



Novel Ironmaking Technology

with Low Energy Requirement and CO₂ Emission

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- Supported by DOE/AISI
- Partner Companies
 - ArcelorMittal, Gallatin Steel,
ArcelorMittal-Dofasco, Ipsco, Nucor,
Praxair, Ternium, Timken, and US Steel



Background

- **Steel industry: One of the largest industries of great national importance.**
- **Current ironmaking technology: Blast Furnace - The largest chem. / metallurgical reactor.**



Background

Blast Furnace

- Merits: Well developed, Large size, Economical
- Issues:
 - Requires **Coke** and **Iron Ore Pellets**
 - **Large** CO₂ Emission
 - **Large** Energy Consumption

U.S. Carbon Dioxide Emissions

(Million Metric Tons)

Sector	2006	%
Residential	1200	20
Commercial	1050	18
Industrial	1650	28
Transportation	1990	34
(Electric power generation)	(2340)	(40)
Total	5,890	100

Adapted from Report DOE/EIA-0573(2006), *Emissions of Greenhouse Gases in the United States 2006, 2007.*

CO₂ Emissions from U.S. Steel Industry

(Million Metric Tons)

Source	2002	%
Net electricity	35.0	27.8
Natural gas	22.0	17.5
Petroleum	1.1	0.9
Coal	66.7	52.9
Other	1.2	0.9
Total	126.0	100

Adapted from Report DOE/EIA-0573(2005), *Special Topic: Energy-Related Carbon Dioxide Emissions in U.S. Manufacturing*, 2006.



Overall Objective

- **Develop a new ironmaking process based on:**

- **Hydrogen (Natural Gas, Coal)**

- **Direct use of concentrate**

- **Without coke**

- **Without pelletization/sintering**

- **Main goal:**

Significant reduction in **energy consumption**
and **CO₂ generation** in the steel industry



