10-Year Outlook for the Global Scandium Market to 2028

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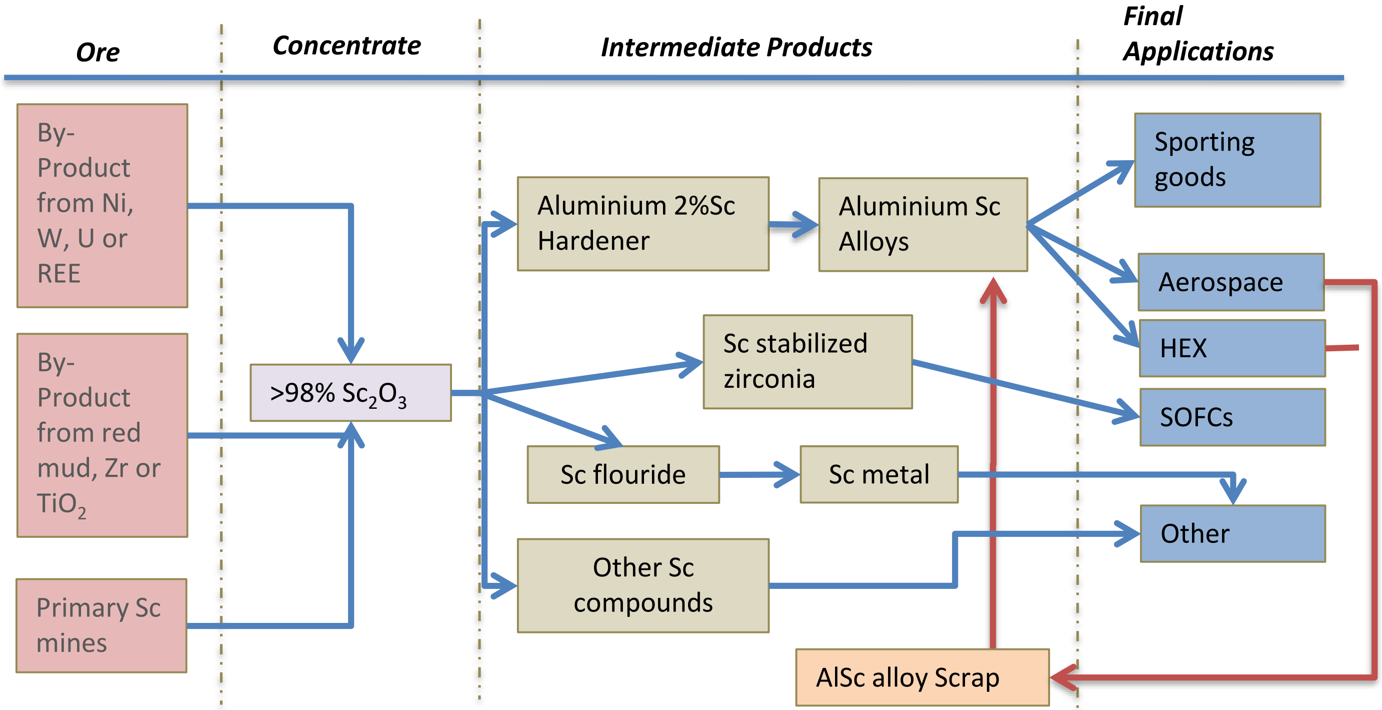
Scandium value chain



Internal process scrap not shown. "Other" includes lighting, ceramics, & electronics.

- Historically U and REE by-product sources
- Current production from TiO_2 and zirconium production in China
- This year red mud (Russia) and nickel by-product (Philippines) started

Source CM

Scandium Resources

- Scandium is not rare but is rarely concentrated
- No shortage -- Total Global resources ~2 megaton Sc
- Non-China resources
  - Red mud Russian (50-250ppm Sc) , Jamaican (135ppm Sc) and Greek red mud (121 ppm Sc)
  - Australian red mud low in Sc ~20 ppm
  - REE deposits
  - Uranium deposits
  - Tungsten deposits
  - Nickel laterites (>300 kt)
  - Primary Sc mines ~50kt
- Chinese resources
  - Titanium pigment acid waste
  - Tungsten deposits (>20kt)
  - REE (140 kt) (Sc_2O_3 content of Baiyun E'bo rare earth iron ore average 50 ppm)
  - Red mud (290 kt) - depending on area can be 40-150 ppm Sc_2O_3
- Total global red mud Sc resources at ~50% of total resources

Source Published figures & CM

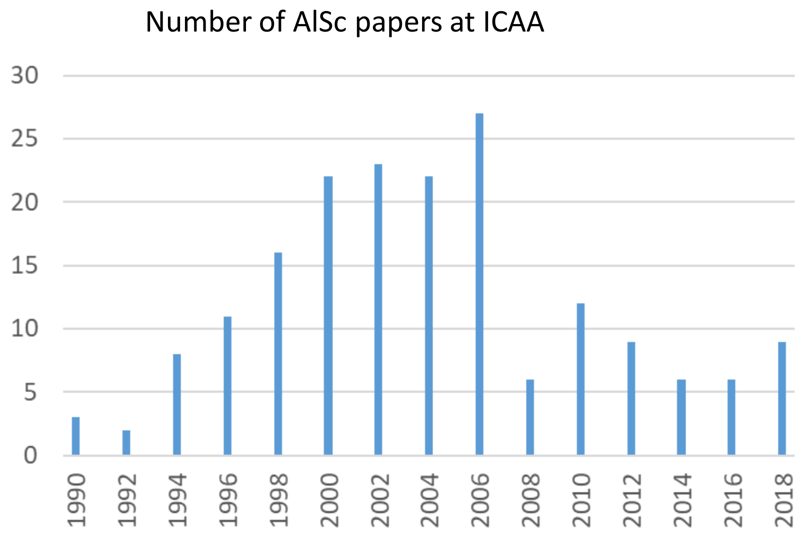
History of Aluminium Scandium alloys

- Early Russian work 1960s – continued through to present
  - Baikov Institute of Metallurgy
  - Lomonosov Moscow State University
  - All-Russia Institute of Light Alloys (VILS)
  - All-Russia Institute for Aviation Materials (VIAM)
  - Various Russian grades developed and commercialized including AlMg, AlLiMg, AlLiCu, AlZnMg
  - Used in fuselage stringers in large aircraft, MiG29, the International Space Station

