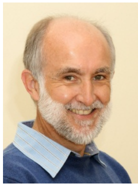
FERRONICKEL –
Thermodynamics, chemistry, and economics



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2021 TMS/EPD Distinguished Lecturer

About the Presenter: Rodney T. Jones

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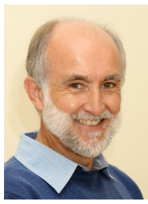


- Consulting chemical engineer and metallurgist with over 35 years of pyrometallurgical experience in a wide variety of processes that have been taken from concept to industrial implementation
- Past President and an Honorary Life Fellow of the Southern African Institute of Mining and Metallurgy (SAIMM)
- Senior Technical Specialist (part-time), Mintek, South Africa
- Honorary Adjunct Professor in the School of Chemical and Metallurgical Engineering at the University of the Witwatersrand (Wits) in Johannesburg
- Known for his work on Pyrosim software, and processes involving DC arc furnaces at Mintek in Randburg, South Africa
- Registered as a Professional Engineer since 1988

SAIMM MINTEK WITS UNIVERSITY Pyro Consulting

Nickel – Introduction

- Nickel is a metal that has become essential to many aspects of our daily lives – from tableware and kitchen utensils, to medical equipment, aircraft, coins, and batteries
- Nickel is a silvery-white metal that is both hard and ductile, and has a melting point of 1455°C
- It is resistant to corrosion and high temperatures

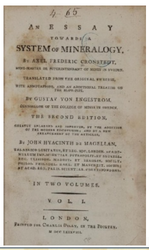
Image: www.snnc.co.kr

- Long before nickel was isolated, an alloy of copper-nickel-zinc was produced in China – called paktong 白銅 / 白铜 or 'white copper' – nowadays known as 'nickel silver'

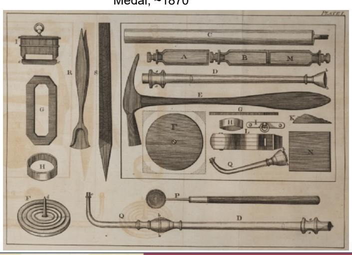
Nickel history

- Nickel was isolated and recognised as a distinct metal by the Swedish mineralogist and chemist, **Axel Fredrik Cronstedt** (1722–1765) in 1751
- Cronstedt is considered a founder of modern mineralogy and mineral analysis
- He introduced the blowpipe as a tool for mineralogists, and proposed a mineral classification system (taxonomy) based on chemical analysis
- At the age of around 40, Cronstedt bought an iron foundry, but then turned to gardening, saying that "roses gave more reward than minerals, which were sorely lacking in monetary return"
- He died at the young age of 42

Medal, ~1870



AN ESSAY
TOWARDS A
SYSTEM OF MINERALOGY.
BY AXEL FREDERIC CRONSTEDT,
TRANSLATED FROM THE ORIGINAL SWEDISH,
BY GUSTAV VON ENGESTROM,
THE SECOND EDITION,
BY JOHN HYACINTH DE MAGELLAN,
IN TWO VOLUMES.
VOL. I.
LONDON,
PRINTED FOR CHARLES DILLY, IN THE POULTRY.



How economically important is nickel?

Metals:		
Steel	1860 Mt	$ 2001.50 bn
Aluminium	63.7 Mt	$ 114.31 bn
Chromium	44.0 Mt	$96.80 bn
Copper	24.5 Mt	$ 147.25 bn
Manganese	19.6 Mt	$ 29.40 bn
Zinc	12.7 Mt	$ 32.39 bn
Lead	4.72 Mt	$ 9.42 bn
Nickel	2.61 Mt	$ 36.32 bn
Tin	0.30 Mt	$ 5.52 bn
Precious Metals:		
Silver	26 500 t	$ 15.15 bn
Gold	3 300 t	$ 162.1 bn
Platinum	186 t	$ 5.66 bn

World production and value, 2019

Nickel is 8th by tonnage, and 5th by value

Nickel is both valuable and common

DS Jacks, 2021, p.5

Prevalence of nickel (Resources and Reserves)

