

Radical Innovation in Steelmaking: Molten Oxide Electrolysis



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Massachusetts
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Technology

requirements of a new extraction technology?

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- reduce metal production costs: capital and operating

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requirements of a new extraction technology?

- reduce metal production costs: capital and operating
- improve metal quality
- provide flexibility in raw materials
- reduce environmental impact

beyond the blast furnace

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- ⇒ e^- is the best reducing agent

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beyond the blast furnace

- ⇒ most metals are found in nature as oxides
- ⇒ e^- is the best reducing agent
- ⇒ “*like dissolves like*”
 - ☞ molten oxide electrolysis:
 - extreme form of molten salt electrolysis
 - where pure **oxygen** gas is the by-product

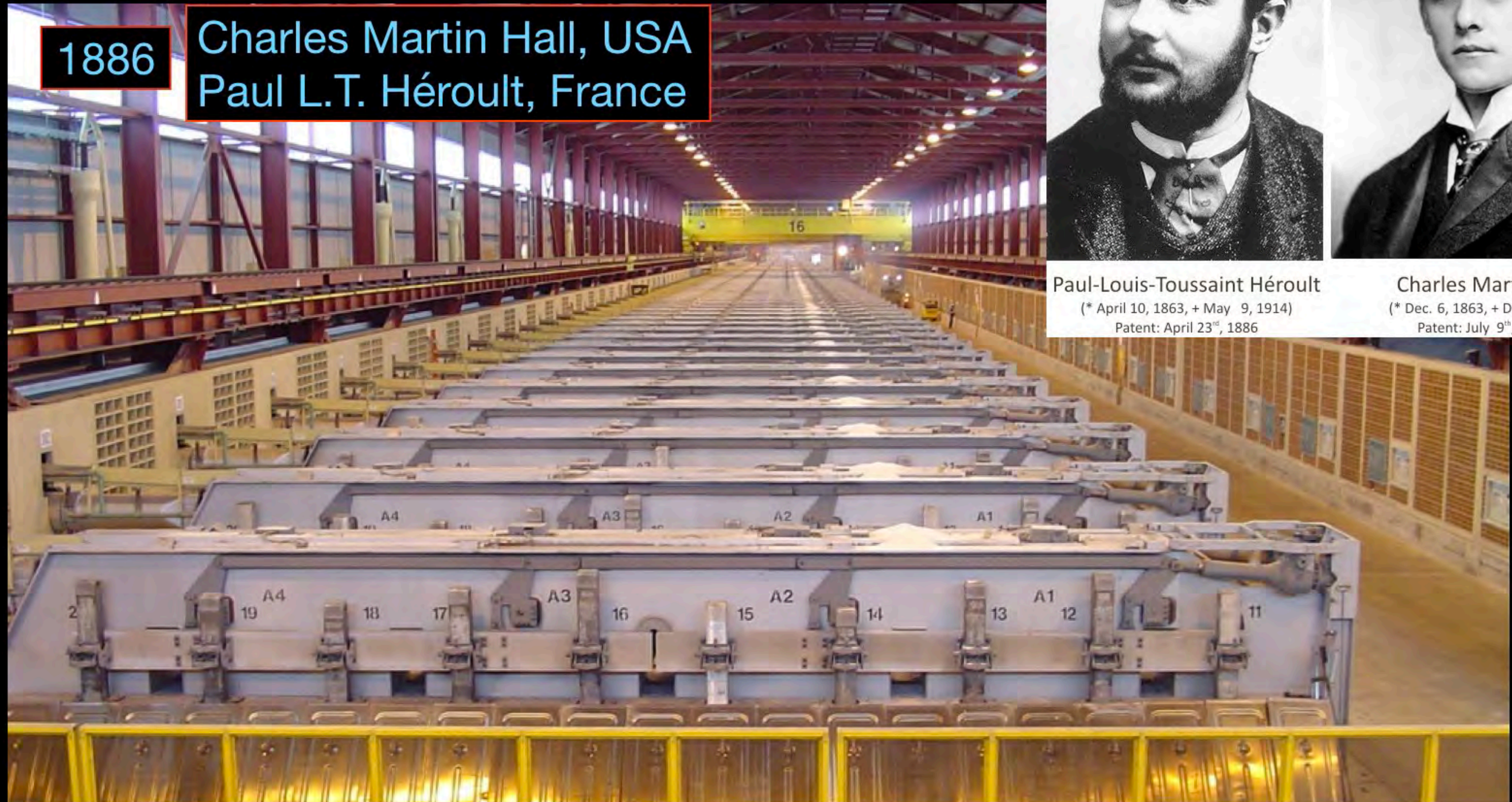
 **disruption**

a modern aluminum smelter



photo credit: "Phase II Makes Alouette the Largest Primary Aluminum Producer in the Americas," *Light Metal Age*, February 2006.

a modern aluminum smelter



1886

Charles Martin Hall, USA
Paul L.T. Héroult, France



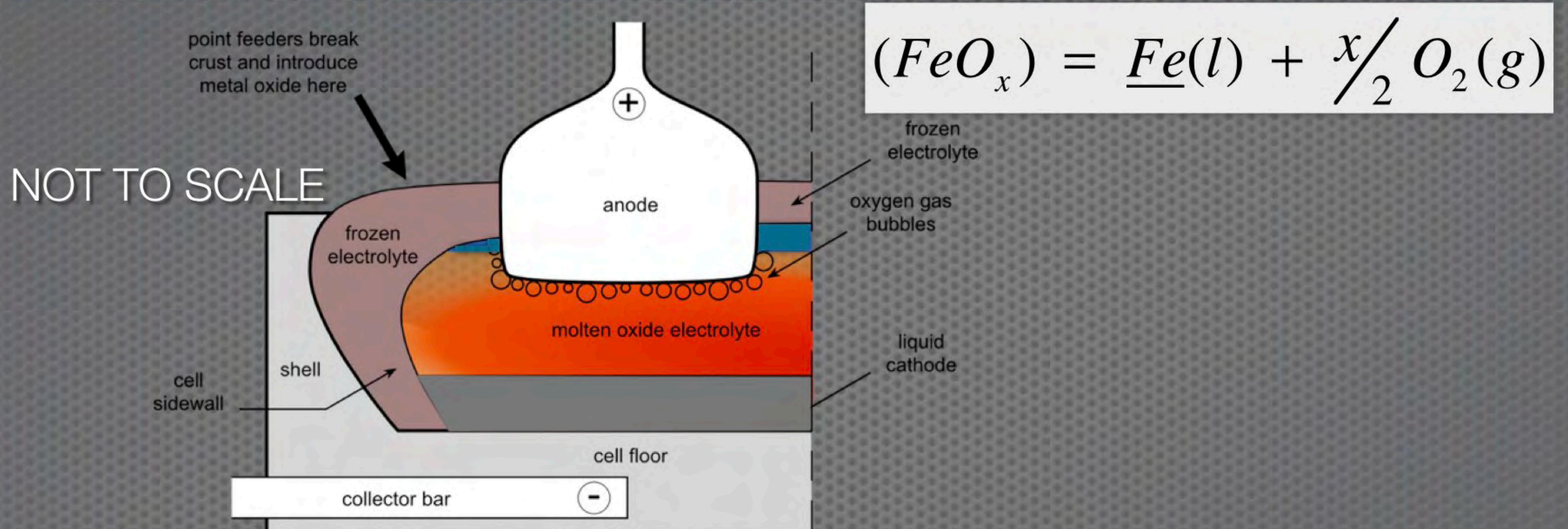
Paul-Louis-Toussaint Héroult
(* April 10, 1863, + May 9, 1914)
Patent: April 23rd, 1886



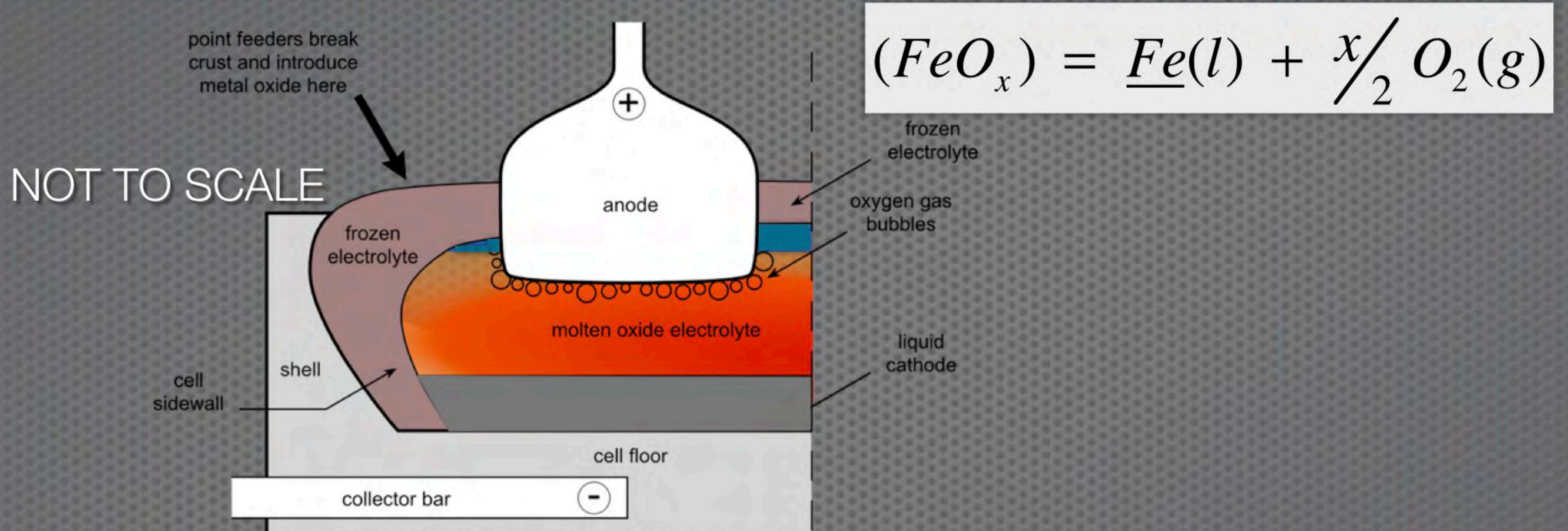
Charles Martin Hall
(* Dec. 6, 1863, + Dec. 27, 1914)
Patent: July 9th, 1886

photo credit: "Phase II Makes Alouette the Largest Primary Aluminum Producer in the Americas," *Light Metal Age*, February 2006.