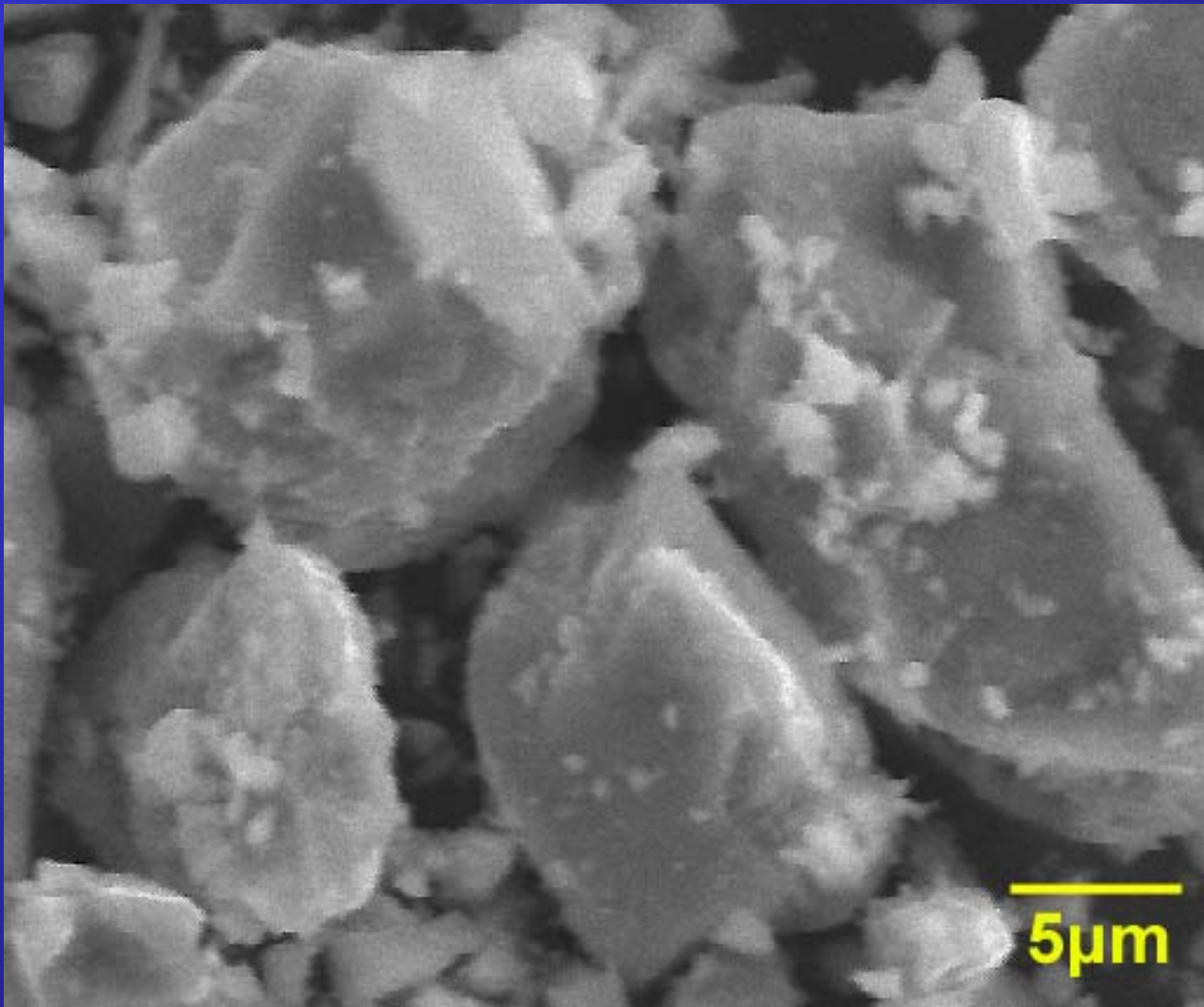
Main Motivation

(Reasons for expected success)

- Needs for CO₂ reduction
- Developments toward H₂ economy
- Availability of less C-intensive fuels/
reductants
- Availability of fine (~30 μm) iron ore
concentrate

Iron Oxide Concentrate

20 - 32 μm (- 500 + 635 mesh)





Proposed Process Concept

- Reduction of fine iron ore particles in suspension with H_2 as reductant
- Possible use of natural gas or coal
- Target: alternative to **BF/BOF** route
- Feed to steelmaking step or part of direct steelmaking process



Major Benefits

- **Eliminate energy consumption and pollution problems in making coke.**
- **Eliminate (or greatly reduce) CO₂ emission.**
- **Eliminate pelletizing/sinter-making.**



Technical Issues

- **Rate of H₂ reduction**
- **Heat supply**
- **Hydrogen utilization – Equilibrium limitation**
- **Impurity behavior**



Heat Supply

- **Burn portion of reducing gas**
- **Nat'l gas or Coal – Overall CO₂ generation still much less**
- **Supplemental: Plasma?**

Material Balance *Preparation process for BF not included into this calculation (7%).

	BF [kg/tonHM]	Prop'd(H ₂) [kg/tonHM]	Prop'd(CH ₄) [kg/tonHM]	Prop'd(Coal) [kg/tonHM]
Input				
Fe ₂ O ₃	1430	1430	1430	1430
SiO ₂	151	100	100	125
CaCO ₃	235	162	162	235
O ₂ (g)	705	227	411	463
N ₂ (g)	2321	749	1354	1525
C (coke)	428			
H ₂ (g)		83		
CH ₄ (g)			211	
Coal (C _{1.4} H)				301
Sub-Total	5270	2751	3668	4079
Output				
Fe	1000	1000	1000	1000
CaSiO ₃	273	191	191	257
Si	5			
CO ₂ (g)	1671*	71 (4% of BF)	650 (39%)	1145 (69%)
H ₂ O		740	473	152
N ₂ (g)	2321	749	1354	1525

