Midrex Research & Development

Inspiration for Innovation & Improvement

MIDREX

RESEARCH & DEVELOPMENT TECHNOLOGY CENTER

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ROLE OF MIDREX R&D

MIDREX IS ALL ABOUT TECHNOLOGY. IT'S IN OUR COMPANY NAME. IT'S THE BASIS OF OUR PRODUCTS AND SERVICES. IT'S OUR HERITAGE AND OUR FUTURE.

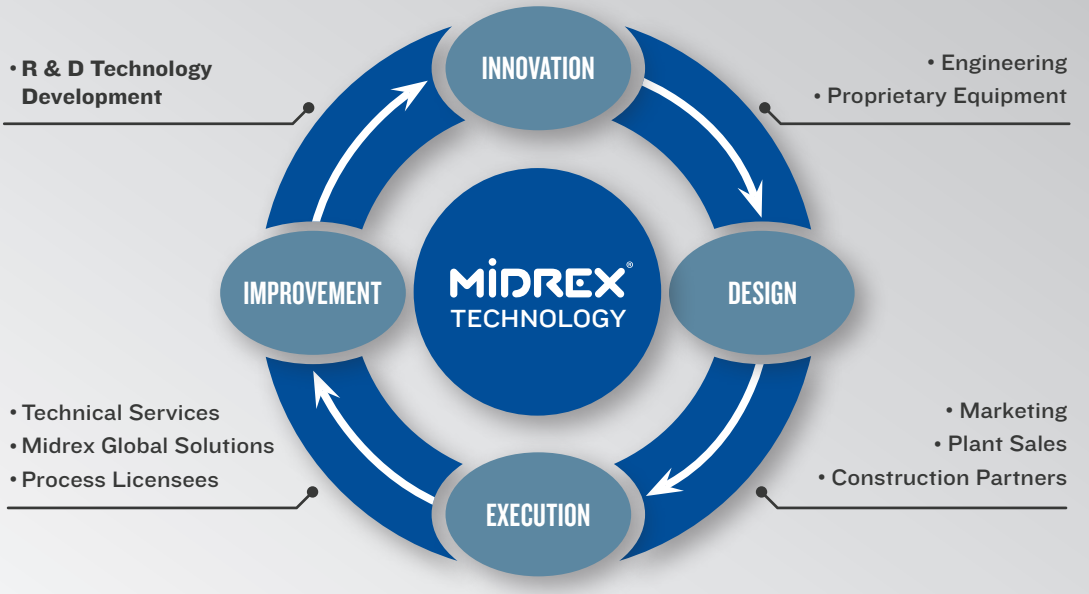
From the outset, research and development (R&D) has been at the forefront of **MIDREX® Technology** because technology by nature is dynamic. Having a good idea is not enough. Research and development can transform that idea into an innovation.

Midrex R&D is guided by the following objectives:

- Maximize long-term return on investment of company's products and services
- Make optimum use of the available human and physical resources
- Maintain a balanced R&D portfolio (between basic, applied and developmental)
- Foster a favorable climate for creativity and innovation

Midrex has built its business on a "renewable technology" concept, a self-sustaining cycle that blends science, engineering and real world experience to constantly renew and improve technologically sound processes and systems. **The MIDREX® Technology Cycle** is powered by the spirit of innovation that is centered on the **Midrex Research & Development Technology Center**, located in Pineville, North Carolina, USA.

MIDREX® TECHNOLOGY CYCLE



Research and Development creates and refines knowledge and proves its feasibility. Engineering converts the knowledge into practical products that Sales and Marketing match with needs in the marketplace in order to provide solutions. Technical Service and aftermarket sales (i.e., Midrex Global Solutions) interact with the users of the products and feedback suggestions and ideas for research and development to use in renewing and expanding the technology.

WORLD CLASS FACILITIES AND EQUIPMENT

BEFORE MIDREX WAS A COMPANY THERE WAS A MIDREX TECHNICAL CENTER, WHICH HAS BEEN AT THE FOREFRONT OF THE EVOLUTIONARY DEVELOPMENT OF ALL MIDREX® TECHNOLOGIES.

