The (New) Gold Standard for Ironmaking

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Agenda

Objective

Overview of Midrex Technologies Inc.

Direct Reduction Fundamentals

- Use of DRI
- Thermodynamics
- Kinetics
- Iron Ore requirements
- Reforming

The MIDREX® Process

- Overview
- Consumptions & Performance
- Hydrogen

Conclusions

Objective

Conference Topic: Scrap Supplement and Alternative Ironmaking

Used – along with scrap – to make steel (in EAF, BOF, etc.)

Not a blast Furnace

A few considerations if we want to make iron from iron ore (or possibly iron oxide wastes)

- Iron ore is thermodynamically very stable (it's rust!)
  - $Fe_xO_y \rightarrow X\ Fe + Y/2\ O_2$ requires a lot of energy
- Metallurgy:
  - **Pyrometallurgy**: Uses high temperatures to reduce (**H_2 and CO**) and refine metals, including roasting and smelting.
  - Hydrometallurgy: Uses water-based solutions to extract metals from ores through processes like leaching, precipitation or solvent extraction.
  - Electrometallurgy: Employs electrolytic processes (e.g. electrowinning or electrorefining) to recover or purify metals using electricity.
  - Others
- Constraints:
  - Less CO_2 emissions than a blast furnace (ideally close to zero)
  - High volume, high throughput, low cost (ideally close to a blast furnace)
  - Energy efficient
  - Minimum waste products; no hazardous wastes

➔ The MIDREX® Direct Reduction Process is the Best Available Ironmaking Technology for Scrap Supplement

Overview of Midrex Technologies Inc.

Midrex at-a-Glance

Midrex has a unique blend of existing and new technologies to create a sustainable future of iron and steel. Our DR plants produce low CO_2 captive steel production for export to steelmakers around the world.

50+
Years of Commercial Operation

20+
Countries with MIDREX® Plants

MIDREX® Process
MIDREX Plants Produce about 80% of the World's Low CO_2 DRI

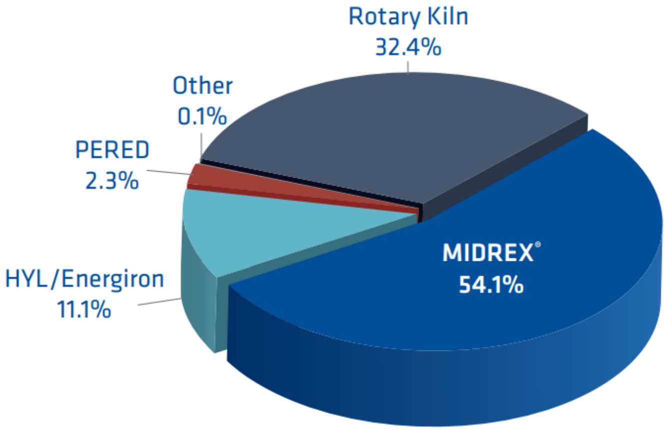
R&D
State-of-the-Art Research and Development

HQ
Charlotte, NC Headquarters +Global Offices

Global DRI Production (2024)

MIDREX Plants produced about 80% of the world's low CO_2 DRI in 2024

2024 World DRI Production by Process



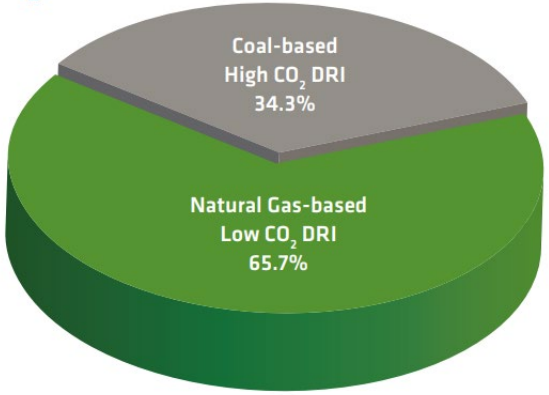
Note: Percentages are rounded to the nearest decimal.

Total World Production: 140.8 Mt

	2022	2023	2024
MIDREX®	57.8%	55.8%	54.1%
HYL/Energiron	12.1%	12.2%	11.1%
PERED	2.2%	2.3%	2.3%
Other	0.1%	0.1%	0.1%
Rotary Kiln	27.9%	29.6%	32.4%

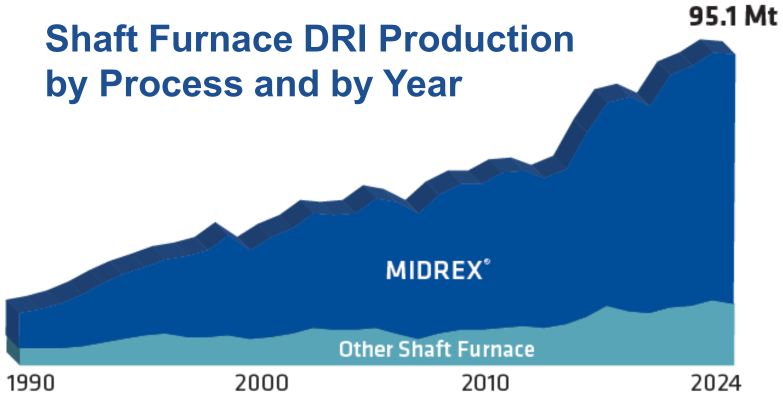
Source: Midrex Technologies, Inc.

2024 World DRI Production by CO_2 Emissions



- Ironmaking is the most energy intensive step in producing steel
- Recycling scrap significantly reduces emissions, but there is not sufficient high-quality scrap to produce high-grade steel
- Decarbonization and the need to supplement scrap are dramatically increasing the demand for DRI
- Not all DRI is low CO_2 : DRI produced in rotary kilns have much higher emissions (mostly in India), and growing

Shaft Furnace DRI Production by Process and by Year



Direct Reduction Fundamentals

(very abbreviated)

Product Requirements

Direct Reduced Iron Products are used as “metallic units” in Steelmaking

- In Electric Arc Furnaces, with various ratios of Scrap and Pig Iron
- In Blast Furnaces to increase productivity

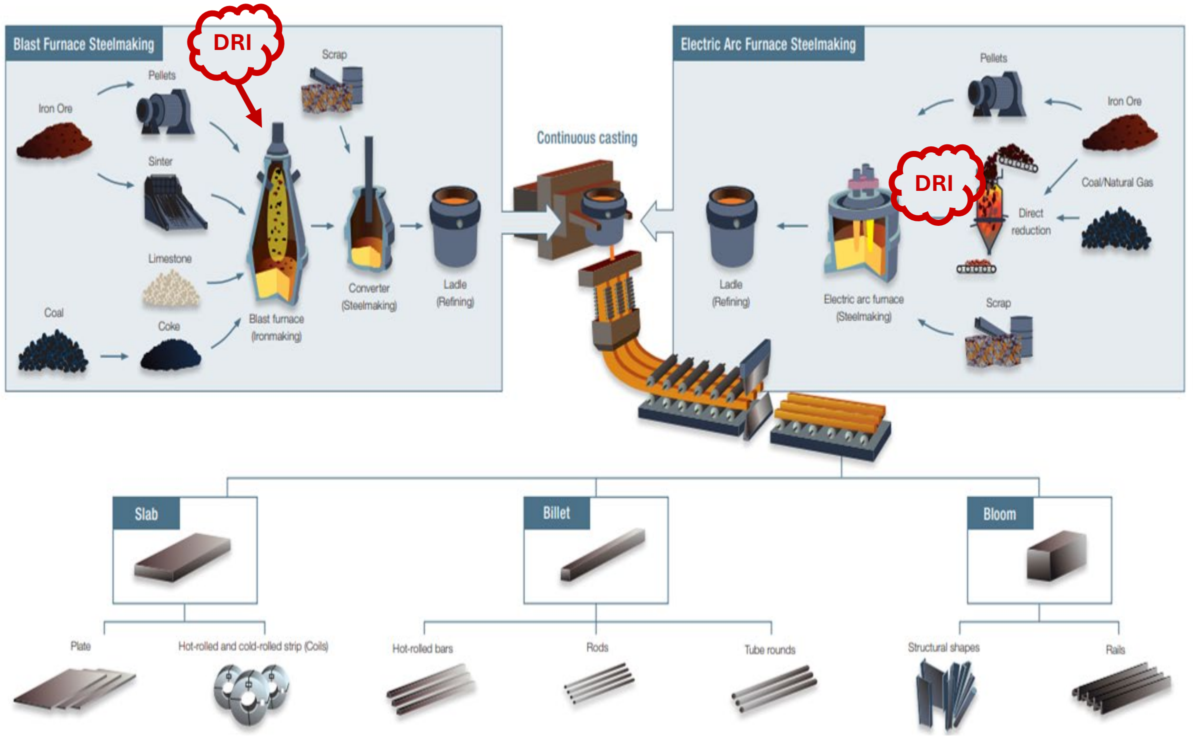
DRI can be produced at a steel plant, or as an independent unit

EAF Requirements:

- If charged directly into an EAF: Temperature
- High (and uniform) Metallization
- Optimum Carbon for (1) reduction of final FeO and (2) energy in the EAF)
- Minimum fines
- Minimum gangue [iron ore selection]
- (density)

Shipping Requirements: Safety and Yield

- International Maritime Organization requirements
- DRI is ‘reactive’ in bulk. It generates heat and hydrogen
- HBI is the ideal form of DRI
  - HBI strength is driven by briquetting temperature



Source: Worldsteel

Principles of Direct Reduction

Gas-solid reactions with Syngas (H_2+CO)

- Net reduction by Hydrogen: $Fe_2O_3 + 3\ H_2 \rightleftharpoons 2\ Fe + 3\ H_2O$ (endothermic)
- Net reduction by Carbon Monoxide: $Fe_2O_3 + 3\ CO \rightleftharpoons 2\ Fe + 3\ CO_2$ (exothermic)

Above 600°C, the reduction reactions take place in steps:

- Fe_2O_3 Hematite (HCP 5.3g/cm^3) → Fe_3O_4 Magnetite (FCC 5.2g/cm^3) → Fe_xO Wustite (FCC 5.7g/cm^3) → Fe Iron (BCC 7.9g/cm^3)
- Molecular structure changes & macroscopic swelling / Crack formations.