- In the West
  - 1971 Alcoa patent
  - Ashurst (in the CIS) developed sporting goods applications with Kaiser
  - Baseball bats are commonly quoted but these have been ruled out now

- The high price of Sc versus the ability to improve existing alloys has held back take up of scandium

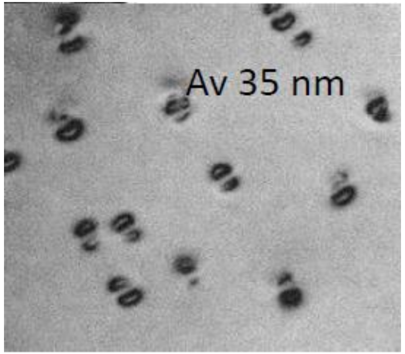
- Lack of diverse supply has also been an issue

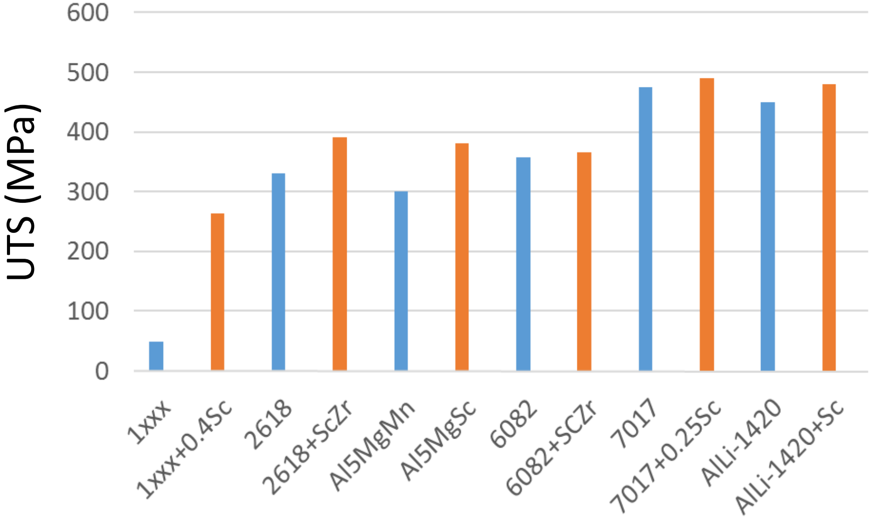


Source CM

Al-Sc metallurgy 101

- Al_3Sc precipitates form that increase strength and ductility
- Biggest effects in 1xxx and 5xxx Al alloys
- Often combined with zirconium to reduce scandium addition and cost $Al_3(ZrSc)$
- Other elements Erbium, Titanium, Vanadium etc also possible Sc substitutes
- Additions can be as low as 0.02% or up to 0.4% but are usually 0.1-0.2% Zr+Sc
- Acts as a grain refiner
- Suppresses recrystallisation
- Increases weld strength
- Improves corrosion resistance
- Can form large problematic AlSiSc intermetallics in high silicon casting alloys
- Still plenty of potential for new alloys that need less Sc (that is good for Sc demand!)

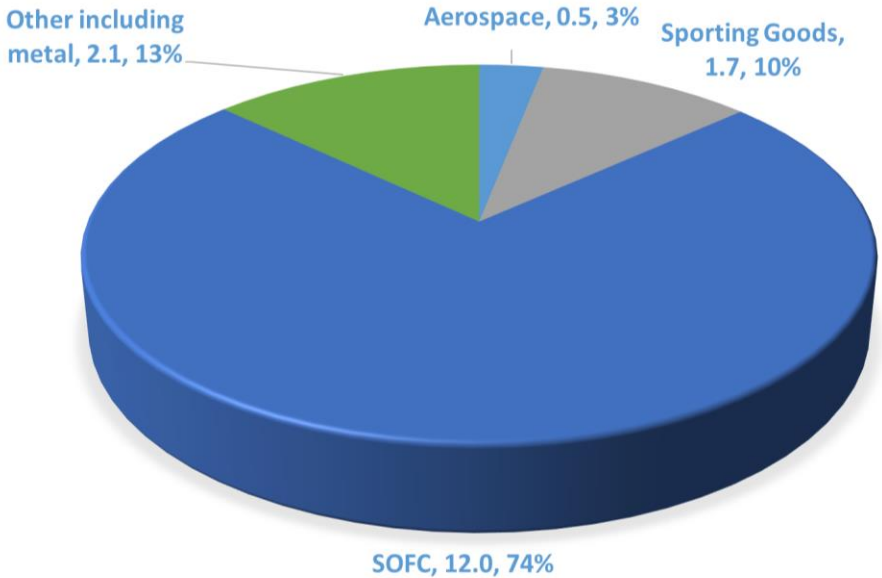




Source CM

Scandium market estimates

Scandium Market by Industry in 2017 (Industry, Demand, Percentage)

