COMPARISON AND DEVELOPMENT OF PROCESSES

FOR PRIMARY MAGNESIUM PRODUCTION

2 CONTENTS

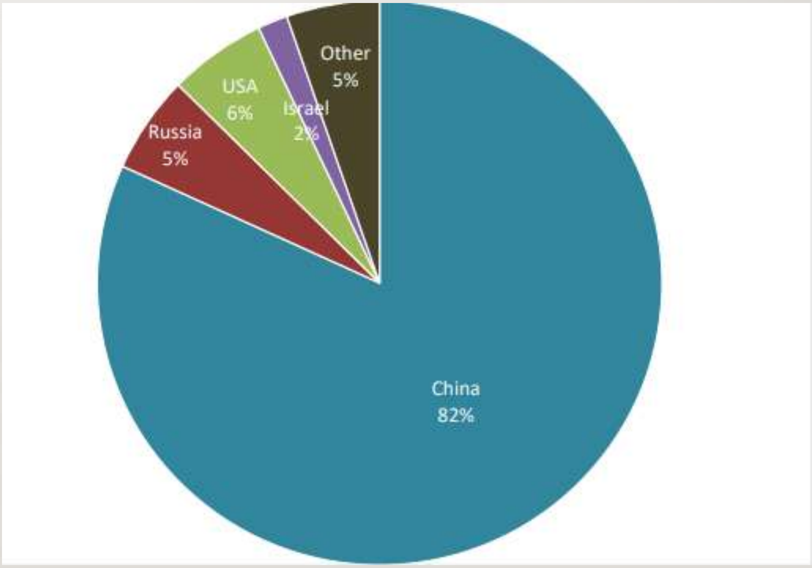
- World Primary Mg production
- Raw materials used for Mg production
- Primary Mg production processes
  - Electrolysis process
  - Carbonothermic process
  - Horizontal Pidgeon
  - Vertical Pidgeon
  - Magnetherm process
  - Al Thermic process
- CO_2 footprint of processes
- SWOT

3 WORLD PRIMARY MG PRODUCTION*

China	82 %
USA	6 %
Russia	5 %
Israel	2 %
Others	5 %

(Brazil, Turkey,Russia,Canada)