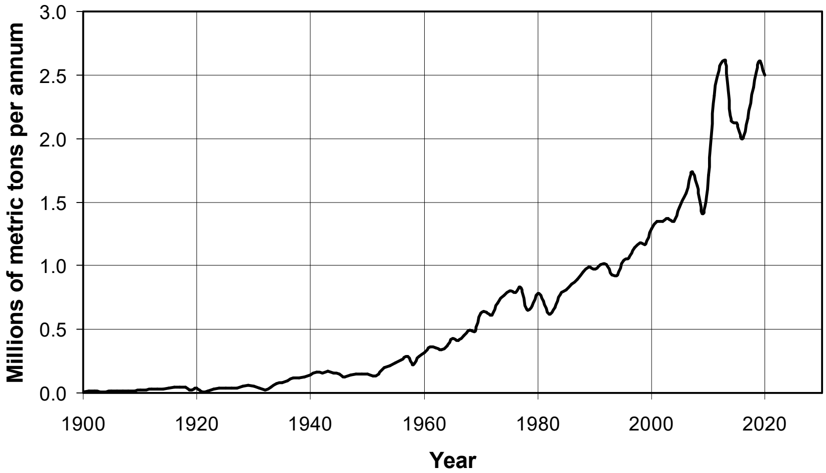
- The earth's core consists mainly of a nickel-iron alloy, but the concentration of nickel in the earth's crust is only 80 ppm
- The world's nickel resources (with reasonable prospects for eventual economic extraction) in classical ore deposits are currently estimated at almost 300 million metric tons (nickelinstitute.org) – about 120 sulfidic and about 180 lateritic
- Recent estimates indicate more than a further 290 Mt of nickel contained in manganese nodules on the deep-sea floor
- World Ni reserves (economically mineable) are currently estimated at 94 million tons (USGS), with about 2.5 million tons mined annually
- Reserve estimates vary with time, as economic viability depends on mining, processing, marketing, legal, environmental, infrastructure, social, and governmental factors
- Nearly 80% of all nickel historically mined was extracted over the past three decades (nickelinstitute.org)
- The global efficiency of recycling Ni from end-of-life products for 2015 was 68% – among the highest recycling efficiencies for the metals industry

Nickel Resources, Reserves, and Mine Production by country

	Resources, Mt			Reserves	Mined
	Sulfidic	Lateritic	Combined	Mt	kt in 2020e
Australia	11.9	31.5	43.4	20.0	170
Indonesia	-	33.3	33.3	21.0	760
South Africa	33.2	-	33.2	3.7	40
Russia	20.5	4.0	24.4	6.9	280
Canada	21.9	-	21.9	2.8	150
Philippines	-	18.0	18.0	4.8	320
Brazil	1.6	14.8	16.4	16.0	73
Cuba	-	16.2	16.2	5.5	49
New Caledonia	-	15.0	15.0	?	200
China	6.0	-	6.0	2.8	120
Other	22.9	45.3	68.3	10.4	338
Total	118.0	178.2	296.2	94.0	2500

USGS & Nickelinstitute.org

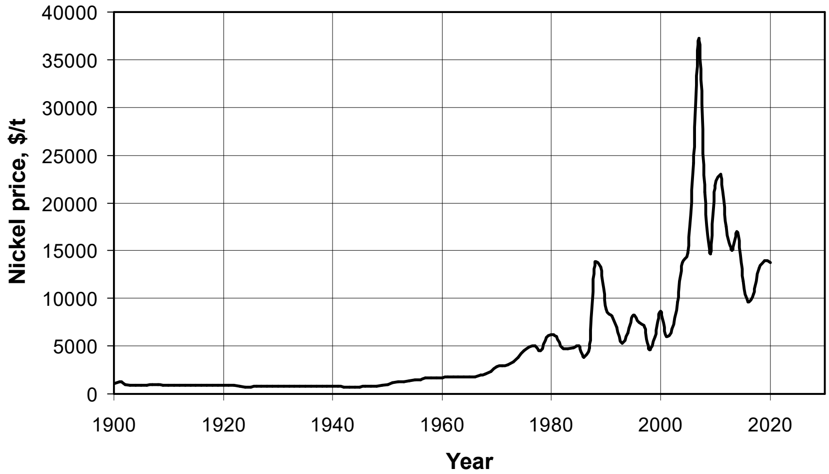
World nickel production between 1900 and 2020