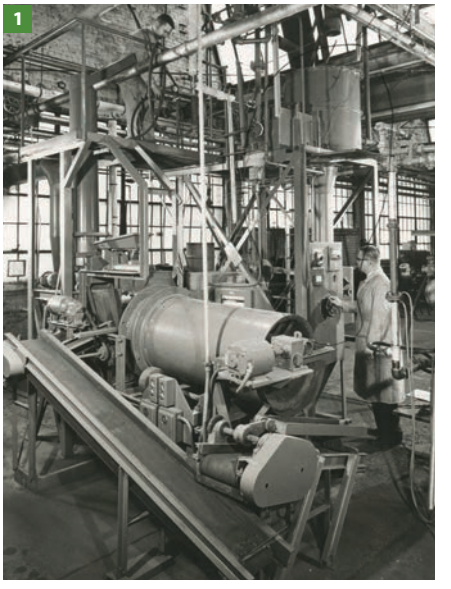
The original Midrex Technical Center was established in Toledo, Ohio, USA, in the 1960s, by Surface Combustion, Inc. Its purpose was to discover and develop a new, better way to transform iron ores into metallic iron. The engineers, scientists and technicians selected for this assignment possessed varied expertise and experience in thermal processing of solids, gas reforming and industrial furnace design. The result was the MIDREX® Direct Reduction Process.

In 2015, the **Midrex Research and Development Technology Center** went through a significant expansion in order to better serve the ever changing demands of the global Steel and Mineral processing industries.

THE MIDREX R&D TECHNOLOGY CENTER

Over the years, the Midrex Technical Center has been relocated, modified and upgraded several times and its name has been changed to reflect its role. The **Midrex Research & Development Technology Center**, as it is now known, is involved in testing and analyzing minerals and materials to increase the performance and scope of the **MIDREX® Process** and in seeking ways to apply Midrex know how and expertise outside the field of direct reduction.

Today the **Midrex Research & Development Technology Center** (Technology Center) is the principal facility for ferrous and non-ferrous reduction technology development for Midrex Technologies Inc. and its parent company, Kobe Steel Ltd. (KSL).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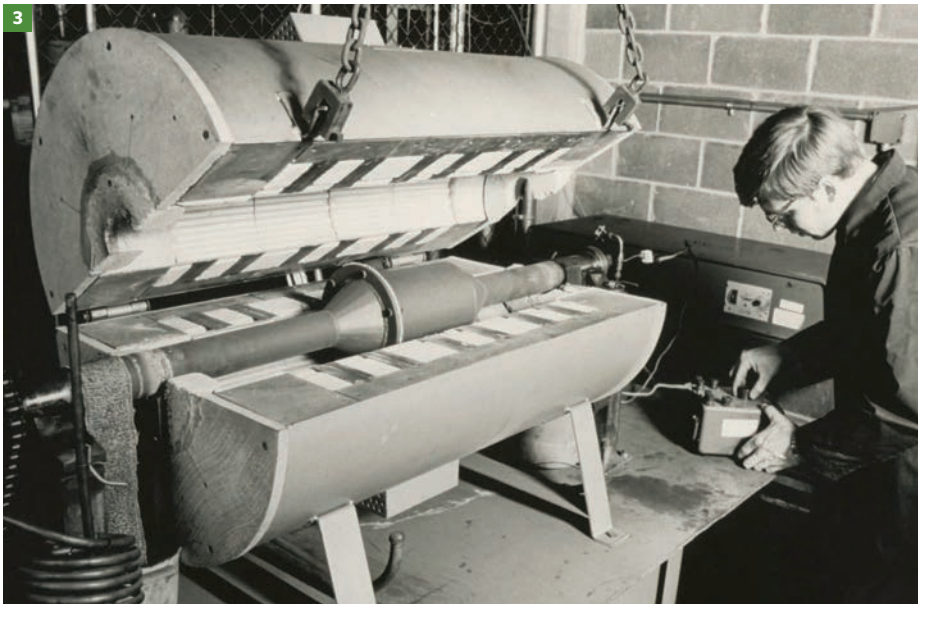
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(1) The original Midrex Technical Center located first in Toledo, Ohio, USA and owned by Surface Combustion, Inc. (circa 1969).

(2) In 1974, when the Midrex Corporation was founded in Charlotte, NC, USA, a modern 15,000 square-foot office/laboratory R&D facility was established in nearby Pineville, NC, USA.

(3) The Linder furnace *(pictured here)* has been a constant fixture of the Midrex R&D center. Linder tests primarily determine low temperature disintegration behavior of oxide pellets and lump ores; it is the standard test for ISO 11257.

(4) Pelletizing and briquetting equipment housed in a weatherized building.