Pyrometallurgy (Pidgeon,Rima)	85 %
Electrolysis	15 %



* CM Group

Raw materials used for Mg production

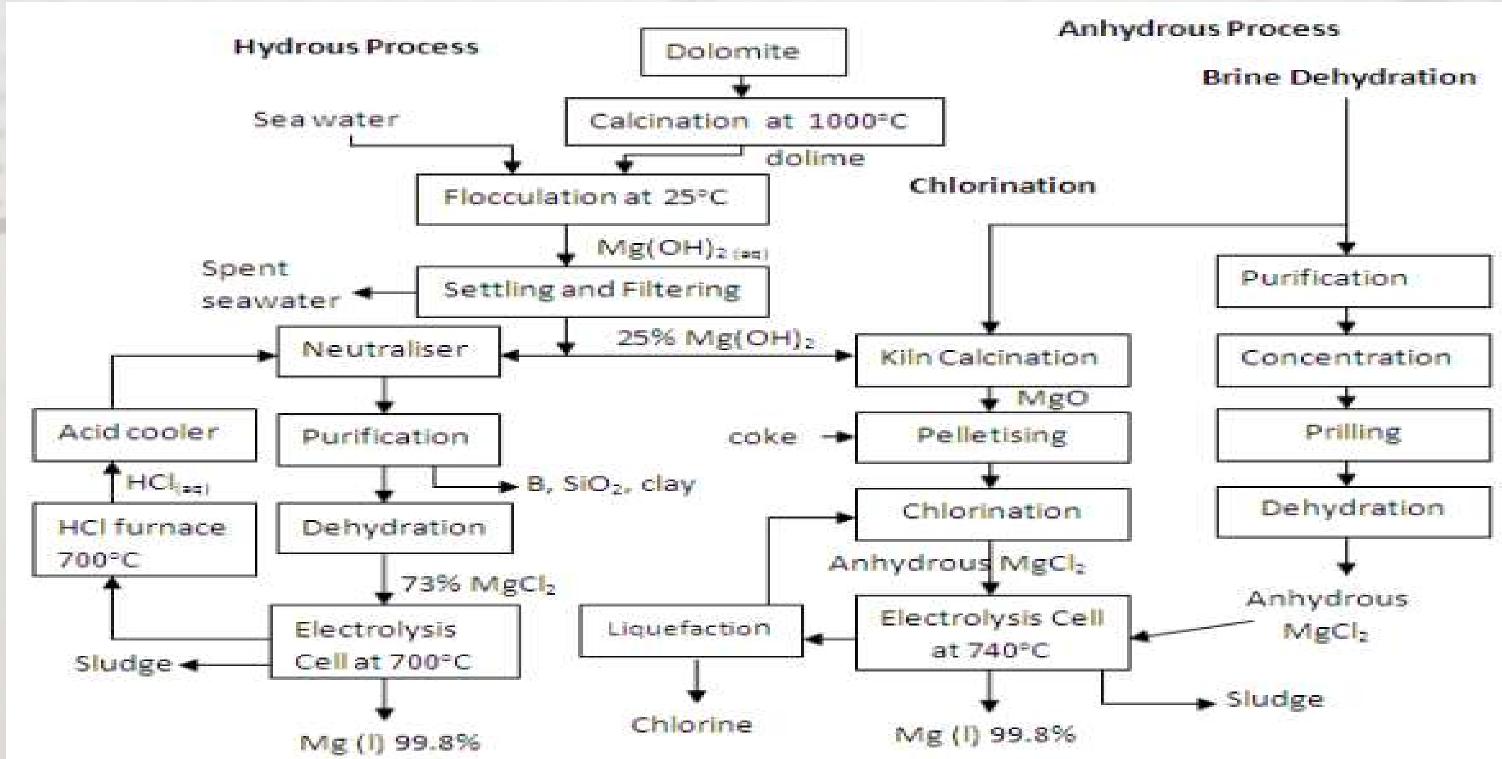
	Formula	% Mg
Mineral Oxides		
Periclase	MgO	60,00
Brucite	**$Mg(OH)_2$**	**41,37**
Carbonates		
Magnesite	$MgCO_3$	28,57
Dolomite	**$MgCO_3.CaCO_3$**	**21,80**
Chlorides		
Carnallite	**$KCl.MgCl_2.6H_2O$**	**8,69**
Bischofite	$MgCl_2.6H_2O$	11,88
Silicates		
Biotite	$K(Mg, Fe)_3.(Si_3Al).O_{10}(OH)_2$	12,31
Augite	$Ca(Mg,Fe,Al).(Si,Al)_2O_6$	6,79
Amphibolite	$(Ca,Mg,Fe)_4.(Si,Al)_4O_{11}(OH)$	10,75
Olivine	$(Mg,Fe)_2.SiO4$	18,75
Serpentine	**$(Mg,Fe)_6.SiO_4.(OH)_8$**	**18,53**

5 PRIMARY Mg PRODUCTION PROCESSES

- **Electrolysis**

- **Pyrometallurgy**
  - **Carbonothermic process**
  - **Horizontal Pidgeon**
  - **Vertical Pidgeon**
  - **Rima Process**
  - **Magnetherm process**
  - **Al Thermal process**