US Geological Survey

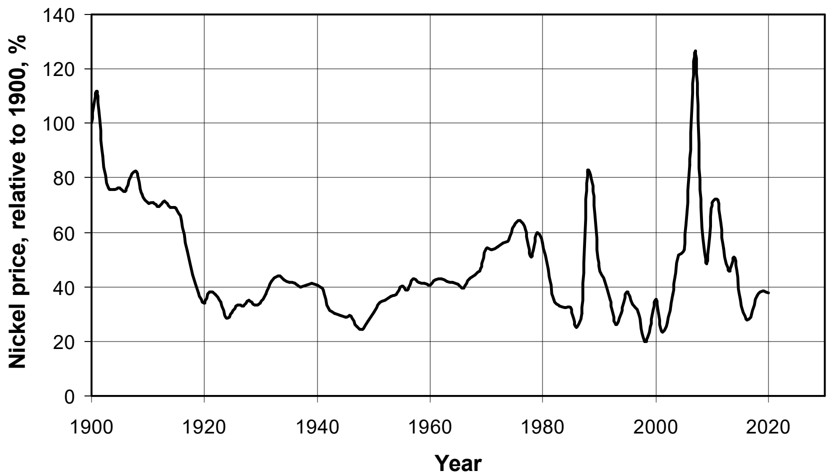
- Between 1980 and 2015, world nickel production increased by 3.1% annually (US Geological Survey, 2017)
- Nearly 80% of all nickel historically mined was extracted over the past three decades (nickelinstitute.org)

Nickel price from 1900 to 2020, US $ per metric ton



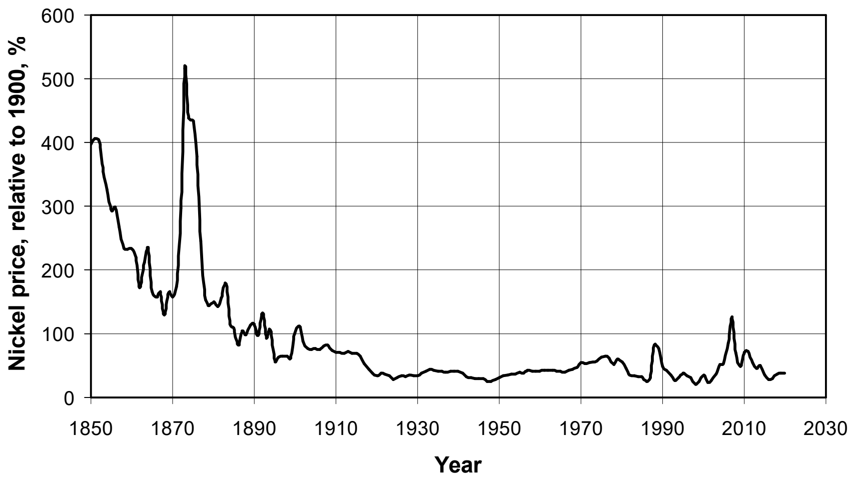
- Nominal cash settlement prices for LME cathodes of 99.8% Ni; tabulated by USGS (annual averages)

Real nickel price from 1900 to 2020, relative to 1900



- Peaks in 1988 and 2007 (followed by the crash of 2008 into 2009)

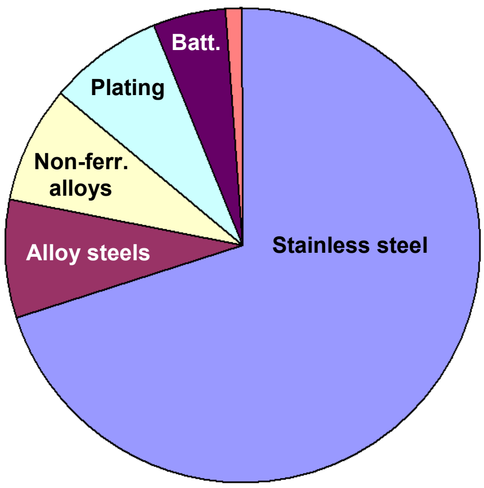
Real nickel price from 1850 to 2020, relative to 1900



- Peak in 1873 makes the peaks of 1988 and 2007 look like minor fluctuations. Usefulness of Ni in alloy steels was recognised in 1870s. Mining of nickel laterite ore in New Caledonia began in 1875.

