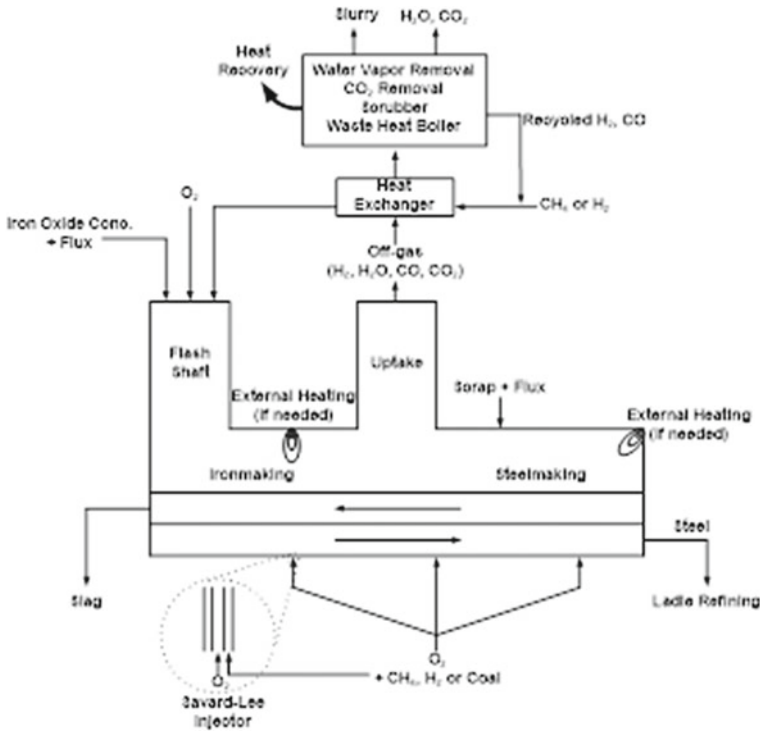
Fig. 1 A sketch of a direct steelmaking process based on the Flash Ironmaking Technology (FIT) (Adapted from Sohn and Choi [10])

Reduction Kinetics of Magnetite Concentrate Particles

Magnetite concentrate from a taconite ore of the Mesabi Range was used in this study. Sohn and coworkers [11–16] investigated the reduction rates of magnetite concentrate under the conditions of the FIT. The results were expressed by the following equation for component gases H_2 or CO:

$$\left.\frac{dX}{dt}\right|_j = k_j \cdot \left[p_j^{m_j} - \left(\frac{p_{jO}}{K_j}\right)^{m_j} \right] \cdot n_j(1-X)[-\text{Ln}(1-X)]^{1-\frac{1}{n_j}} \cdot d_p^{-s_j};$$

$$j = H_2 \ or \ CO$$

(1)

where k_j is the reaction rate constant for gas j, $k_j = k_{o,j}\exp\left(-\frac{E_j}{RT}\right)$; p_j is the partial pressure of gas j; K_j is the equilibrium constant for the reduction of FeO by gas j; m_j is the reaction order with respect to gas j; n_j is the Avrami parameter; $d_p^{-s_j}$ is the particle size dependence; and X is the fraction of the total removable oxygen in the concentrate particles removed by the reaction.

Table 1 Kinetic parameters for reduction of magnetite concentrate by each component gas

Reducing gas, j	Temperature range (K)	$k_{o,j}$	E_j (kJ/mol)	m_j	n_j	s_j
H_2	1423–1623	1.23×10^7 atm^{-1} s^{-1}	196	1	1	0
	1623–1873	6.07×10^7 atm^{-1}·s^{-1}·μm	180	1	1	1
CO	1423–1623	1.07×10^{14} atm^{-1} s^{-1}	451	1	0.5	0
	1623–1873	6.45×10^3 atm^{-1}·s^{-1}·μm	88	1	0.5	1

The relevant kinetic parameters are given in Table 1. The reader is referred to the original papers [11, 13, 14, 16] for other details of the rate measurements and data analyses.

When magnetite concentrate is reduced by a mixture of H_2+CO, the CO enhances the rate of reaction between H_2 and iron oxide. This is most likely due to the effect of CO on the morphology of the reduced iron by forming whiskers, which was observed in a separate study [17]. Taking this into consideration, Fan et al. [13] developed the following rate expression.