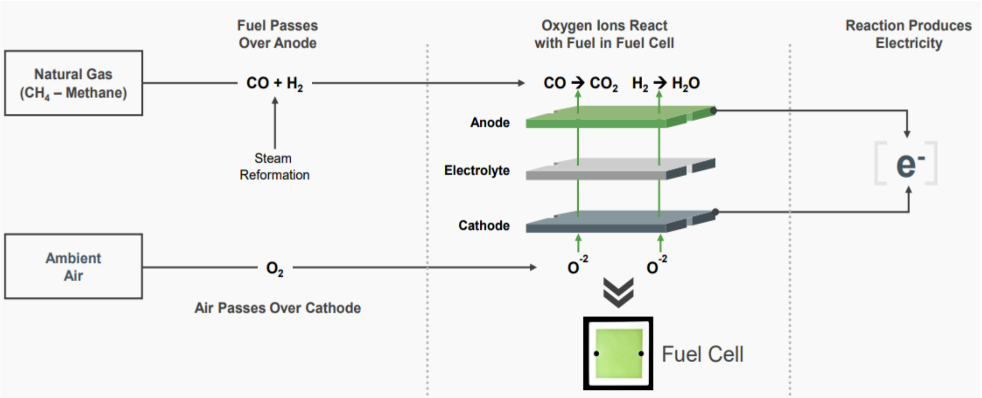


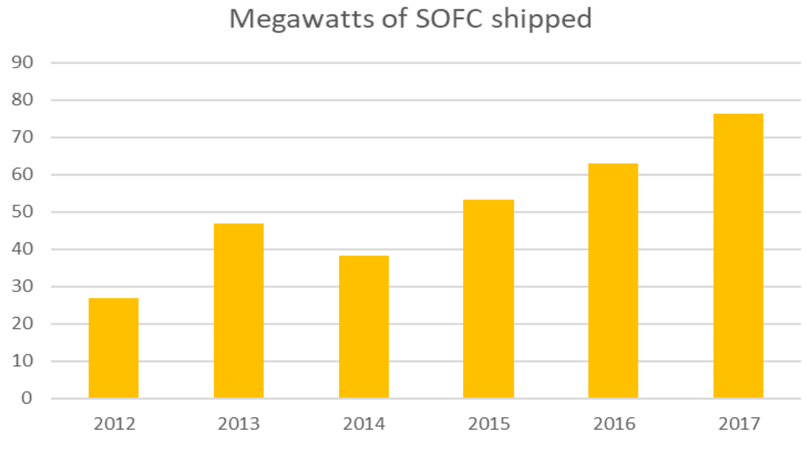
- 16.3 tonne scandia in 2017,
- estimate 18.9 tonne scandia for 2018 (12.3 tonne of metal equivalent)
- Demand dominated by SOFC and Bloom Energy
- Chinese demand <1 tpa Sc

Source CM

SOFC (Solid Oxide Fuel Cell)

- Biggest market for scandium (75% of demand) and dominated by Bloom Energy
- Bloom has considerable purchasing power
- SOFC accounted for 12 tonnes Sc_2O_3 in 2017
- We assume 25% SOFC annual growth in the outlook

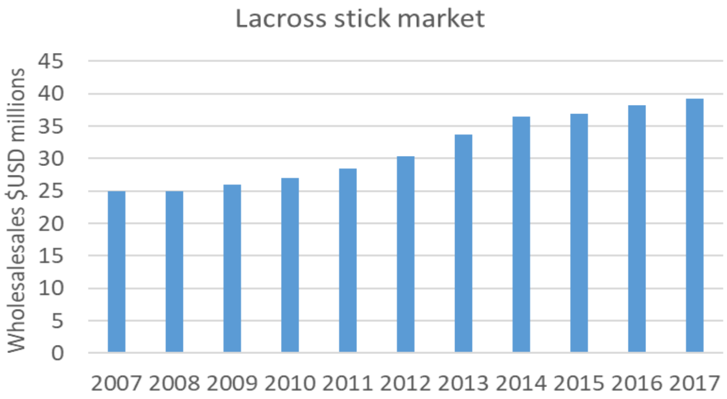


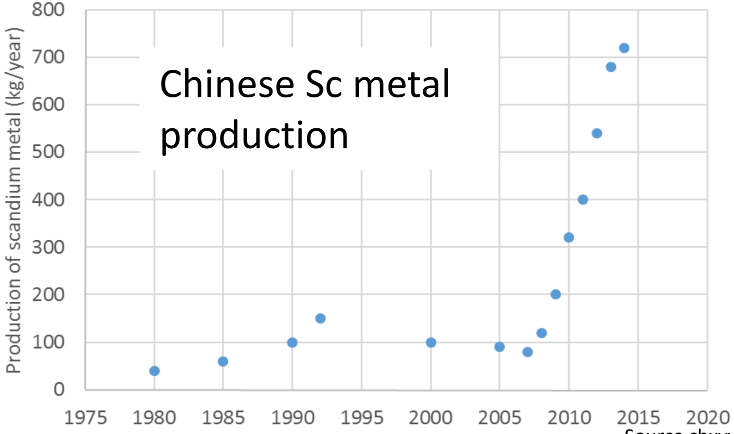


Source FCT and E4tech

Current non SOFC Demand

- Sporting goods
  - Bikes, golf clubs, Lacrosse sticks, baseball bats etc
- Lots of “noise” about sporting goods but current demand small at 1.1 tpa scandium equivalent
- Baseball bats ceased – dangerous
- A certain amount of bicycle activity but much is built upon existing stocks of AlSc tube
- Aero ~0.5 tpa in military – nothing in commercial planes
- Scandium metal (1.4 tpa)– scandium fluoride reacted with calcium
- Scandium Iodide – metal halide lamps
- Specialist scandia applications – lasers, high temperature windows etc.



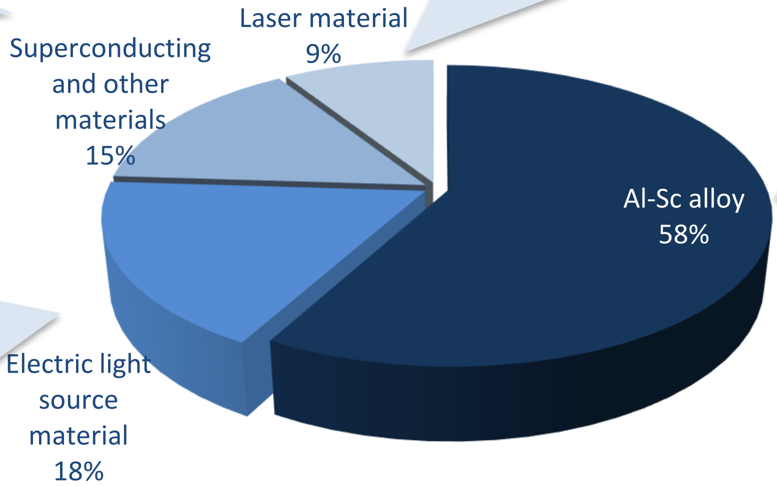


Source chxyy & CM

Consumption Structure of Scandium Products in China

- Mainly used in military, power and medical industry

- Very limited amount of Scandium is added to solid-state lasers, those are widely used in military, processing, medical and scientific research