6 ELECTROLYSIS



7 CARBONOTHERMIC PROCESS

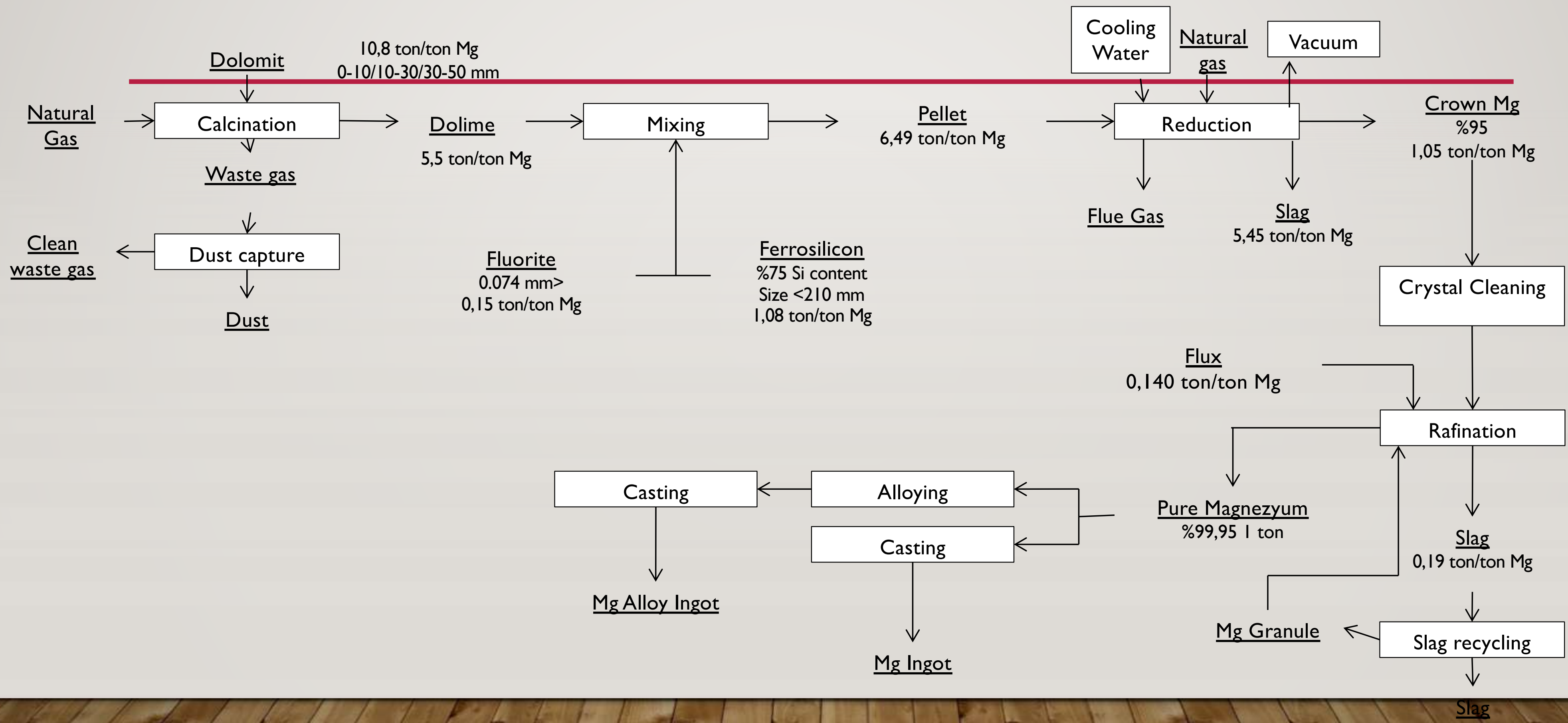
- The carbothermic process also relies on the reduction of magnesium oxide. In this process, magnesium oxide is mixed with petroleum coke or other carbon sources and reduced at an electrical arc furnace. The magnesium produced should be rapidly cooled using natural gas, and the residue fine pyrophoric powder is briquetted.
- Carbothermic methods had previously been attempted in the UK, Korea and the USA, including large-scale commercial operations at the Permanente Metals plant in California during World War II. These operations never proved commercially viable, however, due in part to the reversion of the carbothermic reaction.
- Now a days new technologies are under development aiming a safer and competitive process.