(5) The newly renovated Midrex R&D Technology Center located in Pineville, NC, USA.

(6) Midrex metallurgist tapping the experimental electric ironmaking furnace (EIF).

(7) Samples of Cold DRI (CDRI) and HBI. The Midrex R&D Technology Center has the capabilities to produce and analyze various DRI products.

THE MIDREX R&D TECHNOLOGY CENTER

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CAPABILITIES OF THE MIDREX R&D TECHNOLOGY CENTER

- Physical testing of raw materials (screen analysis, bulk density, compression strength, tumble index)
- Lab-scale/bench-scale testing & evaluation:
  - Catalysts
  - DRI metallization, strength and reoxidation
  - Heat processing/reduction of iron ore (up to 1700° C with atmospheres)
  - Coal reactivity/gasification
  - Coke oven gas (COG) reforming
- Commercial-scale testing & evaluation:
  - Minerals characterization (chemical and physical)
  - Minerals preparation (pulverizing, grinding and beneficiation)
  - Pelletizing (balling, drying and screening)
  - Briquetting (production, separation and cooling)

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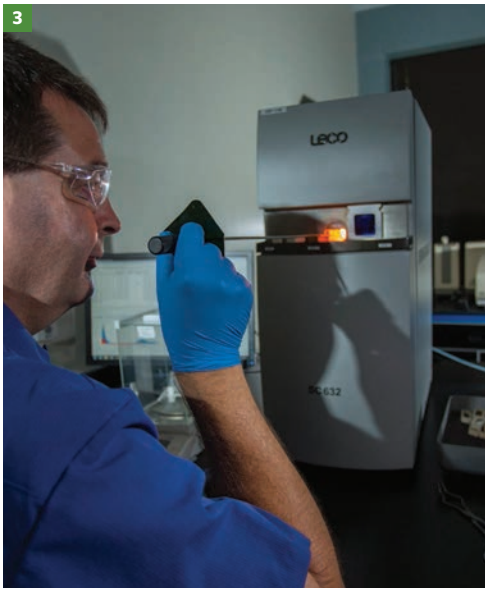
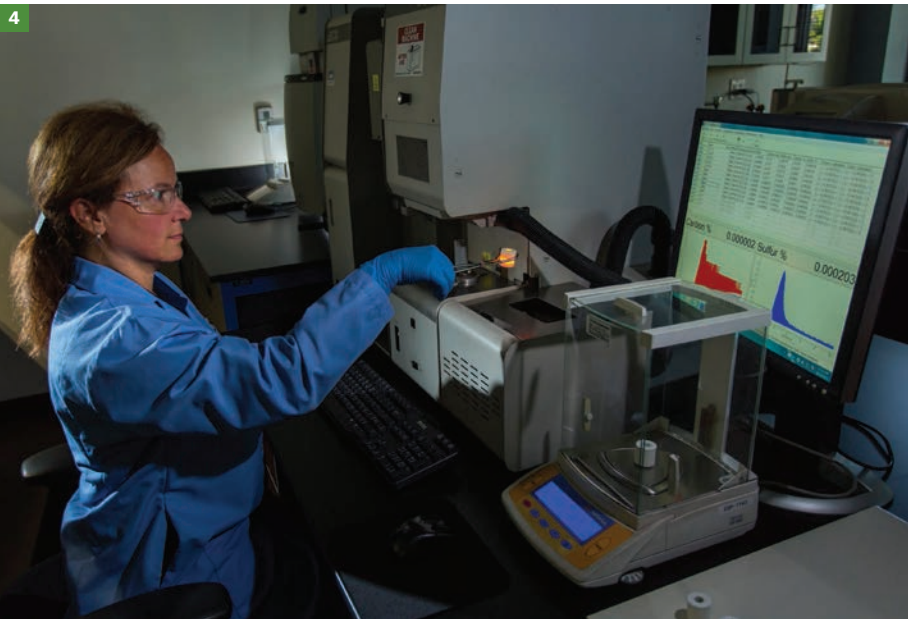
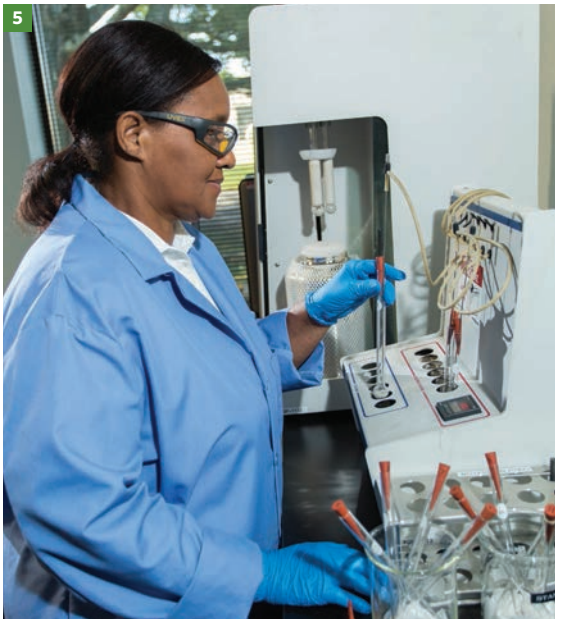
ANALYTICAL OPERATIONS