H_2/CO ratio in the reducing gas has a significant role in the amount of heat required for the process

- FeO reduction by Hydrogen: $FeO + H_2 \rightleftharpoons Fe + H_2O$ ($DH_{800°C}$ = 16.41 kJ/mol)
- FeO reduction by Carbon Monoxide: $FeO + CO \rightleftharpoons Fe + CO_2$ ($DH_{800°C}$ = -17.61 kJ/mol)

→ **More CO is desired to provide heat in the reactor** (MIDREX Gas Composition is 55%H_2, 35%CO)

Carburization Reactions:

- $3\ Fe + CH_4 \rightleftharpoons Fe_3C + 2\ H_2$
- $Fe + 2\ CO \rightleftharpoons Fe_3C + CO_2$
- $3\ Fe + CO + H_2 \rightleftharpoons Fe_3C + H_2O$

Other Reactions:

- **$2\ CO \rightleftharpoons C + CO_2$ (Boudouard)**
- $CO + H_2O \rightleftharpoons CO_2 + H_2$ (water-gas shift)
- $CH_4 \rightleftharpoons C + 2\ H_2$ (methane cracking)
- $CH_4 + H_2O \rightleftharpoons CO + 3\ H_2$ (steam reforming)
- $CH_4 + CO_2 \rightleftharpoons 2\ CO + 2\ H_2$ (CO_2 Reforming)

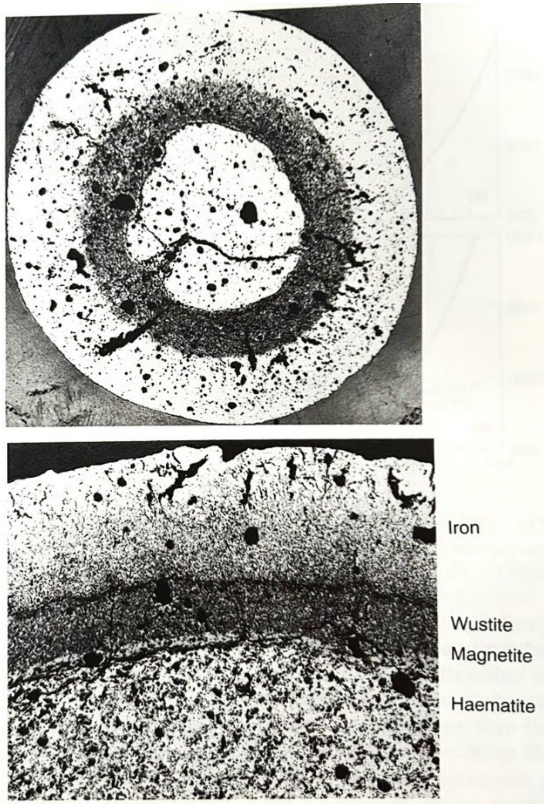
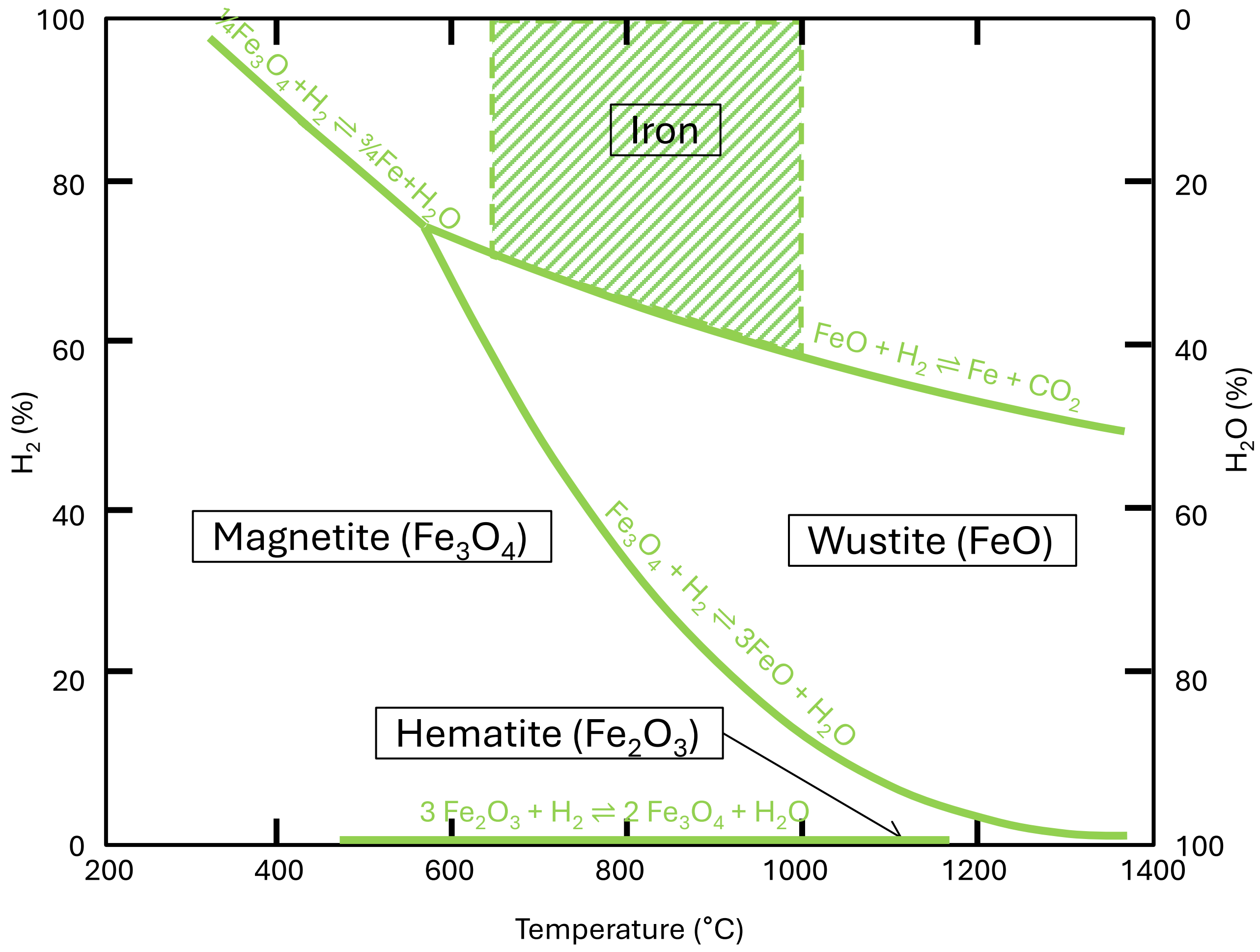


Fig. 2.16 Formation of reaction product layers in the gaseous reduction of haematite pellets.

Source: Turkdogan E.T. Fundamentals of Steelmaking, 1996, The Institute of Materials, London, UK.

Thermodynamic Values from F. Patisson. Hydrogen Ironmaking: How it works. *Metals*, 10, 2020, 10, pp.922

Iron-Oxygen-Hydrogen Equilibrium Gas Composition



Equilibrium Gas Composition vs. Temperature (Thermodynamically possible, but no reaction kinetics constraints)