HORIZONTAL PIDGEON PROCESS

Thermal reduction process proceeds as follows:

- Calcination of dolomite to dolime,
- Blending of the dolime with reductant, such as ferrosilicon , Aluminum
- Heating of the dolime-reductant mixture in a vessel under vacuum,
- Condensation of the liberated magnesium vapor,
- Melting, alloying, and casting of the condensed magnesium.

9 HORIZONTAL PIDGEON



10 HORIZONTAL PIDGEON

Esan Plant built in 2015, capacity 15 ktpa. Horizontal Pidgeon process

11

HORIZONTAL PIDGEON

Reduction kiln of a Horizontal Pidgeon plant

12

HORIZONTAL PIDGEON INDICATORS

Major indicators

Raw material	: Dolomite	11,5	t/t Mg
Energy	: Electricity	2.200	kwh/t Mg
	: Natural gas	2.200	m^3/t Mg
Reductant	: FeSi	1,08	t/t Mg
Flux	: CaF_2	0,19	t/t Mg
Water	:	15	m^3/t Mg
CO_2 footprint	: CO_2	20 – 25	t CO_2 /t Mg
Cycle time	:	11 – 12	h
Crown weight	:	27 – 32	kg
Workforce	:	20 – 25	persons / 1000 t Mg capacity
Slag application	:	None / Cement	

13 VERTICAL PIDGEON

The Vertical process flow is identical as Horizontal Pidgeon.

