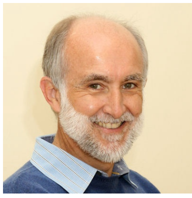
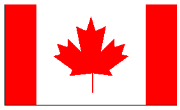
A Brief History of Chromite Smelting





Rodney Jones

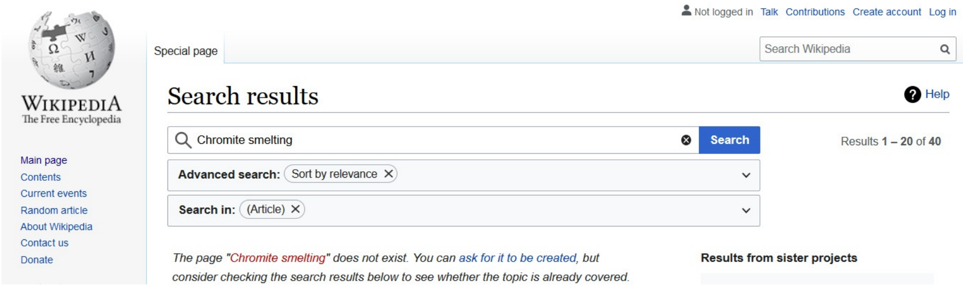
15 October 2020

Some important questions

- What have Victoria Falls and King Solomon's Mines to do with FeCr?
- Was FeCr first smelted commercially in South Africa or in Canada?
- The importance of:
  - People
  - Technology
  - Raw materials
  - Power
- Talk outline:
  - Chromium
  - Smelting
  - South Africa
  - Canada
  - A chromite smelting link between the two countries

Wikipedia contains articles about almost everything …

… except “Chromite smelting”:



The page “Chromite smelting” does not exist

Chromium

- Chromium was discovered and named by the French chemist, **Louis Nicolas Vauquelin** (1763-1829) in 1797, during the years of the French Revolution
- The following year, he isolated the metal by reduction of the Siberian red lead ore (crocoite, $PbCrO_4$) with carbon
- The brilliant hue of this chromate mineral inspired Vauquelin to give the metal its current name (from Greek chrōmos, “colour”)
- Chromium is chemically inert, and has a high melting point, 1907°C
- It is said that the first use of chromium as an alloying agent in the manufacture of steel took place in France in the 1860s
- About three quarters of the chromium produced is used in the production of stainless steel

Michael Faraday’s Fe-Cr-Ni alloys

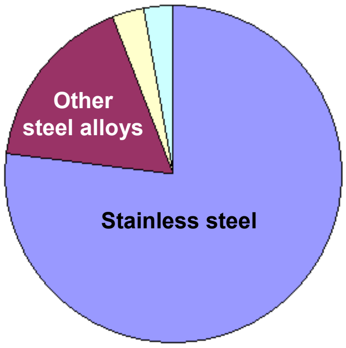
- In about 1820 James Stodart and **Michael Faraday** from England, and French metallurgist, Pierre Berthier recognised that iron-chromium alloys were able to resist attacks by some acids
- Shown here are some samples of 79 experimental steel alloys (to be used for surgical instruments) made by Michael Faraday in a forced-draft furnace, between 1820 and 1824
- The samples were discovered in 1930 (during the rebuilding of the Royal Institution) in a small box labelled in Faraday’s own handwriting

Stainless steel

- While iron has been used for well over a millennium, stainless steel was first produced just over a hundred years ago, and has shaped our modern world
- **Harry Brearley** from Sheffield is widely regarded as the inventor of the first true “Stainless Steel” in 1913; however, his path was laid by a number of scientists and engineers who went before him
- Harry Brearley came from a poor family, started work at the age of 11, and was single-minded about steel
- Brearley discovered a martensitic stainless steel alloy, while seeking a corrosion-resistant alloy for gun barrels during his work at the Brown-Firth research laboratory. He added 12.8% chromium to iron, and produced a metal that was resistant to corrosion and rust.
- The discovery was mentioned in a January 1915 newspaper article in The New York Times. It wasn’t originally called “Stainless Steel”, but was marketed under the “Staybrite” brand by Firth Vickers in England.
- Brearley’s successor, Dr William Herbert Hatfield, in 1924, produced the widest-used 18/8 stainless steel (18% Cr and 8% Ni)

Chromium demand is dominated by stainless steel

- World chromium consumption was 7.1 Mt in 2017 (Roskill, 2018), from 29.8 Mt of chromite
- Market share:
  - 77% stainless steel
  - 17% other steel alloys
  - 3.2% chemical applications
  - 2.7% foundry and refractory applications
- The growth in the world steel industry determines the demand for chromium (as ferrochromium)



Stainless steel

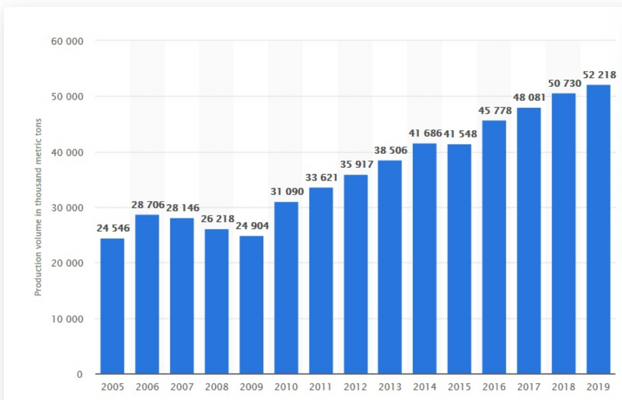
- In 2019, global stainless steel production was around 52 million tons, having doubled over the previous decade (Statista.com, 2020)
- Stainless steel has grown faster than other major metals

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%

Global stainless steel production from 2005 to 2019

(in 1,000 metric tons)