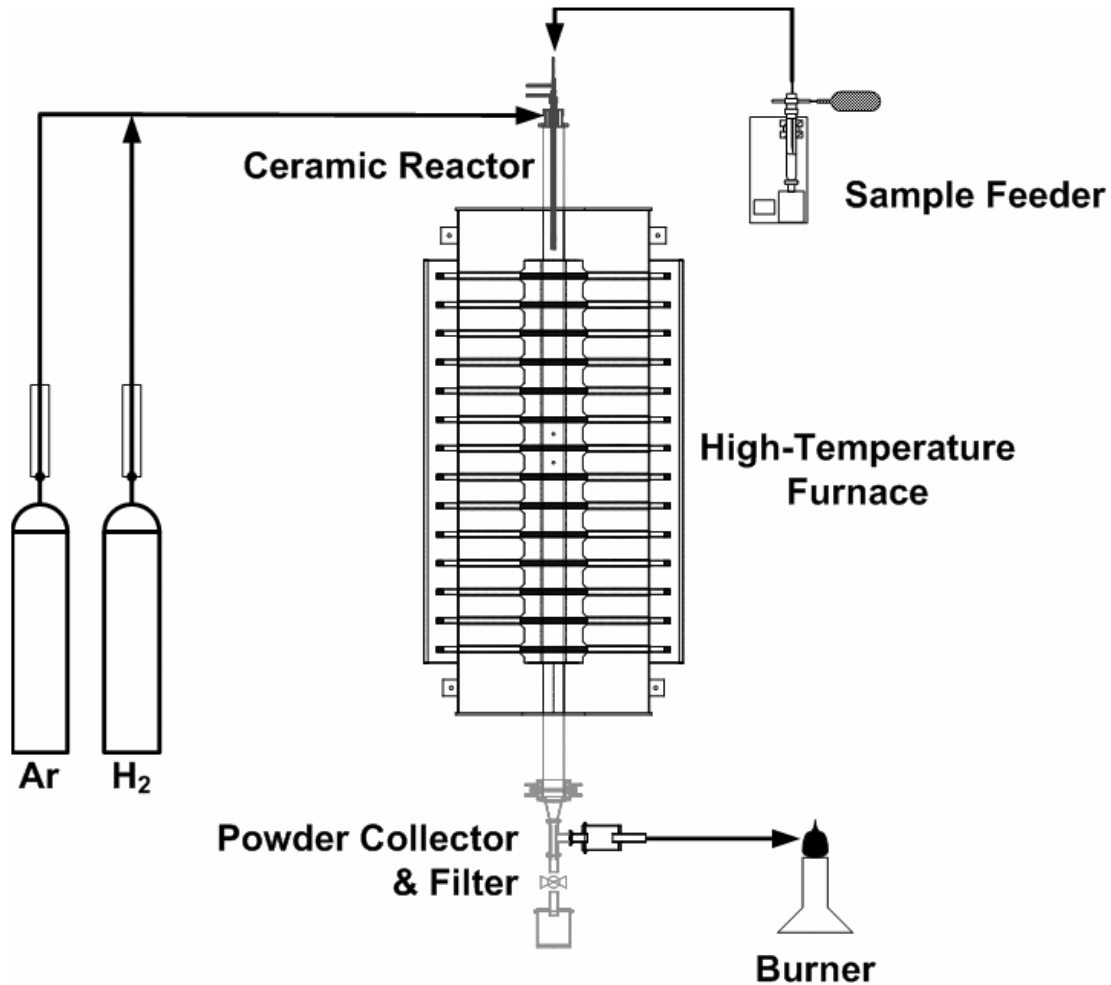
Energy Balance

	BF	Prop'd (H ₂)	Prop'd (CH ₄)	Prop'd (coal)
	[GJ/tonHM]*	[GJ/tonHM]	[GJ/tonHM]	[GJ/tonHM]
Energy required (Feed at 25°C to products)				
1) Enthalpy of iron-oxide reduction (25°C)	2.09	- 0.31	-0.61	1.73
2) Sensible heat of molten Fe (1600°C)	1.36	1.36	1.36	1.36
3) Slag making	- 0.21	- 0.15	- 0.15	- 0.21
4) Sensible heat of slag (1600°C)	0.46	0.32	0.32	0.46
5) SiO ₂ reduction	0.09			
6) Limestone (CaCO ₃) decomposition	0.42	0.29	0.29	0.42
7) Carbon in pig iron	1.65			
9) Heat loss & unaccounted-for amounts	2.60	2.60	2.60	2.60
10) Sensible heat of offgas (90°C)	0.25	0.25	0.21	0.20
Sub-Total	8.70	4.36	4.02	6.56
Heating value of feed used as reductant	5.37	7.70	8.00	5.67
Total for iron oxide reduction	14.07	12.06	12.02	12.23
Preparation				
1) Pelletizing	2.87			
2) Sintering	0.62			
3) Cokemaking	1.93			
Sub-Total for preparation	5.42	0	0	0
Total for molten metal making	19.49	12.06	12.02	12.23