14 VERTICAL PIDGEON

Discharge level

Vertical Retort

15 VERTICAL PIDGEON

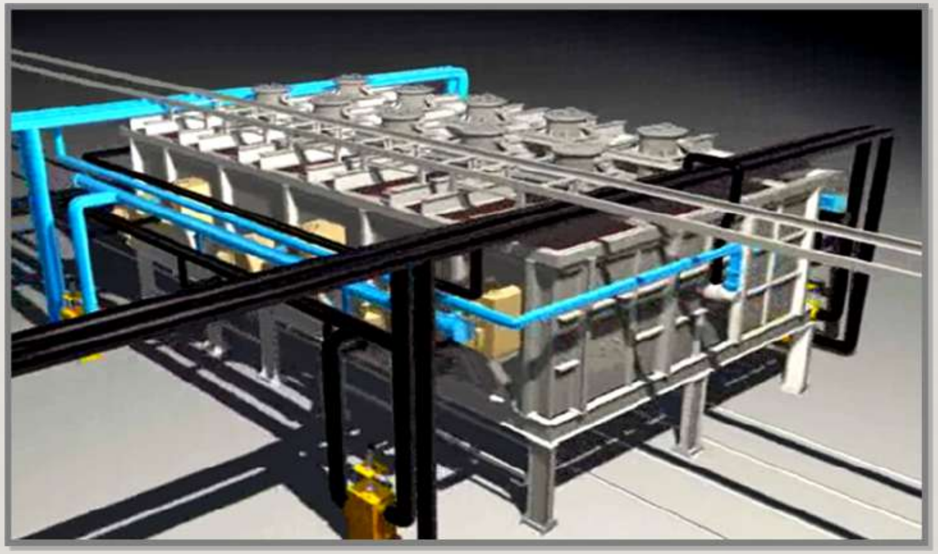


Illustration of Vertical Kilns

16 VERTICAL PIDGEON

Raw material loading

17 VERTICAL PIDGEON INDICATORS

Major indicators

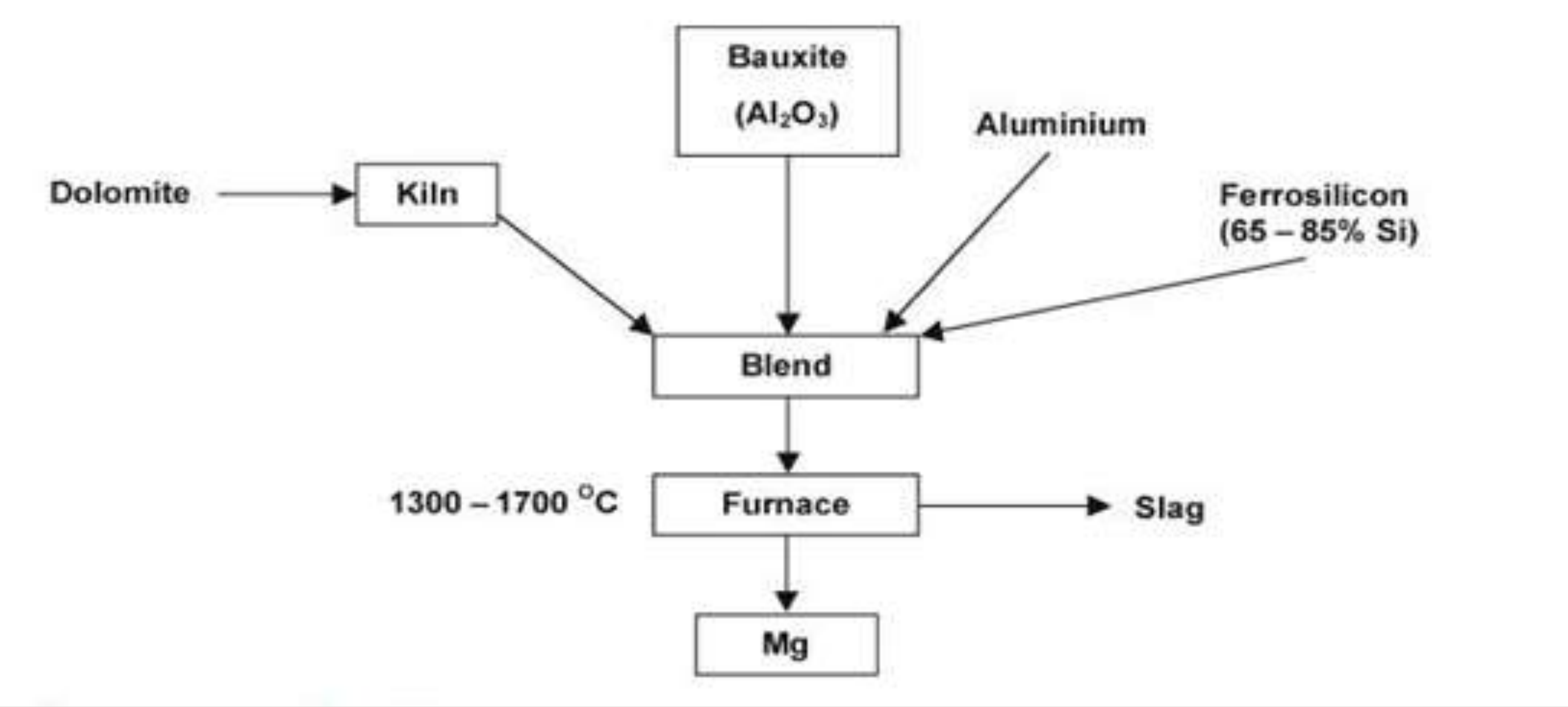
Raw material	: Dolomite	11,0	t/t Mg
Energy	: Electricity	1.700	kwh/t Mg
	: Natural gas	2.200	m^3/t Mg
Reductant	: FeSi	1,05	t/t Mg
Flux	: CaF_2	0,17	t/t Mg
Water	:	15	m^3/t Mg
CO_2 footprint	: CO_2	15 – 25	t CO_2/t Mg
Cycle time	:	8 – 10	h
Crown weight	:	60 – 65	kg
Workforce	:	15 – 20	persons / 1000 t Mg capacity
Slag application	:	None / Cement	