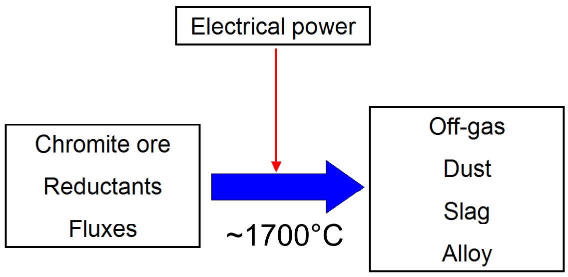


Chromite

- **A large number of minerals contain chromium, but only chromite ($FeO.Cr_2O_3$) is of economic importance as a source of this metal**
- Chromite is one of the group of isomorphous cubic minerals known as spinels. It occurs in ultramafic igneous rocks.
- There can be some isomorphic substitution of Fe with Mg, and Cr with Al, as well as the presence of silica
- The general formula can be written as $(Fe,Mg)O.(Cr,Al,Fe)_2O_3$
- Depending on its quality and end use, chromite can be classified as either metallurgical (typically 42-46% Cr_2O_3, < 2.5% SiO_2), chemical, foundry, or refractory grade (with some overlap between classifications)
- **Chromite ores are typically evaluated according to their Cr:Fe ratio and their Cr_2O_3 content**
- Chromite is chemically inert, and has a very high melting point (2040°C), making it very useful for use in refractories
- World resources are greater than 12 billion tons of shipping-grade chromite, sufficient to meet conceivable demand for centuries

Chromite Smelting – highly simplified

$$FeO.Cr_2O_3 + 4C \rightarrow Fe + 2Cr + 4CO$$



Chromite spinel: $(Fe,Mg)O•(Cr,Al)_2O_3$

Chromite ore compositions (mass %)

Origin	Cr_2O_3	FeO	MgO	Al_2O_3	SiO_2	Cr/Fe
Kazakhstan	51.2	11.9	19.8	6.5	6.9	3.8
Zimbabwe	50.8	13.3	17.9	12.7	3.9	3.4
India A	53.5	16.9	11.4	11.4	1.3	2.8
India B	50.9	17.9	10.9	12.7	1.2	2.5
North America	44.0	18.2	12.8	12.5	5.9	2.1
South Africa LG	46.6	25.0	10.8	15.1	0.6	1.6
South Africa UG2	42.6	27.4	9.3	14.9	1.2	1.4
South Africa MG	42.9	28.5	8.8	15.7	3.0	1.3

FeCr grades

	%Cr	%C
Charge chrome	48 – 55	4 – 7.5
HC FeCr	58 – 65	4 – 8
MC FeCr	55 – 70	> 2
LC FeCr	60 – 70	< 0.1

Typical slag and alloy compositions

	Al_2O_3	CaO	Cr_2O_3	FeO	MgO	SiO_2
Slag	30-40	2-15	4-6	0.5-2	30-40	bal.

	Cr	Fe	Si	C
HC FeCr	50-52	bal.	0.5-1.5	6-8

Chromite and FeCr: Leading producing countries (2014)

- **Chromite ore production**
  - South Africa (12 Mt)
  - Kazakhstan (3.7 Mt)
  - India (3.5 Mt)
  - Turkey (2.6 Mt)
- Most of the chromite ore production was smelted in electric-arc furnaces to produce ferrochromium for the metallurgical industry

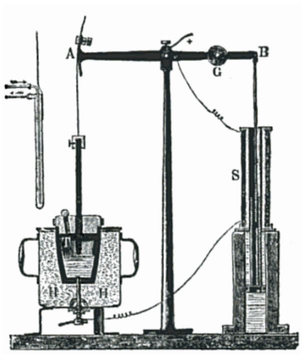
- **Ferrochromium production**
  - China (4.5 Mt)
  - South Africa (3.6 Mt)
  - Kazakhstan (1.2 Mt)
  - India (0.9 Mt)
- Most of the 11.7 Mt of ferrochromium produced worldwide was consumed in the manufacture of stainless steel which totalled 41.7 Mt in 2014

Chromium prices

- Chromite and FeCr prices follow similar trends, because both are impacted by the same macro-economic factors
- Most chromite is used to produce FeCr, and most FeCr is used to produce stainless steel
- Chromite accounts for one third of the production cost of FeCr
- The value (represented by price) increases dramatically as chromium is beneficiated from chromite to ferrochromium to stainless steel

DC arc furnaces for melting metals date back to 1878

- Sir William Siemens used a DC arc furnace in 1878 with a vertical graphite cathode, with the arc transferred to the melt in contact with a water-cooled bottom anode



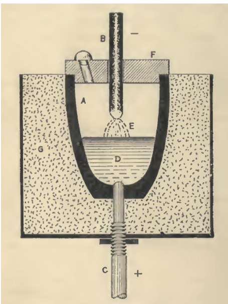


FIG. 2.—Siemens' vertical arc furnace.

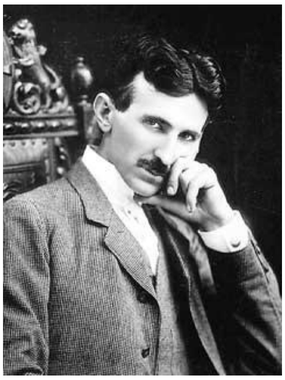
AC furnaces are more recent than DC furnaces

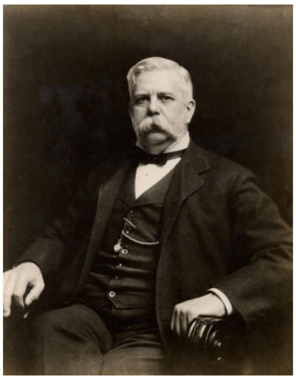
- The AC electric furnace was patented in 1900 by Paul Héroult, and operated in La Praz, France in 1900

First AC electric arc furnace in USA, 1906 (Philadelphia)

However, AC furnaces were widely used for a long time

- AC power was widely used, for reasons of effective power transmission from large central power stations, following developments by Nikola Tesla and George Westinghouse in 1887 and 1888

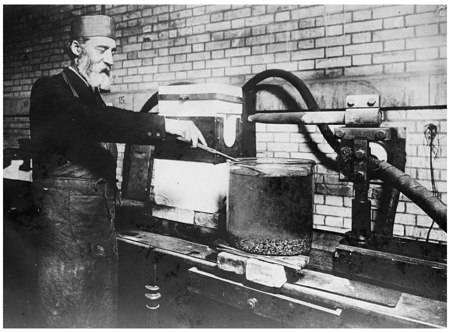


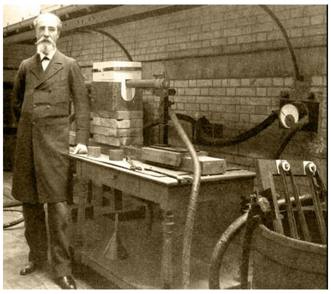


Henri Moissan (1852–1907)

- In 1893, Henri Moissan smelted chromium ore and carbon in an electric furnace and produced ferrochromium; this has remained the basis of the modern commercial method of producing the alloy
- Ferdinand-Frédéric-Henri Moissan, a French chemist who was born and died in Paris, received the 1906 Nobel Prize for Chemistry for the isolation of the element fluorine, and the development of the Moissan electric furnace
- He also devised a commercially profitable method of producing acetylene

Moissan electric furnace





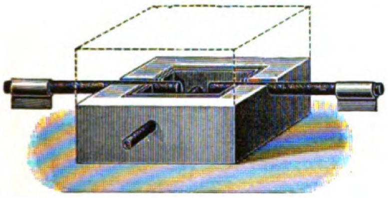


Fig. 173.—Moissan's electric furnace.