Rate of H₂ reduction

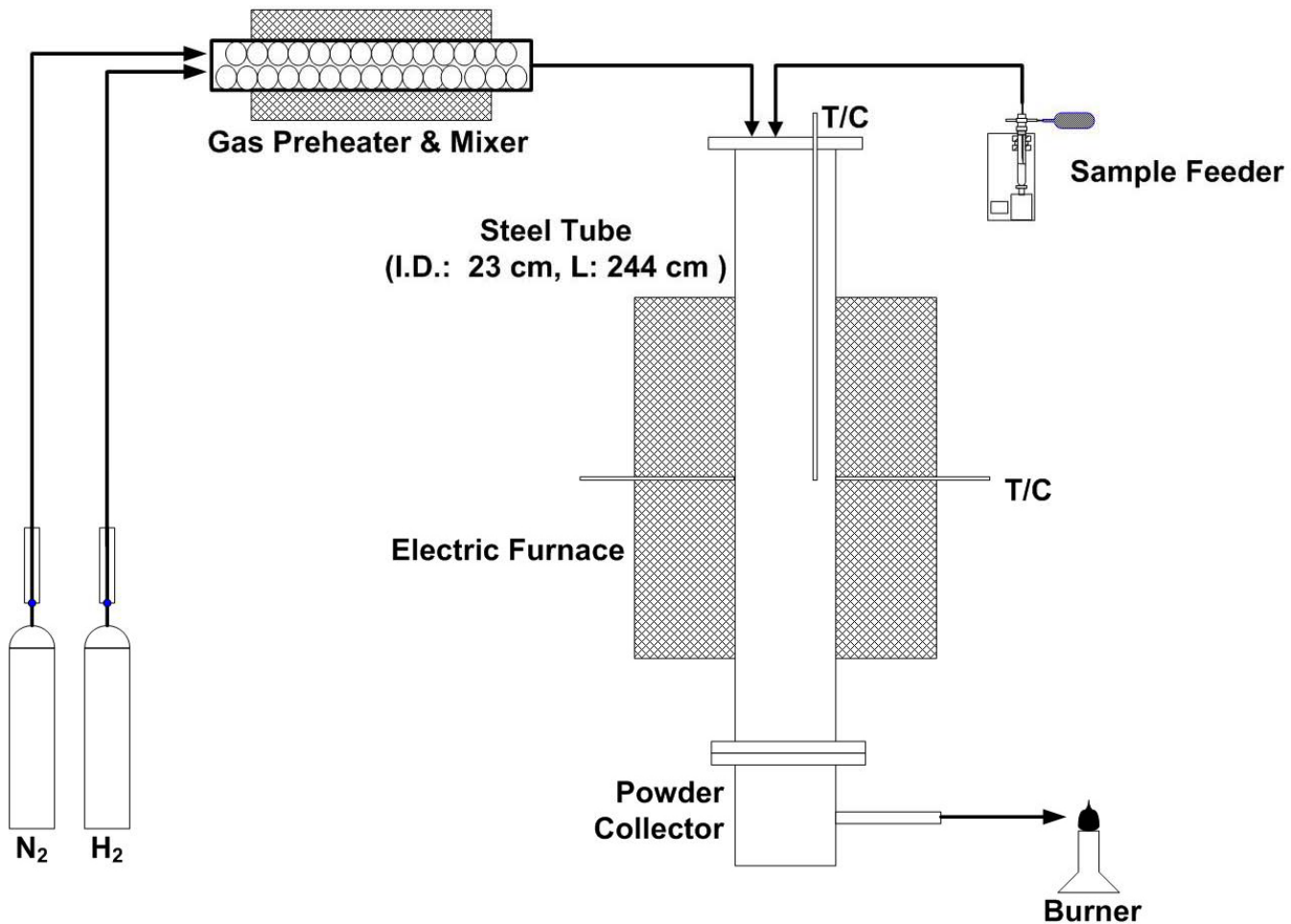
Drop-Tube Reactor System



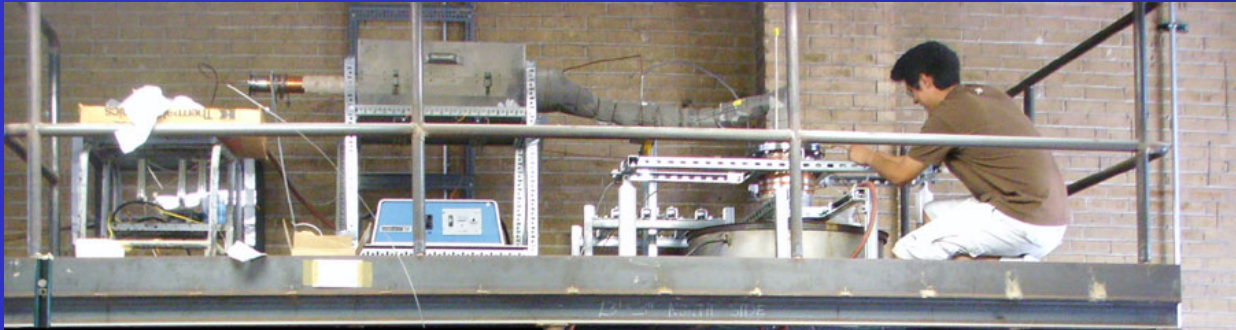
Drop-Tube Reactor System



Bench-scale Test Facility