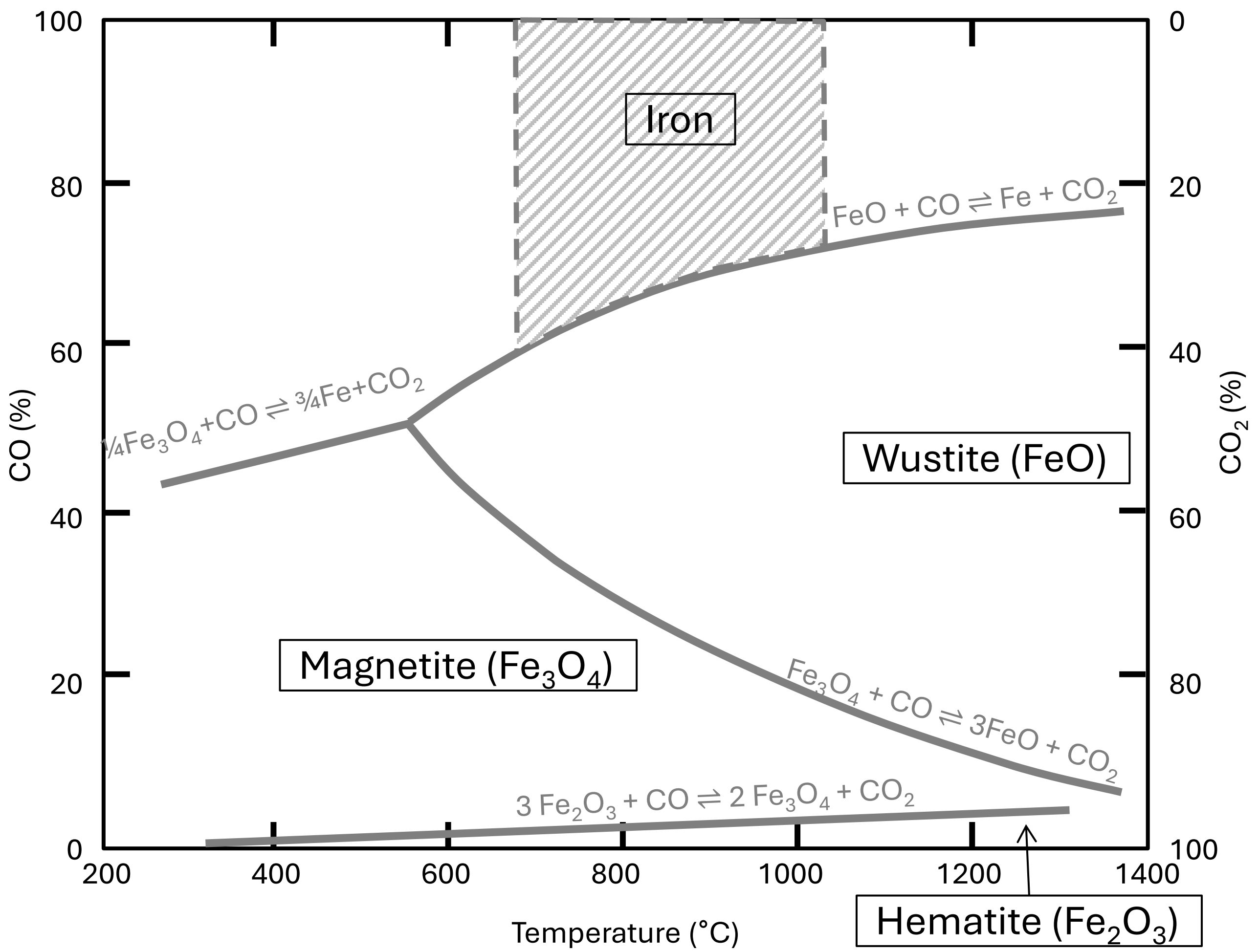
The reduction of iron oxide by Hydrogen happens in sequence:

- $3\,Fe_2O_3 + H_2 \rightleftharpoons 2\,Fe_3O_4 + H_2O$ (H→M)
  Favorable even at low H_2/H_2O
- $Fe_3O_4 + H_2 \rightleftharpoons 3\,FeO + H_2O$ (M→W)
  Requires Temperature > 600°C and higher H_2/H_2O
- $FeO + H_2 \rightleftharpoons Fe + H_2O$ (W→Iron)
  Requires elevated Temperature and excess Hydrogen

➔ The last reaction in the sequence requires more temperature and higher "reducing gas quality" (more oxidants)

Chart Redrawn from Direct Reduced Iron: technology and economics of production and use. The Iron & Steel Society of AIME. Warrendale, PA. 1980

Iron-Oxygen-Carbon Equilibrium Gas Composition



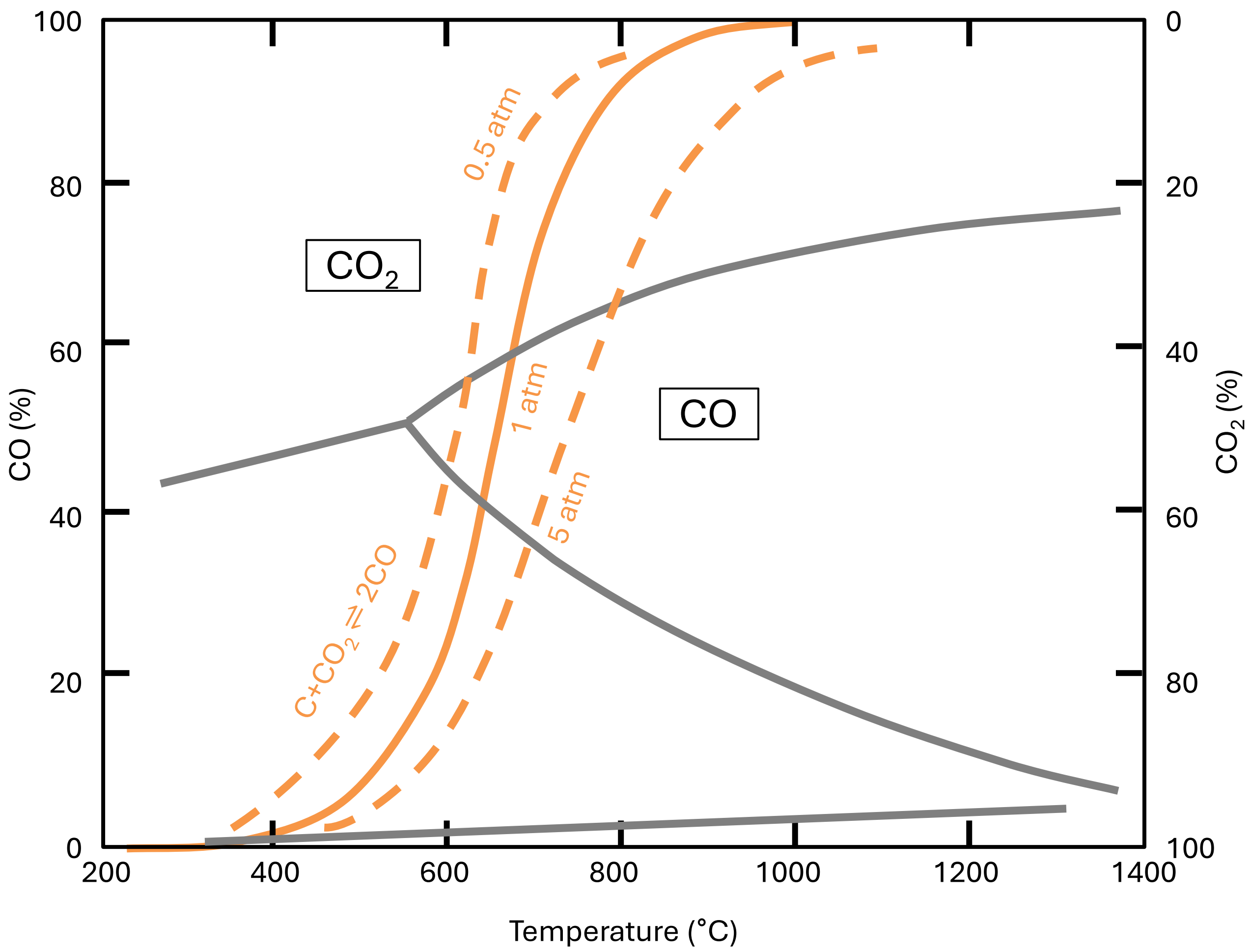
Same as previous chart, but for CO-CO_2

The reduction of iron oxide by Carbon Monoxide also happens in sequence.

- $3\ Fe_2O_3 + CO \rightleftharpoons 2\ Fe_3O_4 + CO_2$ (H→M)
  Favorable even at low %CO
- $Fe_3O_4 + CO \rightleftharpoons 3\ FeO + CO_2$ (M→W)
  Requires Temperature > 600°C and higher CO/CO_2
- $FeO + CO \rightleftharpoons Fe + CO_2$ (W→Iron)
  Requires Excess Carbon Monoxide

Chart Redrawn from Direct Reduced Iron: technology and economics of production and use. The Iron & Steel Society of AIME. Warrendale, PA. 1980

Effect of Pressure on the Boudouard Reaction Equilibrium



The Boudouard Reaction is always in consideration during Direct Reduction:

- $2\ CO \rightleftharpoons C + CO_2$

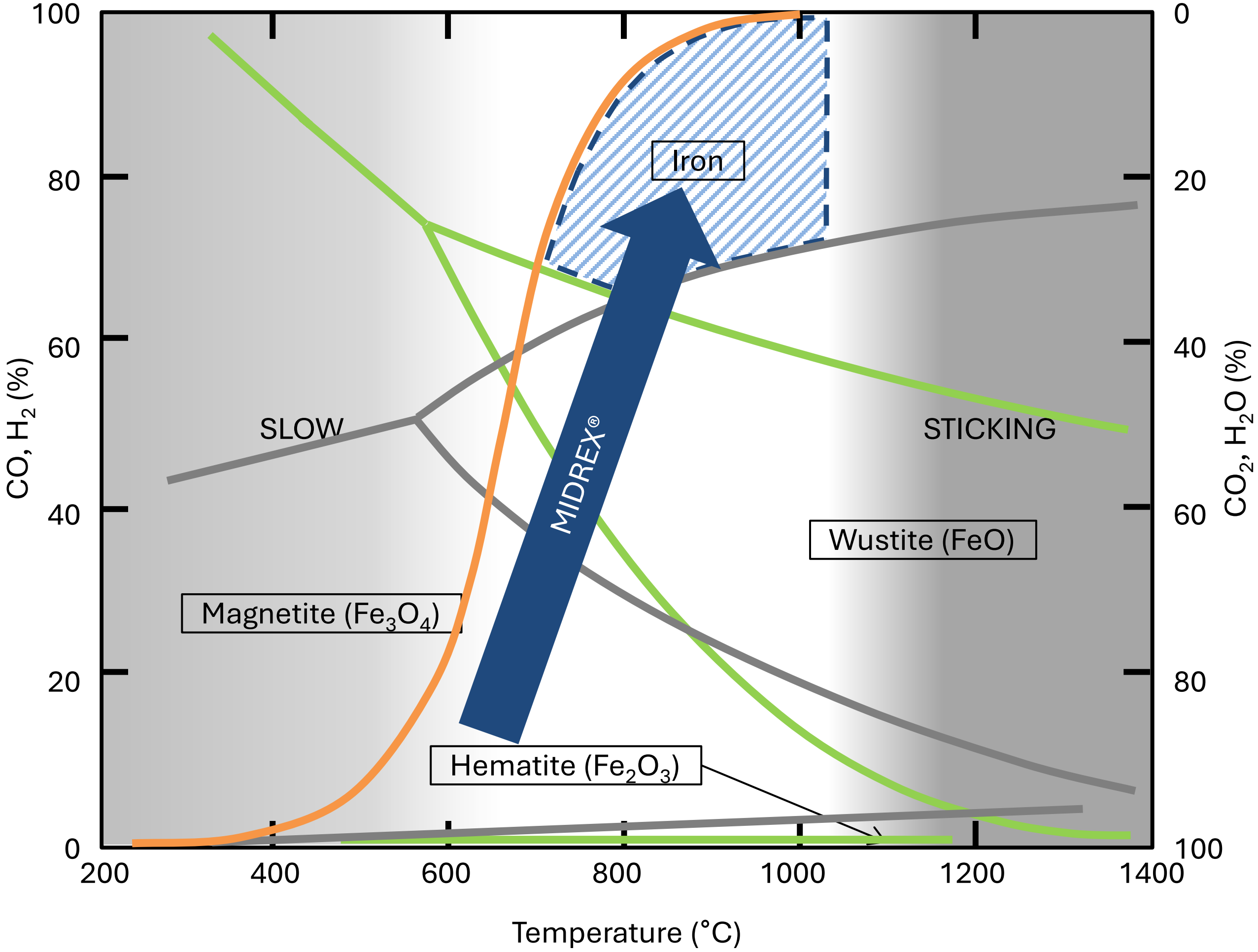
The Boudouard reaction equilibrium is affected by pressure:

- Increasing Pressure shifts the equilibrium toward making more CO_2 and Carbon at high pressure

More critical for reforming than reduction

Chart Redrawn from Direct Reduced Iron: technology and economics of production and use. The Iron & Steel Society of AIME. Warrendale, PA. 1980

Fe-C-H-O Equilibrium Gas Composition



Combining the 3 previous charts shows the equilibrium zone for Iron with a mixture of CO/CO_2 and H_2/H_2O.

Reactions are slow at low temperature, so reduction under ~600°C is not practical

Iron ore sticking occurs above ~1000°C. Reduction above ~1050°C is not possible (depending on pellets and coating)

The preferred reduction path is illustrated in Blue:

- H → M Can start at lower temperature and lower gas quality
- M → W requires higher temperature and gas quality
- W → Iron requires the highest temperature and gas quality
  - $(H_2+CO) / (H_2O+CO_2) > 2$
  - In practice, it is 10-12

Gas utilization = The ratio of the calculated minimum flow requirement to the actual flow supplied

- In practice, gas utilization is 80-90% (excess flow of 10-20%)

➔ **COUNTERFLOW REACTOR**

Residence Time = Reduction Kinetics

There have been many studies over 50 years. One reference quoted 109 studies on Hydrogen alone. These two articles have good summaries:

- D. Spreitzer and J. Schenk. Reduction of Iron Oxides with Hydrogen—A Review. *Steel Research Int.* 2019
- Fradet. F. et al. Thermochemical reduction of iron oxide powders with hydrogen. *Thermochimica Acta* 726 (2023) 179552

There are no universally accepted kinetic models for reduction of iron ores. The measured reaction kinetics (and rate controlling mechanism) depend on the experimental conditions.

- Single pellets: variability in mineralogy, porosity etc., even from the same manufacturer / lot
- Fixed bed: stratification and gas distribution
- Small moving beds: gas distribution (wall effects)
- Non-adiabatic: heat loses + external heating
- Isothermal vs. non-isothermal (temperature ramps up & down)
- Gas composition: fixed vs steps
- Gas composition: Presence of oxidants (CO_2 and H_2O)
- Specific gas flow

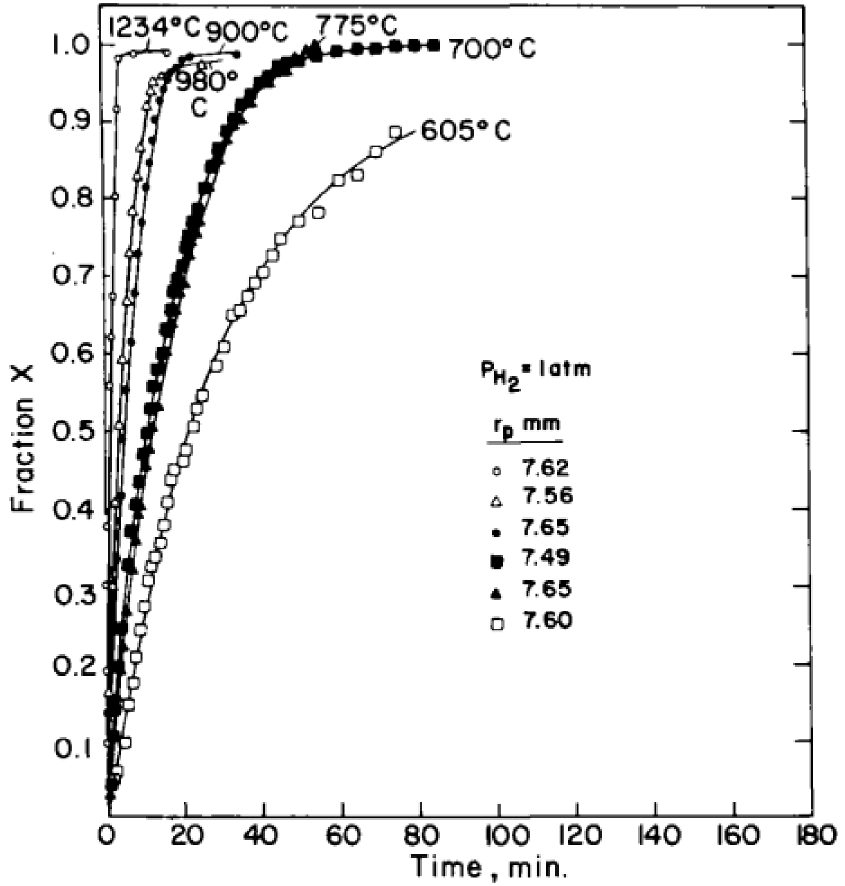


Chart: N. Towhidi and J. Szekely. The Influence of Carbon Deposition on the Reduction Kinetics of Commercial Grade Hematite Pellets with CO, H_2, and N_2. Met. Trans. B. Volume 14B, 1983, pp359-367

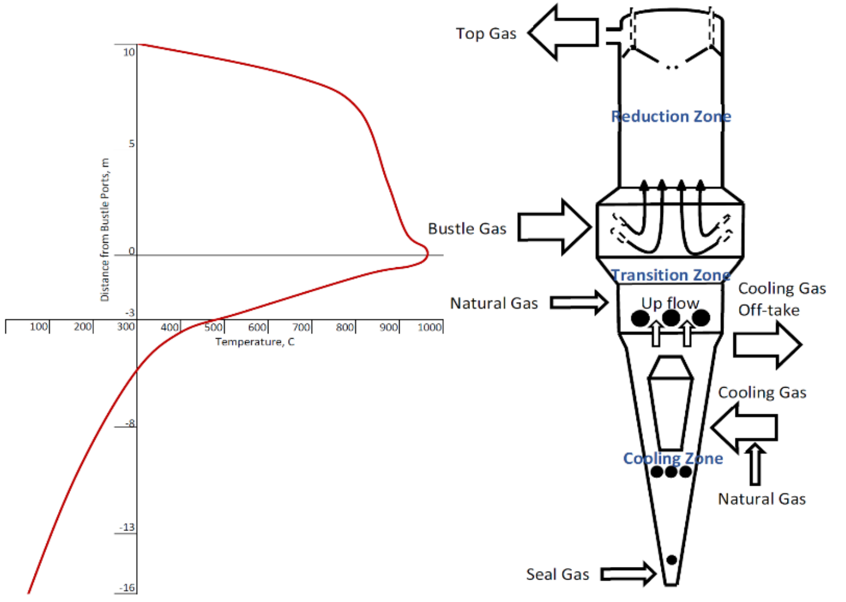
Reduction Kinetics in a Shaft Furnace

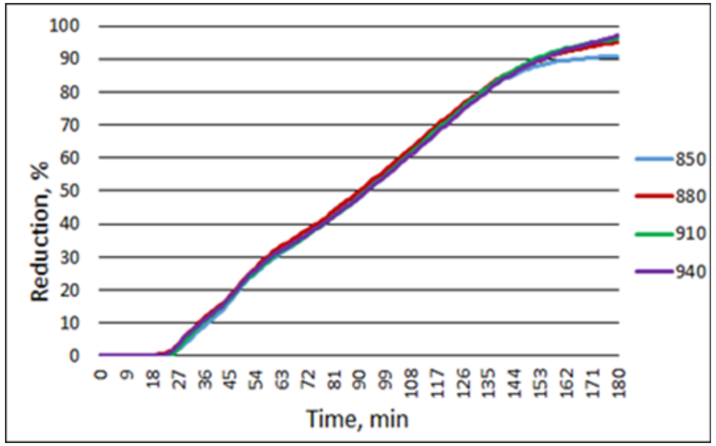
What we know:

- Chemical reaction controlled at low temperature and gas reducing potential
- Diffusion controlled at high temperature and high gas reduction potential
  (Products of Reaction H_2O)
- Temperature is the most important factor
- Pressure has limited to no impact on reaction kinetics
- Pellet size
- Lump ore are harder to reduce
- Magnetite is harder to reduce than Hematite (but pellets are hematite!)
- Iron ore gangue composition may be a factor, but there are no definitive studies
- Starting porosity is important… but cracking during reduction is more important
- Reduction takes ~ 3 hours in a commercial plant (vs. 30-100 min in the lab)
- Changes in discharge rate (residence time) in a plant affects metallization. The curve is not 'flat'.