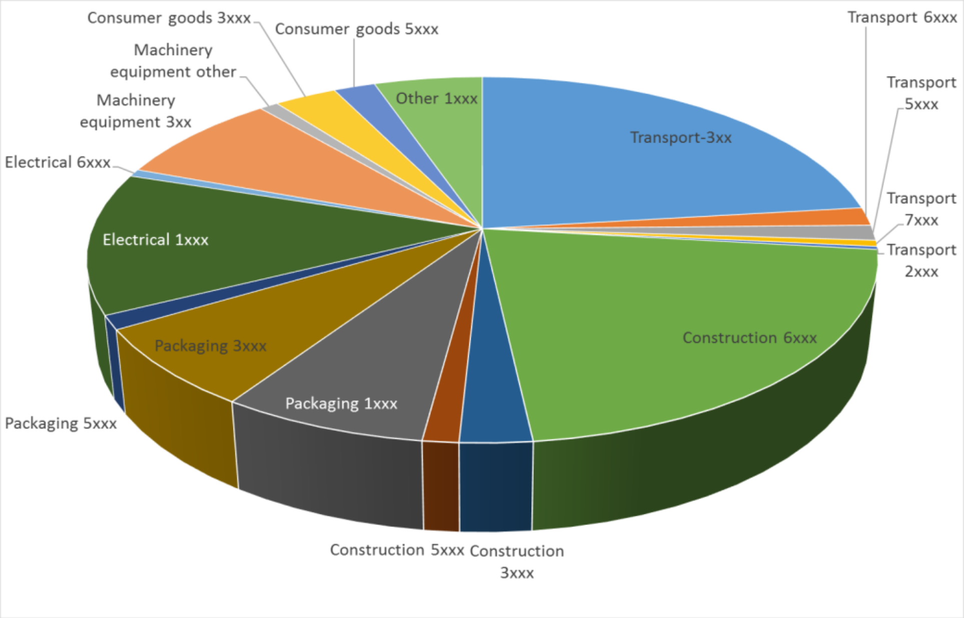
- Al-Sc alloy has been used as structural materials for aerospace, aviation, nuclear reactors and other fields.

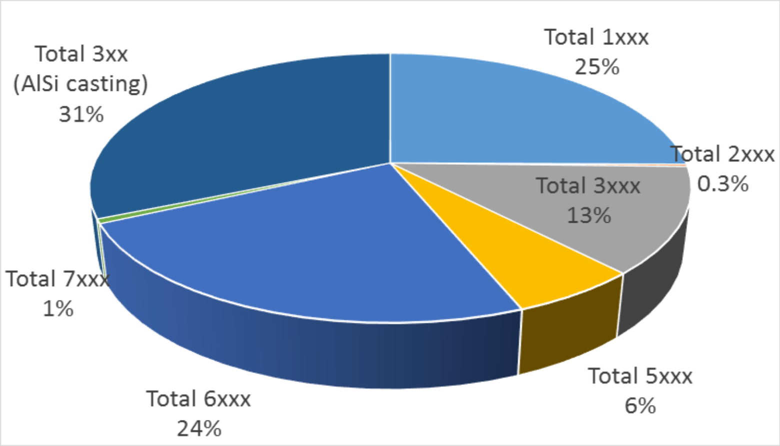
- Sodium lamps with high luminous efficiency, lower power consumption and longer life than ordinary lamp. Scandium sodium lamps a fraction of sodium lamp, there are also many other types in metal halide lamp category.

In China, slow technological development, high price, low usage and no special irreplaceability leads to slow scandium demand growth. Many uses are still in lab research stage.

Source: chxyy

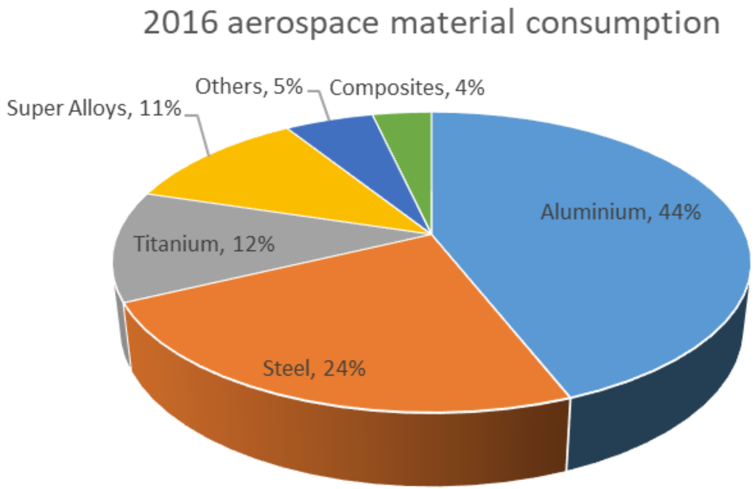
Aluminium markets and alloys context for Scandium

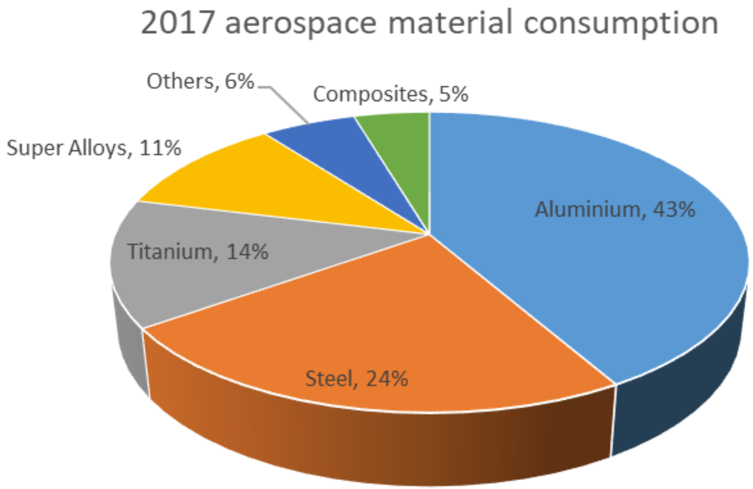




Global aluminium market around 70 million tpa
Aerospace is <1% of the total

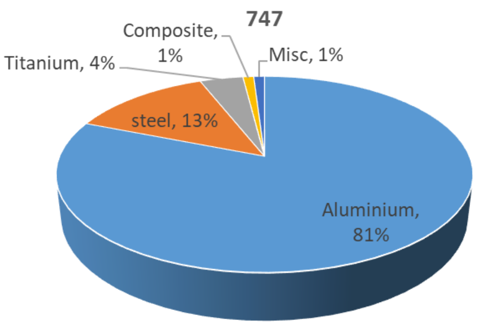
Aluminium share of 770 ktpa aerospace material market