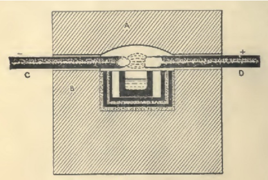


FIG. 6.—Moissan's furnace.

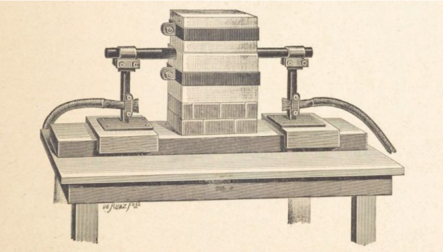
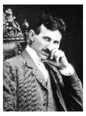


FIG. 4. — Four électrique avec supports pour courants de 110 volts et 1000 ampères.

Timeline

- 1878: William Siemens
  – DC arc furnace




- 1887 & 1888: Nikola Tesla and George Westinghouse
  – AC power was widely used

- 1893: Henri Moissan
  – produced ferrochromium

- 1900: Paul Héroult
  – AC electric furnace

- 1797: Louis Nicolas Vauquelin
  – discovered chromium

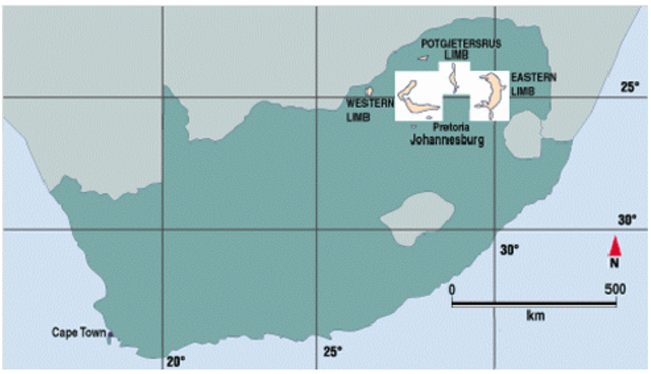
- 1820: Michael Faraday
  – produced Fe-Cr alloys

- 1913: Harry Brearley
  – invented Stainless Steel

- 1924: William Hatfield
  – produced 18/8 stainless
- 1967: AOD process

Chromite in South Africa

- South Africa has the largest known reserves of chromium ores
- Bushveld Complex (PGMs, Cr, V, Ti) – close to surface, but has a lower Cr:Fe ratio (about 1.6) than many other countries
- Largest known layered igneous complex of its type in the world
  - 350 km west to east; 250 km north to south



Chromite in South Africa

- Southern Africa hosts about 90% of the world's chromite reserves and resources, and accounts for close to 60% of global chromite production (Roskill, 2018).
- South Africa has reserves of about 3.1 billion tons, and a further estimated resource of 5.5 billion tons
- South Africa is by far the largest producing country for chromite, accounting for 54% of world output. By comparison, Kazakhstan accounts for 13%, and India 12%. In 2017, six countries produced more than 1 Mt/a of chromite (South Africa, Kazakhstan, India, Turkey, Finland and Zimbabwe).
- Most primary ore comes from the LG6 (Lower Group) or MG (Middle Group) chromite seams, while lower-grade chromite is recovered from the UG2 (Upper Group), which is an abundant by-product from platinum production.

UG2 chromite

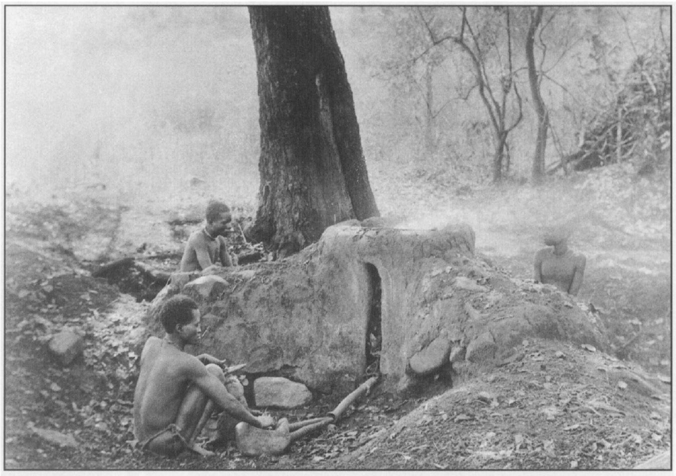
- Over the past decade, UG2 chromite has formed a growing proportion of the world's chromite supply. Over the past two decades the supply of UG2 ores has risen to account for over a quarter of the annual South African chromite supply.
- UG2 chromite is highly reducible, and solid-state pre-reduction is feasible
- Lower energy requirement (per unit of ferrochromium, and per unit of chromium content)
- Much work was done on this subject at the Pyrometallurgy Research Group at the University of the Witwatersrand, from about 1980 to 1983 (Barnes, Finn, 1983)

Smelting (of iron) has a long history in South Africa

- Mason (1974) produced evidence from Broederstroom (near what is now Johanesburg) for the production of iron and copper, the farming of cattle and sheep, and the construction of large villages, from at least AD 460 onwards
- *Earliest traces of iron smelting in the Transvaal. Tuyeres, iron slag, and iron ore, dated AD 460.*

- Low-shaft bloomery furnaces of the Iron Age were found at Melville Koppies (dated to ~1400 AD) and other sites in the vicinity of Johannesburg.