Nickel demand is dominated by stainless steel

- About 70% of the nickel produced is used in the production of stainless steel
- First-use market share: (Nickelinstitute.org / Roskill)
  - **70% Stainless steel**
  - 8% Alloy steels & castings
  - 8% Non-ferrous (Ni-base & Cu-base) alloys
  - 8% Plating
  - **5% Batteries**
  - 1% Other
- End uses fall into 31% Engineering, 22% Metal goods, 16% Building & Construction, 15% Transport, 10% Electronics, and 4% Other
- Rapid growth is anticipated for Ni in batteries, but off a small base; perhaps reaching above 30% over the next decade

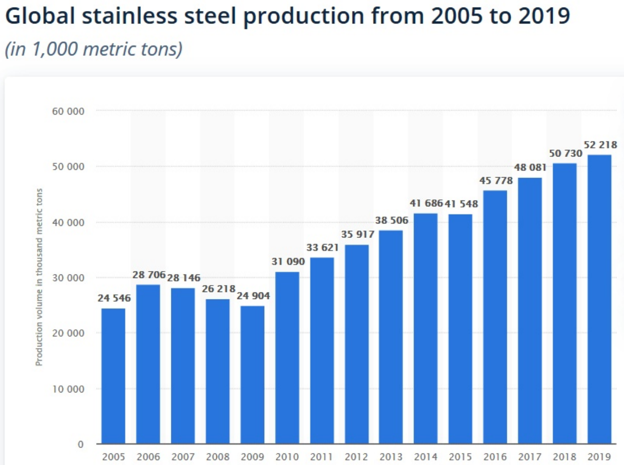


Stainless steel

- In 2019, global stainless steel production was around 52 million tons, having doubled over the previous decade (Statista.com, 2020)
- Stainless steel has grown faster than other major metals

Compound Annual Growth Rate (CAGR), 1980–2018:

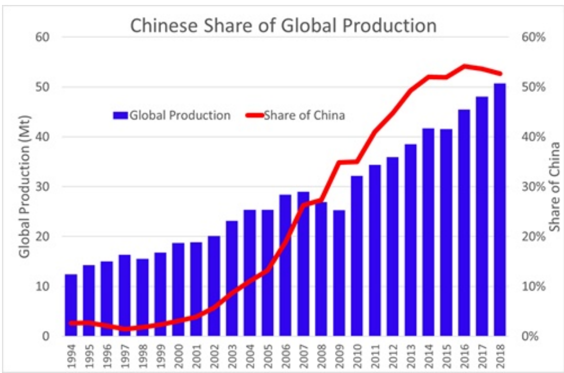
- **Stainless steel 5.6%**
- Aluminium 3.8%
- Copper 2.6%
- Steel 2.5%
- Zinc 2.1%
- Lead 2.0%



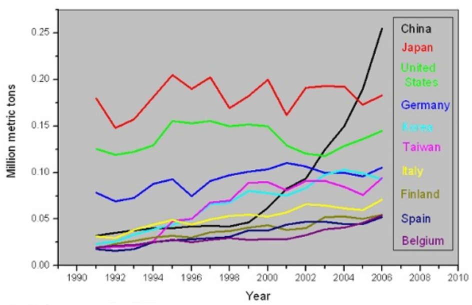
China & Stainless steel

- The minerals boom of the early 2000s was driven primarily by the urbanization of China
- China became the leading stainless steel producer in 2006
- China produces more than half of the world's stainless steel, with demand growing at over 4% per annum

SASSDA, 2019

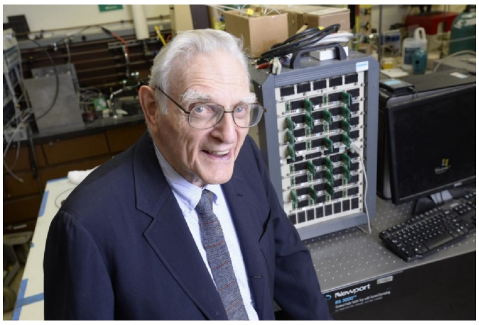


Leading nickel consumers



Lithium-ion batteries

- John B. Goodenough (born 25 July 1922), now 98 years old, is the oldest recipient of a Nobel Prize
- He was awarded a Nobel Prize in Chemistry in 2019
- He is one of the inventors of the lithium-ion battery, and made possible the era of portable electronic devices, as well as battery electric vehicles
- These batteries are expected to require vast quantities of metals such as nickel



Nickel usage in batteries (especially for electric vehicles)