Lab studies and standard tests like ISO 11257 and COREM's R180 are good for comparison, but not for prediction at industrial scale.

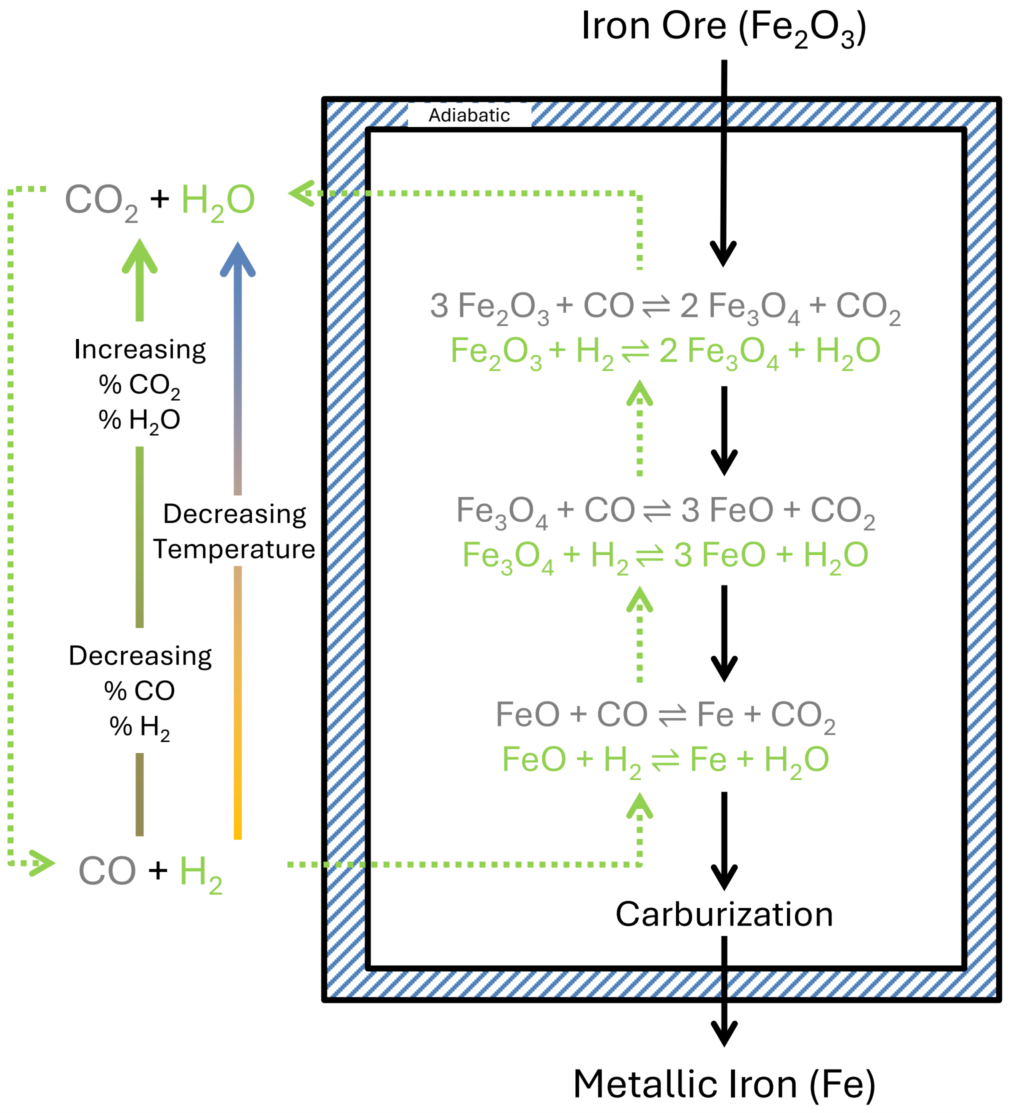
→ Tolerance to various inputs (iron ore suppliers, gas composition etc.) and operation flexibility are far more important than reaction kinetics. The Process needs to be robust to variable inputs over 30 years of operation.





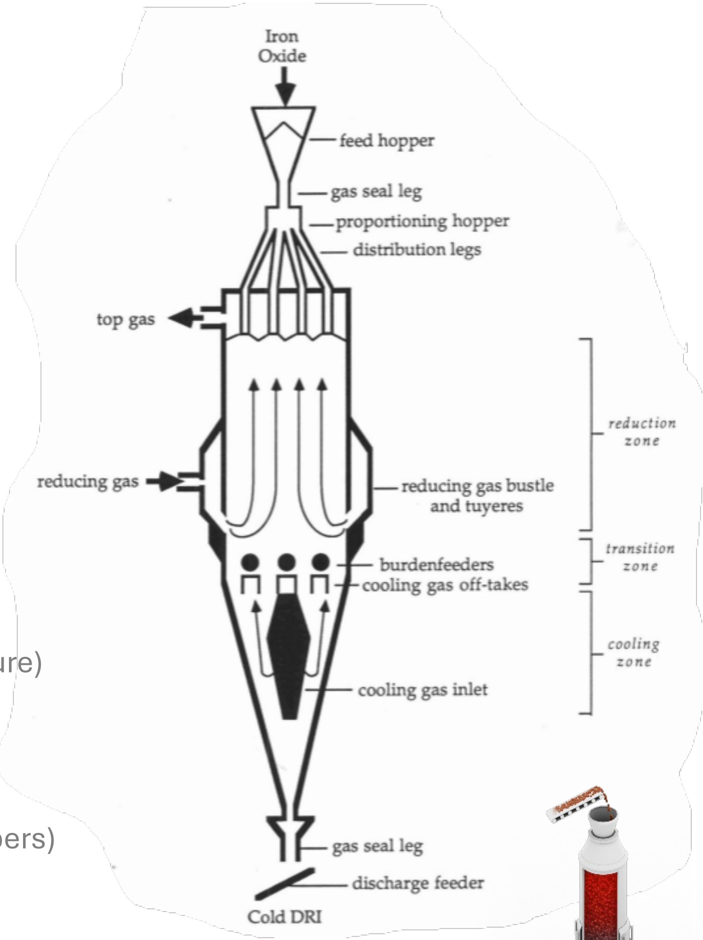
M. Farahani et al. Laboratory Study of Reduction Kinetics in a DRI Shaft Furnace 8th ICSTI Conference, 25-28 September 2018, Vienna, Austria

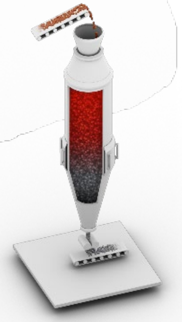
Vertical Reduction Furnace



Design Considerations:

- Uniform Product Quality:
  - Metallization and Carbon
  - Discharge Temperature (HBI and HDRI)
- Time at temperature:
  - Lower H_2 / CO ratio
- Uniform down flow of iron ore
  - Gravity
  - No Bridging
  - No fluidization (Specific flow >> Pressure)
  - Mass flow vs. funnel flow (flow aids)
- Uniform flow of gas (no Channeling)
  - Pellet size distribution
  - Bustle design
  - Avoidance of Clustering (Bustle temperature)
  - Avoidance of Fines (external and internal)
- Minimize internal Fines Generation
  - Pellet Quality (Cold and Hot Strength)
  - Furnace seals (dynamic legs vs. lock hoppers)
  - Cracking (thermal & carbon deposition)
- Low Pressure
  - Reaction kinetics not impacted by Pressure
  - Furnace seals
  - Construction





Iron Ore

Feed: pellets and lump

- Products from mines is either coarse (DSO, lump), fines or ultra-fines.
- Lumps and pellets are typically used in Direct Reduction
  Sinter is generally not available and not strong enough to ship
- Gangue: it is a passthrough. There are no requirement from DR; only from the melter (rebuttal of MIDREX can only use 67% iron ore pellets)

Pelletizing increases cost and CO_2 footprint, but…

- Pelletizing allows blending of various sources of iron:
  - Larger supply chain,
  - Mixing of lower grade Iron Ores (↑ volumes and ↓ costs)
  - Can be done at the mine or on-site
- Pellets are strong and easy to handle (low yield losses)
- Pellets are a very consistent product:
  - Particle size distribution
  - Chemical composition - Hematite
  - Reducibility

Midrex Iron Ore (old) Specifications

- created >30 years ago for nearly 100% DR → EAF
- Mostly a steelmaker requirement
- "DR grade" pellets should be called "EAF grade" pellets
- Not absolute numbers

	Pellets	Lump	
Chemical Characteristics			
Fe	67.0% min	67.0% min	Steelmaking Req's
$SiO_2 + Al_2O_3$	3.0% max	3.0% max	
S	0.008% max	0.008% max	
P	0.03% max	0.03% max	
TiO_2	0.15% max	0.15% max	← Reducibility
Physical Characteristics			
Nominal size	6 x 16 mm	10 x 35 mm	Gas flow
10 x 35 mm		85% min	
9 x 16 mm	95% min		
minus 5 mm	3% max	5% max	
Compression strength	250 kg_f min		Fines Generation
less than 50 kg_f	2% max		
Reduction Characteristics			
Midrex Linder Test (760°C)			Specific Testing (simulation of DR): Metallization, Fines, Clusters
metallization	93% min	93% min	
minus 3.36 mm	2% max	2% max	
Hot Load Test (815°C)			
Tumble strength (+6.73 mm)	90% min	85% min	
Compression strength	100 kg_f min		
Clustering (% +25 mm after 10 rev)	0	0	

Syngas Generation

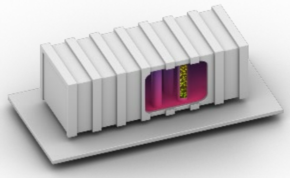
How to make the reduction gas (mixture of H_2 and CO)?