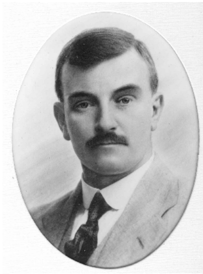
Early smelting in South Africa



'Makaties iron foundry ... east of the Spelonken'. This remarkable photograph, taken in 1888 by H. Gros, shows a typical Venda iron-smelting furnace in operation. The operators are each using two bellows made of hide. Straightened antelope horns channel the air blast through three clay tuyères to the charge in the furnace (Africana Library, Johannesburg)

Iron and steel in South Africa

- Iron was first smelted on a large scale in South Africa in 1901, near Pietermaritzburg, in a primitive blast furnace. The Union Steel Corporation electrically melted steel scrap in 1911. The first industrial-scale smelting of iron ore began in Pretoria in 1918, in a blast furnace constructed by Professor **George Stanley**.



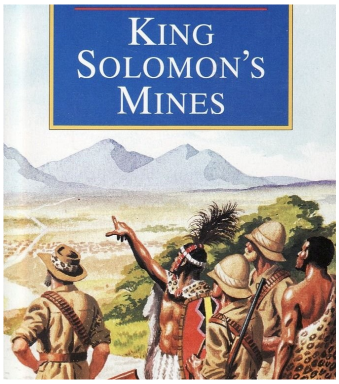
Diamonds and Gold


- Discovery of diamonds in Kimberley in 1867, and the discovery of gold, especially around Johannesburg in 1886, changed South Africa’s economy from being based on agriculture to being based on mining
- The legacy of colonialism dates back to this period
- Mines required expensive machinery, and the consolidation of small claims, thereby ushering in the era of large capital and the mining magnates
- The money accrued from diamond mining in Kimberley provided capital for opening up the new goldfield

Ferro-alloy smelting (and gold mines) needed electrical power

- Sir Henry Rider Haggard suggested to Cecil Rhodes that the Victoria Falls could be used to power gold mining on the Rand. The British South Africa Company (BSA) formed the Victoria Falls Power Company in 1906. Unfortunately, the Victoria Falls has a meagre and unpredictable flow in the dry season, but speculators made a lot of money anyway.

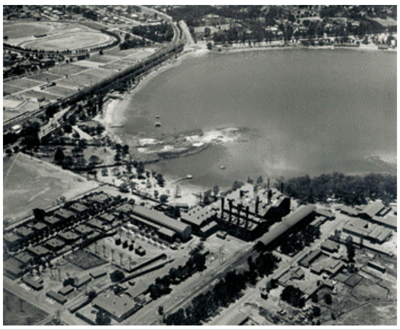
Victoria Falls is not the highest, nor the widest, but has the largest sheet of falling water, 1.7km wide and 108m high

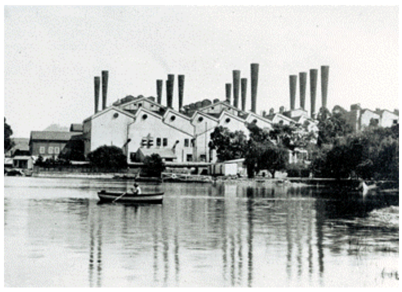


1885 book by Sir Henry Rider Haggard

Simmerpan Power Station

- Power stations were built closer to the gold mines in the 1890s
- The Victoria Falls Power Company changed its name to the Victoria Falls and Transvaal Power Company Limited in 1909, and built **turbine-based power** stations. It became dominant because of **cheaper power** prices.
- Amongst the first, and perhaps the most important was the Simmerpan Power Station (1909–1957) on the banks of Simmer Pan or Victoria Lake (now known as Germiston Lake). This site remains in use as the central control centre of Eskom's power network for all of South Africa.





Start of South Africa's Ferro-alloys Industry – Rand Carbide

- Rand Carbide Limited came into being in **1918 in Germiston** for the production of calcium carbide and ferrosilicon
- Rand Carbide moved to Witbank (now known as eMalahleni in Mpumalanga) in 1926 to avail itself of cheaper power and because it envisaged the use of the coal there as a raw material
- Since those early days, the production of carbide has been greatly expanded, and the company has diversified into the production of ferrosilicon and intermediate products, char, electrode paste, electrode casings, and steel drums, both for its own use and for supply to other manufacturers employing electric furnaces
- (During 1978, Highveld Steel and Vanadium Corporation acquired the total issued share capital of Rand Carbide Limited)

Chromite smelting to produce ferrochromium – Amcor

- Chromite mining in South Africa began in 1921
- The first ferrochromium plant in Africa is sometimes claimed to be Zimbabwe Alloys which was founded in 1949 in Gwelo (now Gweru)
- However, the Vereeniging smelter of **African Metals Corporation (Amcor)** commenced production in **1942** and made FeMn, FeSi, and high-carbon FeCr (having previously produced small quantities of FeMn in 1939)
- The first South African stainless steel was produced in 1943 by Amcor in Vereeniging

Hendrik van der Bijl

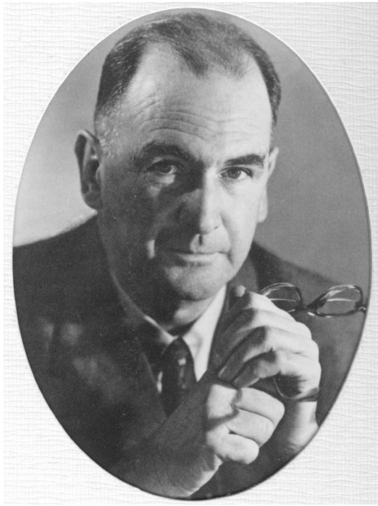
- Dr Hendrik van der Bijl (1887 – 1948), FRS, was one of South Africa's greatest industrialists
- He came from an influential family, and studied physics in Stellenbosch and Germany, then worked in the USA
- He returned to South Africa in 1920, and was asked by Prime Minister Jan Smuts to advise the government in the planning of South Africa's industrial development
- In 1922, he founded the Electricity Supply Commission (Escom) and chaired it until 1948
- He established the South African Iron and Steel Corporation (Iscor) in 1925, with the first steel produced in Pretoria in 1934, followed by Vanderbijlpark steel works and town in 1947. Iscor was later taken over by what is now Arcelor Mittal.
- He also founded the **African Metals Corporation (Amcor)** in 1937, the Industrial Development Corporation (IDC) in 1940, Vecor in 1945, and Safmarine in 1946