- Climate change (and the resulting governmental regulation) has sped up the transition to electric vehicles
- Li-ion batteries for electric vehicles use nickel extensively
- NCM (NiCoMn 8:1:1) and NCA (NiCoAl) cathode materials are dominant because of safety and energy capacity considerations
- There is a preference for higher nickel intensity, rather than expensive and controversial cobalt
- Nickel consumption from the battery sector was nearly 100 kt in 2017 (about 5% of total consumption). [This is expected to grow to more than 440 kt Ni by 2025 (Nornickel.com).]
- Questions about availability of nickel are less about whether there is enough in the ground, but more about whether there is enough production capacity immediately available to meet a rapid increase in demand

Tesla needs nickel for batteries

- A Tesla Model 3 contains around 30 kg of Ni, and an average Tesla car uses ~45 kg of Ni in NCA and NCM 811 batteries
- Tesla wants to produce 20 million vehicles per year by 2030, and will need ~750 kt/a Ni (about 30% of global production) to achieve this
- “Please mine more nickel and don't wait for nickel to go back to some … high point that you experienced some five years ago … Tesla will give you a giant contract for a long period of time if you mine nickel efficiently and in an environmentally sensitive way”
  – Elon Musk, July 2020
- “Nickel is our biggest concern for scaling lithium-ion cell production. That’s why we are shifting standard range cars to an iron cathode. Plenty of iron (and lithium)!” – *LFP (LiFeP) Lithium iron phosphate*
  – Elon Musk, February 2021
- Tesla decided in March 2021 to become a technical partner in Goro nickel mine in New Caledonia, and will buy nickel from the mine.
- Perhaps this shows the fickleness of the nickel industry, or should that be the “nickelness of the fickle industry”?
- Nickel prices still depend much more on stainless steel demand than they do on batteries, but batteries are growing in importance

Nickel laterite ores

- Laterites are formed by the weathering of ultramafic rocks close to the earth’s surface
- The name laterite (from the Latin *later*, meaning ‘a brick’) is used to describe the weathering product of ferruginous rock exposed to strongly oxidizing and leaching conditions, usually in tropical and subtropical regions. This porous, claylike rock comprises hydrated oxides of iron, aluminium, etc.
- Nickel leaches from the upper layers and subsequently precipitates in the lower layers, substituting NiO for MgO and FeO in the lattice of respectively silicate and iron oxide minerals

Goro mine, New Caledonia

- **The major impurity in nickel laterite ores is water**
- Mined laterite ore, being of a porous nature, can hold a large content of free moisture, commonly 25 to 30% H_2O, although it can contain even 40% or more. In addition to this, chemically combined water, which requires temperatures of 700 to 800°C to drive it off, can amount to as much as 15% based on the dry ore weight. Because of the quantity of water present, and because water requires so much energy to evaporate and heat up, it is clear that some pretreatment of the ore (at least drying and calcining) is required before smelting.

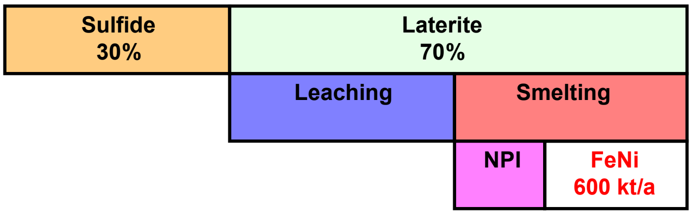
Nickel laterite ores …

- **Nickel laterite ores are typically evaluated according to their Ni content, Ni:Fe ratio (by mass) and their SiO_2:MgO ratio**
- The ‘oxidized’ ores of nickel constitute by far the world's largest known reserves of this metal
- The ores include the true laterites (in which the nickel oxide is intimately associated with limonitic iron oxide) and the silicate ores which often contain the mineral garnierite. These oxidized ores are found in regions of the world where tropical weathering occurs, or where at least sub-tropical conditions have prevailed in past geological times.
- In 1865, Jules Garnier discovered large deposits of silicate ores in New Caledonia, a French possession in the Pacific
- Mining was started in 1875, and this soon became the main source of nickel, the price falling within three years to about one-third