heart of the technology: MOE cell

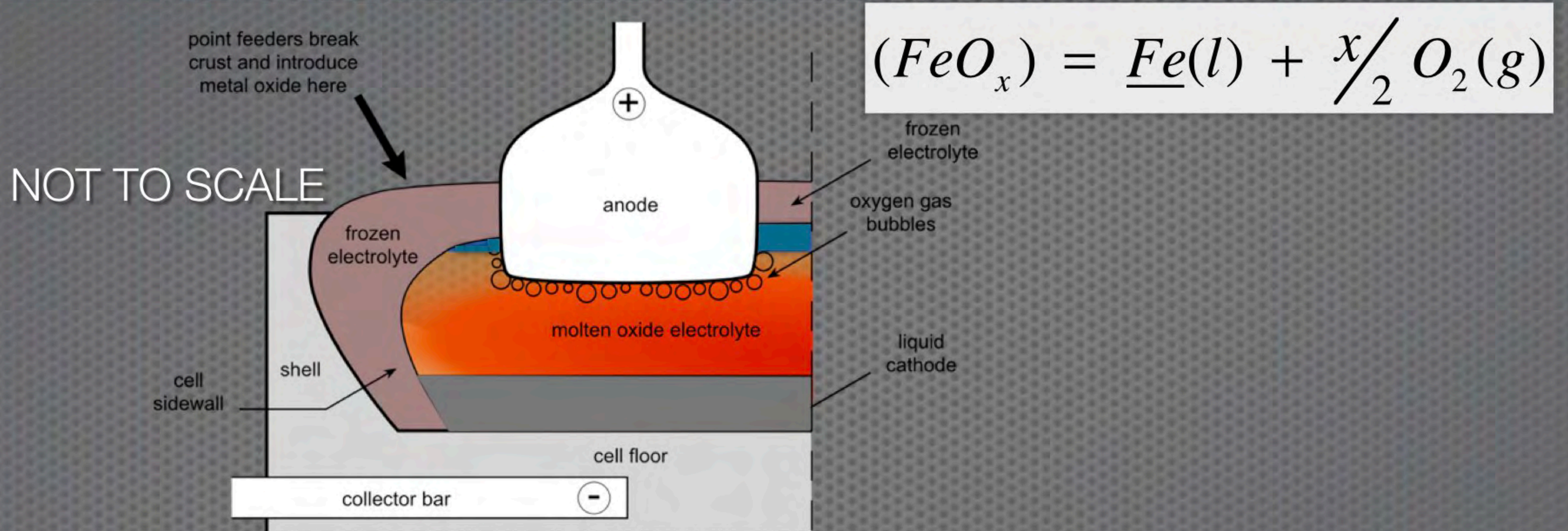


heart of the technology: MOE cell



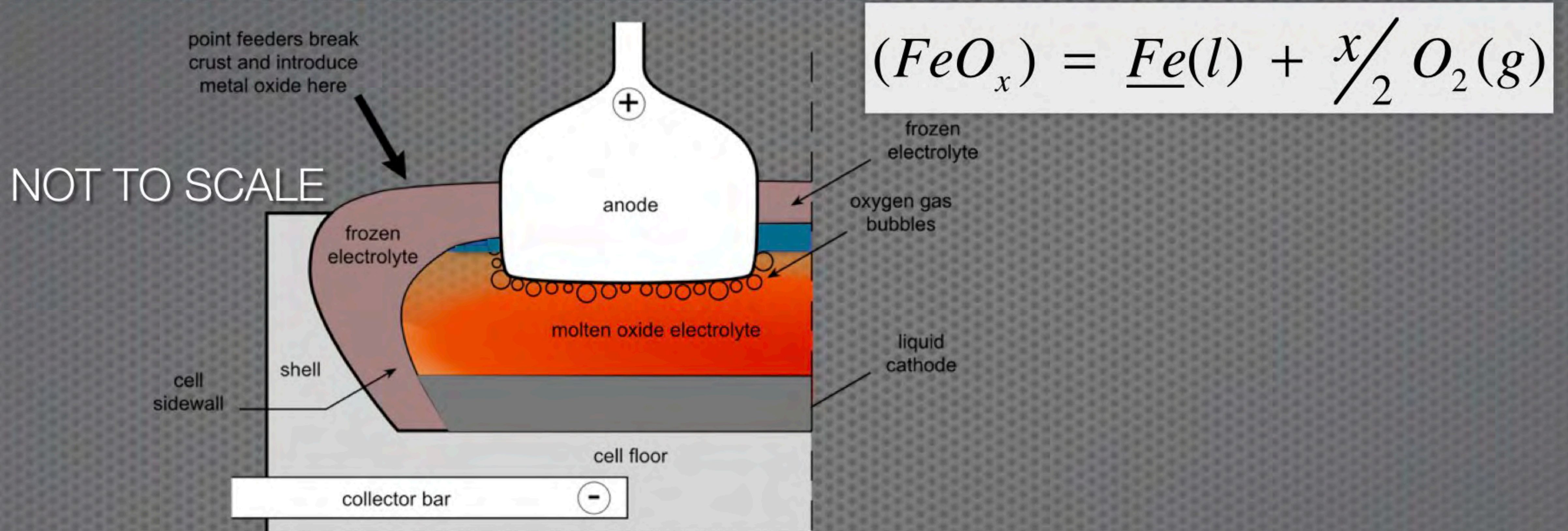
- lower capital cost per cell

heart of the technology: MOE cell



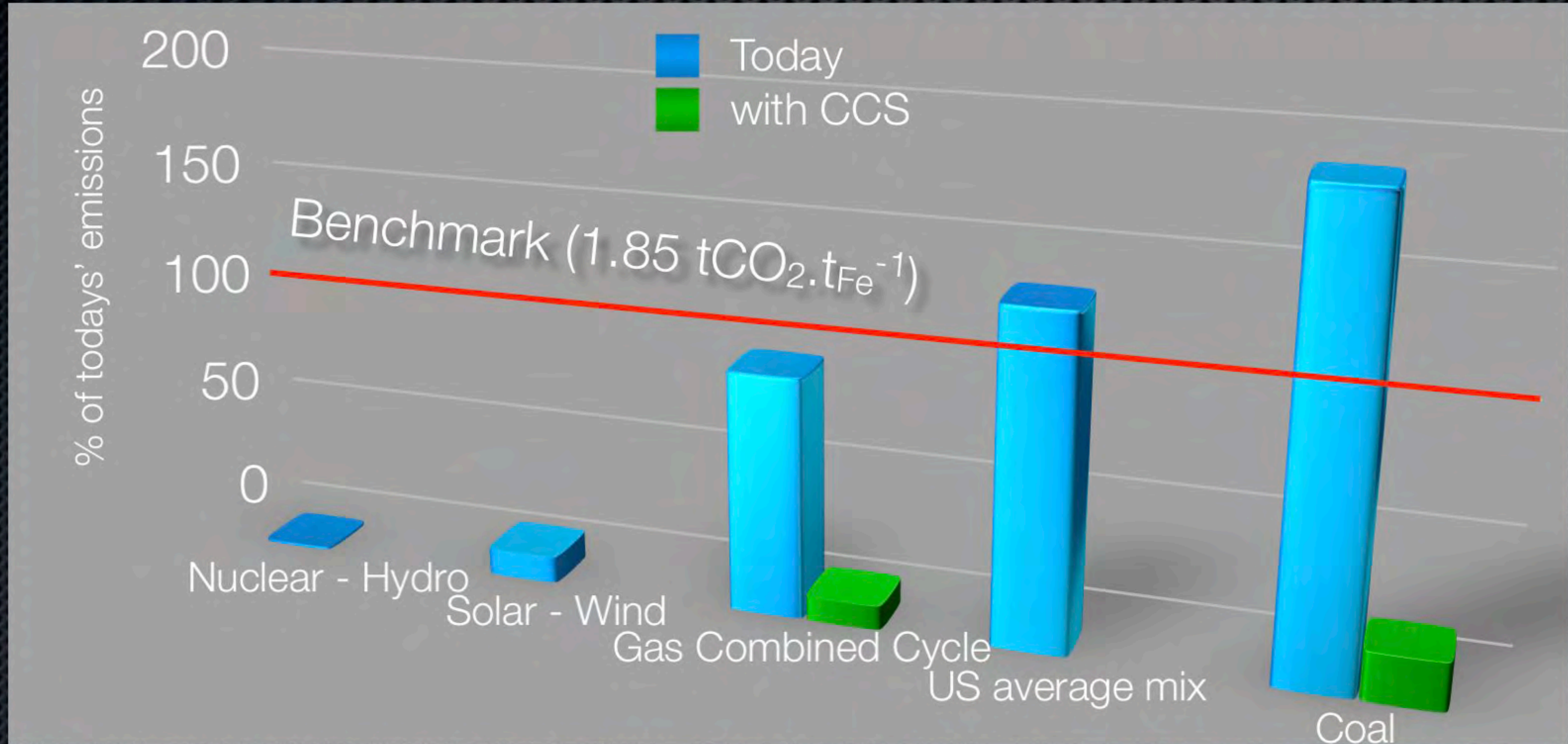
- lower capital cost per cell
- smaller minimum production capacity (lower barrier to entry)

heart of the technology: MOE cell

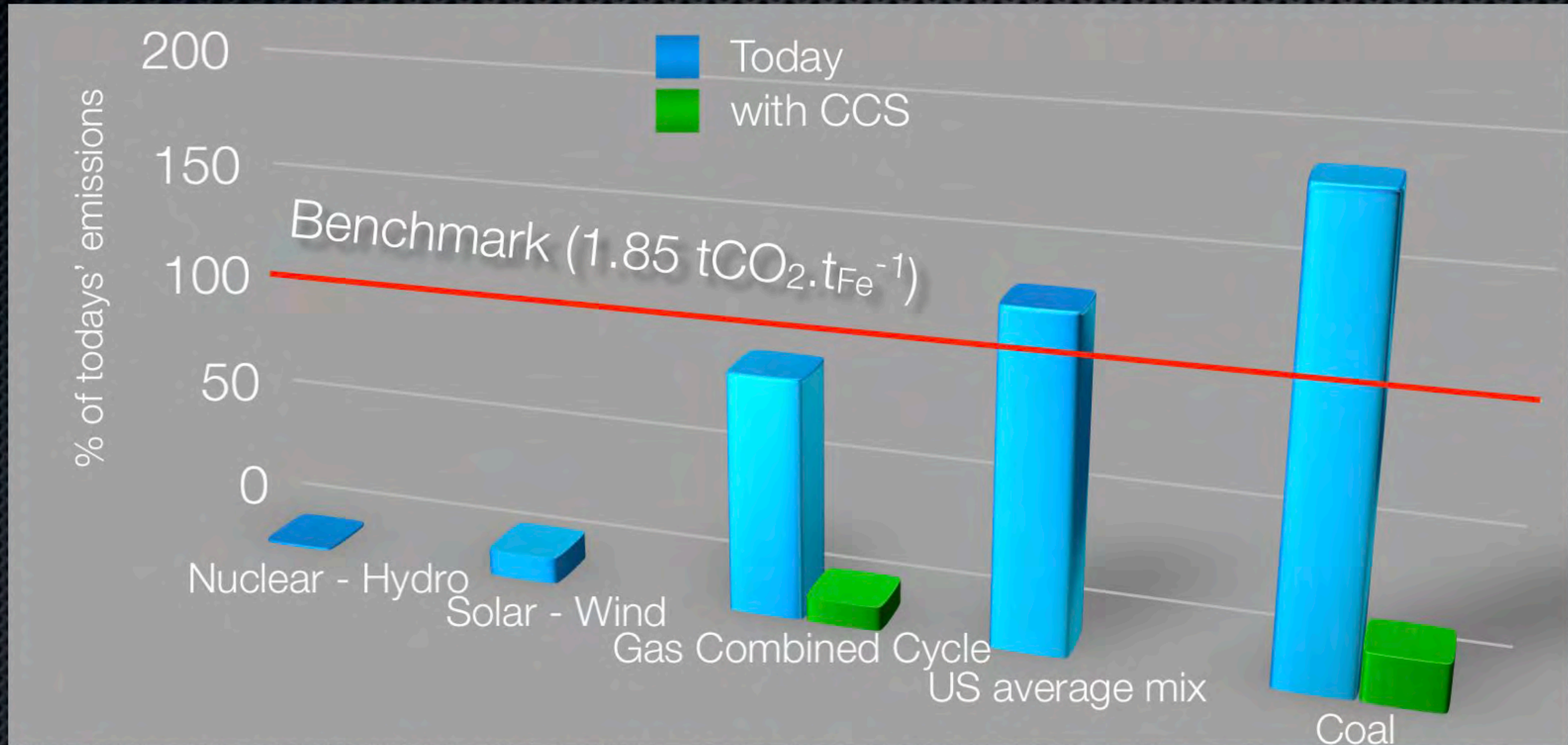


- lower capital cost per cell
- smaller minimum production capacity (lower barrier to entry)
- direct processing of oxide ore (existing supply chain, expanded)