- Reforming:
  - Steam Methane reforming (SMR). High-temperature steam under pressure (3 to 25) bar) with catalysts. H_2:CO ~ 3:1
  - Dry Methane Reforming (DMR) or CO_2 Reforming: Methane reacts with carbon dioxide instead of steam. H_2:CO ~ 1:1 to 2.5:1
  - Auto Thermal Reforming (ATR). Uses pure oxygen instead of air. H_2:CO ~ 1:1
- Partial oxidation (POX): Combustion of methane with limited supply of oxygen to produce CO instead of CO_2. H_2:CO ~ 2:1
- Methane Pyrolysis: Methane is reacted with a limited amount of oxygen. Makes solid carbon. H_2:CO ~ 1:1
- High Temperature co-electrolysis (e.g. Solid Oxide Electrolysis Cells)
- Coal, Biomass and Waste Gasification
- Waste Gases (COREX® gas, Coke-Oven Gas etc.)

Near-stoichiometric reforming (Combination of SMR and DMR)

- Using produced CO_2 and H_2 from the top gas
  - $CH_4 + H_2O \rightleftharpoons CO + 3\ H_2$ ΔH_{900C}= 2784 kJ/Nm^3_{CH4} (endothermic)
  - $CH_4 + CO_2 \rightleftharpoons 2\ CO + 2\ H_2$ ΔH_{900C}= 2425 kJ/Nm^3_{CH4} (endothermic)
- Avoid formation of carbon from CO and heavy hydrocarbon cracking
  - Higher Temperature → Reformed Gas can enter the furnace at ~1,000°C
  - Lower pressure
  - Catalysts design and loading
- External vs. In-situ reforming → both
- Volume expansion (+33%) → Gas needs to be removed from a loop (beyond water condensation) → use for burner fuel
- No need for CO_2 removal: carbon looping

- **$2\ CO \rightleftharpoons C + CO_2$ (Boudouard reaction)**
- $CO + H_2O \rightleftharpoons CO_2 + H_2$ (water-gas shift)
- $CO + H_2 \rightleftharpoons C + H_2O$ (water-carbon reaction = B-RWGS)
- $CH_4 \rightleftharpoons C + 2\ H_2$ (methane cracking)



The MIDREX® Process

Typical DR Plant Layout

Typical Project:
1 year engineering + 2 years construction
0.5-1 B$

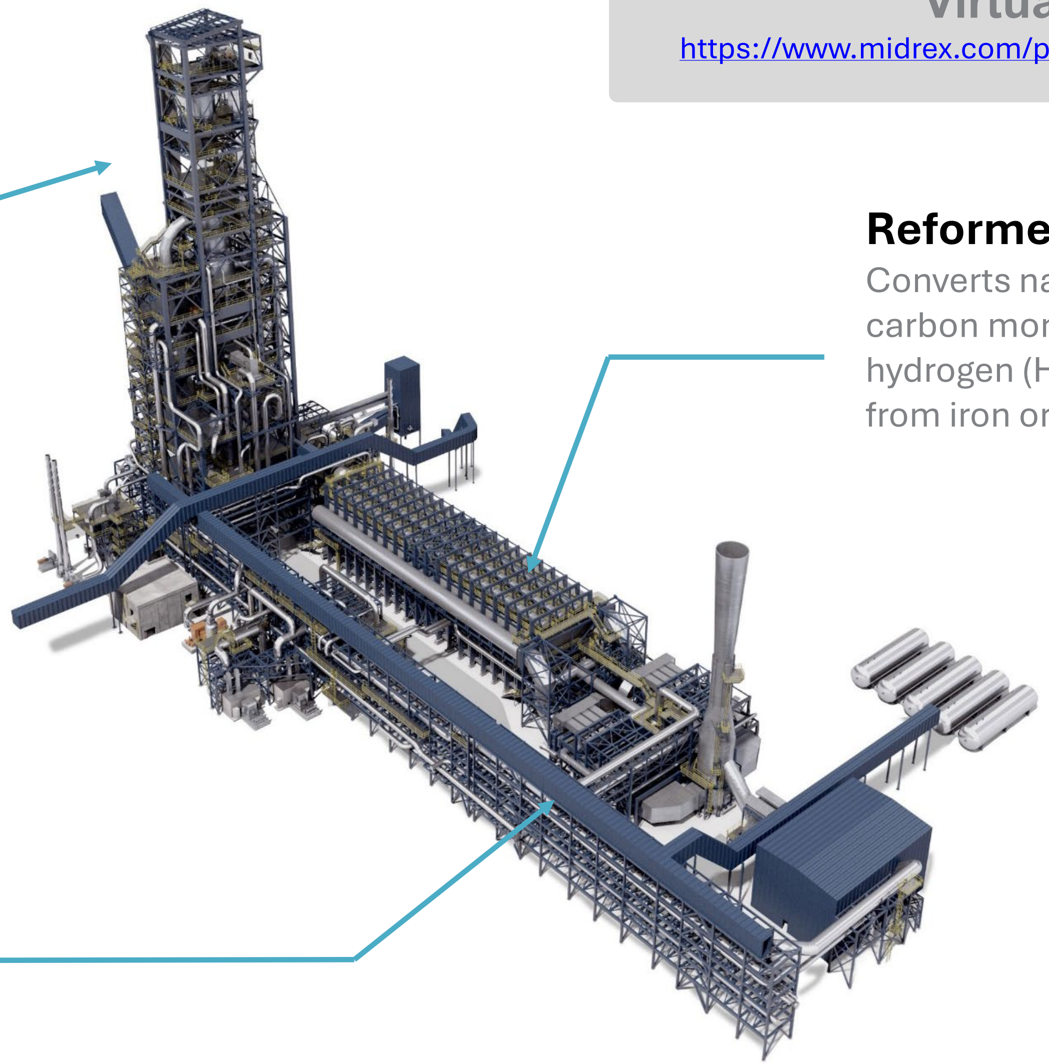
Space requirements (typical): ~70 acres

Arial view of Lebidinsky GOK in Gupkin, Russia

Typical MIDREX® Plant

Virtual Plant Tour:
https://www.midrex.com/process-technologies/virtual-plant-tour

Shaft Furnace
Oxygen is removed from iron ore using CO and H_2
120 – 150 meters tall