Open-pit nickel mine on mainland New Caledonia

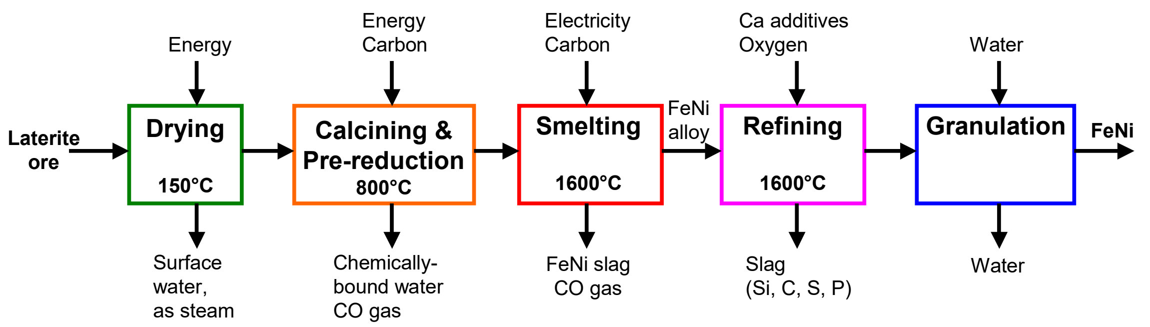
Where does FeNi fit into overall world Ni production?

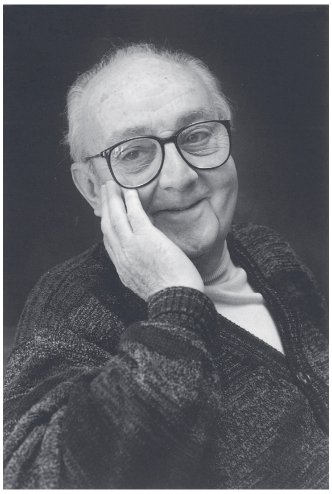
- The split in nickel production between sulfide and laterite nickel ore sources has shifted from about one third being from laterites in the 1980s to about 70% from laterites in 2020
- Nickel production from laterite ores is further subdivided between leaching (limonite) and smelting (saprolite / garnierite)
- The laterite smelting processes are further subdivided by alloy product into those producing nickel pig iron (NPI) containing < 15% Ni, and those producing ferronickel (FeNi) 15–40% Ni
- Nickel pig iron, a low-grade FeNi, has become popular in the past decade
- Our focus here is on FeNi smelting, which produces around 600 kt/a of contained nickel, which is about 23% of the overall world nickel production of 2610 kt/a of nickel (in 2019)



Ferronickel Smelting – highly simplified

- The first processing treatment for recovering nickel from laterites was developed in 1879 in New Caledonia, based on the iron blast furnace technology of the day
- Almost all current FeNi production is now based on the rotary kiln – electric furnace (RK-EF) process





"All models are wrong but some are useful"

George Box (1919–2013), Statistician, 1978

Chemical reactions and Kγ recovery equation

- $FeO + C \rightarrow Fe + CO$
- $NiO + C \rightarrow Ni + CO$
- $CoO + C \rightarrow Co + CO$
- $CrO + C \rightarrow Cr + CO$

- **$NiO + Fe \rightarrow Ni + FeO$**

$$K = \frac{a_{Ni} \cdot a_{FeO}}{a_{NiO} \cdot a_{Fe}} = \frac{\gamma_{Ni}\, x_{Ni} \cdot \gamma_{FeO}\, x_{FeO}}{\gamma_{NiO}\, x_{NiO} \cdot \gamma_{Fe}\, x_{Fe}}$$

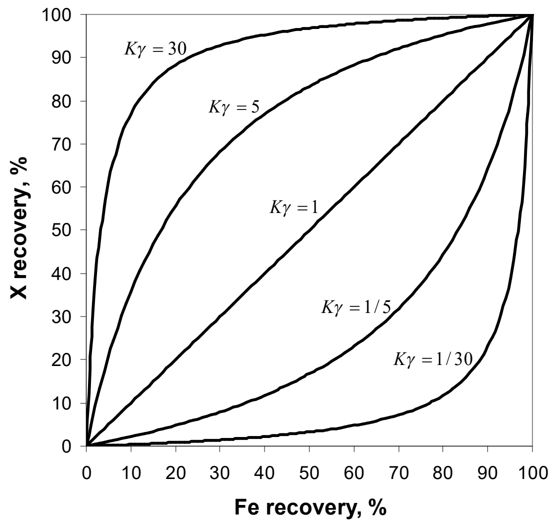
$$\gamma = \frac{\gamma_{NiO} \cdot \gamma_{Fe}}{\gamma_{Ni} \cdot \gamma_{FeO}}$$