The complete rate equations for magnetite concentrate reduction by a H_2+CO mixture at 1423 K (1150 °C)–1623 K (1350 °C) and 1623 K (1350 °C)–1873 K (1600 °C) are given, respectively, as:

$$\frac{dX}{dt} = \left(1 + 1.3 \cdot \frac{p_{co}}{p_{co} + p_{H_2}}\right) \cdot \left.\frac{dX}{dt}\right|_{H_2} + \left.\frac{dX}{dt}\right|_{CO} \quad 1423\text{K} < T < 1623\text{K} \quad (2)$$

$$\frac{dX}{dt} = \left[1 + (-0.01T + 19.65) \cdot \frac{p_{co}}{p_{co} + p_{H_2}}\right] \cdot \left.\frac{dX}{dt}\right|_{H_2} + \left.\frac{dX}{dt}\right|_{CO} \quad 1623\text{K} < T < 1873\text{K} \quad (3)$$

where $\left.\frac{dX}{dt}\right|_{H_2}$ and $\left.\frac{dX}{dt}\right|_{CO}$ represent the rates of reduction individually by H_2 and CO, respectively, obtained from Eq. (1) with the parameters listed in Table 1.

These kinetics measurements confirmed the fact that a few seconds of residence time in a flash reactor at temperatures of 1473 K or higher are sufficient to reduce iron ore concentrate.

Tests in a Laboratory Flash Reactor

Tests were then performed in a laboratory flash reactor shown in Fig. 2 [18, 19], based on the partial oxidation of methane, generating H_2+CO mixtures, and/or hydrogen with oxygen. The heating was supplemented by electrical heating.
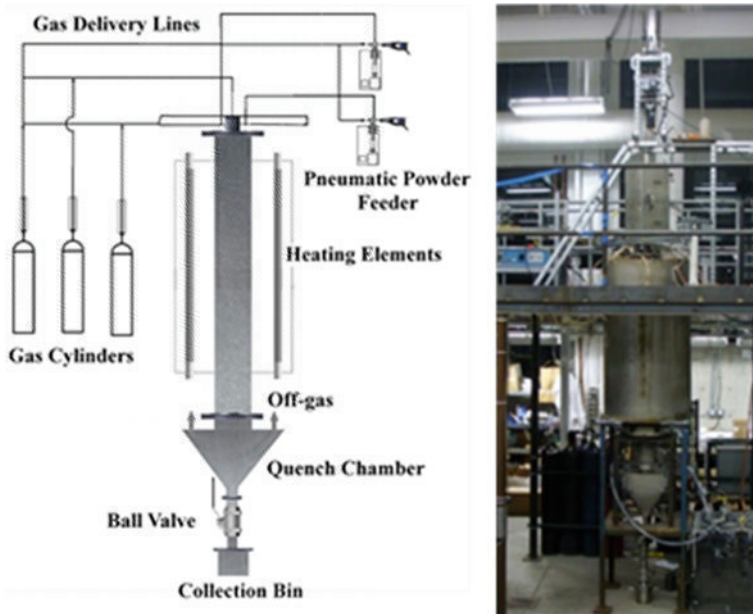
Fig. 2 The Utah laboratory flash ironmaking reactor (I.D. 0.19 m and height 2.13 m) (Adapted from Sohn et al. [3])

In these tests, a number of aspects that are relevant to the operation of an industrial flash ironmaking reactor were investigated. In addition to the effects of the main operating conditions of temperature and gas composition, other important features such as the position of concentrate feeding relative to the flame and the configuration of the flame in terms of the injection of fuel *vis-à-vis* that of oxygen were evaluated. For details of the significant test results, the reader is referred to the published articles by the author and coworkers [3, 18, 19].

In addition to the experimental test work, a CFD simulation model of the laboratory flash reactor operation was also developed to analyze and interpret the experimental results [18, 19].

The test work in the laboratory flash reactor confirmed the technical feasibility of ironmaking by the *in-situ* partial oxidation of natural gas or hydrogen in a flash reactor and established a number of useful operating conditions.