Midrex R&D labs have tested more than 7,000 iron-bearing materials, and some of the testing protocols developed over the years by Midrex have become ISO standards. The state-of-the-art minerals testing laboratories that comprise the Analytical Operations in the Technology Center allow Midrex to thoroughly evaluate various iron ores and alternative iron-bearing materials, as well as non-ferrous materials. The facilities, equipment and personnel also are valuable resources for supporting **MIDREX® Process Licensees** and potential clients.

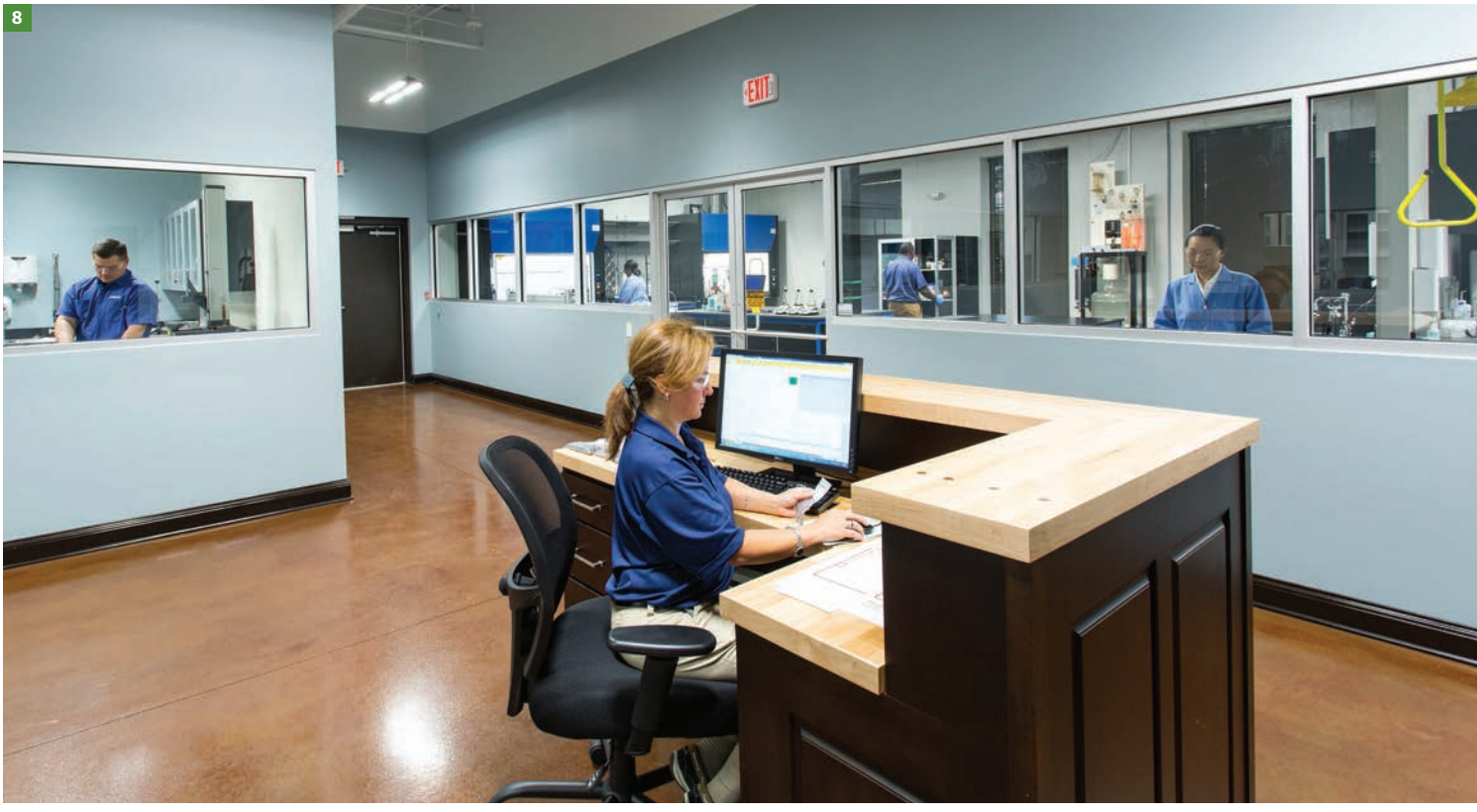






(1) X-Ray Lab – A Thermo Scientific™ XRF/XRD Analyzer has two uses: 1) to determine the elemental composition and concentration of a material, such as iron, and 2) to measure the crystal structure of a material in order to determine if the iron sample is hematite (Fe_2O_3), magnetite (Fe_3O_4) or metallic Fe_0. **(2) Microscopy Lab** – A TESCAN Scanning Electron Microscope (SEM) is used for high magnification imaging of samples. SEM produces high resolution, high depth-of-field photomicrographs which provide information about the topography and structure of the sample and detect contrast between areas of different chemical compositions. **Instrument Lab** – **(3)** LECO 632 and **(4)** 230 Carbon/Sulfur Analyzers are used to expose samples to high temperatures under high concentration of oxygen in order to accurately determine carbon and sulfur concentrations. Carbon and sulfur are oxidized to CO_2 and SO_2 and measured with infrared absorption detectors. **(5)** A Micromeritics Instruments Surface Area Analyzer, also known as BET for its inventors (Brunauer, Emmett and Teller), is used to determine the specific surface area of a fine-sized sample.

ANALYTICAL OPERATIONS



(6) Wet Chemistry Lab – Titration is used for accurate individual elemental or specific ion analysis, such as for total iron, ferrous iron, metallic iron, nickel or zinc. **(7) ICP Lab** – A Perkin-Elmer Inductively Coupled Plasma-Optical Emission Spectrometer (ICP-OES) analyses a sample digested in liquid instead of in solid form (like XRF), which has the advantage of detecting trace element content. ICP-OES and XRF results, along with SEM and titration, often are compared to improve confidence in results.
