“Carbon-Free Technology : Implications for Steel and Aluminum”

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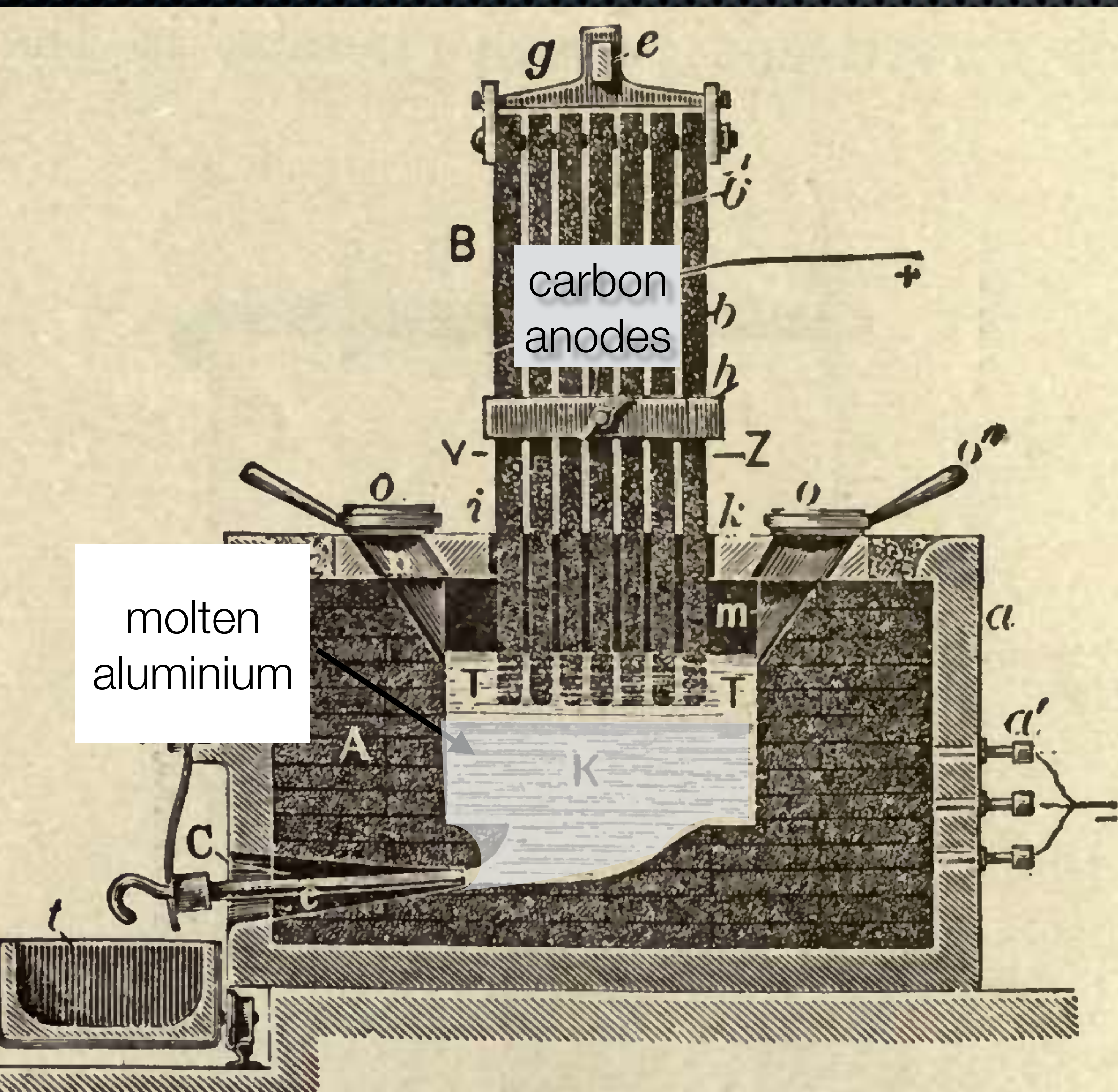
Aluminium by electrolysis