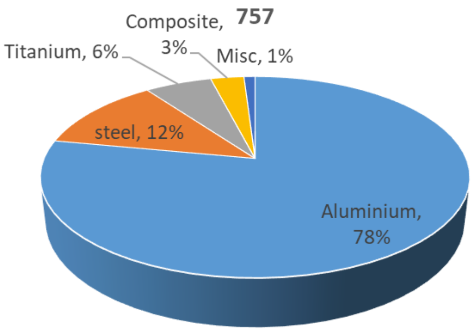


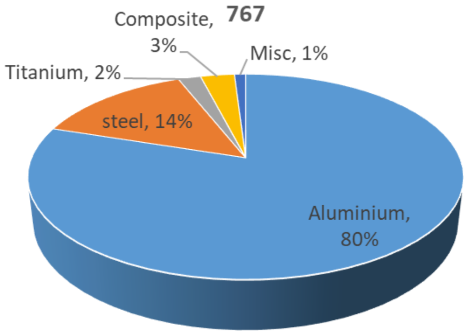


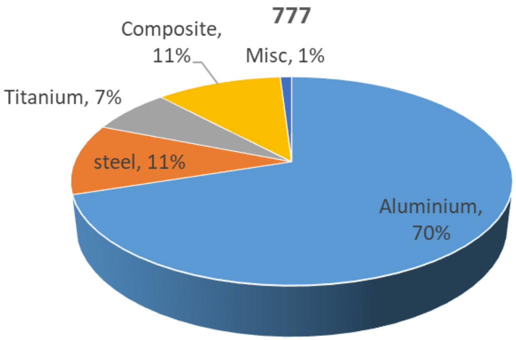
Source: ICF

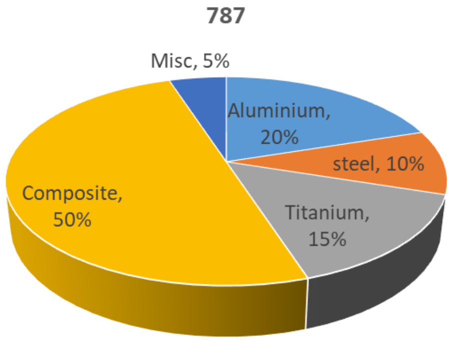
Trends in material usage at Boeing





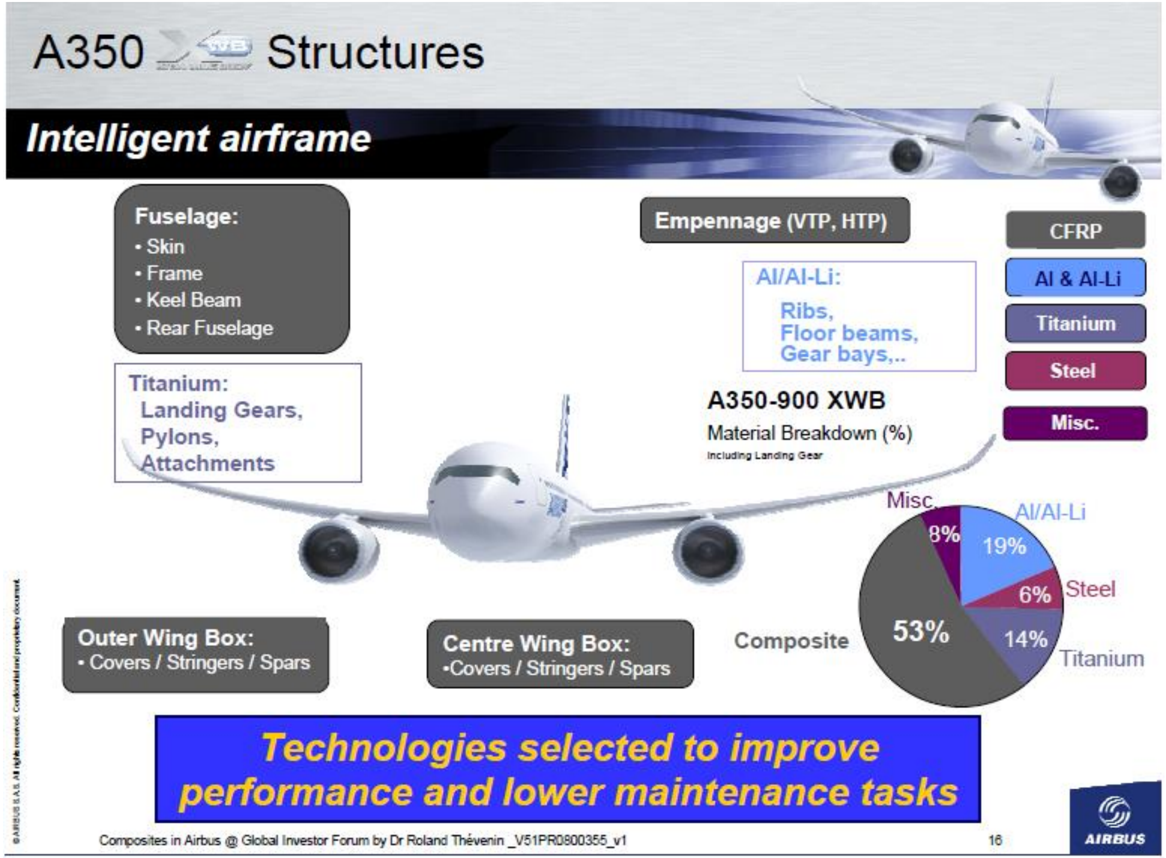






Source Boeing

A530 Structures



Also moving to composites and Ti

Source Airbus

In 2017 Airbus and Boeing consumed 75 ktpa (fly) 336 ktpa (buy) aluminium alloy

Airbus	2017 deliveries	Weight (tonne)	Total material demand (t)	%Al	Al demand (t)
A320	558	64	35,712	80%	28,570
A330	67	173	11,591	79%	9,157
A350	78	196	15,288	19%	2,905
A380	15	394	5,910	20%	1,182
			68,501		41,813