(8) Central Lab Station – Samples are received and logged at the central station of the Analytical Operations area before being sent to the various laboratories for preparation, testing or analysis. ***Pictured from left to right are the Sample Preparation Lab, Physical Testing Lab, Wet Chemistry Lab and ICP Lab.***

BENCH-SCALE TESTING

Bench-scale tests typically are used to study specific basic reactions under controlled conditions.

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(1) There are three main parameters in testing iron ores for direct reduction use: low temperature disintegration, reducibility and clustering. Midrex uses a Linder test furnace, a custom furnace and a thermal gravimetric analyzer (TGA) to evaluate these parameters *(pictured from left to right)*. The Linder test primarily determines low temperature disintegration behavior of oxide pellets and lump ores, and is the standard test for ISO 11257. The custom furnace and TGA reduce the iron ore samples and measure the weight change under specific gas compositions, atmospheres, residence times and temperature profiles. The results of these tests are used to determine clustering tendencies (ISO 11256) and reducibility characteristics (ISO 11258).

(2) Mass spectrometer is used to identify the amount and type of chemicals present in a gas sample by measuring the mass-to-charge ratio and abundance of gas-phase ions. Mass spectrometry has both qualitative and quantitative uses, which include identifying unknown compounds, determining the isotopic composition of elements in a molecule, and determining the structure of a compound by observing its fragmentation. Other uses include quantifying the amount of a compound in a gas sample and studying the fundamental chemistry of ions and neutrons in a vacuum.

2

FABRICATION, ELECTRICAL & INSTRUMENTATION

Innovation often is not readily supported by off-the-shelf items. Even when equipment and controls are available, there is a good chance they will need to be reconfigured to meet the specifications and requirements of Midrex. Therefore, it is essential for the Technology Center to have the equipment, skills and expertise to maintain its facilities and pilot operations and support simulator operations.

(3) Custom machining and welding are among the fabrication activities performed by Technology Center personnel.

(4) Instrumentation and process controls are installed, programmed and maintained by skilled technicians.