environmental attributes of MOE



environmental attributes of MOE



- lower specific energy consumption

scientific and technical challenges

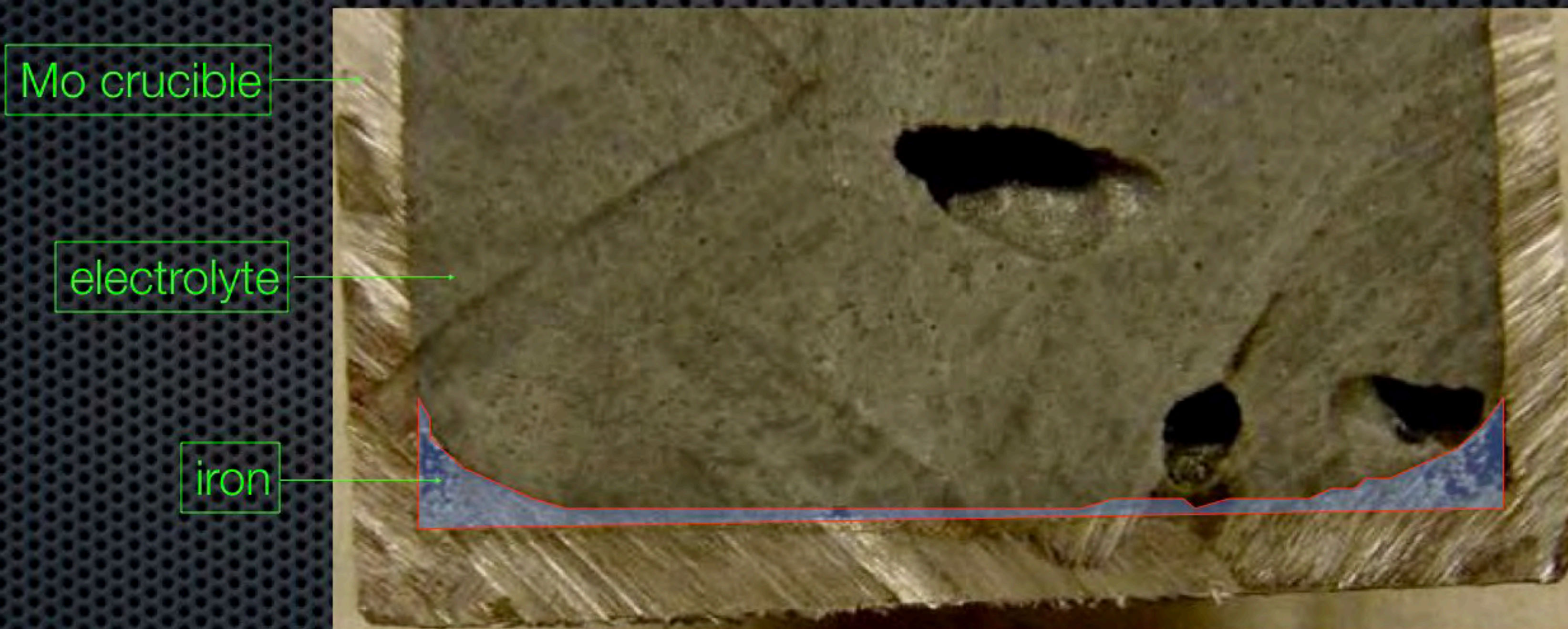
- ⇒ molten oxides of transition metals exhibit electronic conduction
- ⇒ inert anode operable at temperatures as high as 1700°C in an oxide melt

scientific and technical challenges

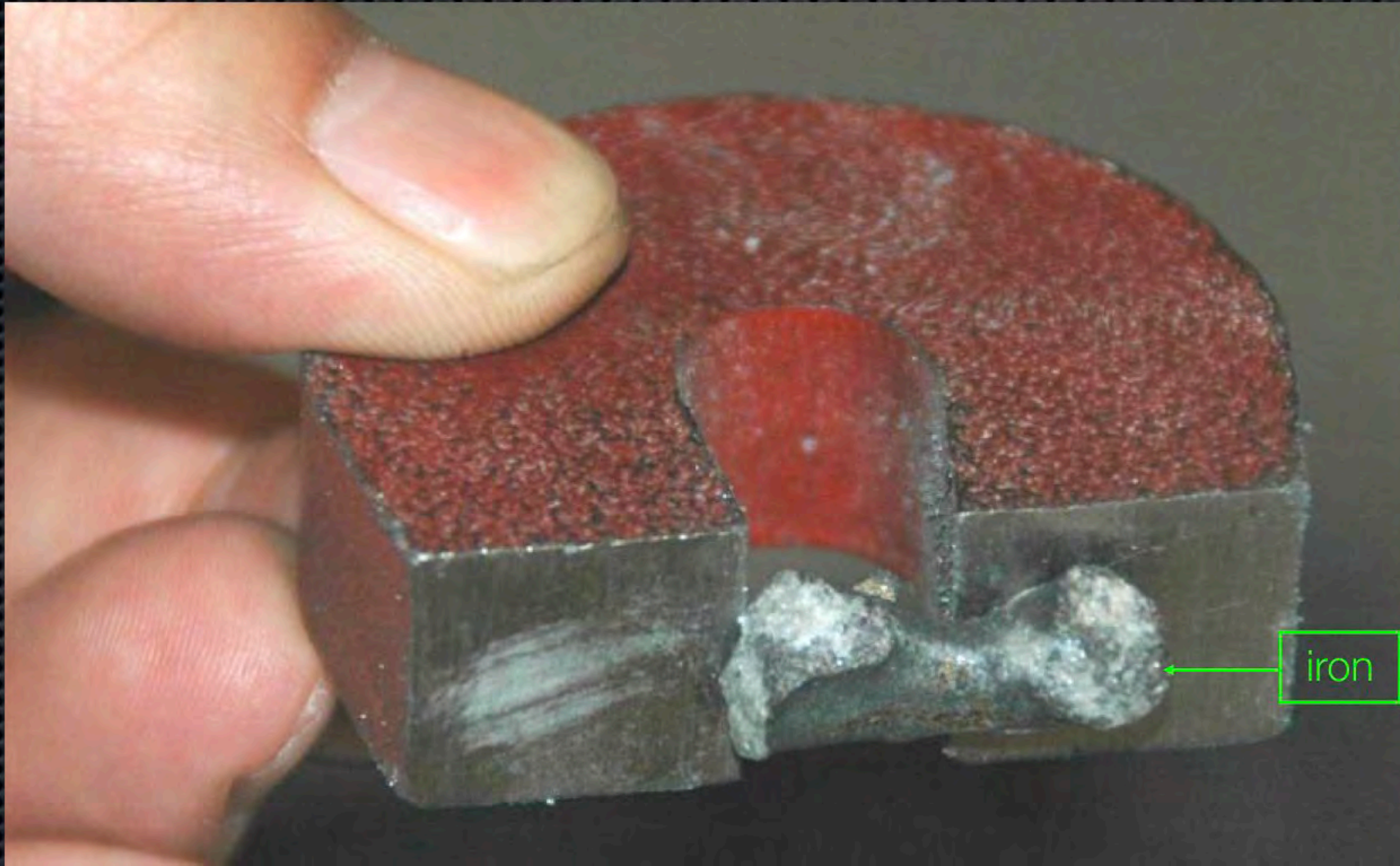
- ⇒ molten oxides of transition metals exhibit electronic conduction
- ⇒ inert anode operable at temperatures as high as 1700°C in an oxide melt
- ☞ both have been addressed

constant-current electrolysis at 1575°C

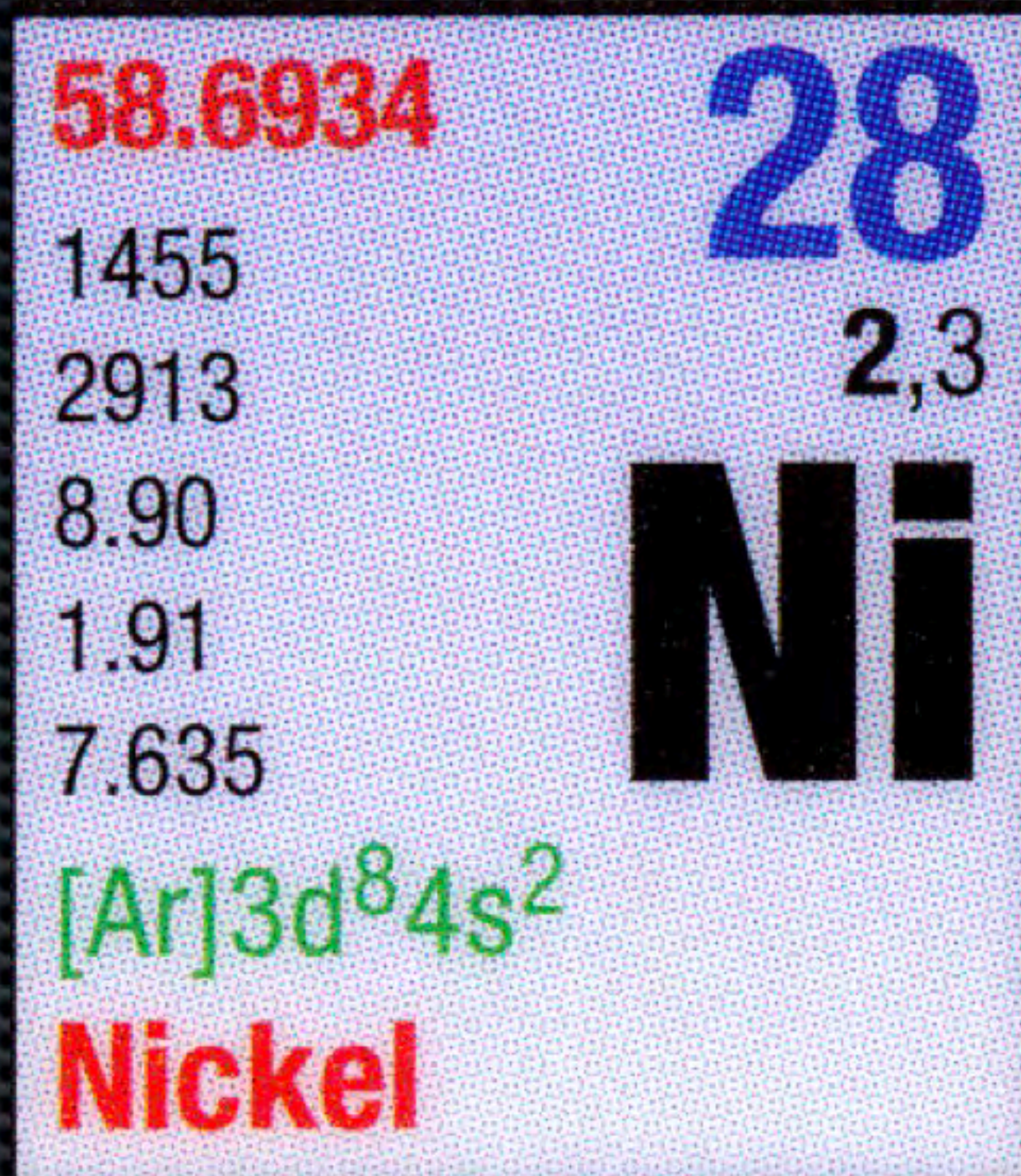
current density: $\sim 1 \text{ A cm}^{-2}$



more electrolytic production of molten iron:



production of nickel by MOE

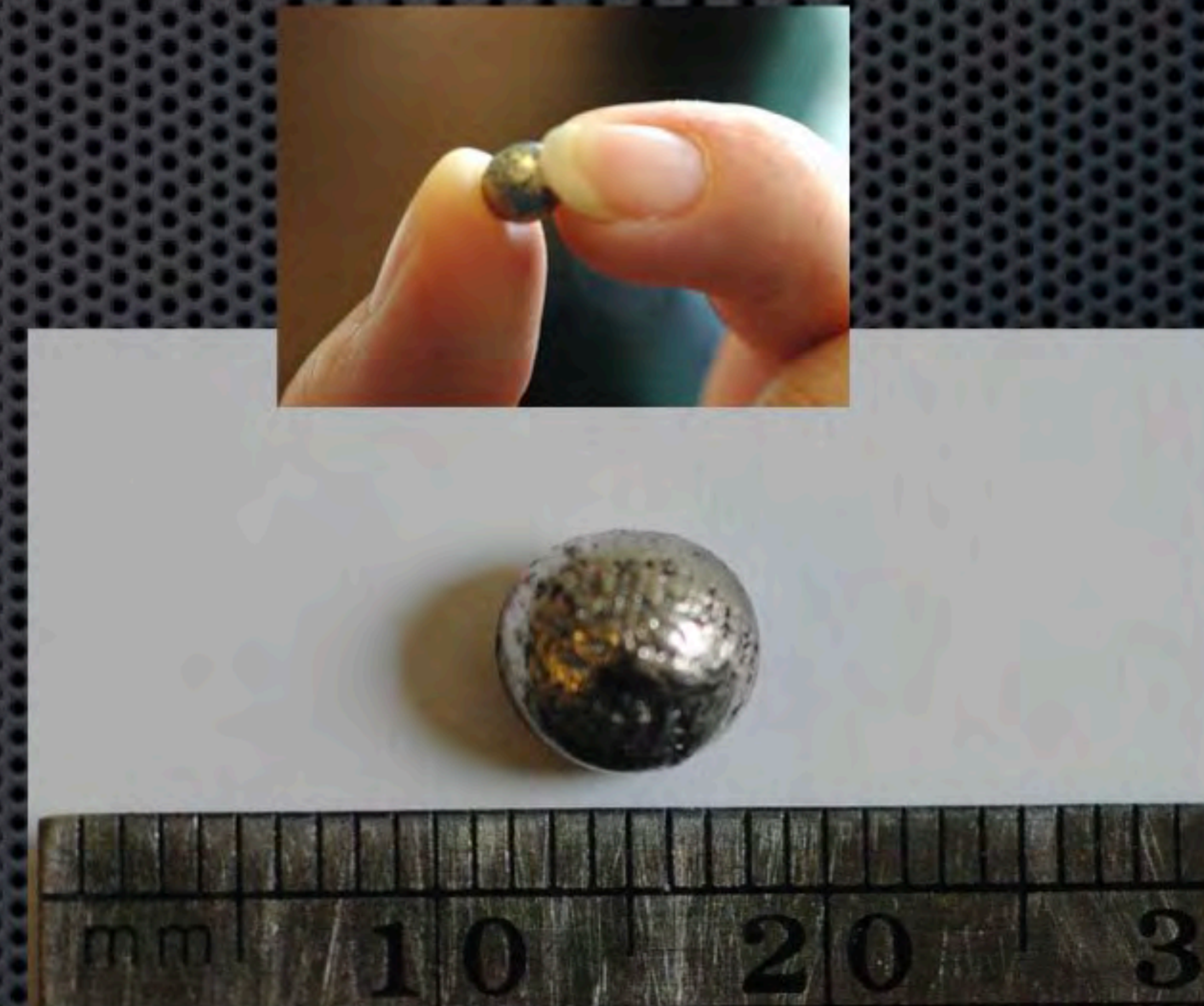


production of nickel by MOE

58.6934	28
1455	2,3
2913	
8.90	
1.91	
7.635	
[Ar]3d ⁸ 4s ²	
Nickel	

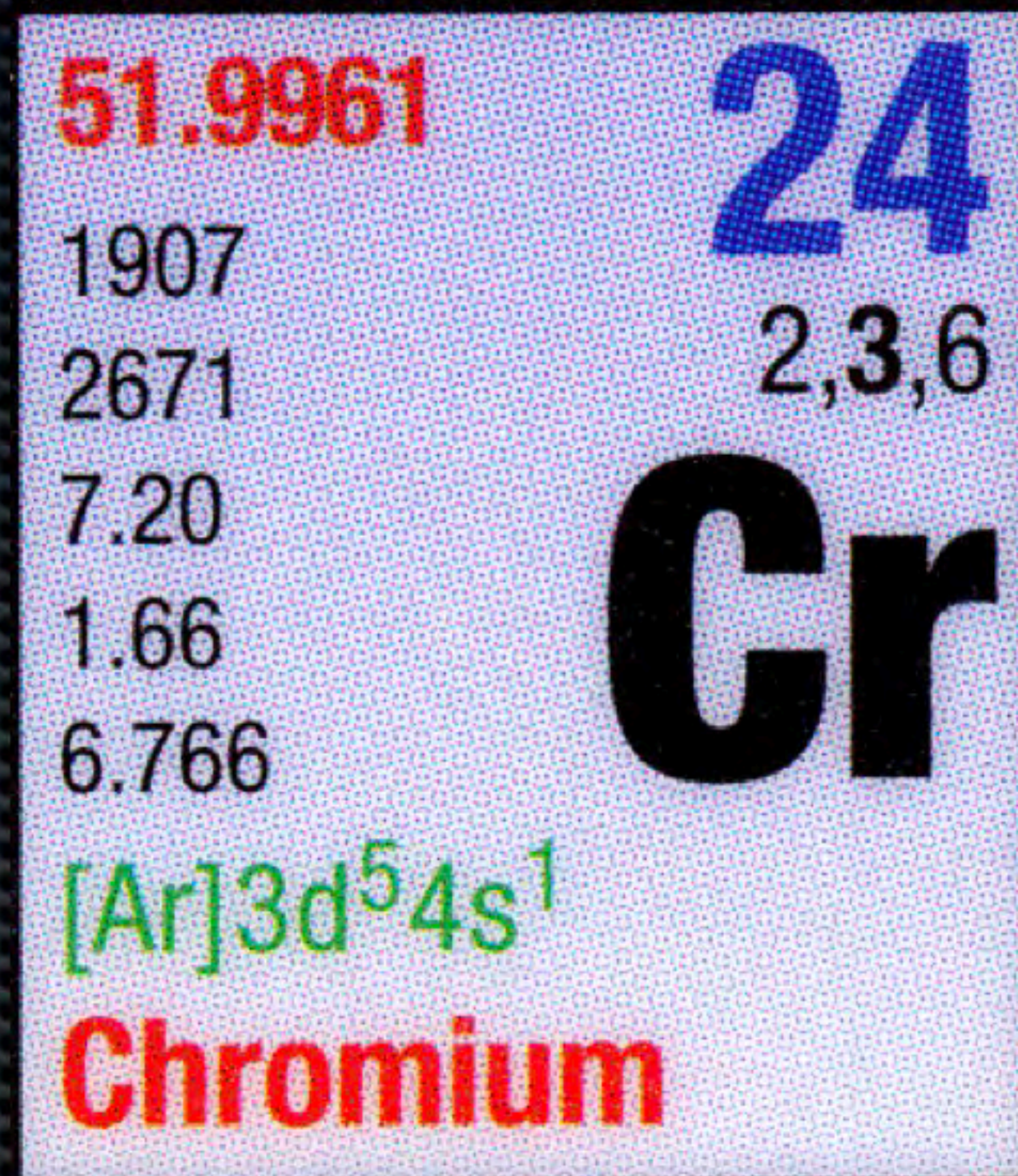


metal ball at bottom of cathode



metal ball on floor of cell

production of ferrochromium by MOE

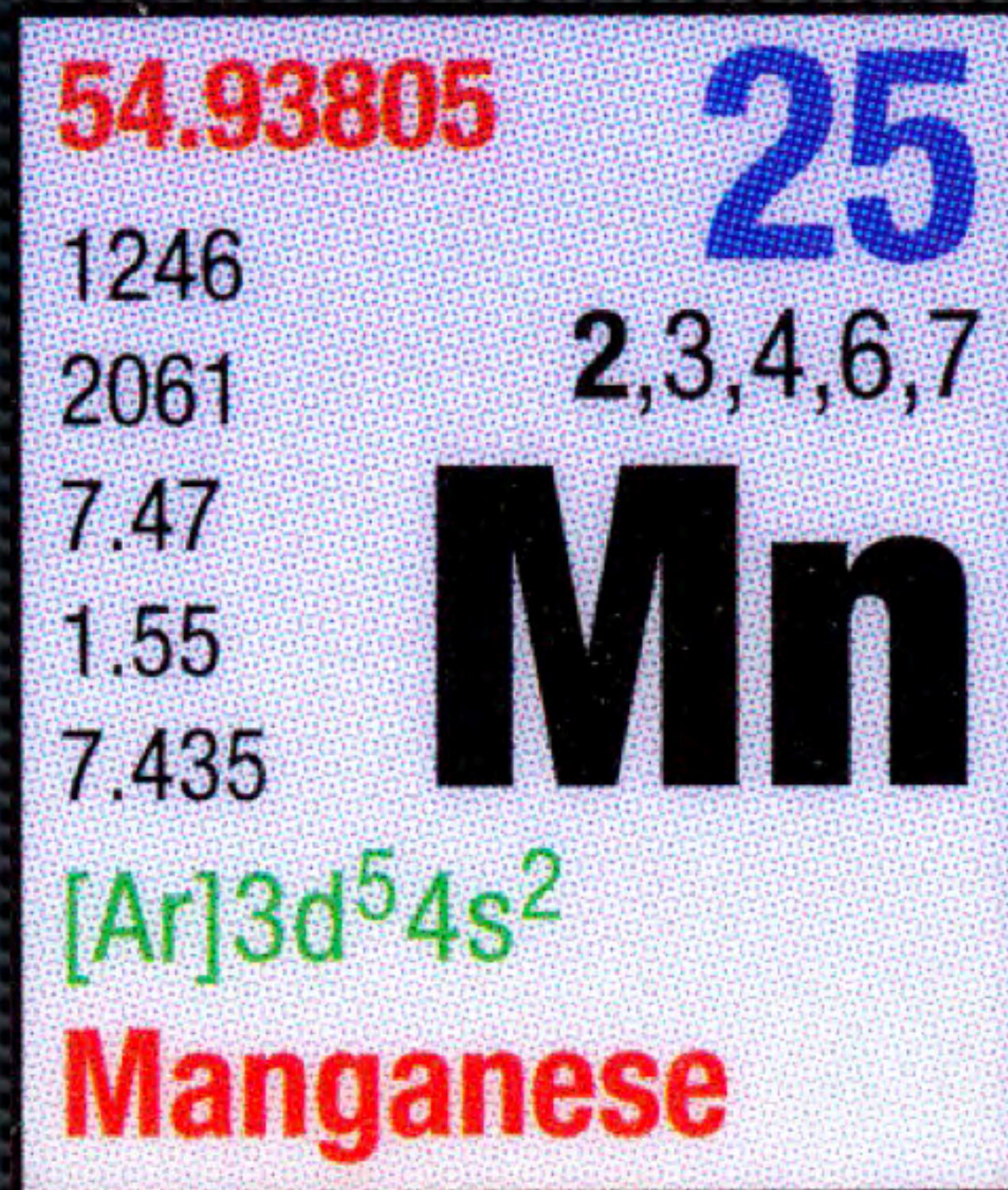


production of ferrochromium by MOE

51.9961	24
1907	2,3,6
2671	
7.20	
1.66	
6.766	
[Ar]3d ⁵ 4s ¹	
Chromium	

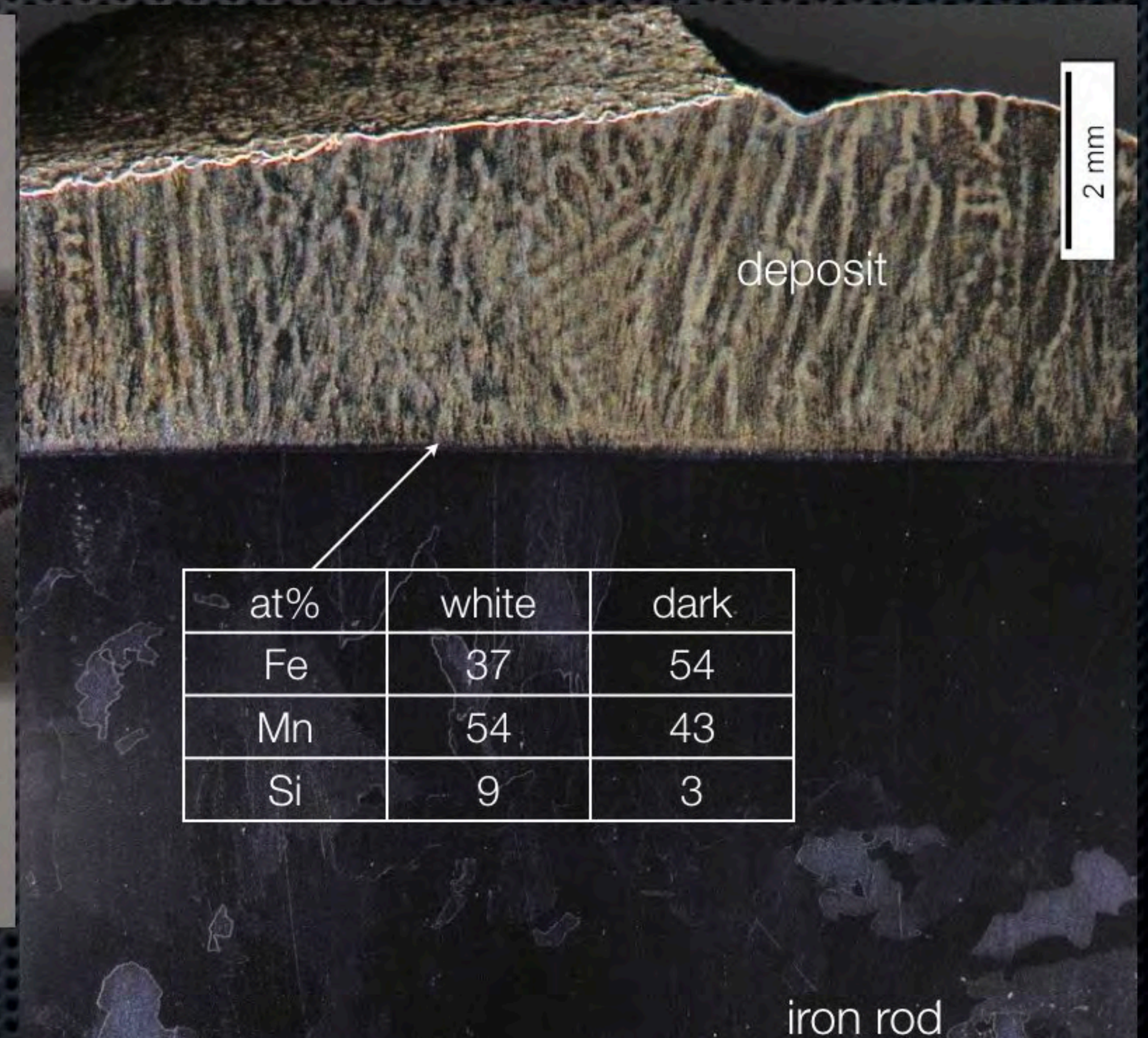


production of ferromanganese by MOE



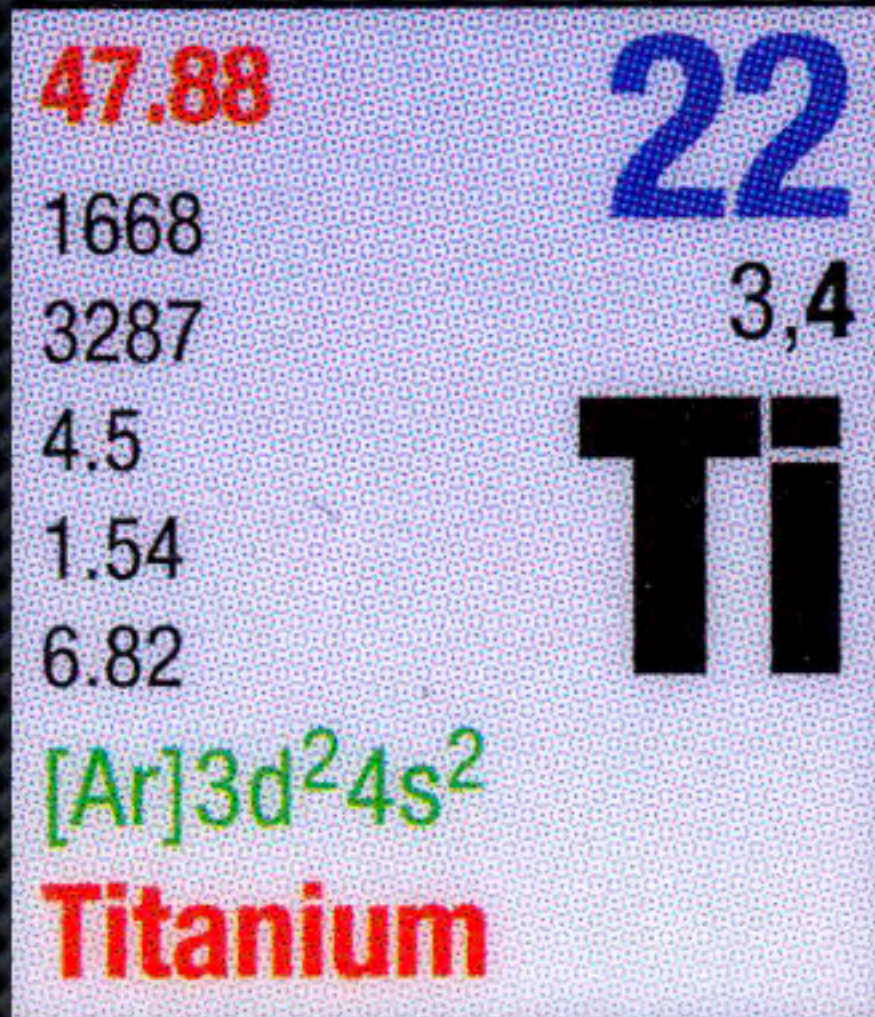
production of ferromanganese by MOE