Design, Installation, and Operation of a Pilot-Plant Scale Flash Reactor

The laboratory flash reactor work was followed by the installation and operation of a Pilot Flash Reactor run at 1200–1550 °C with a solid feed rate of 1–7 kg/h, shown

Fig. 3 The pilot plant with a flash reactor installed at the University of Utah (Adapted from Elzohiery [20])

in Fig. 3. In this reactor, natural gas was used as the fuel/reducing gas instead of methane, as would be in an industrial flash ironmaking process.

This Pilot Flash Reactor system was designed to be fully computer-controlled with an emphasis on numerous safety aspects as well as high levels of operational control features. The facility consisted of a main reactor vessel, various burners, a quench tank for product collection, a stack, a concentrate feeding system, an off-gas analyzer, and human-machine interface for computer control and inputs from various sensors.

The reactor roof housed an opening for the main burner and a separate preheat burner with a pilot flame and provided a number of ports for gas and solid feeding as well as an emergency off-gas conduit equipped with a rupture disc. The configuration of the main burner in terms of injecting natural gas and oxygen was designed based on what was learned from the laboratory flash reactor.

The Human Machine Interface (HMI) consisted of the main PLC and a PC. The operator monitored all parts of the facility and ran the reactor through the computer to which the main PLC continuously fed information. All the safety and emergency procedures relied on the PLC. Details of the facilities and operation of the Pilot Reactor are described elsewhere [3].

Results from Pilot Flash Reactor Runs

The experiments in the pilot plant were performed at different temperatures and reducing powers of the gas with the aim of obtaining enough data for designing the

industrial flash reactor. The results from the Pilot Flash Reactor runs were reported in Elzohiery [20]. The results showed good reproducibility within ±5% of the average reduction degree by repeating the same experiment at least 3 times. This represents a very high degree of reproducibility, considering the complexity of the operation and design of this large unit.

These results were used to develop a CFD model that would be used to optimize the operating conditions and reactor sizes to be used in an industrial reactor [5]. Different experimental runs were designed and made in this reactor to yield a range of reduction degrees, deliberately at less than complete reduction, to better examine the effects of the operating conditions and validate the CFD model.

CFD Simulation of the Pilot Reactor Operation

The same CFD model for the laboratory flash reactor discussed above was used for the pilot reactor runs [5]. The run conditions used for CFD simulation and the results are compared with the experimental results in Table 2.

The CFD model predicted the H_2 and CO concentrations within 93% accuracy for most runs. The experimental values of % reduction are compared with the CFD results in Table 2. The reduction degrees agree well for the first three runs. The agreement is not as good for the last three runs. The reason for this is likely to be because of the neglect of particle interactions for Runs 4–6. The temperature of the particle-gas stream in the main reaction zone was largely uniform, and this value is used to represent the reactor temperature. These runs had higher ratios of oxygen to natural gas and thus higher temperatures than the other runs, above 1577 °C, which is higher than the melting point of iron at 1538 °C. Particle agglomerates together more readily at these high temperatures, as shown previously during flash smelting of copper [21]. This might have caused lower reduction rates in the actual cases than in the simulation. This points to the need for improving the CFD model to account for particle coalescence at high temperatures.

The temperature of the particle-gas stream in Run 1 was also above 1577 °C, but the solid feed rate in this run was only about one-half of the values in Runs 4–6. The lower solid feed rate in Run 1 together with the fact that portions of the particles usually get stuck on the wall significantly lowered the possibility of particles in the gas stream to agglomerate in Run 1.

Process and Economic Analysis of Flash Ironmaking Technology

Based on the potential advantages of the new technology and the results of the process feasibility studies, process and economic analyses have been performed [7, 8, 22,

Table 2 Run conditions for the pilot reactor and CFD simulation results

Run #	Inner wall temperature[b] (°C)		Magnetite concentrate feeding rate (kg/h)	Main burner gas flow rate (SLPM)[a]		Particle size (μm) (Mass average used for simulation)	O₂ to natural gas molar ratio	Experimental RD (%) (± 5%)	CFD simulation RD (%)
	Average used for simulation	Range during run		NG	O₂				
1	1253	1483–1563	2.5	419	331	45	0.79	94	99.8
2	1275	1483–1563	4.3	509	328	32	0.64	80	84.5
3	1353	1483–1563	5	339	238	32	0.7	94.5	99.6
4	1167	1483–1563	5	413	359	45	0.87	74	99.8
5	1321	1483–1563	4.6	289	273	32	0.94	72.5	99.5
6	1326	1483–1563	4	264	247	32	0.93	50	85