(5) Immediate repairs and "on-the-fly" adjustments to test equipment and facilities can be made during a test campaign.

PELLETIZING, BRIQUETTING & MELTING

Direct reduced iron is an intermediate phase in the journey of iron from the oxide state to becoming the primary ingredient in many steel products. Therefore, Midrex has the equipment and expertise to study the processing of iron from grinding and beneficiating, agglomerating and indurating through hot briquetting and melting.

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- **(1) Pelletizing** – The Technology Center has the capability to prepare various iron oxide materials for pelletizing including raw material preparation, forming the material into green balls *(shown here)*, indurating the green balls and cooling and storing the finished pellets.

  (2) A commercial-scale Köppern briquetting machine is installed at the Technology Center and used to produce **(3)** HBI from various DRI pellet chemistries.

  (4) Midrex uses an **electric ironmaking furnace (EIF)** to analyze the melting characteristics of ferrous and non-ferrous materials.

4

PILOT/DEMONSTRATION PLANT OPERATION

Pilot plants typically have small reactors and supporting auxiliaries with the goal of defining mass balance and operating principles. What starts as an idea can be further pursued and examined at the Technology Center and then eventually be realized at a Demonstration Plant site. **Demonstration Plants** are used to study the viability of a process on a pre-commercial scale. The progressive scale-up of technology from bench-scale to pilot to demonstration plant is a responsible way of commercializing technology that minimizes business risk.

(5) Catalyst testing facility (CTF) simulates typical commercial activity of catalyst in a MIDREX® Reformer. The CTF is used for fundamental catalyst research into optimizing shape and chemistry and measuring strength and reactivity.

(6) From 1992-94, Midrex and Kobe Steel Ltd. (KSL) operated a 150 kilogram/hour FASTMET® rotary hearth furnace (RHF) pilot plant at the Technology Center. Based on the success of these test campaigns, KSL constructed a **demonstration plant at its Kakogawa Works in Japan**. KSL has since built six FASTMET® Plants in Japan for reclaiming useful iron units from iron-bearing dust generated by steel mill operations. The original FASTMET® RHF pilot plant has been repurposed and is currently used for coal-based direct reduction testing.

(7) Midrex and Praxair have teamed up to develop a technology to reform COG for use in a MIDREX® Shaft Furnace. It is known as the Thermal Reactor System™ (TRS®). This unique approach utilizes partial oxidation to create a high quality, high temperature syngas for use as reductant gas. **A large-scale demonstration facility at the Technology Center** has been operated for more than 1000 hours to prepare the Thermal Reactor System™ (TRS®) for commercialization by Midrex and Praxair.

PEOPLE, EXPERTISE AND VISION

A COMMON PURPOSE: TO SUSTAIN THE TECHNICAL EXCELLENCE AND COMMERCIAL RELEVANCE THAT HAVE COME TO BE EXPECTED OF MIDREX® TECHNOLOGY

What has made Midrex so successful is how its people apply technology to solve problems and achieve results. The Technology Center is the technical learning center for the company and the catalyst for innovation and improvement.

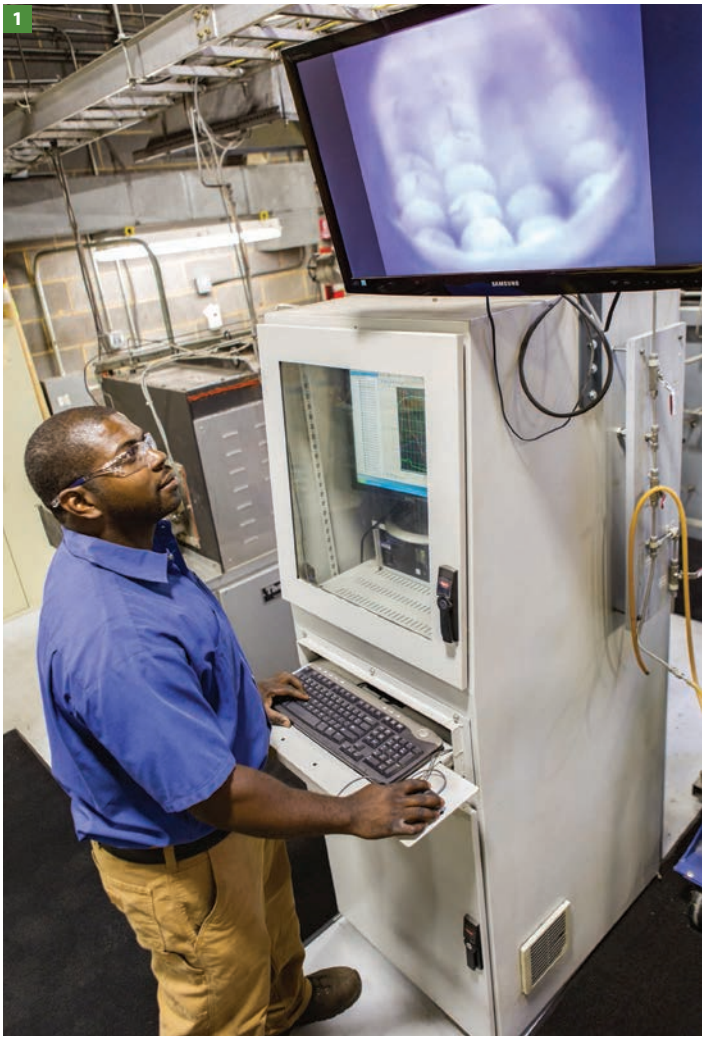
Midrex R&D personnel at the newly expanded Technology Center.