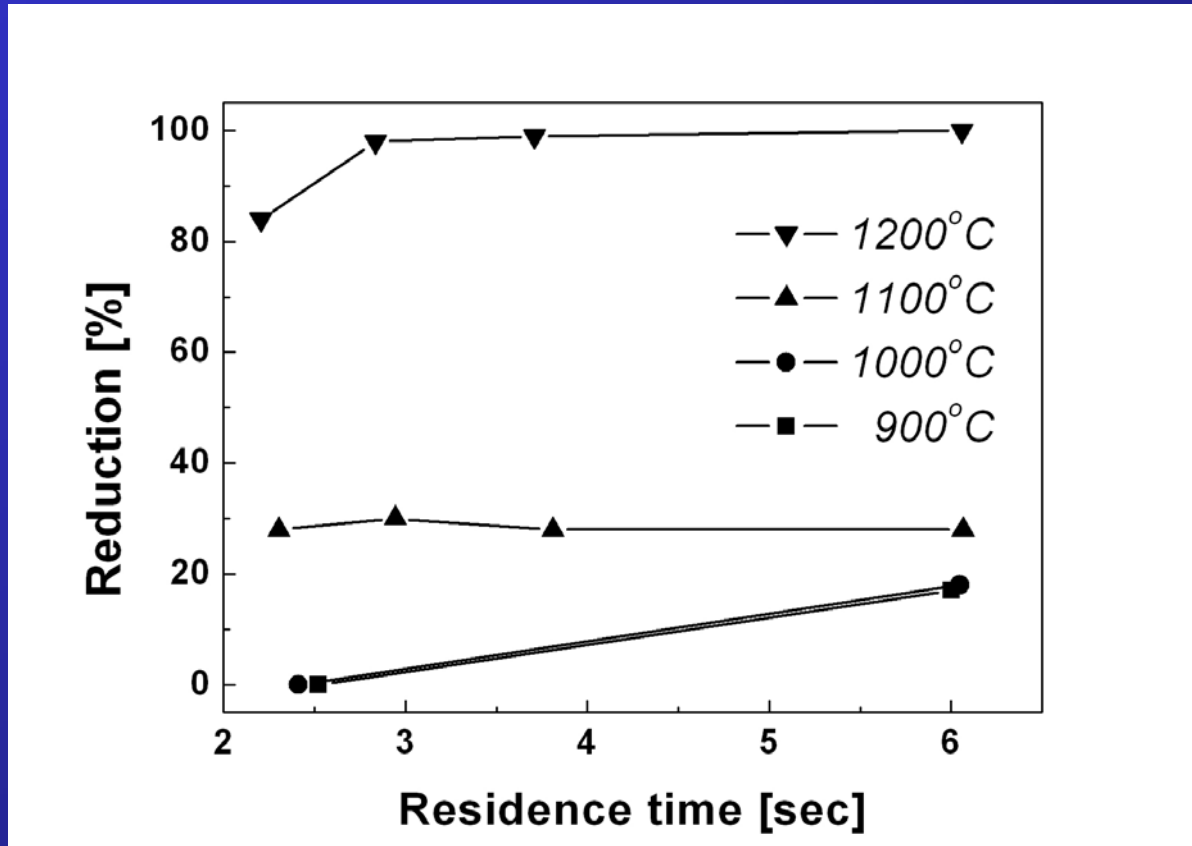


Bench-Scale Test Facility



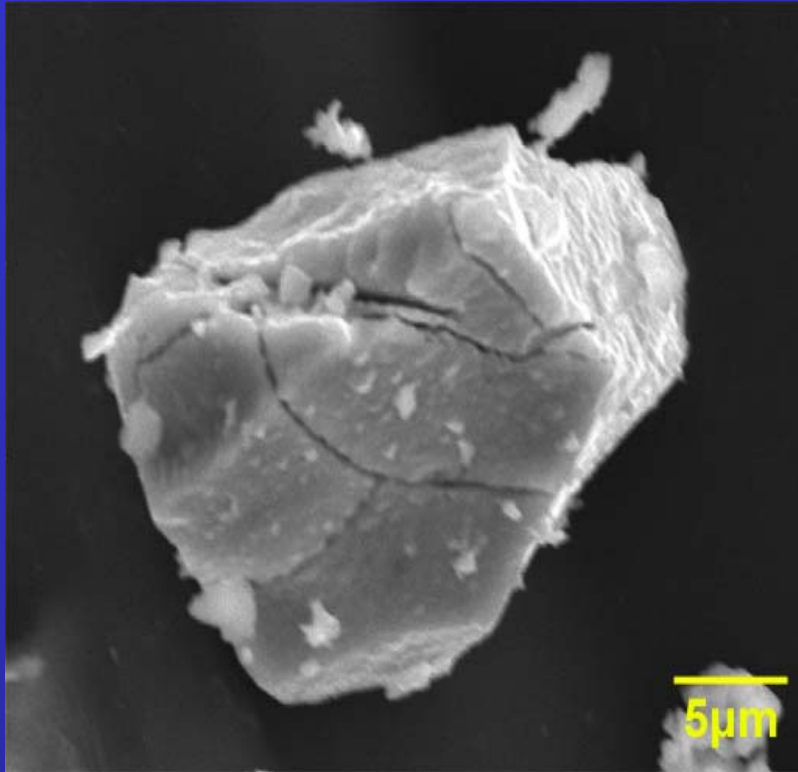
Rate Determination

- Rate is fast enough for a suspension process in H_2 above $1200^\circ C$.