18

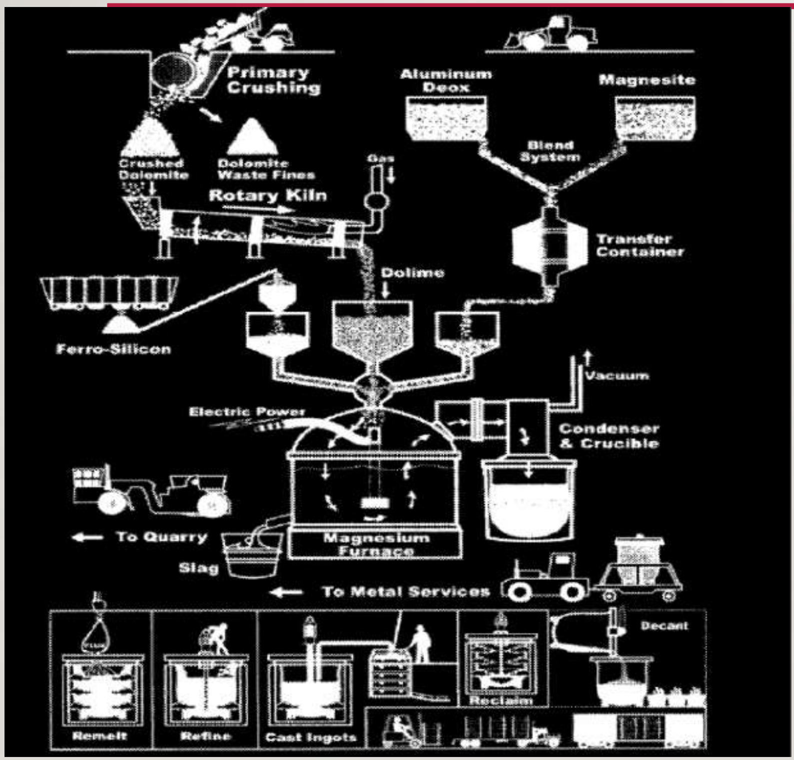
MAGNETHERM PROCESS

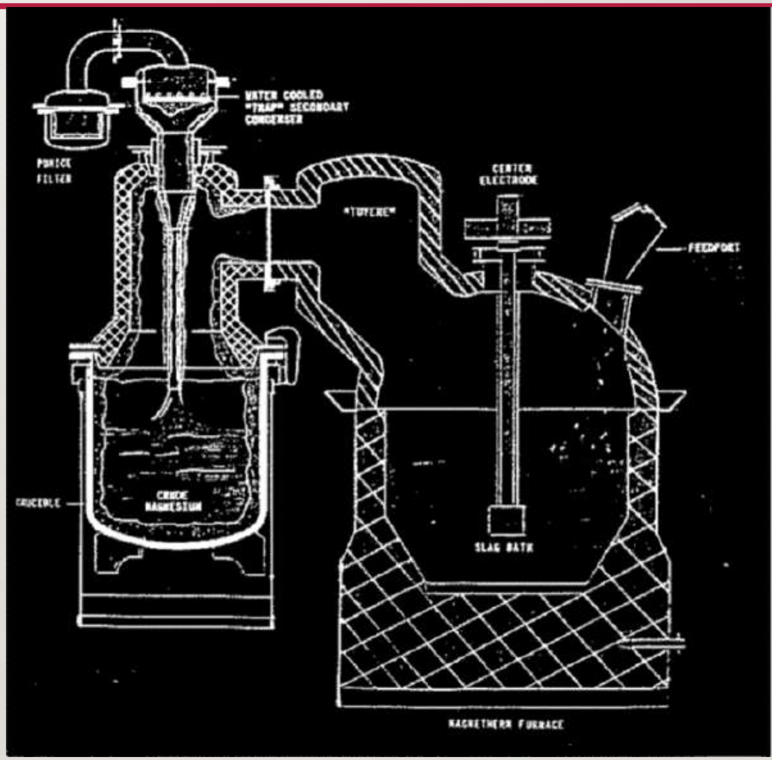
- This process can be considered as a transition from pidgeon to Al Thermic process
- Main raw material is dolomite which is calcined and mixed with reductants such as FeSi and Al
- Mg is produced in arc furnaces and collected in liquid form