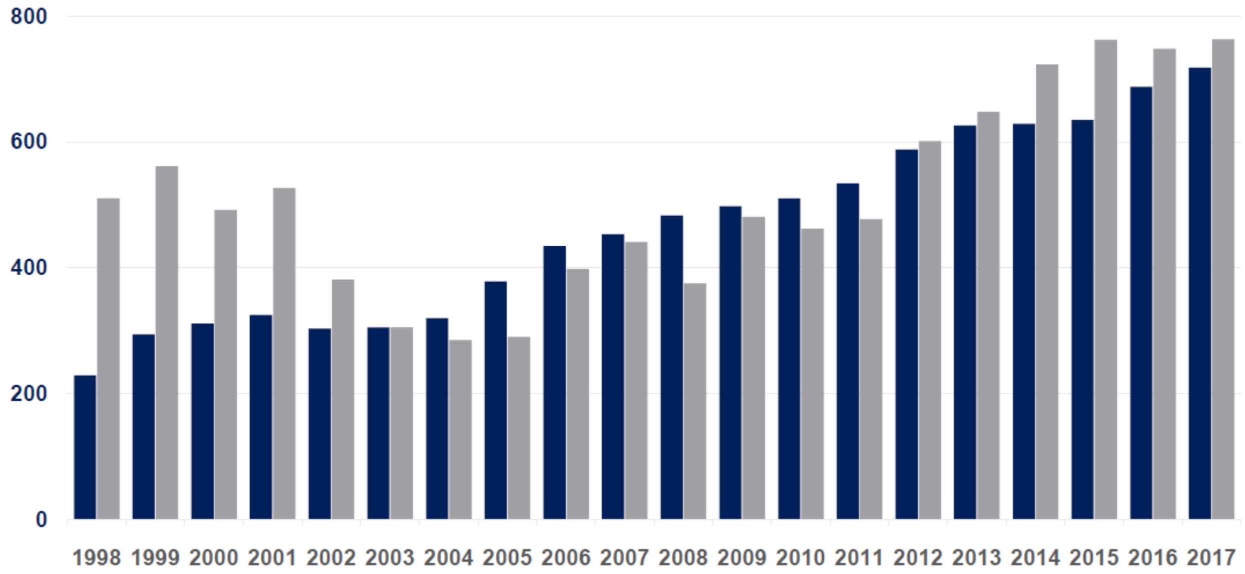
Boeing	2017 deliveries	Weight (tonne)	Total material demand (t)	%Al	Al demand (t)
737	529	42.5	22,483	80%	12,986
747	14	212	2,968	81%	2,404
767	10	86	860	80%	688
777	74	158.5	11,729	70%	8,210
787	136	154	20,944	20%	4,189
			58,984		33,477

- Boeing and Airbus account for ~2/3 of aerospace material demand
- Bombardier and Embraer most of the rest

Source Airbus, Boeing & CM

Growth in Aircraft Production

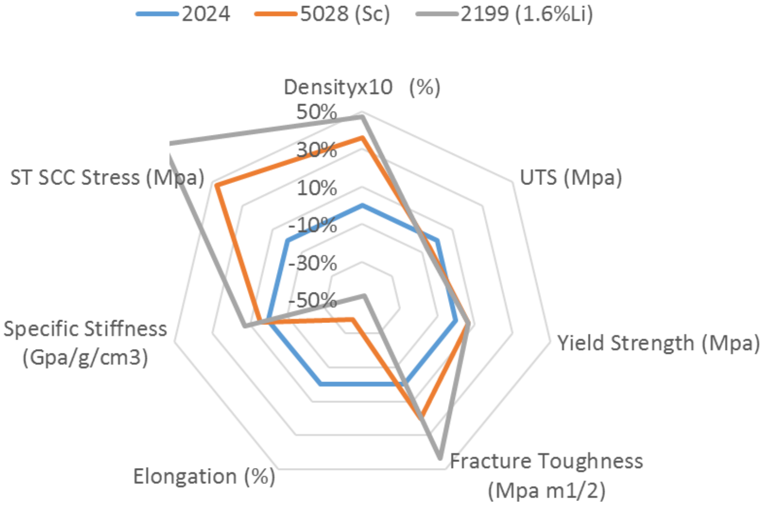
Boeing in grey Airbus in blue



- Solid growth expected to continue
- A good market for AlSc in terms of growth potential
- Competition with AlLi

Source: Airbus

Aleris 5028 alloy



Alloy	2024	5028 (Sc)	2199 (1.6%Li)
Density reduction (%)	0%	4%	5%
UTS (Mpa)	428	405	400
Yield Strength (Mpa)	324	345	345
Fracture Toughness (Mpa $m^{1/2}$)	37	44.4	53
Elongation (%)	21	13	10
Specific Stiffness (Gpa/g/cm^3)	26.6	27.7	30
SCC Stress (Mpa)	170	250	310
Density (kg/m3)	2770	2670	2640

- Designed as a “drop in” replacement for 2024 fuselage
- Properties lie between 2024 and Al-Li (2199)
- 5082(Sc) is stronger than 2199 but the specific strength is less due to the lower density of AlLi

Source Aleris & Arconic

Examples of potential aero take up

- Aleris 5xxx+Sc adopted by Airbus for A320
  - Fuselage mass ~2.4 tonne
  - 558 A320 built per year
  - Assume 0.1% Sc addition
  - 5% aero market growth

- 6.8 tonnes Sc needed for this application by 2023

- 2024 lower wing skins on A320s order of 12 tonnes Sc needed

Demand - Auto

- For general parts - no chance unless came in at <$100 /kg
- Questions over Sc in silicon alloys – so possibly not in auto sheet (6xxx alloys) or castings Al7%Si
- Security of supply and price stability also very important

D. Emadi et al. / Materials Science and Engineering A 527 (2010) 6123–6132

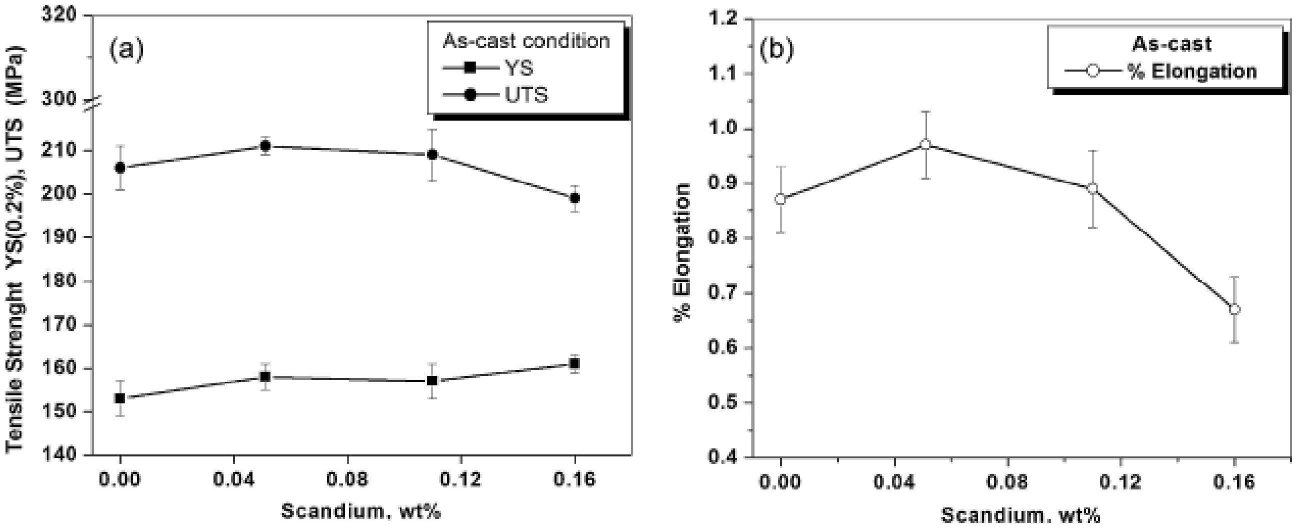


Fig. 8. Effect of Sc addition on the (a) tensile strength and (b) % elongation of A319 alloy in as-cast condition.