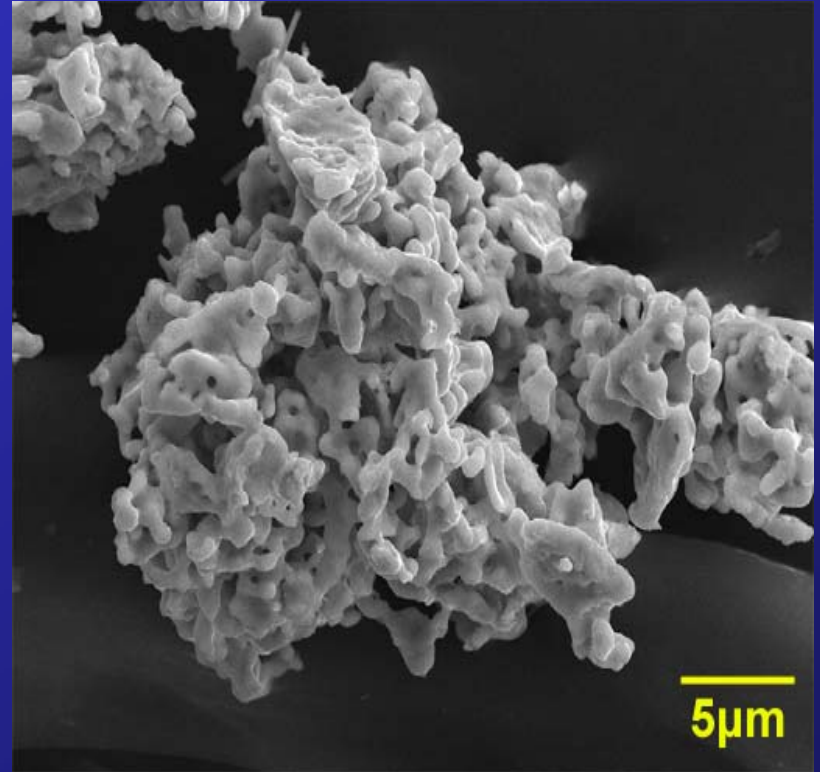


Reduction at 1000°C

20 - 32 μm (- 500 + 635 mesh)