Using electricity and carbon since 1886



$$2Al_2O_3 + 3C = 4Al(l) + 3CO_2(g)$$

- C as a fuel
- e^- as a reductant

☛ Hall-Héroult

Global Metal Industry Carbon Foot Print (2018)

Metals	World Production (MMT)	CO_{2eq} (MT/MT)	% Global GHG
Iron & Steel	1,809	1.0	4-5
Aluminum	64.4	12	1-2
Copper	20	5.5	<1
Zinc*	10	3	<<1
Magnesium*	1	>18	<<1
Titanium*	0.1	>20	<<1

Source : Das, Allanore * estimated

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Alternative Aluminum Production Routes

Processes	t CO_{2eq} /t Al	Change
Average Hall- Héroult (H-H)	12	Base
Best H-H	10	-15%
Wetted drained cathode	9	-25%
Wetted cathode and inert anode	**8**	**-33%**
Carbothermic electric furnace	8	-33%
Clay carbochlorination & chloride electrolysis	8	-33%

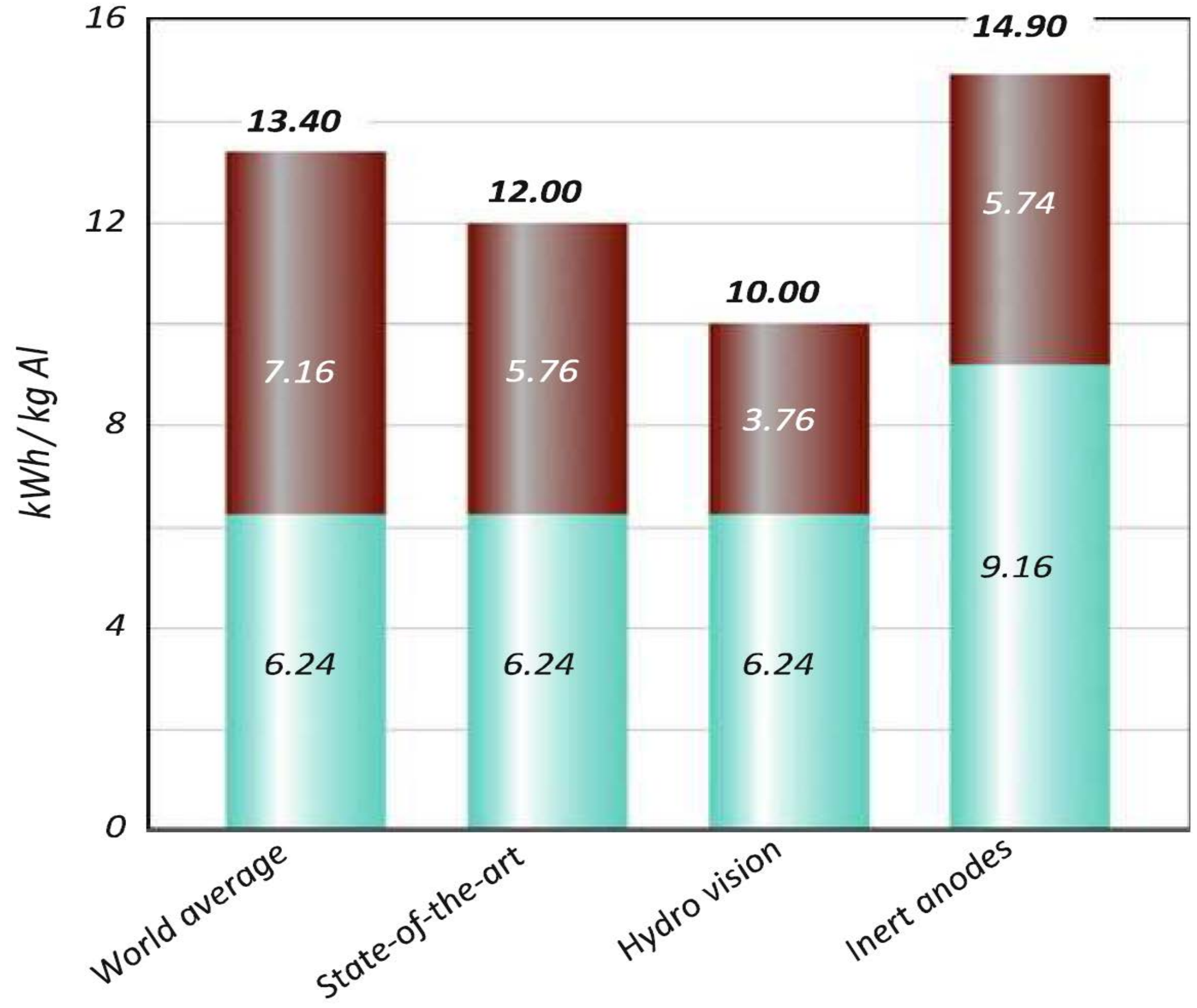
Source : Das, JOM

Hall- Héroult CO_{2eq} Emissions

	kg CO_{2eq} / tonne Al					
Emissions	Mining	Refining	Anode	Smelting	Casting	Total
Process			388	1,626		2,014
Electricity		58	63	5,801 *	77	5,999
Fossil Fuel	16	789	135	133	155	1,228
Transport	32	61	8	4	136	241
Auxiliary		84	255			339
Per Fluoro-Carbons (PFC)				2,226		2,226
Total	48	992	849	9,790	368	12,047 **

Source : Das, JOM *Average Grid ** 12 t CO2eq /t Al

Energy Consumption – Competing H-H Processes



Actual

Theoretical

Source : LMA (2019)

Technology Terminology Description

Phrase	Implications	Focus
Oxygen Anode	Pure oxygen released	Aspirational Utopian
Zero- Carbon -Free	No C / energy required	Marketing/ Societal
Inert/Non-Consumable Dimensionally Stable	Zero anode dissolution	Technical
Low Carbon-footprint	**Lower GHG processes**	**Most appropriate**

