Hydrogen uses in ironmaking
Overview of the steel production process

Coke Oven

Blast Furnace
- Hot 'air' blast
  - \( \text{O}_2 \)
  - Coke breeze
  - \( \text{H}_2 \)
- Coke
  - fuel
  - reductant
  - structure

Lump Iron Ore
- Fine Iron Ore
- Pellets

BF/BOF
- Liquid 'Hot Metal'
- \( \text{O}_2 \)
- Scrap/HBI

Scrap

EAF

Direct Reduction

Solid Pig Iron
- \( \text{H}_2 \)
- \( 850 ^\circ \text{C} \)
- Pellets

Coke
- fuel
- reductant
- structure

Natural Gas
- \( \text{H}_2 \)
- Electrical

Electricity

CDRI
- HBI
- 600 °C

Option: 1

Option: 2

Option: 3

Steel

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CO$_2$ Emissions from steelmaking

- Steel accounts for 4-5% of the total CO$_2$ emitted
- Emissions strongly depend on boundary
  - Majority of CO$_2$ emissions come from power generation, conversion of iron ore to iron and re-heating
  - Emissions varies based on how electricity is generated (e.g. coal or nuclear)
- BF-BOF route:
  - 1,600 – 2,000 kg CO$_2$/ton HRC
  - Limited potential to reduce further (mature technology)
  - Capture / re-use if possible
- EAF (scrap) route:
  - 500-600 kg CO$_2$ / ton HRC
  - EAF can be misleading: scrap / OBM were previously converted from iron ore
- EAF+DR route:
  - 1,100 – 1,200 kg CO$_2$ / ton HRC for 100% HDRI charge
  - Lowest commercially proven CO$_2$ emissions from ore
Role of carbon in steelmaking:
- Reduces melting point
- Provides energy (with oxygen)
- Steel products contain carbon as alloying element

Carbon-free steelmaking is very unlikely but significant reductions in CO$_2$ emissions can be achieved with H$_2$

Source: Durand-Charre M. The Microstructure of Superalloys. 1999
Midrex® NG process

- First plant built in 1969
- Over 70 units constructed worldwide
- Over a billion tons of iron produced by the MIDREX® process
- Iron ore is reduced to metallic iron in the MIDREX® Shaft Furnace by Hydrogen and CO
- MIDREX Reformer reducing gas composition is typically 55% H₂ and 36%CO (ratio ~1.5)
- Midrex plant with SMR has operated since 1989 ~75% hydrogen

Reactions (w/ Hydrogen only)

<table>
<thead>
<tr>
<th>Reaction</th>
<th>Heat</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fe₂O₃ + 3 H₂ ↔ 2 Fe + 3 H₂O</td>
<td>Endothermic</td>
<td>Reduction by H₂</td>
</tr>
<tr>
<td>3 Fe + CH₄ ↔ Fe₃C + 2 H₂</td>
<td>Endothermic</td>
<td>Carburization</td>
</tr>
<tr>
<td>3 Fe + CO + H₂ ↔ Fe₃C + H₂O</td>
<td>Exothermic</td>
<td>Carburization</td>
</tr>
</tbody>
</table>
Midrex® NG process

- Reducing gases are generated in MIDREX® Reformer.
- Process can use any Natural Gas source regardless of sulfur or heavy hydrocarbon content
- NG consumption ~2.35 Net Gcal / ton DRI

Reactions (w/ Hydrogen only)  | Heat          | Description                                      
-------------------------------|--------------|--------------------------------------------------
CH₄ + CO₂ ↔ 2CO + 2H₂          | Endothermic  | CO₂ reforming                                    
CH₄ + H₂O ↔ CO + 3H₂           | Endothermic  | H₂O reforming                                    
CH₄ ↔ C + 2H₂                  | Endothermic  | Methane cracking                                 
CO + H₂ ↔ C + H₂O             | Exothermic   | Beggs or Water/carbon shift                      
CO + H₂O ↔ CO₂ + H₂            | Exothermic   | Water/gas shift                                  

TYPICAL COMPOSITION

<table>
<thead>
<tr>
<th></th>
<th>INLET</th>
<th>OUTLET</th>
</tr>
</thead>
<tbody>
<tr>
<td>H₂</td>
<td>35</td>
<td>55</td>
</tr>
<tr>
<td>CO</td>
<td>19</td>
<td>35</td>
</tr>
<tr>
<td>CO₂</td>
<td>15</td>
<td>2</td>
</tr>
<tr>
<td>H₂O</td>
<td>13</td>
<td>6</td>
</tr>
<tr>
<td>CH₄</td>
<td>17</td>
<td>1</td>
</tr>
<tr>
<td>N₂</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>Temp. (°C)</td>
<td>580</td>
<td>980</td>
</tr>
</tbody>
</table>

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Newest MIDREX® Plants in North America

Voestalpine (Corpus Christi, Texas USA)
• 2.0 MTPA HBI
• Performance test passed February 19, 2017

Cleveland-Cliffs (Toledo, OH USA)
• 1.6 MTPA HBI
• Completion: 2020
MIDREX® NG with H₂

- Up to 30% of NG can be substituted by Hydrogen without changing the process.
- Hydrogen may need to be pre-heated depending on quantities added.
- Rough calculations for Cleveland-Cliffs: 1.6 MTPA (200 ton/h), up to 16,000Nm³/h of NG* can be replaced by 48,000Nm³/h of H₂.
- Hydrogen can be increased in the process as it becomes available.

* Assumes net heating value 8800 kcal/Nm³
• Bustle gas composition is ~90% hydrogen, balance CO, CO₂, H₂O and CH₄ (for 1.4% carbon in DRI)
• Hydrogen consumption is approx. 650 Nm³/t DRI (54kg/t)
• For a Midrex plant the size of Cleveland-Cliffs, that’s approx. **130,000Nm³/h of H₂**
• ~650MW per Midrex plant (at 200Nm³/h of H₂ per 1MW)
Conclusions

- MIDREX-NG® is a proven technology for industrial production of iron, using “fossil” hydrogen at scale. The process can reduce CO₂ emissions by 50%-80% over traditional BF-BOF.
- Direct reduction can be a bridge technology for ironmaking as Hydrogen becomes available at scale
  - New plants can be built or existing plants can be converted to 100% H₂ as the Hydrogen economy evolves
- Green hydrogen production volumes need to increase by 50x – 125x to supply one MIDREX® plant
  - Scale up to Demonstration plant will be needed
- Hydrogen production costs must be competitive: steelmaking is a very competitive business with small margins
- European steelmakers are very active