54.93805	25
1246	2,3,4,6,7
2061	
7.47	Mn
1.55	
7.435	
[Ar]3d ⁵ 4s ²	
Manganese	

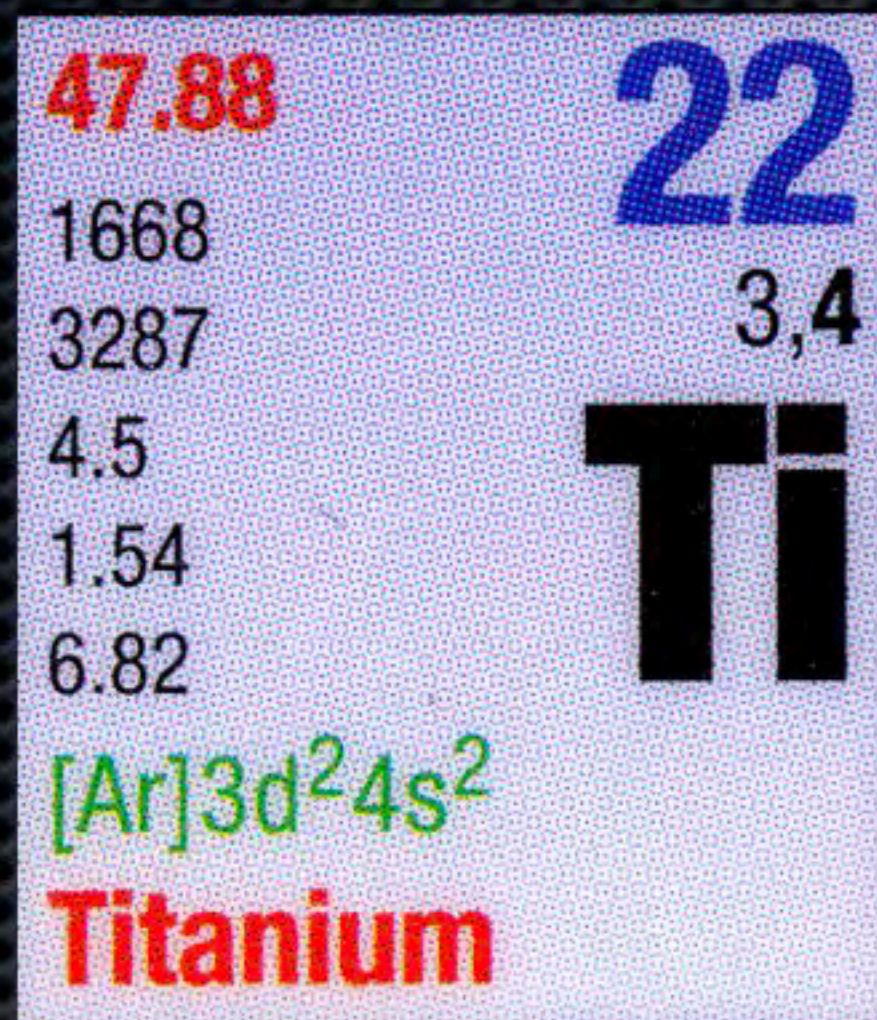


at%	white	dark
Fe	37	54
Mn	54	43
Si	9	3

production of titanium by MOE



production of titanium by MOE

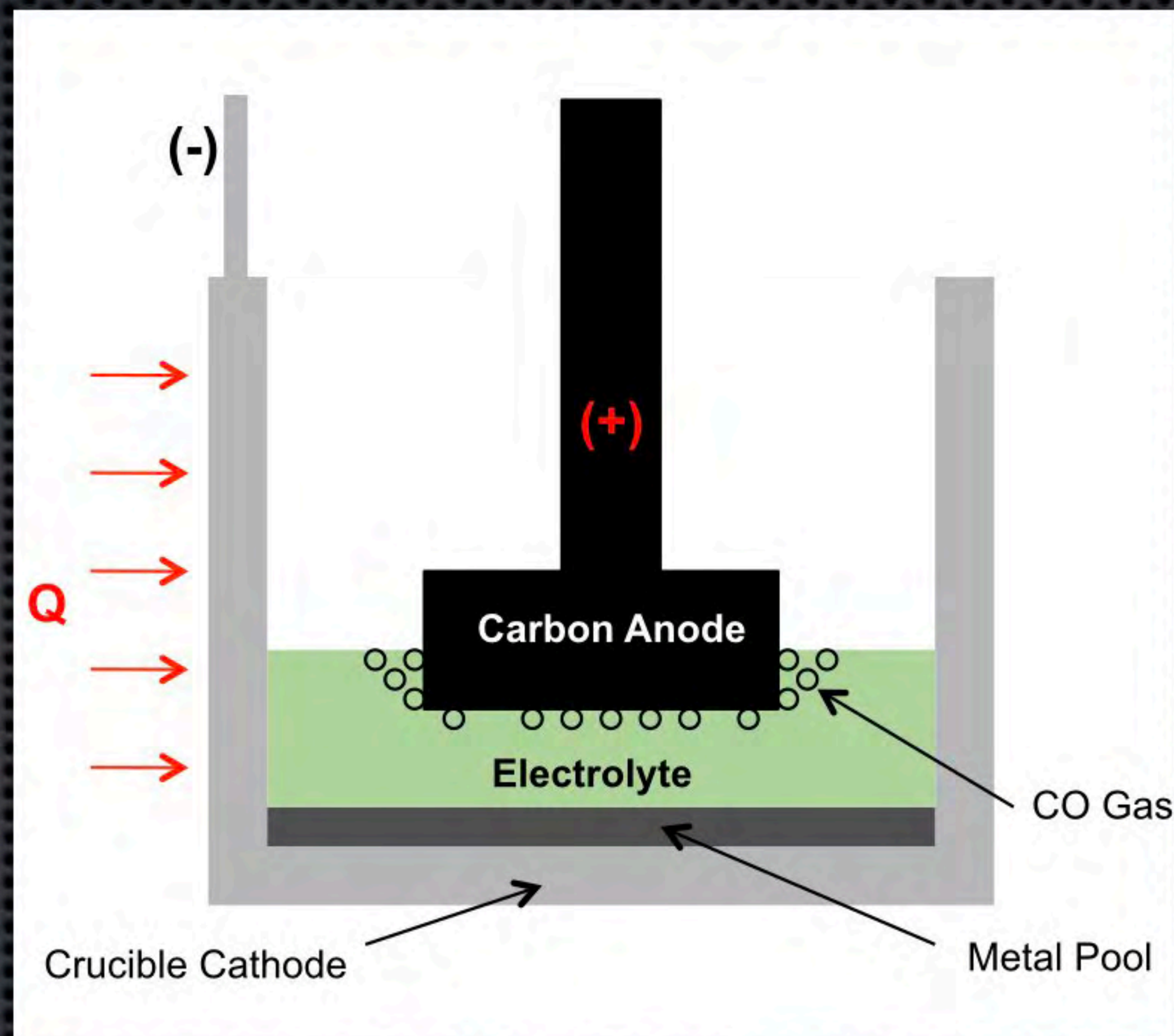


$T = 1725^{\circ}\text{C}$

cathode: Mo

anode: C

current density $\sim 1 \text{ A/cm}^2$



production of titanium by MOE



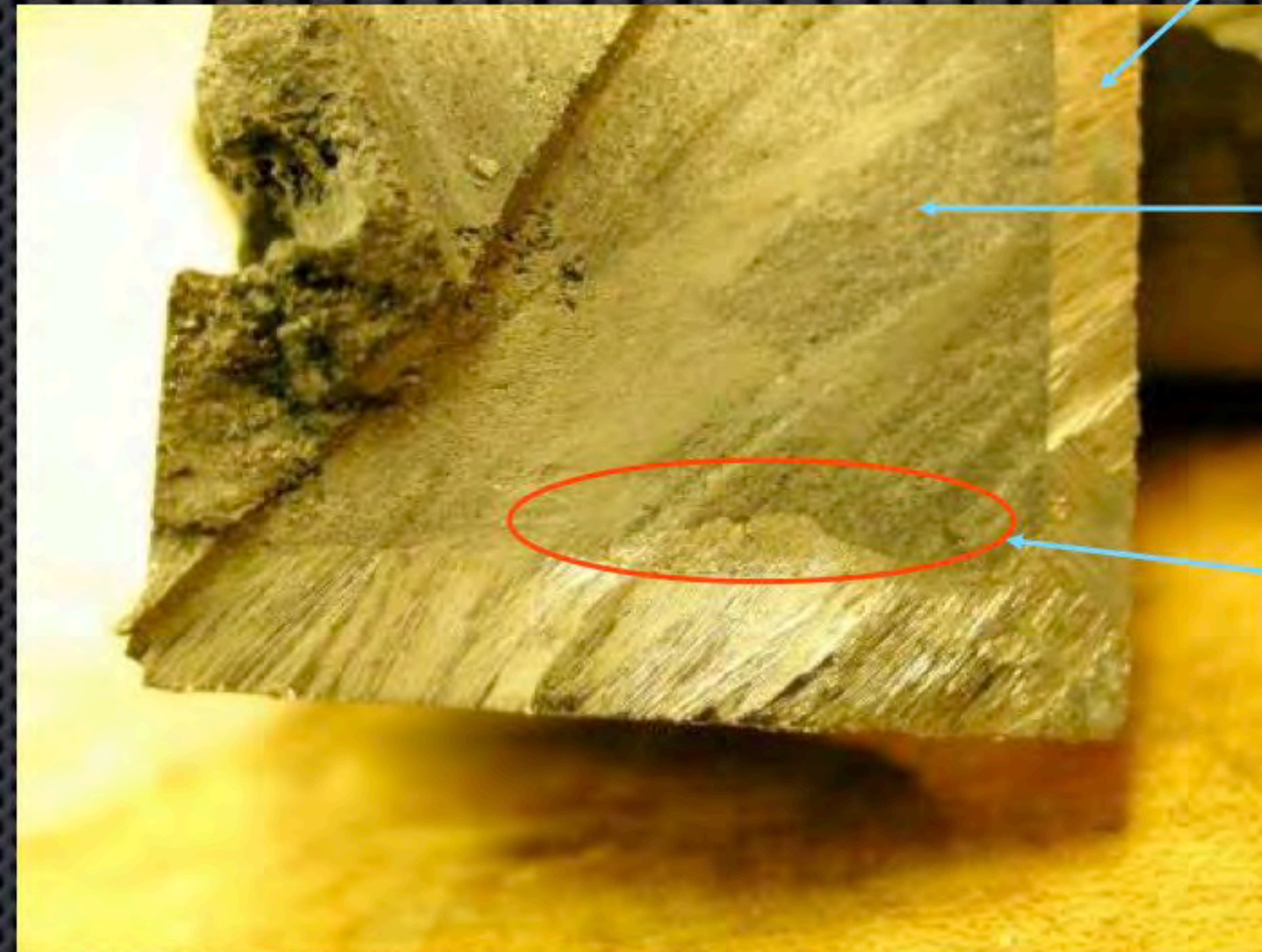
47.88	22
1668	3,4
3287	
4.5	
1.54	
6.82	
[Ar]3d ² 4s ²	
Titanium	Ti

$T = 1725^{\circ}\text{C}$

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current density $\sim 1 \text{ A/cm}^2$