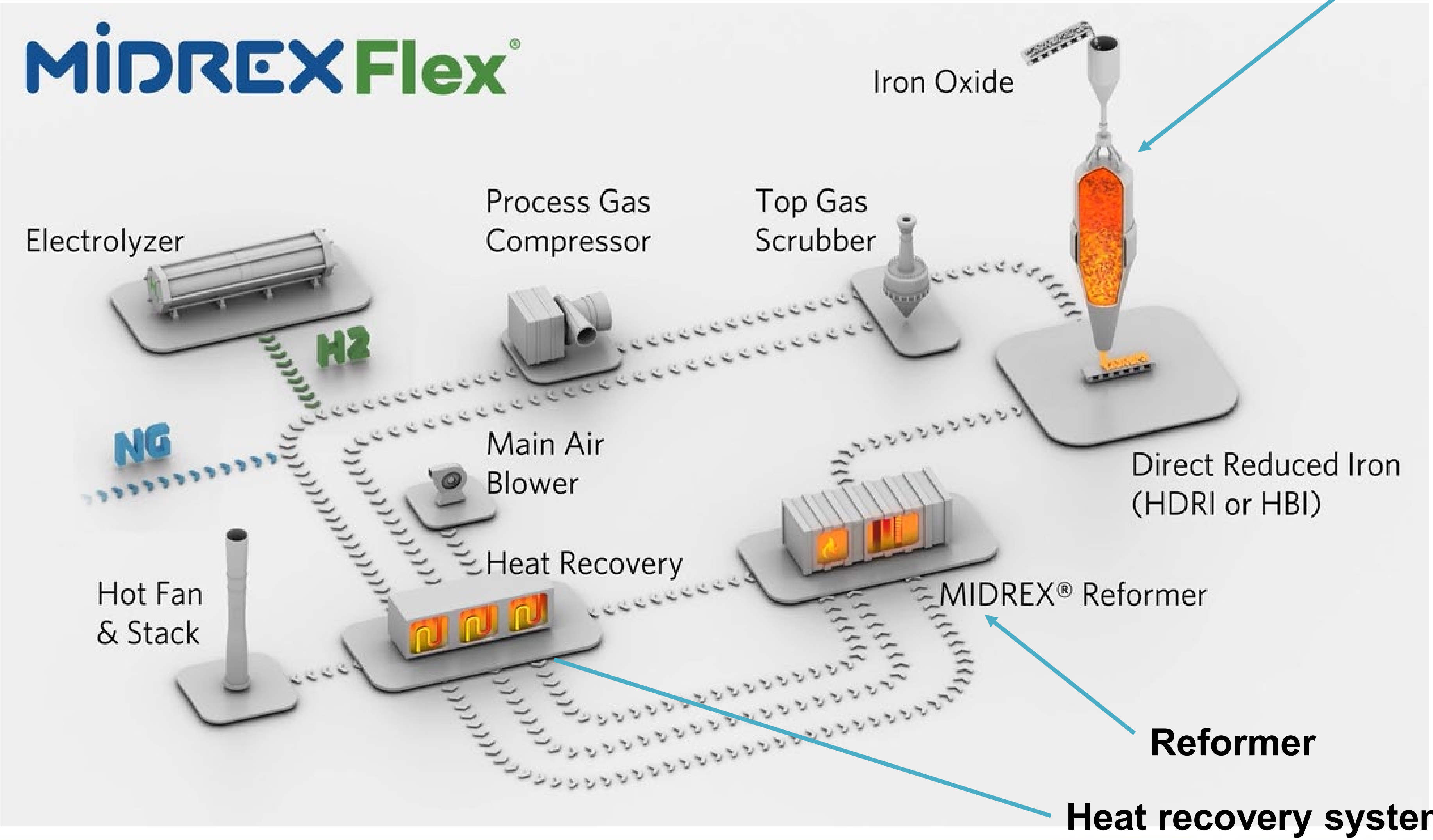


Reformer
Converts natural gas (CH_4) to carbon monoxide (CO) and hydrogen (H_2) to remove oxygen from iron ore

Heat recovery system
Heat is recovered from flue gas to preheat other gases which saves energy

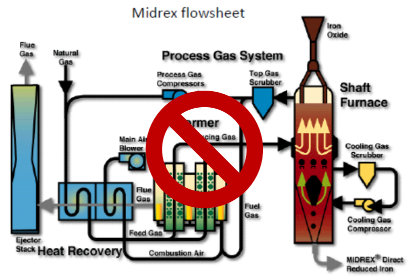
Process Overview

Shaft Furnace



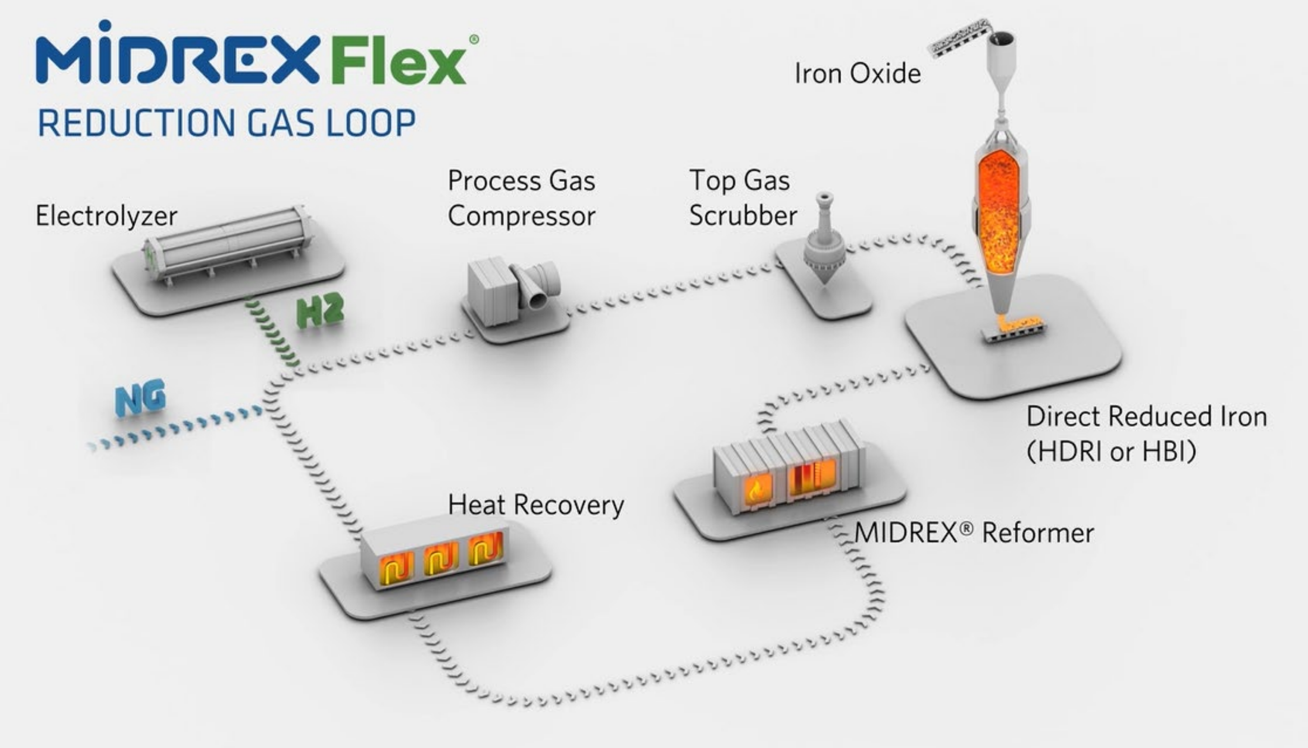
Reformer

Heat recovery system



source: kobelco.co.jp

Reduction Gas Loop



Reducing Gas enters the shaft furnace

- ~1000°C
- ~ 55%H_2, 35% CO, 5%H_2O, 2%CO_2, 1%CH_4, 1%N_2 (*)

Top Gas leaves the shaft furnace

- ~250-300 °C
- ~ 35%H_2, 25%H_2O, 20% CO, 15%CO_2, 3%CH_4, 1%N_2 (*)

Top Gas Scrubber

- Lowers gas temperature to condensate water
- Splits excess gas (due to volumetric expansion) to the combustion system

Process Gas Compressors

- Recirculates gas loops
- Compensates for pressure losses: shaft & reformer

Addition of Natural Gas and Hydrogen

- NG and H_2 are used as chemical molecules, not fuel

Heat Recovery

- Gas-Gas heat exchanger for process efficiency

Reformer

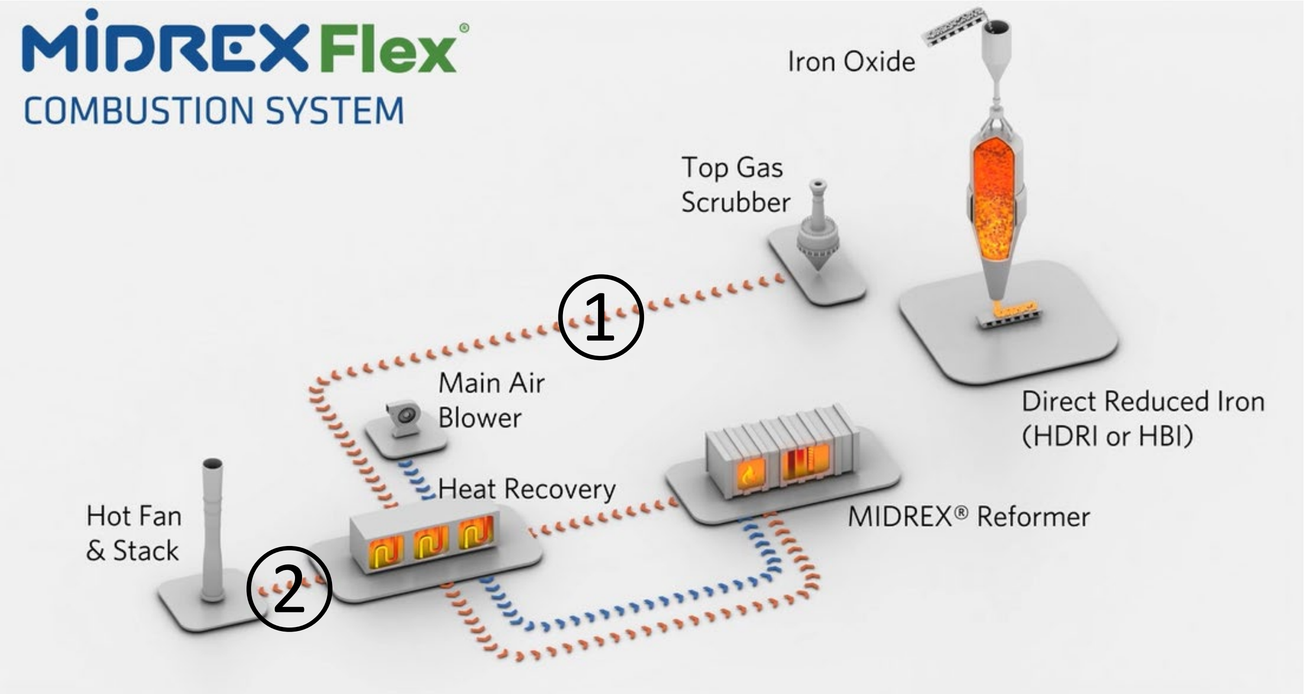
- Converts CO_2, H_2O and CH_4 into reducing gas
- Process Gas inside the reformer tubes, filled with catalysts

Temperature control:

- Reformer roof temperature
- Oxygen injection
- Reformed Gas Cooler

(*) Rounded values – does not add up to 100%

Combustion System



Top Gas Scrubber

- Splits excess gas (due to volumetric expansion) to the combustion system

Main Air Blower

- Provides air to the Reformer burners

Heat Recovery

- Preheats Top Gas Fuel and Combustion Air for efficiency and lower NOx

Reformer

- Combustion of TGF and Combustion Air in specially designed low-NOx burners

Reformer Flue Gas

- Products of combustion at ~1000C
- A portion is used for internal uses (e.g. Seal Gas)
- The hot Flue Gas is used to preheat other gases in the Heat Recovery bundles