- Add mass balance equations
- Add definitions of recovery

$$R_{Ni} = \frac{K\gamma \cdot R_{Fe}}{1-(1-K\gamma)R_{Fe}}$$

https://www.pyrometallurgy.co.za/Mintek/Files/2009Jones-Recovery.pdf

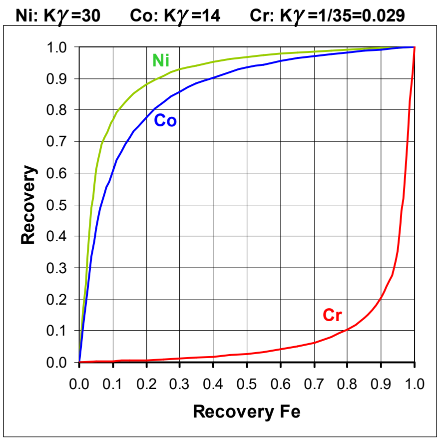
Shape of recovery curve, and values of Kγ



$$R_X = \frac{K\gamma \cdot R_{Fe}}{1-(1-K\gamma)R_{Fe}}$$

- $K\gamma = 1$ represents Fe
- Most ‘noble’ at top left
- Kγ can be calculated from equilibrium constant and activity coefficients, or fitted empirically

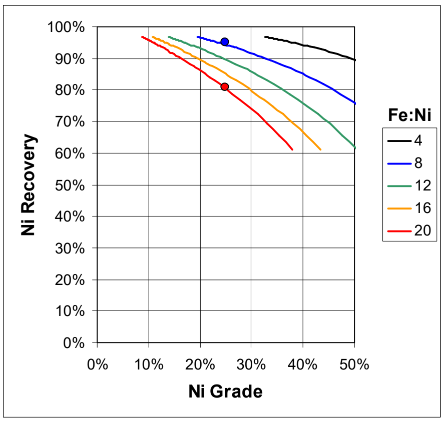
FeNi Grade-Recovery model



<u>Simplified calculation of grade – recovery relationship for FeNi alloy:</u>

- Assume for now that the alloy contains only Ni and Fe
- The recovery of Fe (R_{Fe}) to the alloy determines the recovery of Ni (R_{Ni}) to the alloy
- $R_{Ni} = (K\gamma \times R_{Fe}) / [1 - (1 - K\gamma) \times R_{Fe}]$
- $K\gamma = 30$ (maybe 20) for Ni. Should ideally be based on testwork.
- Mass fraction of Ni in alloy (%Ni) = $(Ni_{feed} \times R_{Ni}) / [(Ni_{feed} \times R_{Ni}) + (Ni_{feed} \times \text{Fe/Ni ratio} \times R_{Fe})]$
- Mass fraction of Ni in alloy (%Ni) = $R_{Ni} / [R_{Ni} + (\text{Fe/Ni ratio} \times R_{Fe})]$
- The grade – recovery relationship can now be plotted for different values of Fe/Ni ratio in the feed

FeNi Grade-Recovery model (results of simplified calculation)