Source : Das

Advantages of Low C-footprint Process

Source : Image - LMA

Reduced Carbon Footprint

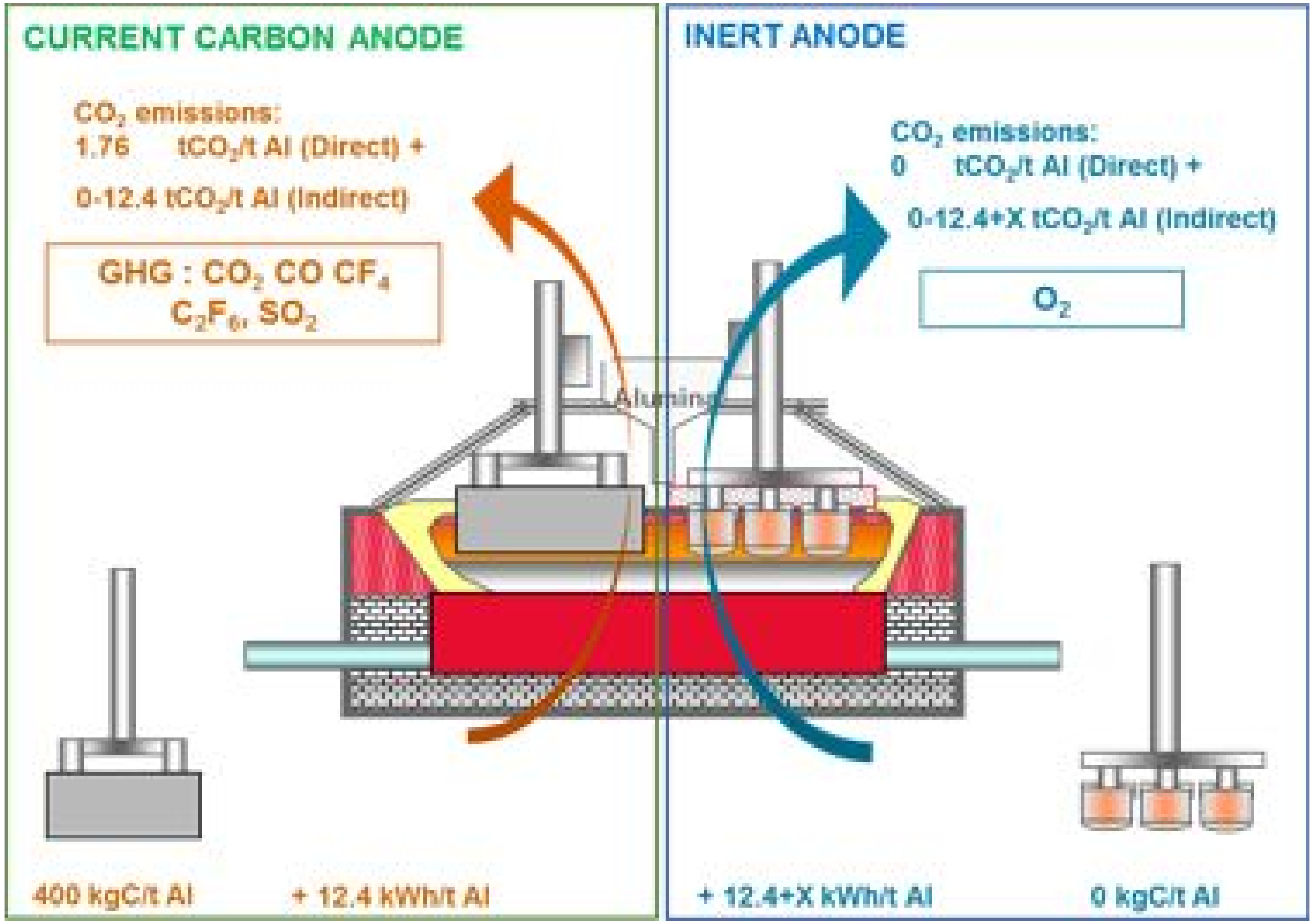
Carbon Dioxide

PerFluoroCarbon (PFC)

Salable Product - Oxygen

Better Work Environment

Carbon Vs. Low C-footprint Process



Source : Image - AGRAL Process

Barriers, Challenges and Solutions

Barriers	Challenges	Solutions
High Temperature Fluoride Corrosion	“universal solvent”, dissolves alumina	“long lasting” Material Miracle
High Conductivity Lower “theoretical” kWh/kg	IR Losses 500 kA Heat Balance	Lower resistivity Innovative Design
Thermal Shock	C high thermal shock	Innovative Cell Designs
Physical Stability Retrofittable/Cost	Carbon - “cheap”, abundant	Innovative Design , Low Cost
Electrochemical Stability	Al Reactive	Dissolved elements more acceptable

Source : Modified by Das from Sadoway (JOM 2001)

Notable Efforts

- Has been a “dream” since H-H process in 1886
- Aluisuisse (now RTA) – Tin Oxide (1970)
- DeNora – Chlorine DSA Fame (1970)
- Alcan/Pechiney – Oxide Ceramics /Cermets (1980)