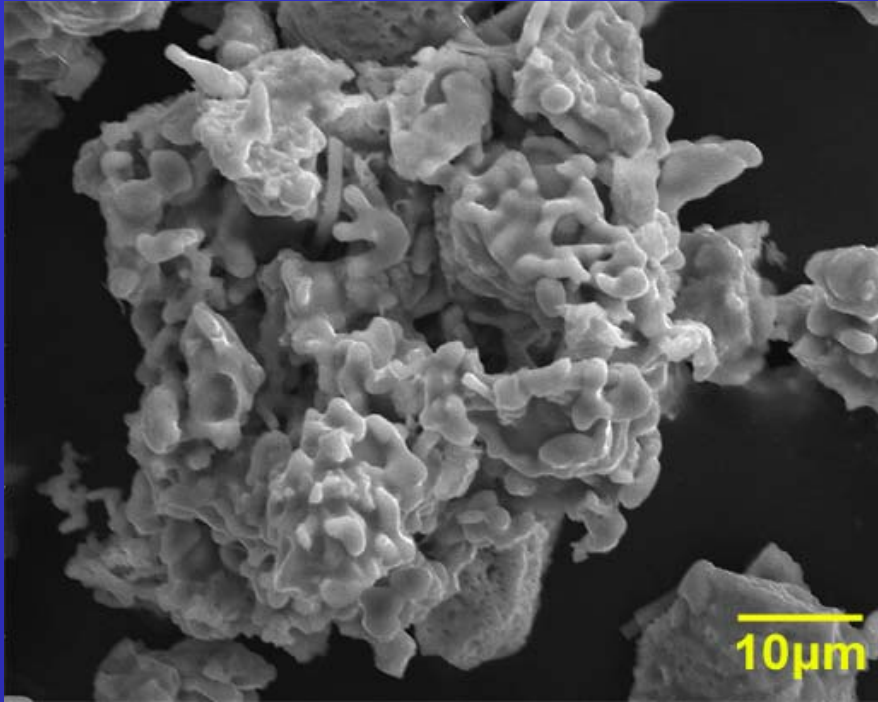


**2-second reduction
(32% metallization)**

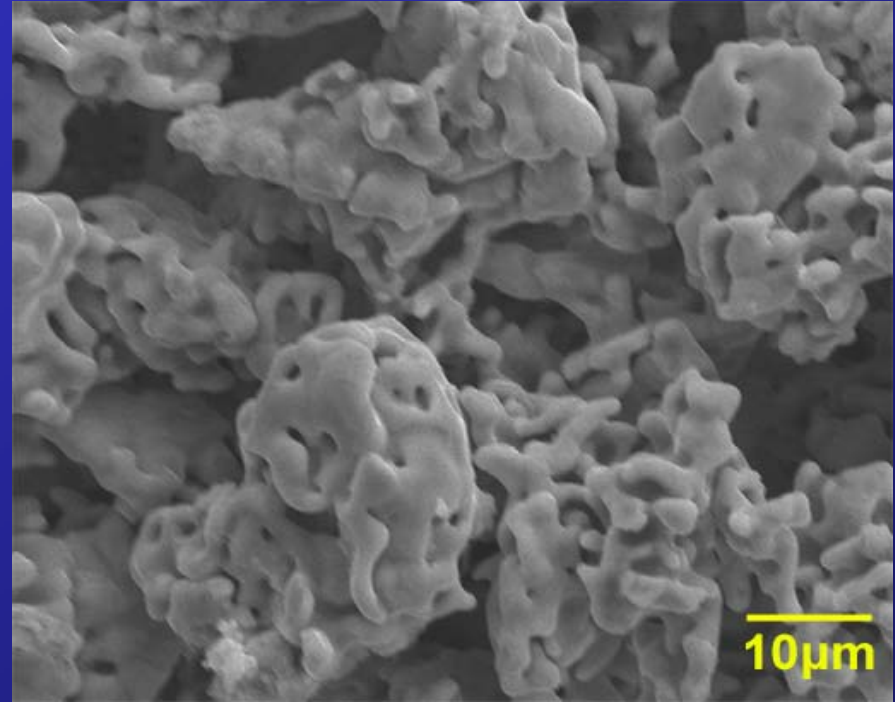


**30-second reduction
(100% metallization)**

Reduction at 1100°C

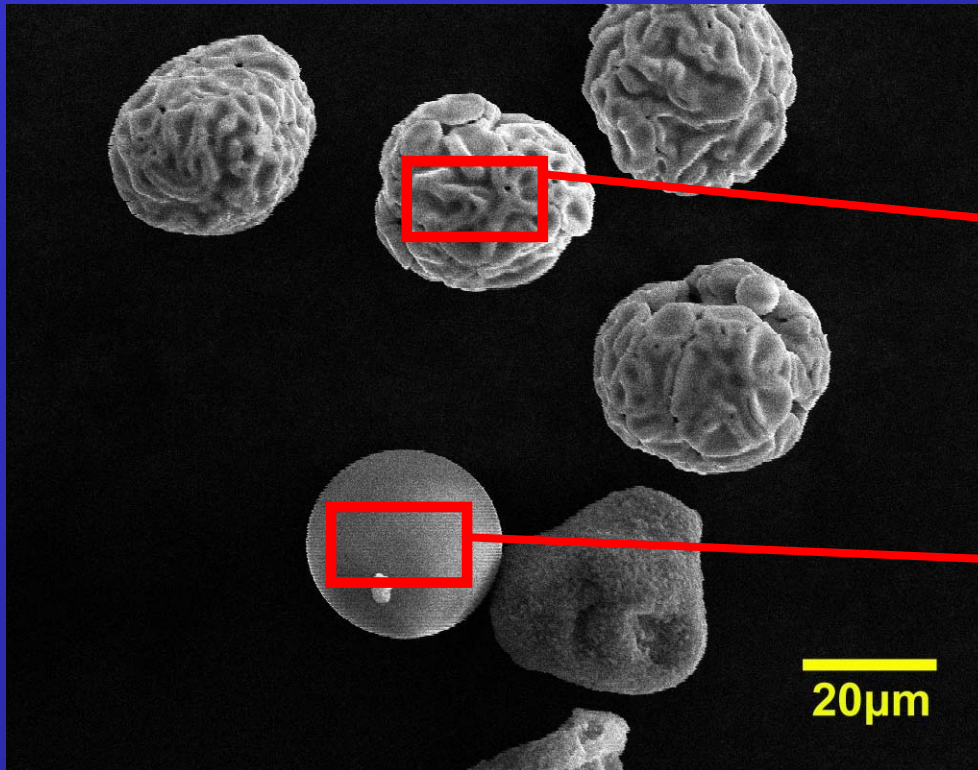


**2-second reduction
(50% metallization)**



**10-second reduction
(100% metallization)**

Reduction at 1350°C



EDS Quantitative Results

Element	Wt%	At%
O K	1.27	4.26
SiK	1.18	2.24
FeK	97.55	93.50

EDS Quantitative Results

Element	Wt%	At%
C K	3.09	9.88
O K	7.78	18.66
NaK	1.49	2.50
SiK	12.81	17.52
FeK	74.83	51.45

**100% reduction,
2.7 seconds**



Summary of **Important Results**

- **Calculated energy savings up to 38% of BF process.**
- **Complete elimination or Drastic reduction of CO₂ emission from ironmaking.**
- **Reduction rate determined to be sufficiently fast to apply a gas-solid suspension process to ironmaking.**
- **Possibility of eliminating the use of coke and pelletization/sintering as well as the associated generation of pollutants.**