Hot Fan + Stack

- Main emission point of the MIDREX Process

Optional Carbon Capture

- Not required for Process reasons (due to near-stoichiometric reforming)
- ① Top Gas Fuel ~ 50% of CO_2
- ② Flue Gas ~100% of CO_2

Proven Industrial Performance

	Value	Unit
Annual Capacity	Up to 2.5	Mt_{HBI} / year
Operating Production (Calendar Year Record)	2.43 (1)	Mt_{HBI} / year
Operating Availability (Design)	8,000	hours / year
Operating Availability (Calendar Year Record)	8,726 (99.3%) (2)	hours / year
Hourly Production (Calendar Month Record)	327.6 (1)	t_{HBI} / hour
Iron Oxide Pellets (screened & dry)	1.40-1.45	t_{oxide} / t_{HBI}
Natural Gas	2.4 – 2.6	net GCal / t_{HBI}
Electrical Energy (*)	~100	kWh / t_{HBI}
Oxygen (*)	0-15	Nm^3 / t_{HBI}
Nitrogen (*)	10-50	Nm^3 / t_{HBI}
Water (*)	1.0-1.5	m^3 / t_{HBI}
Steam (not needed)	Not Needed	t_{steam} / t_{HBI}
Oxide coating	1.5	kg / t_{oxide}
DRI Metallization	93 - 96	%
DRI Carbon	1.0 – 3.0	%

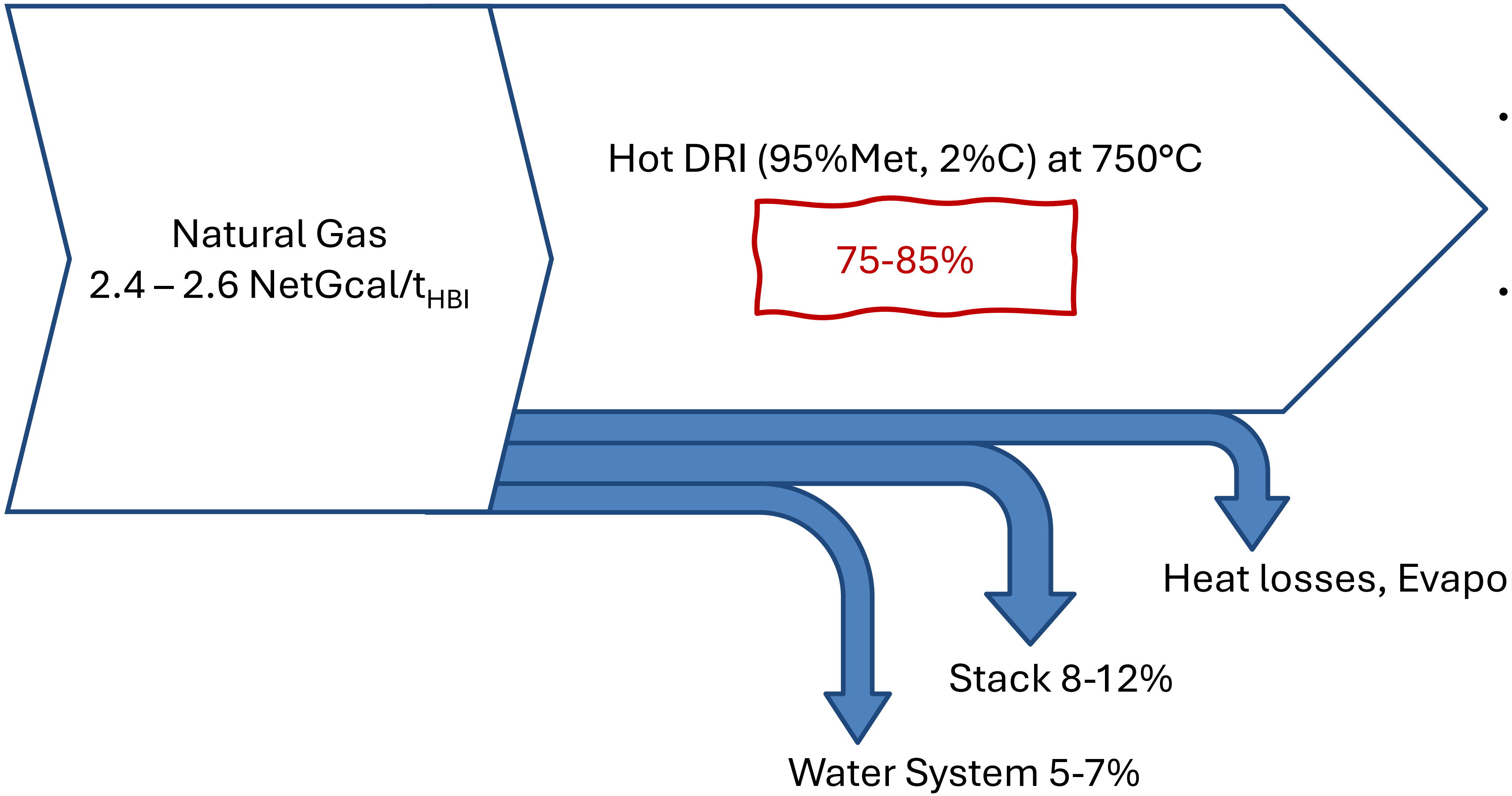
(*) Can vary significantly with plant design, such as HBI vs. HDRI

Emissions (**)	Value (dry)
NOx	50 – 90 mg/m^3
SOx	5 – 50 mg/m^3
CO	15 – 80 mg/m^3
Particulates (Filterable + Condensate)	5 – 20 mg/m^3

(**) Can vary significantly with equipment options
Wet dust collection is used for safety and to lower PM emissions

(1) Tosyali II, 2025
(2) Jindal Steel Sohar, 2024

Energy Efficiency



- **NO EXCESS ENERGY GENERATED**
  - No steam or electricity
  - No Export Gas (like COREX® or BFG)
- Ideal for stand-alone units / decoupling Ironmaking from Steelmaking

Using External Hydrogen as Reductant

The MIDREX process is flexible to a wide range of H_2/CO

- MIDREX already uses Hydrogen for direct reduction (up to 80% at FMO)

Hydrogen cools the bed.

- From Slide 10: Reduction with Hydrogen is Endothermic
- Kinetics is driven by temperature: it is critical to maintain bed temperature.

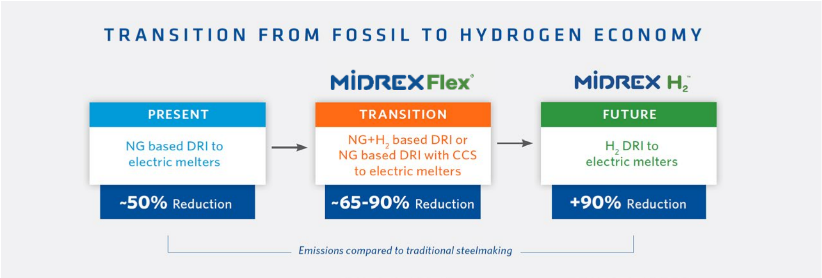
Our R&D and Engineering teams have been working for over 5 years on Technical Risk mitigation for the transition from Natural Gas to Hydrogen-based DRI / HBI

- Process Design:
  - 100% H_2
  - NG → H_2 transition
- Equipment Design
  - Electrical Heater
- DRI and HBI Quality:
  - Furnace sticking and disintegration
  - Product quality for steelmakers

Introduction of H_2 from external sources only make sense if it is green or pink.

- H_2 from SMR generally does not make sense (cooling + reheat).

The MIDREX process is flexible to a wide range of H_2, not just up to 30%.



Hydrogen Reduced HBI
Produced at the Midrex Tech Center

Conclusions

Reference Plants Under Construction

Large, commercial-scale plants only

Under contract for engineering + construction

Name	Location	Flowsheet	Capacity	Product	Construction Licensee
Stegra	Boden, Sweden	MIDREX H2	2.1	HDRI / HBI	SMS
ThyssenKrupp	Duisburg, Germany	MIDREX Flex	2.5	HDRI / CDRI	SMS
Rogesa	Dillingen, Germany	MIDREX Flex	2.0	HDRI / CDRI	Primetals
Tosyali Solb	Benghazi, Libya	MIDREX Flex	2.5	CDRI	SMS
QazIron	Rudny, Kazakhstan	MIDREX Flex	2.0	HBI	Primetals

Conclusions

MIDREX® is the Gold Standard in ironmaking, not the Blast Furnace :

- Rooted in fundamental metallurgy
- Energy Efficient
  - Natural Gas is (mostly) used as a chemical molecule, not at a source of thermal energy
  - Overall Efficiency is ~75%-85%.
  - No Export gas generated (like COG or BFG): decoupling of ironmaking from steelmaking, and co-locating Ironmaking and Energy
- Proven at scale: High TRL and improved over the years
- Reliable
- Profitable
- Flexible: Product
  - HDRI: Hot charging in EAF for energy efficiency
  - HBI: is the safest form of DRI for shipping
- Flexible: iron oxide
  - DR does not need 67% Fe iron ores; it can run on much lower grades. It is (mostly) a melting requirement
- Flexible: Energy Source
  - Process can operate on 100%H_2, or any mixture of green H_2 with Natural Gas.

Challenge accepted!

COG = Coke Oven Gas, BFG = Blast Furnace Gas