Amcor

- The secretive ferro-alloys industry did not share much information (especially around the war years), so Amcor relied heavily on Rand Carbide for furnace expertise
- Amcor's Meyerton smelter (Kookfontein) was commissioned in 1951
- The Vereeniging smelter was decommissioned in 1954, and the furnaces were transferred to Meyerton
- In 1959, Ferrometals (Witbank) was acquired for the production of charge chrome

William Bleloch

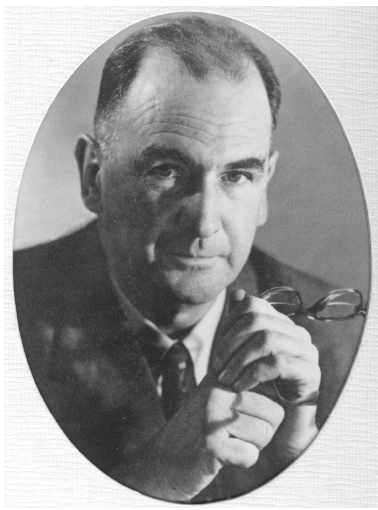
- William Bleloch (1906–1991) was a chemical engineer and metallurgist
- Best known for recovery of vanadium and pig iron from vanadiferous magnetite. In 1948 he conducted large-scale tests overseas on the magnetite of the Bushveld Complex. He demonstrated that vanadium could be recovered, and that pig iron suitable for steelmaking could be produced.
- He acted as Technical Adviser to Rand Mines Limited during the development of a process to produce chromium steel from Bushveld ore, and during the construction and initial operation of the commercial plant



Dr William Bleloch
SAIMM President, 1956–1957

William Bleloch

- He often stressed the importance of producing metal from the country's ores, rather than exporting them at much lower profit
- When the University of the Witwatersrand conferred upon him the degree of Doctor of Science and Engineering *honoris causa*, the citation said 'William Bleloch can truly be called the father of our electrochemical and electrometallurgical industries, the importance of which to our economy and the welfare of our people can scarcely be overstated'

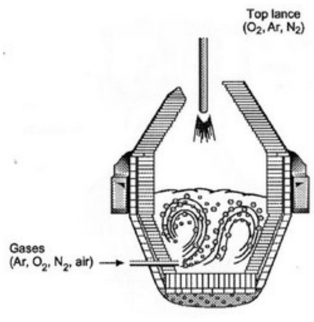


Dr William Bleloch
SAIMM President, 1956–1957

William Bleloch and RMB Alloys

- The years 1959/1960 signalled the start of unprecedented metallurgical developments, resulting in the commissioning of the RMB (Rand Mines Bleloch) Alloys low-carbon ferrochromium plant (April 1964), the Transvaal Alloys low-carbon ferrochromium plant (1964), the Southern Cross Steel plant (December 1966), and the Highveld Steel and Vanadium plant (February / December 1968)
- The first low-carbon ferrochromium in South Africa was made in Middelburg by RMB Alloys in 1964
- RMB later merged with Southern Cross Steel to form the Middelburg Steel Company, which provided flexibility in the production balance of steel and alloys
- The formation and development of Highveld Steel and Vanadium under William Bleloch's guidance is a separate story

Argon-Oxygen Decarburization (AOD) in 1967



- The argon-oxygen-decarburization (AOD) process for the manufacture of stainless steel was invented by Bill Krivsky of Union Carbide in the USA in 1967
- This created a significant market for ‘charge chrome’ and high-carbon ferrochromium containing 50–55% Cr (which is what South African chromites typically produce) instead of the conventional 65–70% Cr
- This facilitated the expansion of the South African FeCr industry, as the Transvaal chromite ores (which have a lower Cr:Fe ratio than many other ores) became acceptable as raw materials
- The AOD process substantially decreased demand for low-carbon FeCr
- Southern Cross Steel installed an AOD facility

Abundant power drove growth – 1960s and 1970s

- Abundant and cheap electricity in the 1960s and 1970s provided the impetus for a rapid expansion of industrial smelting capacity
- During the oil crisis of the 1970s, South Africa's plentiful and cheap coal-based thermal power helped to grow the ferro-alloys industry
- South Africa's coal and anthracite provide the primary energy source for the generation of electricity, as well as reductants, as well as feed for the manufacture of electrodes
- In the 1960s, various substantial plants were established in the basic metals sector (such as Highveld Steel, RMB Alloys, Southern Cross Stainless Steel, and the Alusaf aluminium smelter)
- Installed power of SA's ferro-alloy furnaces grew by a factor of four during the 1970s

Ferro-alloys developments – 1960s and 1970s

- Transalloys was started in 1960 in Witbank as an integrated HCFeCr / LCFeCr plant, based on the Perrin process. (During 1967, the plant was converted from FeCr to FeMn production.)
- The origins of Middelburg Ferrochrome (now part of Samancor Chrome) can be traced back to the RMB Alloys Ferrochrome Pilot Project in 1963
- Palmiet Chrome Corporation started producing charge chrome on 22 February 1963 at the plant near Krugersdorp. (On 28 December 1983, the first DC plasma arc furnace for ferrochromium production was commissioned at Palmiet.)
- In 1971 Feralloys Limited erected a ferrochromium smelter at Machadodorp for the production of charge chrome and LCFeCr
- Amcor and SA Manganese merged in 1975 to become Samancor Limited

Further developments – 1970s to current

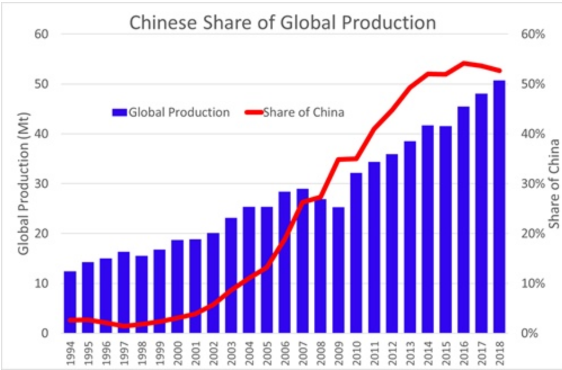
- The CMI plant of JCI at Lydenburg (now part of Glencore) came into being during 1975 for the production of charge chrome, based on the Showa Denko SRC process
- A number of smelters were built over the coming years. These included: Tubatse Ferrochrome (1975), Chromecorp (1987), SA Chrome (1987), Purity Ferrochrome (1991), Hernic Ferrochrome (1995), ASA Metals (1997), Tata Steel (2006), and International Ferro Metals (IFM)
- Many of the independent producers have been taken over by either Samancor Chrome (owned by Kermas) or Glencore (previously Xstrata Alloys). These two groups dominate the production of FeCr.
- Throughout the industry, business restructuring and consolidation is currently underway