- Alcoa – Metals/Oxide Cermets (1980)
- US DOE/Alcoa – Retrofittable concepts (2010)
- Rusal – (2016)
- **Elysis – RTA/Alcoa/Apple/Quebec (2018)**

Source : Das

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Commercialization – Brownfield

POSITIVE	NEGATIVE	OUTLOOK
Sunk Capital	China > 50 % world capacity	**1-3 years** for Pot Rebuilds
Existing Infrastructure	“Old” technology fights	**4 -6 years** for Line Restarts
Swing Capacity “Life Line”	Alcoa /RTA/Hydro marketing low C Al	**7 -10 years** for Plant Conversions
Low C Products Markets	Elysis/RUSAL Licensing terms	**> 10 years** for wide spread use

Source : Das

Commercialization – Greenfield

POSITIVE	NEGATIVE	OUTLOOK
“Leap Frog” – New “Material Science” Age	Many develops. needed ↑ “theoretical” kWh/kg	**1-3 years** R&D
Elysis -“Apple Magic” Alcoa/RTA “dream” team	IP , Financing $ New Capacity Location /	**4 - 6 years** Limited
“Green” Products	Will customer pay	**7-10 years** Likely
New Capacity Demand	New technology Chloride/Carbothermic	**> 10 years** More Likely

Source : Das