PEOPLE, EXPERTISE AND VISION

Technology Center personnel can be found in offices, labs, testing stations and plant sites – anywhere Midrex is involved. They are a diverse group – engineers, metallurgists, chemists, mathematicians and skilled technicians and administrators. The majority have earned advanced degrees or Professional Engineer credentials. They are a blend of youthful enthusiasm, proven experience and shared focus.

It is normal operating practice for Midrex engineers to be assigned temporarily to the Technology Center, where they participate in developing new technologies, improving existing ones and experiencing first-hand hand what goes into making a direct reduction plant work. Often Technology Center personnel travel to a plant site where they participate in commissioning and start-up activities and assisting Midrex clients with testing and troubleshooting.

In addition, Midrex and its R&D group are committed to providing a safe and healthy working environment for its employees and the community at large.



(1) Midrex Lab technician conducting a coal-based reduction test using a specially configured box furnace.

(2) From lab to the field, Midrex R&D onsite in a MIDREX® DRI Plant in Egypt.

(3) Kobe Steel President and CEO, Hiroya Kawasaki, *(pictured 2nd from the right)* oversees the latest modifications and expansion to the Midrex R&D Technology Center.

(4) Midrex lab personnel use titration to calculate the concentration of a dissolved substance in the expanded wet chemistry laboratory.

(5) Outside of the lab -Engineers discuss preparations for tapping the electric ironmaking furnace during a melting trial.

(6) Reviewing results - Technology Center personnel meet regularly to review safety procedures and discuss R&D projects.

(7) Measuring compression strength of catalyst.

(8) R&D personnel closely monitor controls and instrumentation during TRS® pilot plant operations.

PEOPLE, EXPERTISE AND VISION

MIDREX COMMITMENT

"MIDREX IS A TECHNOLOGY COMPANY FOUNDED ON THE PURSUIT OF INNOVATION AND DEDICATED TO CONTINUOUS IMPROVEMENT," - *DON BEGGS, INVENTOR OF THE **MIDREX® PROCESS***

Forty-five years ago a group of insightful scientists and enterprising engineers came together to forge a partnership that continues to drive Midrex today. It is part of the name. It is manifested in the processes, systems and equipment designs. It is what defines Midrex...Technology.

Throughout its history, R&D has been central to the Midrex business model because technology can never become static...it must be constantly re-engineered and re-invented to remain relevant. To that end, Midrex and KSL have made the Technology Center a center of excellence for advancing the knowledge and understanding of the techniques, methods, materials and equipment that comprise technologies that are reliable, productive and safe.

The **Midrex Research & Development Technology Center** is where vision leads to innovation and creativity spawns improvements to established products and services.