Samancor Chrome

- Samancor Chrome's history goes back as far as 1975, when it was established as a listed entity on the Johannesburg Stock Exchange, as a result of a merger between SA Manganese Ltd and Amcor Ltd. SA Manganese was formed in 1926 to mine manganese ore deposits in the Northern Cape, whilst Amcor was established in 1937 to exploit mineral deposits for the steel industry and to process those minerals into ferro-alloys.
- The Kermas Group, acquired Samancor Limited from Billiton and Anglo American after the unbundling of the manganese business during 2005 and 2006, and renamed the company, now holding only the chrome business, Samancor Chrome Limited.
- During the early part of 2016 and latter part of 2017, Samancor Chrome successfully acquired the ferrochrome smelting assets and chrome mining assets from the business rescue practitioner of International Ferrometals, and likewise the smelting assets from the business rescue practitioners of ASA Metals through a series of transactions, the latter together with Sinosteel.

China & Stainless steel

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



SASSDA, 2019

China & FeCr relative to South Africa

- By 2006, 90% of the chromite that South Africa produced was converted to ferrochromium (FeCr) in South Africa, making SA by far the world's largest producer of this ferro-alloy
- China, by comparison, has very little chromite, and has to either import it (much of it from South Africa) to produce FeCr, or has to import the FeCr necessary for its stainless steel production
- In 1986, China was in seventh place for FeCr production, producing only 120 kt/a. By 2006 (twenty years later), China's FeCr production had grown to 1.0 Mt/a, and they had moved up to third place (after South Africa with 3.0 Mt/a, and Kazakhstan with 1.2 Mt/a).
- China continued to grow rapidly, and South Africa's production of FeCr declined as a result of power shortages and higher costs
- China overtook South Africa as the world's leading producer of ferrochromium in 2012
- In 2017, China accounted for just under 40% of global ferrochromium output

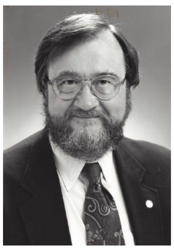
Power shortage in South Africa – a major failure

- Long-term problems with the supply and price of electricity have posed serious challenges to South African FeCr producers
- Electricity demand grew faster than supply (South Africa has ~40 GW of power generating capacity)
- Load-shedding crisis in 2008
- Electricity price tripled in next six years (25% increase each year)
- Mining industry uses ~15% of the country's electricity (~6 GW), with over 4 GW smelting capacity
- 2 GW of electrical power is used for ferro-alloy smelting in South Africa
- FeCr industry constrained by lack of power
- Many ferro-alloy smelters are currently shut, and some are paid by Eskom to not use electricity to make it available to others

Pyrometallurgical research in South Africa

- Early South African research into chromite smelting took place largely under the auspices of the Pyrometallurgy Research Group, located at the University of the Witwatersrand, and jointly funded by Mintek's predecessor the National Institute of Metallurgy
- This was established in the late 1960s to serve the industrial boom in the ferro-alloys industry
- Significant work was done under the direction of Professors D.D. (David) Howat, [and R.P. (Peter) King], C.W.P. (Charlie) Finn, and R.H. (Hurman) Eric, and many leading pyrometallurgists came out of this group

David Howat



Charlie Finn

Charlie Finn & Peter King

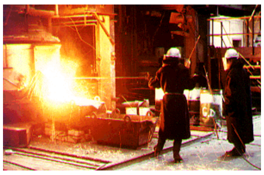
Hurman Eric

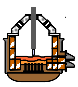
INFACON: International Ferro-Alloys Congress

- INFACON (International Ferro-Alloys Congress) was founded in South Africa in 1974 by the SAIMM (Southern African Institute of Mining and Metallurgy), Mintek (then the National Institute for Metallurgy), and the Ferro Alloys Producers' Association (FAPA) when the first INFACON was held in Johannesburg, chaired by **Robbie Robinson**
- The intention of INFACON is to stimulate technical interchange on all aspects of ferro-alloy production. All past conference papers are freely available on the website.
- INFACON is controlled by the International Committee on Ferro-Alloys (ICFA) – Brazil, China, European Union, India, Japan, Kazakhstan, North America, Norway, Russia, South Africa, Turkey, and Ukraine – whose objective is to promote the holding of the congress approximately every three years in appropriate locations and to retain the established high technical standard

Mintek's DC furnaces

MINTEK

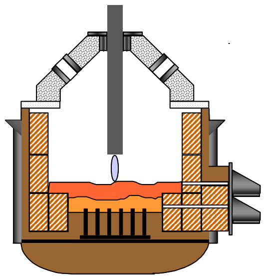




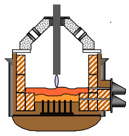
Mintek's largest DC furnaces

Features of DC arc furnaces

- **Operates with open arc, open bath**
- **Can accept fine feed materials** (< 10 mm)
- Does not require coke (no burden porosity required)
- Can achieve high temperatures (> 1500°C)
- Lower electrode consumption
- No arc repulsion (and resulting hot spots)
- DC furnaces carry higher currents per electrode (no 'skin effect')
- Energy supplied by open plasma arc, so less sensitive to electrical properties of slag
- Power supplied to furnace is mostly independent of slag composition, so slag can be changed to one that allows higher Cr recovery

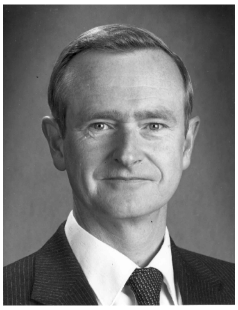


Features of DC arc furnaces …



- DC arc furnaces have some wonderful features
- The open bath surface is good at accommodating finely sized feed materials
- Lower dust losses, as bulk gas flow is directed downwards
- DC arc furnaces are not a panacea for all metallurgical problems, but are **very well suited to a number of reductive smelting processes** (such as FeCr, TiO_2, FeNi), but less so in the case of processes involving a gaseous intermediate such as SiO, or those with a low-melting (super-heated) product
- Geometrically simple, reducing uneven wear on side-walls
- Lower cost for furnace vessel and roof, but somewhat higher cost for electrical rectifier
- However, thermal efficiency is decreased by the hot off-gas, as the absence of a burden does not allow for capture of volatile species
- The thermal efficiency can be improved if the off-gas is used to preheat feed materials