Oxygen and natural gas input temperature was 25 °C
[a]Flow rates are calculated at 25°C and 0.85 atm, the barometric pressure at Salt Lake City
[b]Temperatures of inner wall were recorded during the main experiment

23]. The results of these analyses indicated that the new ironmaking technology will consume up to 44% less energy than the blast furnace when the former is run in the reformerless mode, i.e. direct partial combustion in the reactor, and it will emit up to 51% less carbon dioxide. When hydrogen is used, the proposed process would consume up to 60% less energy with little CO_2 emissions. However, it is noted that a more accurate comparison must include the energy consumption and CO_2 emissions for the production of natural gas, hydrogen, or coal.

An economic feasibility analysis [23] indicated that the new technology using natural gas with in-situ partial combustion would be economical at this time, owing to the small capital and operating costs as well as the low price of natural gas. The sensitivity analysis performed on the estimated NPV indicated that the price of natural gas affects the NPV most strongly. These economic analyses point to the fact that the proposed ironmaking technology would be economically feasible at this time if it is operated using natural gas.

Summary on Flash Ironmaking Technology

The overall process of developing a novel Flash Ironmaking Technology (FIT) has been described in this article.

Rate equations for the reduction of iron ore concentrate by hydrogen, carbon monoxide, and a mixture of the two formulated in this work established the fundamental feasibility of the concept of the flash ironmaking and form the basis of the design of a reactor to realize the process. Scale-up experiments were performed in a laboratory flash reactor that operated at conditions similar to those of the industrial flash ironmaking reactor, and >90% reduction degree was obtained at temperature as low as 1175 °C.

A pilot reactor that operated in the temperature range 1200–1550 °C was installed and operated to collect the data necessary for scaling up the process to an industrial scale. This reactor was used to validate the design concept of the Flash Ironmaking in terms of heat supply, residence time, reduction degree, and the determination of optimum operating conditions. These tests also identified a number of technical hurdles. This investigation proved the technical feasibility of the flash ironmaking technology for large-scale iron production. The results of this work will facilitate the complete design for the industrial flash ironmaking reactor.

The new technology does not require pellets, sinters, and coke. Instead, it would produce iron directly from concentrates using natural gas or hydrogen. As a result, the energy consumption is expected to be up to 44% less than that for the average blast furnace process when the Flash Ironmaking Technology (FIT) is operated with natural gas in the reformerless mode, i.e. in-situ partial combustion, and it will emit up to 51% less carbon dioxide. When hydrogen is used, the proposed process would consume up to 60% less energy with little carbon dioxide emissions.

Moving-Bed Ironmaking Technology (MBIT)

A novel horizontal moving-bed ironmaking process has been developed at the University of Utah. This process uses iron concentrate directly without sintering or pelletization and reduces it with hydrogen in the temperature range of 500–1000 °C. The work started with the determination of the particle kinetics, which was then combined with diffusional effect to analyze the reduction rate of a particle bed. Based on the kinetics formulation, a mathematical model of the furnace for the proposed technology was developed for a modest industrial ironmaking operation designed to produce iron at a rate of 0.1 million tonnes per year (Mtpy).

Process Concept

The Flash Ironmaking Technology (FIT) described above requires an operating temperature of 1300–1600 °C and could produce either solid-phase iron or molten hot metal. Further, it is thought to be more suitable for a large-scale ironmaking plant. For medium-level steelmaking operations, sponge iron produced at a lower temperature would make a suitable feed. Even in the latter case, direct use of iron concentrate with its high reactivity would be advantageous. Based on this reasoning, a process using a moving-bed reactor has been developed [9].

Configuration of a Horizontal Moving-Bed Furnace

The furnace to be used for the proposed process would continuously carry iron concentrate placed as a layer on a moving grate in a counter-current flow with the reducing gas. A sketch of such a counter-current moving-bed reactor is shown in Fig. 4.

The evaluation of the feasibility of such a moving bed for direct reduction of iron concentrate requires a quantitative information on the kinetics of reduction of concentrate particles in the anticipated temperature range, that of a particle bed including diffusional effects, and finally a mathematical model of the moving-bed reactor.

Fig. 4 Sketch of a counter-current horizontal moving-bed reactor (Adapted from Roy [24])