19 MAGNETHERM PROCESS FLOW SHEET



20 MAGNETHERM PROCESS





21 MAGNETHERM PROCESS INDICATORS

Major indicators

Raw material	: Dolomite	9,5 – 10,0	t/t Mg
	: Magnesite	0,60 – 0,72	t/t Mg
Energy	: Electricity	12.000 – 13.000	kwh/t Mg
	: Natural gas	1.100 - 1.200	m^3/t Mg
Reductant	: FeSi	0,80 – 0,90	t/t Mg
	: Aluminum	0,30 – 0,40	t/t Mg
Water	:	20 - 25	m^3/t Mg
CO_2 footprint	: CO_2	N/A	
Cycle time	:	11 – 12	h
Slag application:		None	

22 AL THERMIC PROCESS

The core of the new process of dolomite clean magnesium smelting has two parts*:*

I. The first part is a process for the comprehensive utilization of calcium and magnesium separation of dolomite.
II. The second part is the use of an aluminothermic reduction at magnesium smelting process, which not only solves the waste gas residue of traditional magnesium smelting, but also uses the microwave heating technology for preheating and induction for reduction.

Breefly a combination of existing technologies

23 AL THERMIC PROCESS - BASICS

- Most efficient process with comparatively low temperatures and low CO2 emissions
- No waste but by-products (Mg-Al-Spinel, Calcium Carbonate and Dry Ice) that can be sold in the market

INPUTS

- Dolomite ($CaMg(CO_3)_2$)
- Al scrap (> 99% Al) or Al alloy scrap (> 90% Al)
- Water (H_2O)
- Natural Gas
- Electricity

OUTPUTS

- Magnesium (Mg)
- Calcium Carbonate ($CaCO_3$)
- Dry Ice (CO_2)
- Mg-Al-Spinel ($MgAl_2O_4$)

AL THERMIC DEVELOPMENT

- The relatively new Al Thermic process was developed and published already years ago but used in Mg production recently.
- A combination of well known and widely used processes
- This process was tested and matured at a large-scale Pilot plant that has been active since 2013.
- Five new major projects using the Al Thermic process are under construction with a total capacity of 180 kt p.a.

25 AL THERMIC PROCESS BY-PRODUCTS*

$CaCO_3$:

$CaCO_3$	%	95,14
MgO	%	2,02
SiO_2	%	0,036
Al_2O_3	%	0,086
Fe_2O_3	%	0,038
Water absorption	ml/100gr	88,00
Oil absorption	ml/100gr	90,00
Whiteness	%	92,50
Acid non soluble substances	%	0,59

Spinel:

Al_2O_3	%	61,88
MgO	%	36,43
CaO	%	0,61
SiO_2	%	0,22
Fe_2O_3	%	0,78
P_2O_5	%	0,064
K_2O	%	0,099
NiO	%	0,0061
Density	g/cm^3	3,6

* Analysis for information only quality varies on the raw material and reductant composition

AL THERMIC PROCESS & ENVIRONMENT

- Low CO_2 footprint
- No industrial wastewater discharge
- Very low solid waste
- Local supply of reducing agent (Al & Al Alloy scrap) possible
- Al/Al alloy scrap possibility to Hedge, cost control
- Producing valuable by-products
- Higher level of mechanization
- Powered mainly by electricity