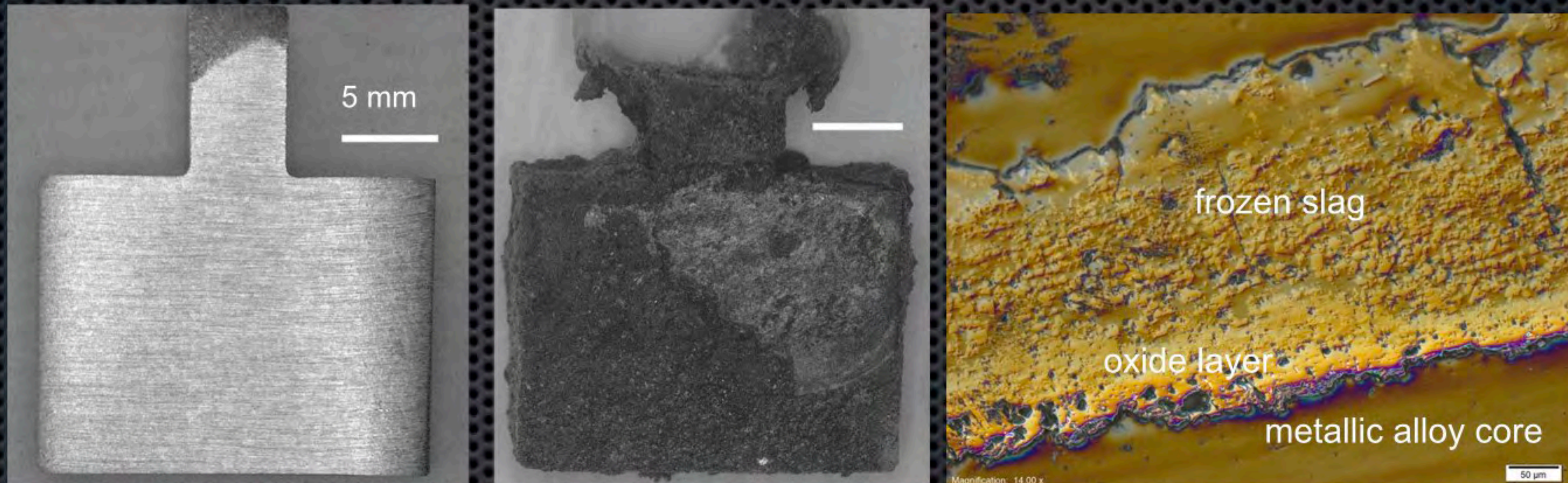
Mo crucible

frozen
electrolyte

titanium puddle

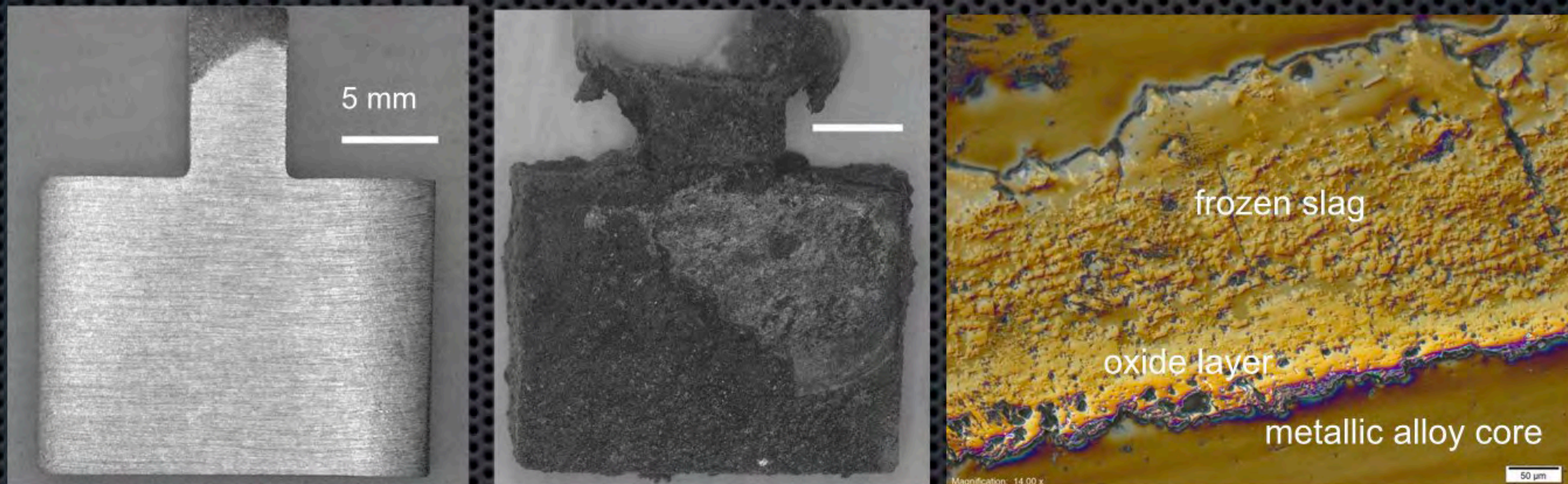
producing oxygen on an inert anode

anode after 2.5 h electrolysis at 1.5 A.cm^{-2} , $T = 1565^\circ\text{C}$



producing oxygen on an inert anode

anode after 2.5 h electrolysis at 1.5 A.cm^{-2} , $T = 1565^\circ\text{C}$



👉 newly discovered Fe-Cr alloy as inert anode

producing

and

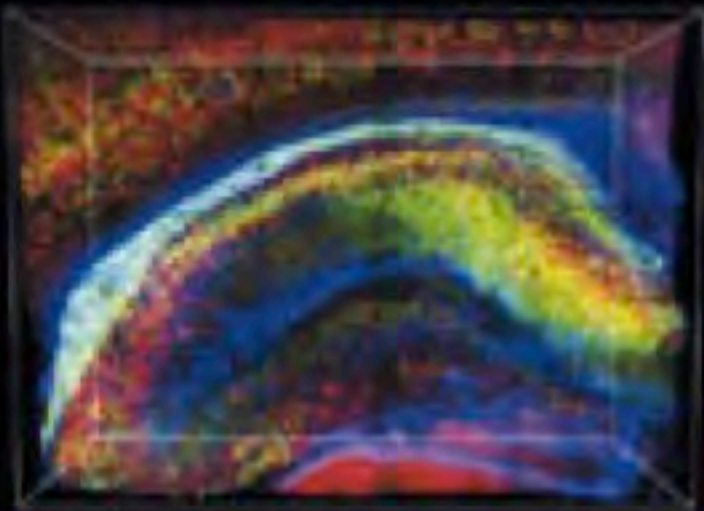
LETTER

doi:10.1038/nature12134

A new anode material for oxygen evolution in molten oxide electrolysis

Antoine Allanore¹, Lan Yin^{1†} & Donald R. Sadoway¹

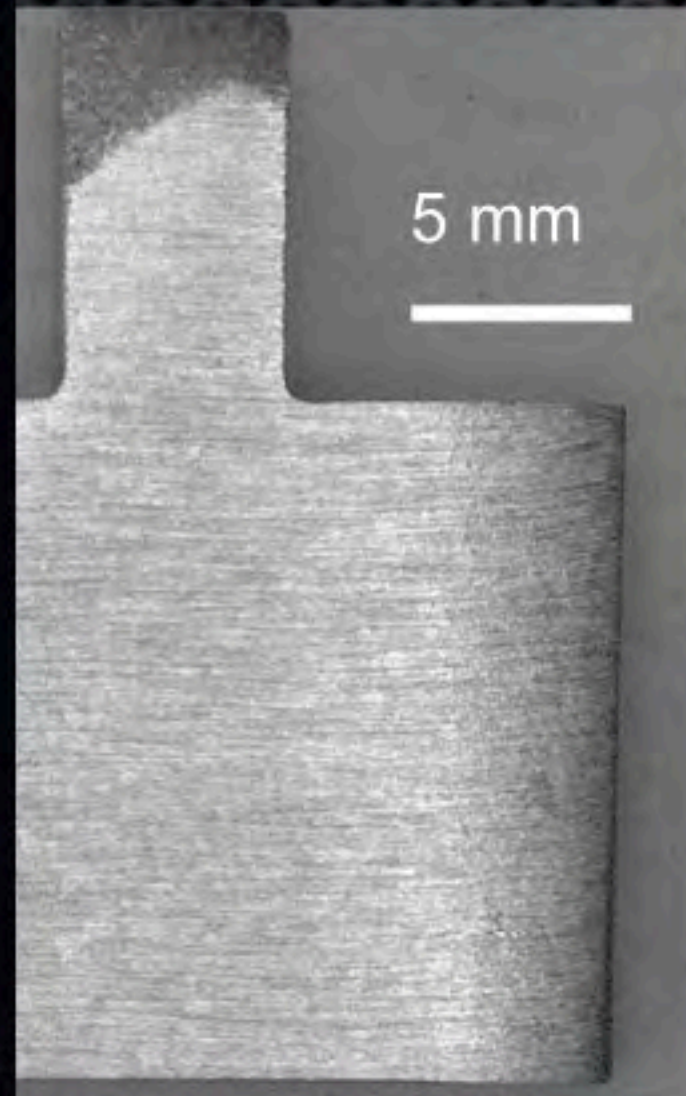