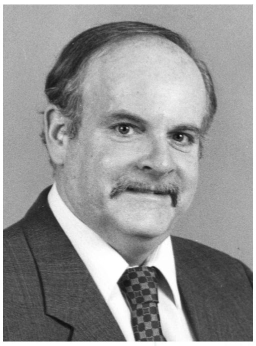
Mintek's initial work on 'plasma furnaces'

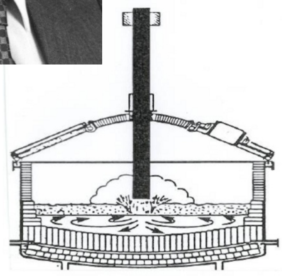


- **Peter Jochens** identified 'plasma furnaces' as a possible solution to the 'chromite fines' problem
- Mintek and Middelburg Steel & Alloys (now part of Samancor Chrome) conducted smelting trials on Tetronics' pilot transferred-arc plasma furnaces in 1979/80
- Successful metallurgy, but difficult to scale up to very large furnaces

Mintek’s early work with DC arcs from graphite electrodes

- **Nic Barcza** recognised the synergy between the metallurgy proven at Tetronics, and the scale-up potential of ASEA’s DC arc furnace
- Mintek built a 1.2 MW DC arc furnace in 1983 to support this development
- MS&A converted an existing AC furnace at Palmiet Ferrochrome (now Afarak Mogale Alloys) in Krugersdorp to a 12 MW DC arc furnace of ASEA design in 1984



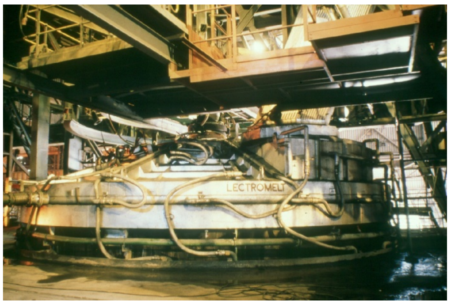


Chromite smelting testwork at Mintek

- DC arc furnace studies commenced in 1976 as a means of smelting chromite fines (< 6 mm)
- First ferrochromium was produced in a bench-scale DC furnace in 1979
- 1 t/h DC arc furnace pilot plant commissioned in 1984
- Tested at 0.3 - 0.5 MW, 1 – 2 m

Chromite smelting – DC arc furnaces

- A major breakthrough in the treatment of chromite fines occurred with the first industrial application, at Palmiet Ferrochrome, of a 12 MW (16 MVA) DC arc furnace for the production of ferrochromium in 1984
- This furnace was upgraded to 40 MVA (25–30 MW) in 1988, and an additional smaller furnace was added later
- This site (now Afarak Mogale Alloys) currently has one **30 MW** and one **10 MW** DC arc furnace



Chromite smelting – largest DC arc furnaces

- Over the next 25 years, the largest individual DC furnace capacity increased to **two 60 MW** furnaces in South Africa, owned by Samancor Chrome
- [A 44 MW (62 MVA) DC arc furnace was installed at Middelburg Ferrochrome in 1997; a 60 MW DC furnace was installed in 2009; and the 44 MW furnace was later upgraded to 60 MW]

- In 2013, **four 72 MW** DC arc furnaces for chromite smelting were built in Kazakhstan

World FeCr production in 2017

- Four countries produce more than 1 Mt/a of HC FeCr / charge chrome
- In 2012, China overtook South Africa as the leading FeCr producer
- Canada aspires to become one of the major producers of FeCr

– China	4486 kt	37%
– South Africa	3673 kt	31%
– Kazakhstan	> 1000 kt	11%
– India	> 1000 kt	11%
– Finland	400 – 500 kt	
– Zimbabwe	100 – 250 kt	
– Russia	100 – 250 kt	
– Brazil	100 – 160kt	

– Sweden, Turkey, Oman, and Albania producing below 100 kt

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– China	4486 kt	37%
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– Kazakhstan	> 1000 kt	11%
– India	> 1000 kt	11%
– Finland	400 – 500 kt	
– Canada	268 kt	
– Zimbabwe	100 – 250 kt	
– Russia	100 – 250 kt	
– Brazil	100 – 160kt	

– Sweden, Turkey, Oman, and Albania producing below 100 kt

Early ferro-alloy production in Canada

- In 1907, Robert Turnbull, a Scottish engineer from Glasgow, (who worked closely with Paul Heroult from France) established Canada's first commercial ferro-alloy production in Welland, Ontario, attracted by favourable energy rates in the Niagara region
- The company, Electro Metals Ltd (later Electro Metallurgical Company of Canada, a division of Union Carbide Corporation), produced both calcium carbide and ferrosilicon
- (In 1919, Turnbull assisted in the setting up of a ferrosilicon plant in Niagara Falls, N.Y. This plant, which added ferrochrome to its list of products in 1921, was subsequently acquired by Vanadium Corporation of America)

Chromium Mining and Smelting Corporation

- In 1928, Turnbull was approached by Great Lakes Power Co. in Sault Ste. Marie, Ontario to set up a ferro-alloy facility to serve Algoma Steel in that city
- A 2.0 MW furnace commenced production of ferrosilicon in early 1929, but closed down a year later due to the depression, briefly opening between 1934 and 1935
- Shortly thereafter, the plant was acquired by **Chromium Mining and Smelting Corporation Ltd.** who re-activated the plant and operated the facility until 1959, producing both ferrosilicon and ferrochromium. During this time, the plant was expanded to four furnaces, the largest of which was rated at 5.5 MW, plus one tilting furnace for speciality alloys.
- In 1959, Chromium Mining and Smelting Corporation Ltd acquired another plant in Beauharnois, Quebec to produce FeSi, FeMn, and SiMn.