27 AL THERMIC PROCESS INDICATORS

Major indicators

Raw material	: Dolomite	12,0	t/t Mg
Energy	: Electricity	+/- 8.900	kwh
	: Natural gas	+/- 1.000	m^3
Reductant	: Al/Al Alloy scrap	0,80	t/t Mg
Water	:	12	m^3/t Mg
CO_2 footprint	: CO_2	< 5	tCO_2 /t Mg
Cycle time	:	5 – 7	h
Crown weight:		60 – 65	kg
Workforce	:	10 – 15	persons / 1000 t Mg capacity * CM Group
By product	:	Yes	PCC, Spinel,Dry ice

28 AL THERMIC PROCESS

Laboratory scale trials:

- Vacuum : 5 – 10 Pa
- Reduction temperature : 1.000 - 1.150 ^{0}C
- Reductant : min. 99% Al scrap or min 90 % Al alloy scrap
- Utilization rate of reductant : > 90%
- Mg recovery rate : > 90 %

29 COMPARISON OF PROCESS INDICATORS

- Available Technologies

	Unit per 1t Mg	Electrolysis	Horizontal Pidgeon	Vertical Pidgeon	Alumino-thermic
Water	m3	N/A	15	10	12
Electricity	kWh	18.500	2.200	1.700	8900*
Natural Gas	m3	-	2.200	2.200	1000*
Dolomite	mt	N/A	11,50	11,00	12,00
FeSi	mt	-	1,08	1,05	-
Fluorite	mt	-	0,19	0,17	-
Alu (Alloy) Scrap	mt	-	-	-	0,80
Solvents	mt	-	0,50	0,50	-
Retort	qty	-	0,25	0,15	-
Vacuum	Pa ºC	-	<15	<15	<15
Temperature		-	1.250	1.250	1.000
Workforce	qty	75-125	300-350	175-225	150-200
Cycle	hour	continuous	10-12	8-10	5-7
By-Product		no	no	no	yes
Slag		yes	yes	yes	no
Automization		yes	limited	advanced	advanced

* Energy input for 1mt Mg + 2 mt Mg-Al-Spinel + 6,5 mt CaCO3

The Aluminothermic Process has a number of clear advantages

- Significantly lower operating costs than other processes (Electricity vs. Gas)
- No waste material, no water contamination
- By-Products Calcium Carbonate, Dry Ice, Mg-Al-Spinel can be sold in the market and generate further income
- Can work with significantly lower temperatures which improves the energy consumption
- High automatization and fewer employees on the work floor
- Close to zero emissions** (<5 t CO_2 /mt Mg compared to > 20 mt CO_2 per mt Mg in Pidgeon process)

** Depending on the energy source

CO_2 FOOTPRINT

Electrolysis[1)]

10 – 17,7 t CO_2/t Mg

1) 5,2 t CO2 / t Mg Qinghai

Pidgeon

10,5[2)] – 23 t CO_2/t Mg

2) 40 % Recycled Mg for Mg alloy

Al Thermic

1[3)] – 5 t CO_2/t Mg

3) Using Al scrap as reductant and 100 % renewable energy

SWOT

	S	W	O	T
Horizontal Pidgeon	-Matured technology	-Labor intensive -Dependent on tech provider	-Low Capex	-Expired technology -High CO_2 Footprint
Vertical Pidgeon	-Matured technology	-Labor intensive -Dependent on tech provider	-Low Capex	-High CO_2 footprint
Al Therm	-New technology -Low CO_2 footprint -No slag -Producing by Products -Less workforce	-Process not known -Dependent on tech provider	-Low Capex -Increased Turnover -Reducing agent from local source -Low energy consumption of t Mg	-High Reducing agent costs
Electrolysis	-Matured technology -Low CO_2 footprint	High Capex High OPEX	-High mechanization	-High energy intensive

32 # THANK YOU

Ilhan Göknel

E-mail : igoknel@hotmail.com

Mobile :+90 533 394 59 58