Heat Exchangers HEX

- Radiators, transmission oil coolers, condensers, evaporators etc.
- High thermal conductivity and good formability needed
- A growing market for aluminium ~2 Mtpa current

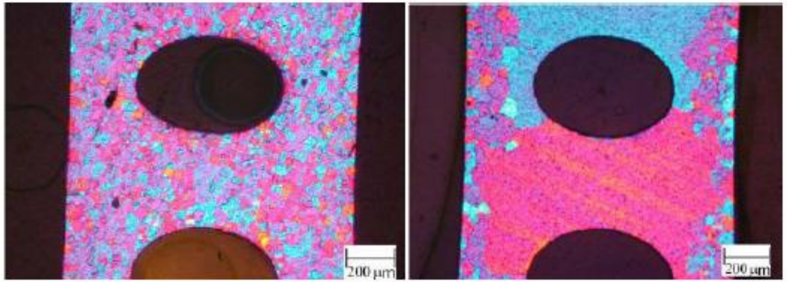



Source Hydro

Demand - HEX

- Heat exchangers a large volume possibility for Sc **(x10 of Aero potential)**
  - Move to CO_2 to replace R134a – higher temperatures pressures (13MPa vs 3 MPa) need double wall thickness. Strength loss due to Rx during brazing – Sc can prevent this
  - Sc allows to keep same geometry, can also use 1xxx alloy high thermal conductivity
  - Some previous and current work in this area
  - No competition from composites
  - 1.38 million tonnes of aluminium assemblies global in 2015
  - Current production around 2 million tpa
  - Impact of Evs-keep curb weight down to maximise range
  - Growth 8% p.a. expect 3 million tpa by 2028

- **Could amount to >1,000 tpa of Sc demand**



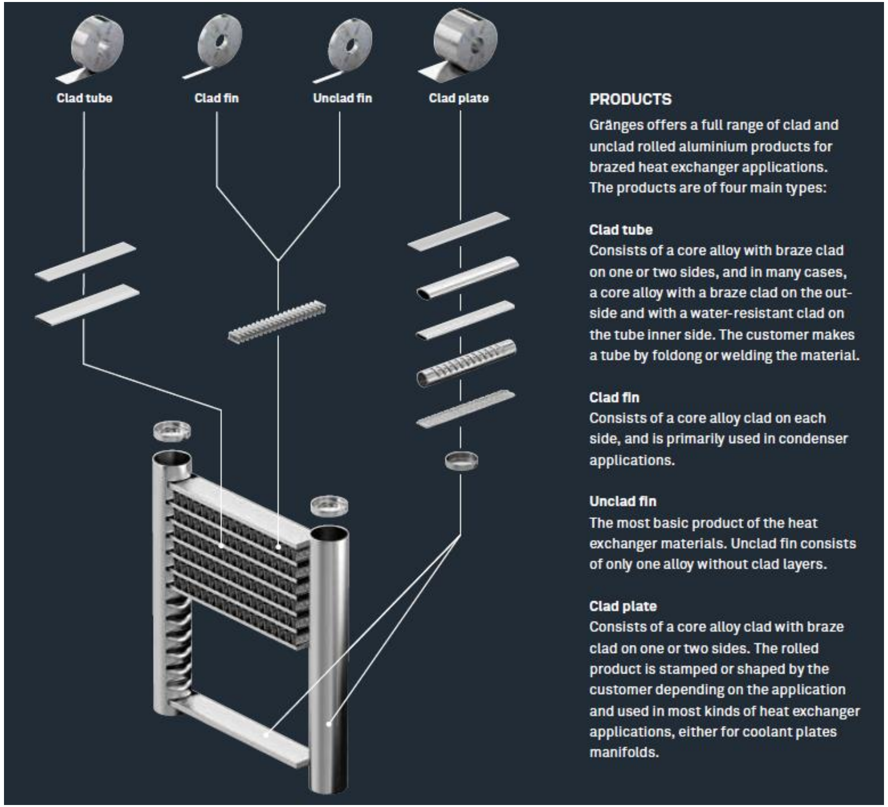
(a) (b)

Figure 2: AA 3102 aluminum multi-channel tubing with 4% reduction in thickness (a) Pre-braze [4] and (b) Post-braze [4].

Source CM

Aluminium Company HEX producers

- Alcoa, Hydro, Constellium, UACJ etc
- Gränges and Scandium International exploring aluminium scandium alloy opportunities in brazing sheet
- Hydro aware of this application for Sc but little activity to date
- Alcereco are also involved in Sc HEX material development.