Chromium Mining and Smelting Corporation

- The Chromium Mining and Smelting Corporation Ltd. was founded in 1934 with its head office in Hamilton, Ontario. At that time the company had a drilling operation near Collins, Ontario. By the following year the company had established a plant in Sault Ste. Marie, occupying the facility previously held by Superior Alloys. Leo H. Timmins, of the Hollinger Gold Mine in Timmins, joined the company as president. In 1984 the company changed its name to Timminco Co. Ltd. In 2012, the company declared bankruptcy.
- Sault Ste. Marie's Chromium Mining and Smelting Corporation plant was located on Queen Street West between Huron and Hudson, in the area of what is now the city's transit facility.
- **The plant first began smelting chromium in the 1930s, when it was the first instance of chromium smelting in the British Empire.** From there, the plant quickly expanded to meet demand.
- In 1947, a fire roared through part of Sault Ste. Marie, originating from the plant.

St Lawrence Metals and Alloys Ltd / Electro Metallurgical Company

- In 1935/1936, excess power available from Beauharnois Light, Heat and Power Company led Robert Turnbull to set up **St Lawrence Metals and Alloys Ltd** in Beauharnois, Quebec, to manufacture ferrosilicon
- The first of three 3.5 MW submerged-arc furnaces commenced operation in August 1936, and the rest started by January 1937
- A 1.5 MW ferrochromium furnace was added in early 1937
- St Lawrence Metals and Alloys Ltd was acquired by the Ore and Metals Division of **Union Carbide and Carbon Corporation** in 1938
- During the 1939–1945 period of World War II, further furnaces were added, bringing the total to thirteen
- In January 1949, the Electrical Metallurgical Company of New York took over direction of the company and, in January 1954, the company became known as the **Electro Metallurgical Company**, a Division of Union Carbide Canada Ltd.
- The thirteen furnaces were replaced with four modern furnaces in 1953.

Algoma Steel, Sault Ste. Marie, Ontario, Canada

- Algoma Steel (now the second largest steel producer in Canada) was founded in 1902 in Sault Ste. Marie, Ontario
- During the 1940s, the steel and chromium operations of Algoma Steel were of substantial importance to the war effort in Canada and the United States. Algoma Steel and the Chromium Mining and Smelting Corporation were key producers for transportation and military machines.

Other uses of chromium at Sault Ste. Marie

- The Northwestern Leather Company tannery once stood in this area. From 1900, until it closed in 1958, it dumped toxic chemicals on site. Testing in the late 1970s, by Sault Ste. Marie State College and the Michigan Department of Natural Resources, found especially high levels of hexavalent chromium in the soil and groundwater.
- The Michigan tannery site was remediated in 2007, but data obtained by a non-profit organization, the Environmental Working Group, shows the area still has unhealthy amounts of chromium-6 in its drinking water.

Ferro-alloys in Canada

- At the end of 1968, there were seven ferro-alloy producers in Canada: plants of Union Carbide Canada Ltd at Welland, Ontario, and at Beauharnios, Quebec; Masterloy Products Ltd, near Ottawa; and Chromium Mining and Smelting Corporation Ltd at Beauharnois
- Canada's ferro-alloys were primarily FeMn, FeSi, SiMn, and FeCr; with about 17 kt/a of FeCr being produced
- Most ferro-alloys for manufacturing alloy steels were largely imported

- In 2000 (according to the USGS), Allican Resources planned to build a 19 kt/a low-carbon ferrochromium smelter at Thetford Mines, Quebec

Ring of Fire

- Large reserve of high-grade chromite (and Ni-Cu-PGMs) in northern Ontario – a greenstone belt about 200 km long – perhaps the world's largest untapped chromite resource, and the only major chromium resource in North America
- Remote location and lack of infrastructure
- **Cliffs Natural Resources (USA) acquired mineral rights, and conducted engineering studies and metallurgical testwork on the largest Black Thor chromite deposit** (measured resource of 108 Mt; Cr:Fe ratio of 2.0, and a Cr_2O_3 grade of 32%), but struggled with infrastructural issues
- KWG Resources worked with XPS to develop a process involving pre-reduction using natural gas
- **Noront Resources is currently the largest holder of mineral claims**
- Plan to mine and smelt chromite first from the Blackbird mine, then later from the Black Thor mine
- The Ferrochrome Processing Facility will be designed to smelt lumpy and fine ore which (after ore sorting) is expected to have 40% Cr_2O_3 and Cr:Fe of ~2.0
- 675 kt/a of upgraded ore is expected to be produced, trucked, and railed to the proposed smelter at Sault Ste Marie, Ontario, to produce 268 kt/a of HC FeCr (58% Cr)
- All-season road access is currently being assessed

Noront Resources

- **In 2015, Noront acquired Cliffs Natural Resources' (Cliffs) Ring of Fire assets, including mineral rights and Cliffs' in-house feasibility study** for its proposed Black Thor chromite project. (The feasibility study was prepared primarily by Hatch, with other consultants contributing in specific areas.) Supporting the feasibility study, extensive work had been completed by Cliffs in flowsheet selection and design, as well as supporting testwork. Cliffs basic concept was to preheat chromite concentrate from the Black Thor deposit in rotary kilns using recycled furnace off-gas as fuel, and then smelt to high carbon ferrochrome in closed DC furnaces.
- **Mintek carried out smelting testwork for Cliffs Natural Resources in a DC arc furnace around 2011 on 144 tons of chromite from the Black Thor deposit**
- Noront Resources Ltd plans to develop and operate a ferrochromium smelter within the brownfield **site of Algoma Steel in Sault Ste. Marie, Ontario**. The site was chosen in May 2019.
- Amongst the lowest greenhouse gas footprints per unit of chromium
- Minimize the potential for formation of hexavalent chromium
- Environmental best practice
- **DC furnaces coupled with rotary kiln preheating**
- Stage 1 requires one rotary kiln and **two 65 MW DC furnaces**
- Granulated slag will be sold as road building material

Technology for the future

- The chromite smelting technology of the future will be selected on its environmental credentials. Responsible users of stainless steel care about how FeCr is produced.
- Clean and cheap sources of electrical power (such as hydropower in the case of Canada) will be used
- Great care will be taken to avoid the presence of Cr(VI)
- Open or semi-closed submerged-arc furnaces will not be considered, due to their low chromium recovery using lumpy feed, and poor performance with respect to Cr(VI) generation and control, and implications for worker and community health
- Leading proven chromite smelting technologies are the DC arc furnace, and the closed submerged-arc furnace with sintered pelletised feed
- The current choice for Ring of Fire chromite smelting is the DC arc furnace

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