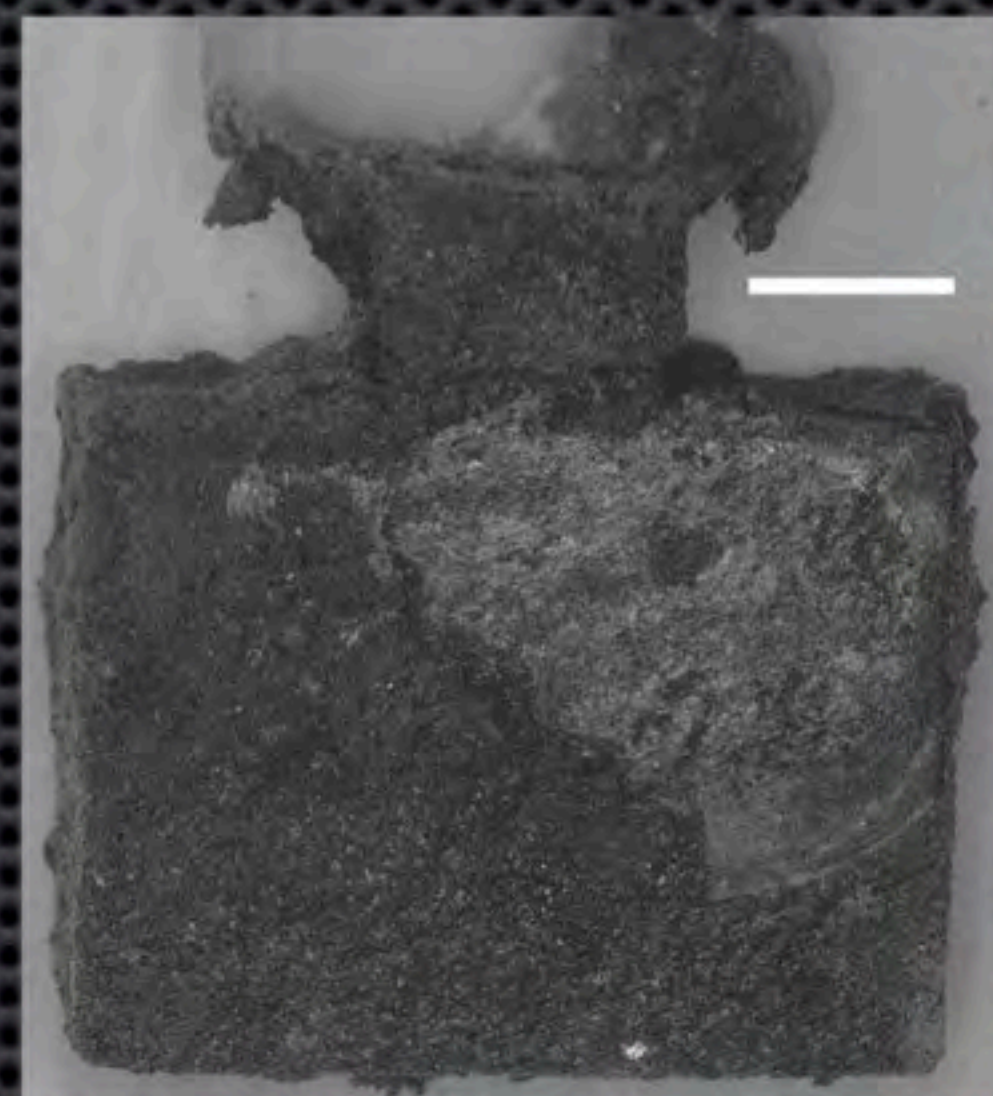
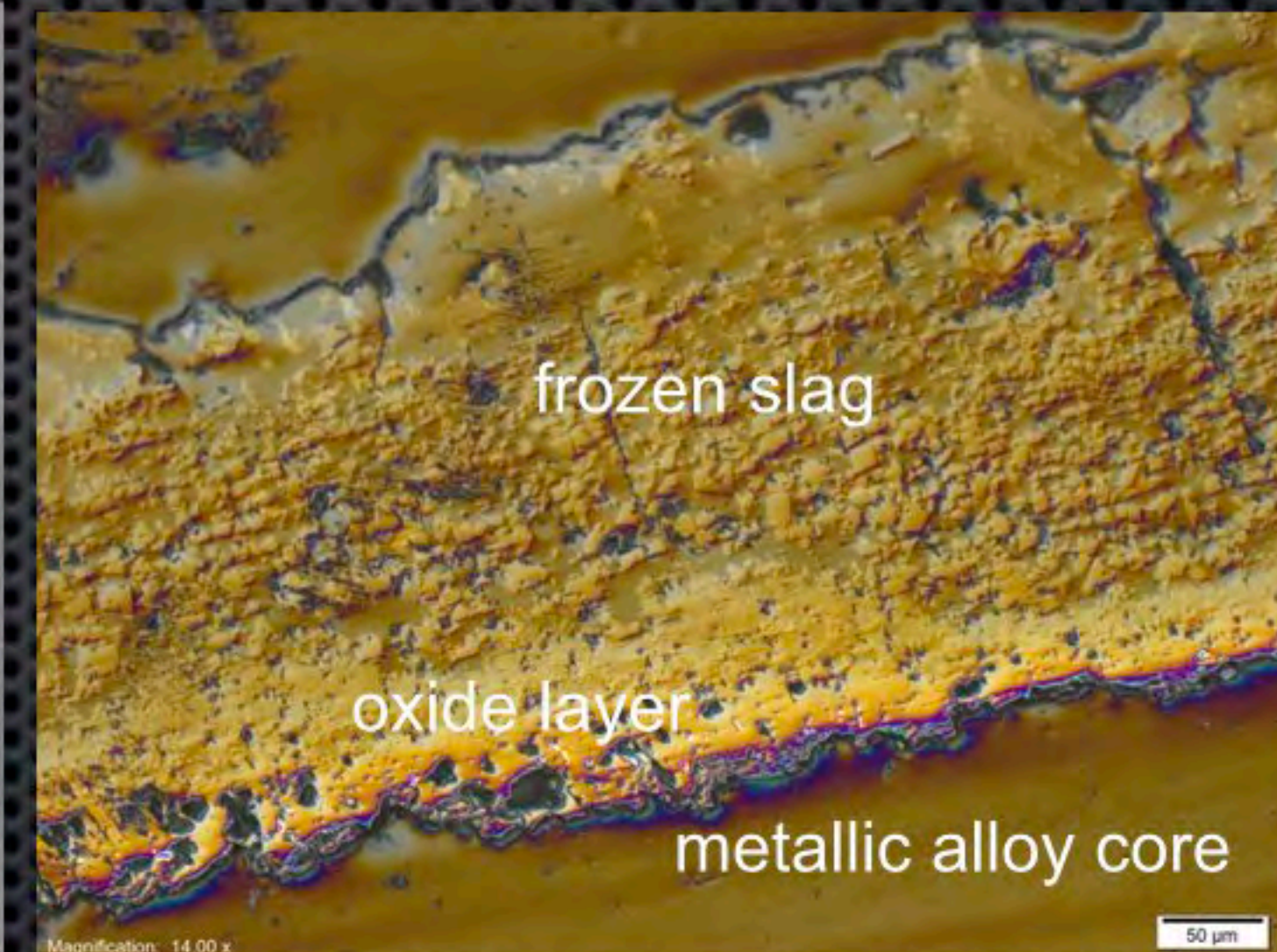
nature



A WINDOW ONTO THE BRAIN

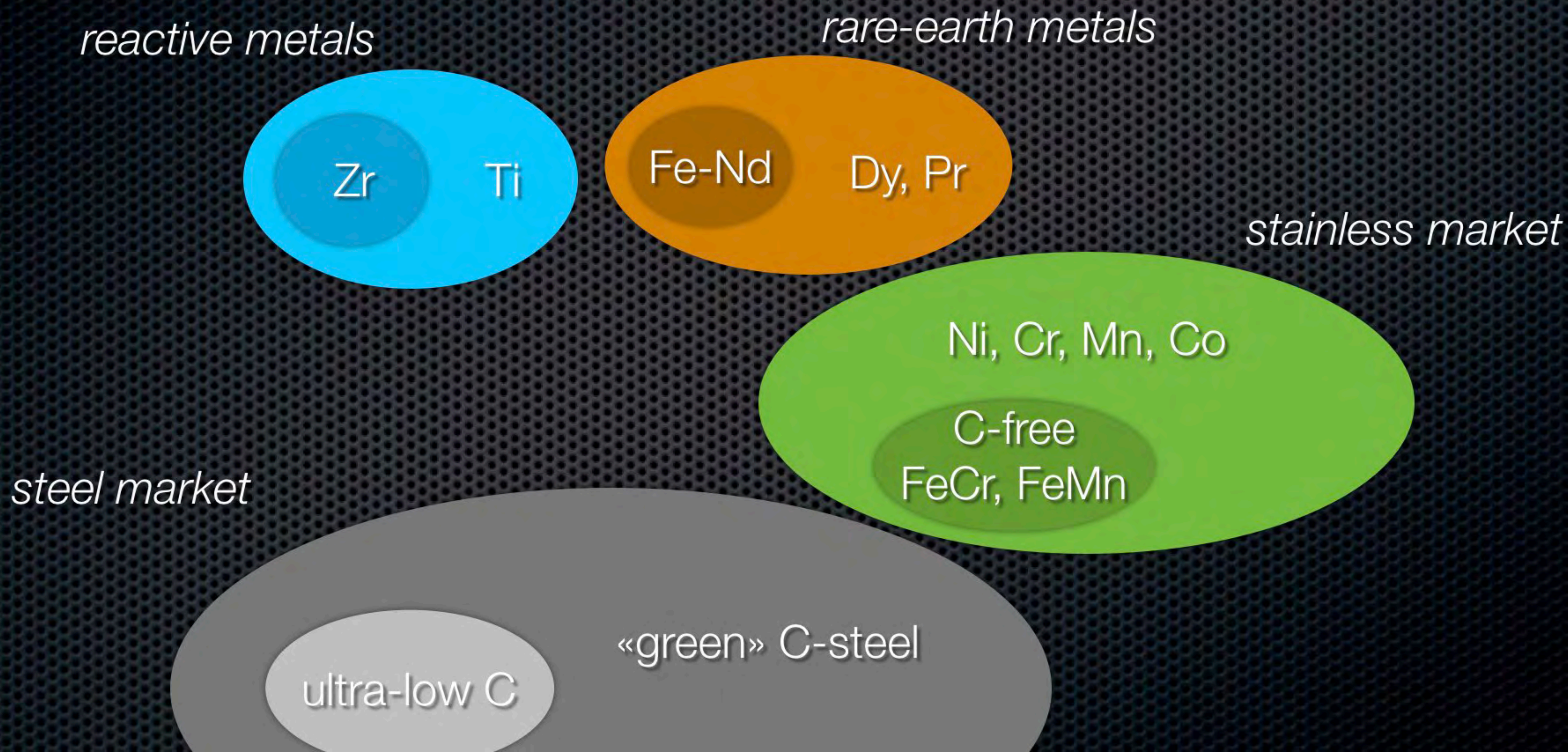
Transparency: brain technology provides a three-dimensional view of neural connections

THE RISE OF THE RISE
THE RISE OF THE RISE
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👉 newly discovered Fe-Cr alloy as inert anode

MOE is a platform



MOE status report

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⇒ scale-up to self-heating electrolyzer

MOE status report

⇒ scale-up to self-heating electrolyzer

☞ startup company: Boston Electrometallurgical Corp.