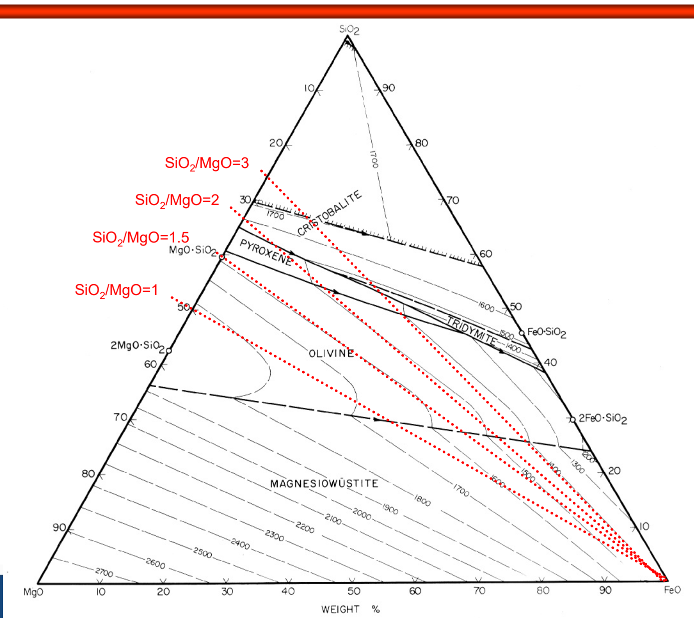


- The relationship between Ni grade and recovery to the alloy depends on the Fe:Ni ratio in the ore
- Different colour curves represent different values of Fe/Ni ratio in the feed
- For Fe:Ni = 8, it is possible to produce an alloy containing 25% Ni at a recovery of about 95%
- For an iron-rich ore with Fe:Ni = 20, an alloy containing 25% Ni could still be produced, but the recovery would be only about 80%

Choice of FeNi product grade

- By varying the amount of carbon fed to the furnace, it is possible to greatly vary the composition of the ferronickel alloy
- Low iron reduction results in a high-grade FeNi alloy up to about 40% Ni (~60% Fe)
- High iron reduction lowers the nickel grade of the alloy to 15% Ni (~85% Fe) or even lower
- For convenience, low-grade alloys below about 15% Ni are referred to as nickel pig iron (NPI)
- High iron reduction requires more carbon, more electrical energy, more refining of the increased impurities, and higher transport costs per ton of Ni
- Generally, high reduction of iron (lower content of nickel in ferronickel) is favoured when:
  - (i) high recovery of nickel is critical
  - (ii) a reasonable payment is made for the additional Fe in the ferronickel
  - (iii) transport costs of the ferronickel to the market are low
- The opposite conditions favour a higher nickel content in the ferronickel (Solar et al., 2008)

Effect of SiO_2 / MgO ratio on slag liquidus temperature



FeNi production by country, 2017, gross weight kt/a

China NPI	2100
Indonesia NPI	245
Indonesia FeNi	109
Japan	312
New Caledonia	270
South Korea	237
Brazil	214
Colombia	140

Myanmar	98
Greece	86
Ukraine	73
Dominican Republic	44
Kosovo	39
Guatemala	38
Macedonia	33
Austria	3
Total	4039

- Data from USGS ferro-alloys table, with NPI accounted for as FeNi equivalent with a Ni content of 20%

Ferronickel smelters (active; excluding NPI)

Sorowako (PT Inco)	●●●●	Indonesia		72
Le Nickel Doniambo (SLN / Eramet)	■■■	New Caledonia		60
Koniambo (Glencore / SMSP)	●●	New Caledonia	(28)	60
Cerro Matoso (South32)	●●	Colombia	(49)	55
Onca Puma (Vale)	■■	Brazil	(25)	53
Hachinohe (Pacific Metals - Pamco)	●●●	Japan		41
Barro Alto (Anglo American)	■■	Brazil	(21)	36
Gwangyang (SNNC: POSCO & SMSP)	●	South Korea		30
Falcondo	■■	Dominican Republic		29
Hyuga (Sumitomo)	●●	Japan		22
Tagaung Taung (CNMC / TISCO)	■■	Myanmar		22
Pobuzhsky (Solway Industries)	■■	Ukraine	(16)	22
Fenix (Solway Industries)	●	Guatemala		20
Larymna (Larco)	●●●●	Greece		19
Loma de Niquel (Anglo American / PDVSA)	●●	Venezuela		17
Oheyama (Nippon Yakin Kogyo)	▭	Japan		15
Pomalaa (PT Aneka Tambang)	●●	Indonesia		11
Codemin (Anglo American)	●●	Brazil		9
FENI - Kavadarci (Cunico Resources / Euronickel)	■■	Macedonia		7
Total				600 kt/a Ni

● Circular furnace
■ Rectangular furnace
▭ Kiln only

Concluding remarks

- The world is poised on the brink of some massive changes – where we work, how we travel – given the current challenges we face, such as a global pandemic and climate change. We are living in an exciting time of new developments, and have the opportunity to shape the world for the better.
- The contributions that nickel, stainless steel materials, and batteries can make to a cleaner and kinder world are very significant. Think of buildings, food production, medical care, electric vehicles, and you will see what I mean. Nickel is an essential metal in our modern world.
- The challenge to ferronickel metallurgists will be to develop projects and devise processes that makes production of this valuable commodity more energy-efficient and less carbon-intensive. I am sure you will be up to this challenge.