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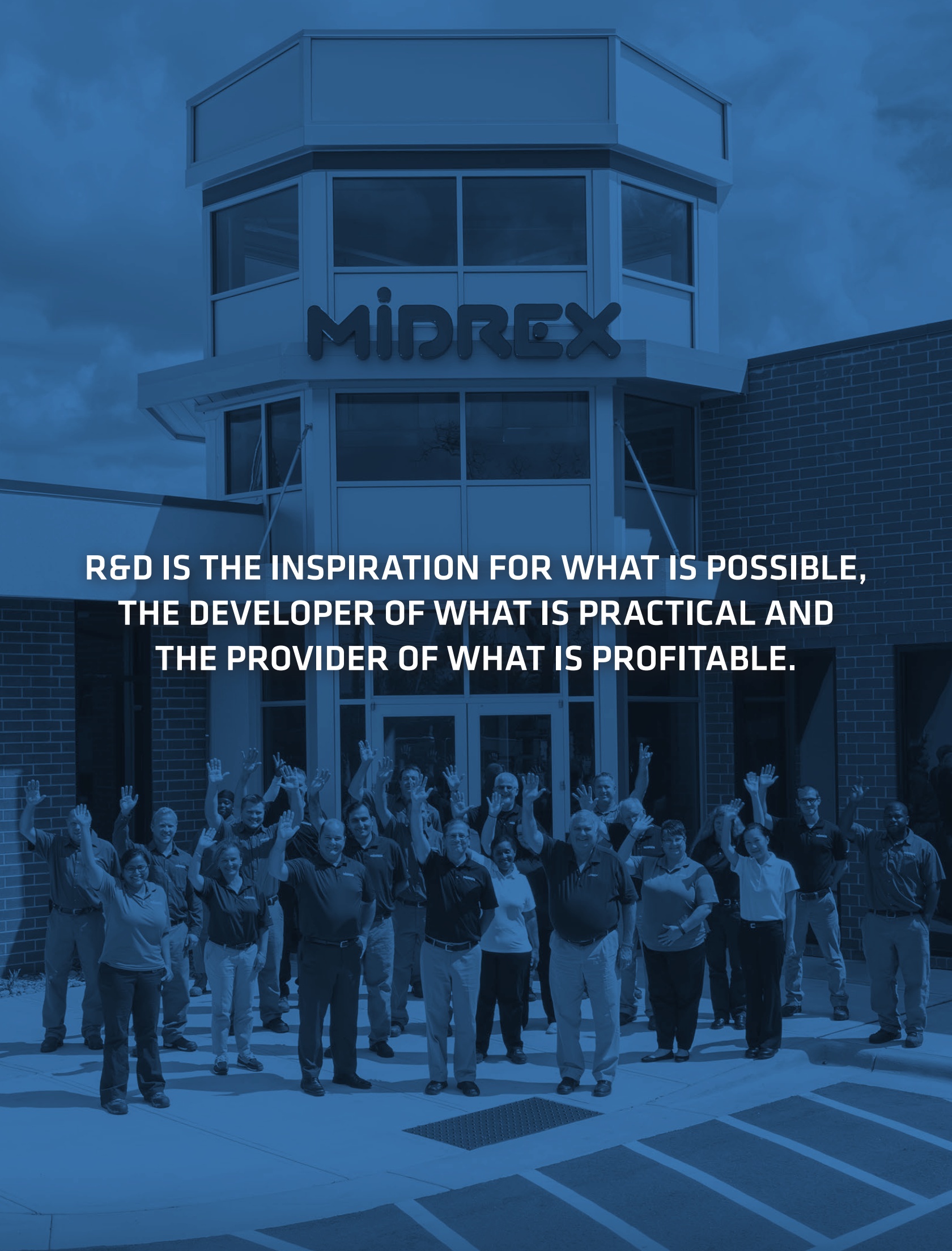
MAJOR MIDREX® TECHNOLOGY DEVELOPMENTS

- In-situ reforming
- Standard/alternate flowsheet configurations
- Lump ore use
- Larger module sizes
- Improved catalysts
- Gas preheating
- Hot discharge shaft furnace
- Hot briquetting
- Top gas fuel preheat
- Iron oxide coating
- Oxygen injection
- Reducing gas options
  - Coal gasification
  - Coke oven gas - Thermal Reactor System™ (TRS®)
- Steam reforming
- Briquette slow cooling
- Use of centrifugal compressors

(1) First MIDREX® Plants built at Oregon Steel Mills in Portland, Oregon, USA, 1969.

(2) Dual product plant Hadeed Module E, Al-Jubail, Saudi Arabia, is the first and currently only plant to have produced 2 million tons within a single calendar year, 2013. Hadeed Module E features many of the major MIDREX® Technology developments listed above.



R&D IS THE INSPIRATION FOR WHAT IS POSSIBLE, THE DEVELOPER OF WHAT IS PRACTICAL AND THE PROVIDER OF WHAT IS PROFITABLE.

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