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ELECTROMETALLURGICAL
CORPORATION

Unlocking our Natural
Resources with Technology

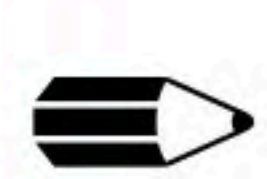




BEMC

BOSTON
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founded in 2012



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\$\$\$ lone investor \$\$\$



BEMC

BOSTON
ELECTROMETALLURGICAL
CORPORATION

Unlocking our Natural
Resources with Technology

- founded in 2012
- \$\$\$\$ lone investor \$\$\$\$
- from the mining industry!!!

MOE status report

⇒ scale-up to self-heating electrolyzer

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⇒ 8 people at 6000 ft² facility in Woburn, MA

MOE status report

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⇒ designed, built, & commissioned reactor 1000x lab scale

MOE status report

⇒ scale-up to self-heating electrolyzer

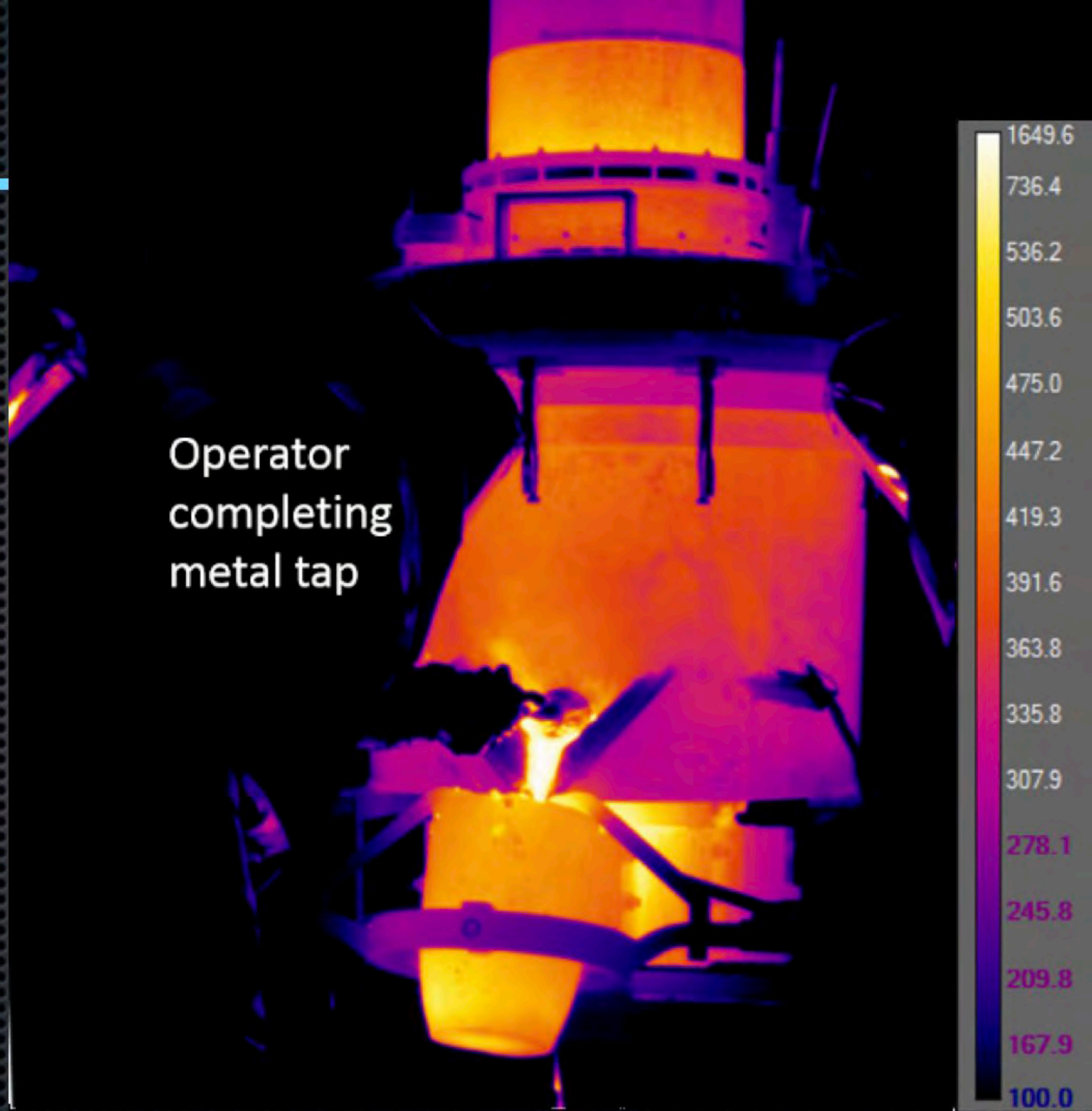
☞ startup company: Boston Electrometallurgical Corp.

⇒ 8 people at 6000 ft² facility in Woburn, MA

⇒ designed, built, & commissioned reactor 1000x lab scale

⇒ pilot-scale metal production by the end of 2015

tapping liquid metal



100s of kg of metal product



LOW CAPITAL AND OPERATING COSTS

Premium Product at Commodity Cost

- Reduce iron oxide with electrons, not carbon.
- Byproduct is oxygen, not CO₂.
- Product is higher quality: ultra-low carbon steel.
- Make new premium steel grades cost-competitive.

Capital Cost

- Aluminum electrolysis cell has similar layout, equipment.
- Iron has more mass/charge.
- MOE operates at higher current density.
- Projected CAPEX for MOE iron is low.
- Flexible capacity.

Operational Cost

- OPEX projections put MOE between BF+BOF and DRI.

PRODUCTIVITY – COMPARISON WITH ALUMINUM

Aluminum electrolysis cells

- Up to 650 kA @ 94% current efficiency.
- Produce 1800 tpa Al per cell.
- Up to 400 cells/potline.
- Largest smelter is 1440 cells.

MOE Iron productivity

- 650 kA MOE cell @ 94% CE would produce 3700 tpa Fe.
- 270 cells needed for 1M tpa
- Good labor utilization for plant size ~20 cells = 74,000 tpa.

TIMELINE AND NEXT STEPS FOR STEEL AND FE-ALLOYS MOE DEVELOPMENT

2014-2015

Succeeded with first product

- 12 experimental campaigns in 7 months.
- Met all ASTM specifications for product in 5 months.

2015-2017

Initial funding for scale-up of steel

- NSF Phase II awarded September 2015.
- Pilot-scale testing of inert anode MOE.

Future Steps

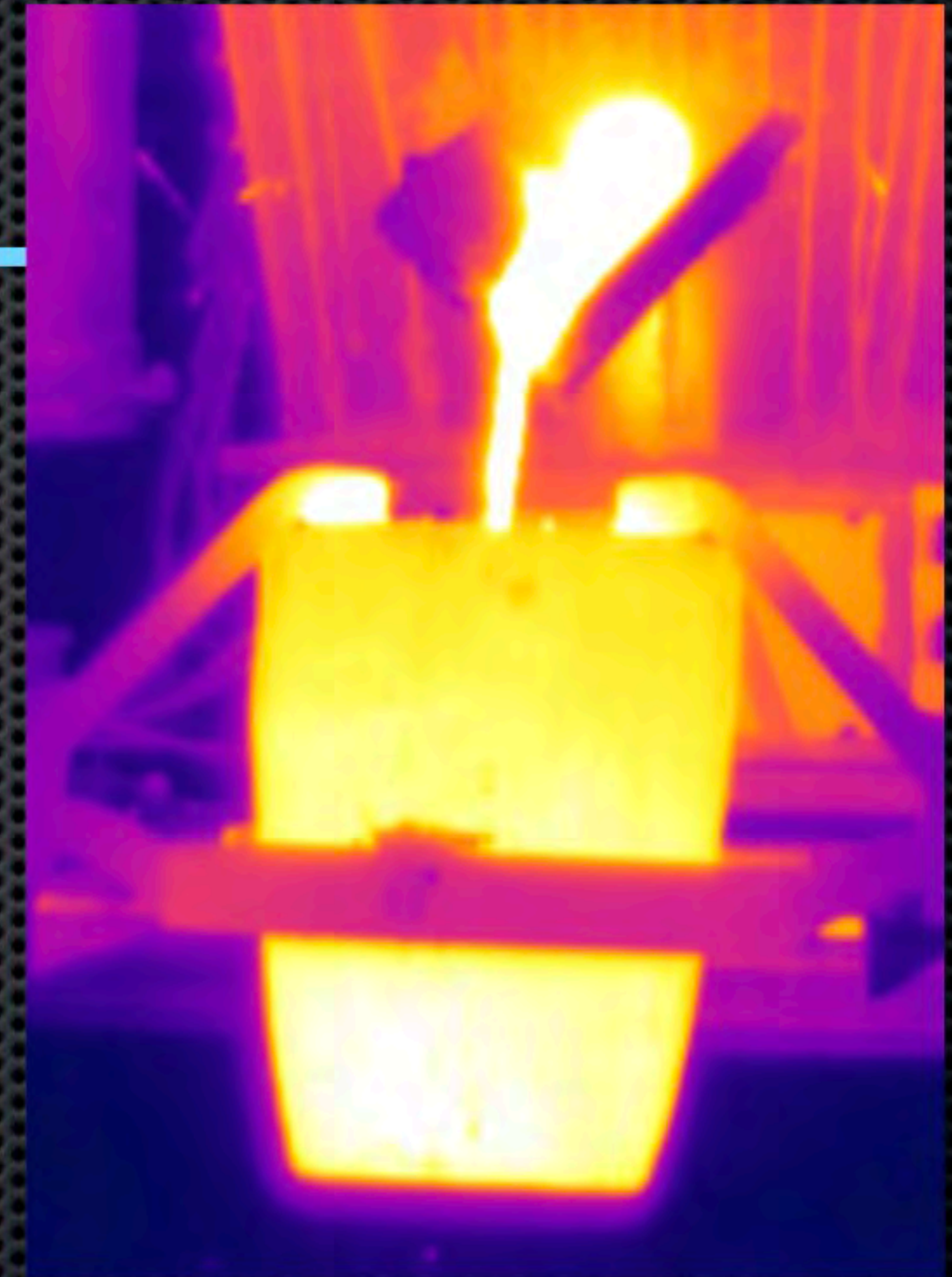
Aggressive development

- 2018-2024: Demonstration plant: Full-scale cells.

CONCLUSION: MOLTEN OXIDE ELECTROLYSIS – TECHNOLOGICAL ADVANTAGES

- Premium product at commodity cost.
- No carbon in cell = no carbon in product.
- Enable new premium steels.
- Save about 1/3 energy.
- No direct CO₂ emissions.
- Modular capacity additions.
- Scale-up like Hall-Héroult plant for aluminum.
 - Balance of plant
 - Labor productivity
 - Capital cost
- Combine best features of Hall-Héroult and Electric Arc Furnace.

This is not a science project.





Soyez réalistes.

Demandez l'impossible!

- Paris, 1968