Source CM

Aluminium industry attitude to Sc

- Typical old story
- “We did some R&D in AlSc years ago but found it was too expensive”
- Many not aware prices have dropped sunstantially
- “Optimizing existing alloys is easier”
- Some invested heavily in AlLi -- don’t want to switch to AlSc
- Some barely aware of scandium
- Others very active in Sc e.g. Rusal, Aleris, etc

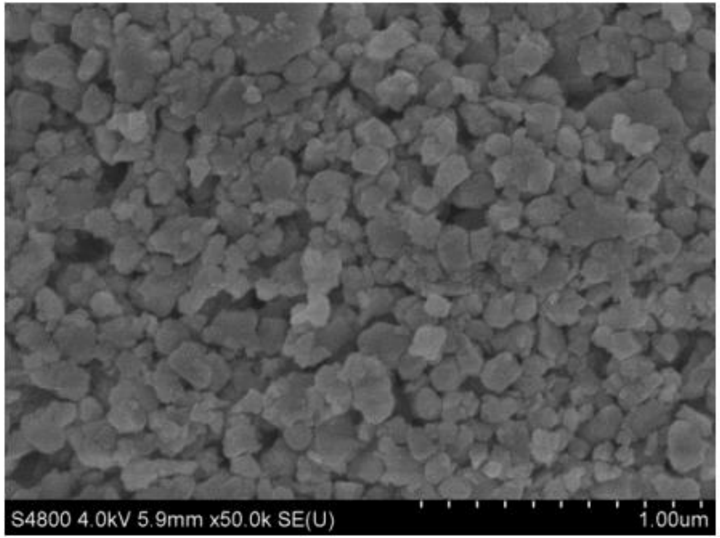
Source CM

Potential niches for aluminium scandium alloys

Application	Likelihood	Notes
Overhead power cable – high current market	low	Too expensive – would need to be at $200/kg
Rail	moderate	Some studies in the past
Marine	moderate	Improved welds, improved 5xxx+Sc alloys
Auto	Very low	Too expensive for auto – need $100/kg Sc
HEX	high	Big market with big potential due to market changes i.e. EVs and coolants
Welding rod	moderate	Small market
3Cs	moderate	Cameras, phones, computers
mobility	moderate	E-bikes, wheel chairs
3D printing WAAM	moderate	
others	moderate	Magnesium alloys, spectacles, cookware, body amour

Source CM

SOFC in China



- SOFC in China still at an early stage
- Jiangxi Size Materials Co., Ltd make Fuel Cell Electrolyte Powder
- CCTC produce SOFC electrolyte diaphragm plate
- SOFCMAN –by Ningbo Materials Institute of Technology and Engineering (NIMTE)
- Also makes Scandia-Stabilized Zirconia (SSZ)

Source CM

Scandia Supply

Historical Supply

- Zhovti Vody (Nova uranium, iron mine also known as Zhelty Vody)
- Nova mine was flooded and closed in 2002
- China (Bayan Obo deposit) – no longer active in Sc
- Crystal Mountain fluorite tailings in Montana – recently finished

Current Supply

- 12.5 tonne produced in 2017 in China mostly as by-product from TiO_2 pigment acid waste and some by-product from zirconia oxychloride liquor
- Remainder ~1 tpa from CIS in 2017
- In 2018
    - Rusal commissioned 3 tpa red mud plant in Russia
    - THPAL (Sumitomo) commissioned 7 tpa nickel laterite by-product plant in Philippines

Source CM

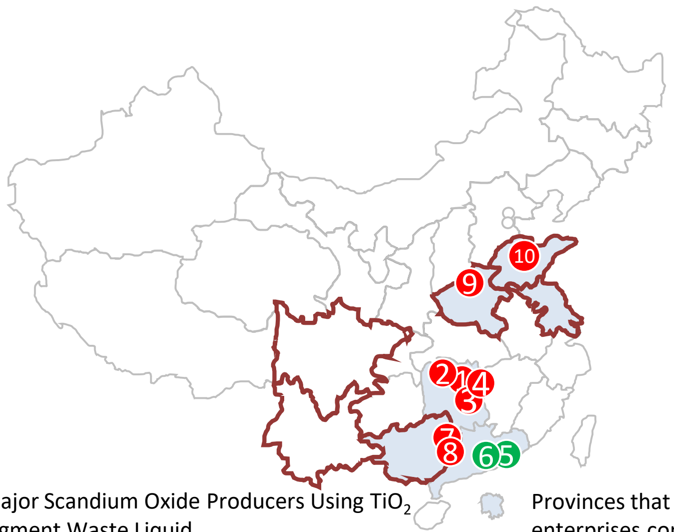
Chinese supply

- Mostly from TiO_2 pigment production acid waste
- Less than 10% of sulphate pigment producers have downstream scandium extraction
- Some from Zirconium oxychloride liquor
- Rapid growth in capacity to 60 tpa over the last three years
- Total production for 2017 was 12 tonne of scandia 20% utilisation
- Another 20 tpa capacity in the pipeline

Direct extraction method

Source CM

Production Status in China

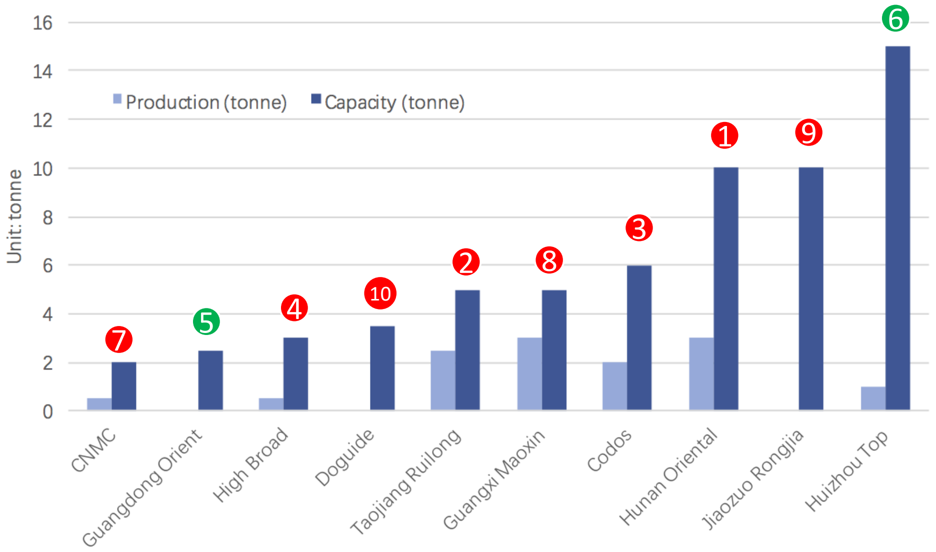


Major Scandium Oxide Producers Using TiO_2 Pigment Waste Liquid

Major Scandium Oxide Producers Using Zirconia Mother Liquid

Provinces that Scandium oxide enterprises concentrate

Provinces that TiO2 pigment enterprises concentrate



- Scandia enterprises are mainly concentrated in the TiO_2 pigment main production area, many manufacturers cooperate with raw material (acid waste) producers.
- Overcapacity is particularly serious in China. There are many reasons for manufacturers’ over-entry into the market, as in order to obtain plant land, and TiO_2 pigment plants to increase the industrial value of by-products.

Source CM

Proposed Australian supply

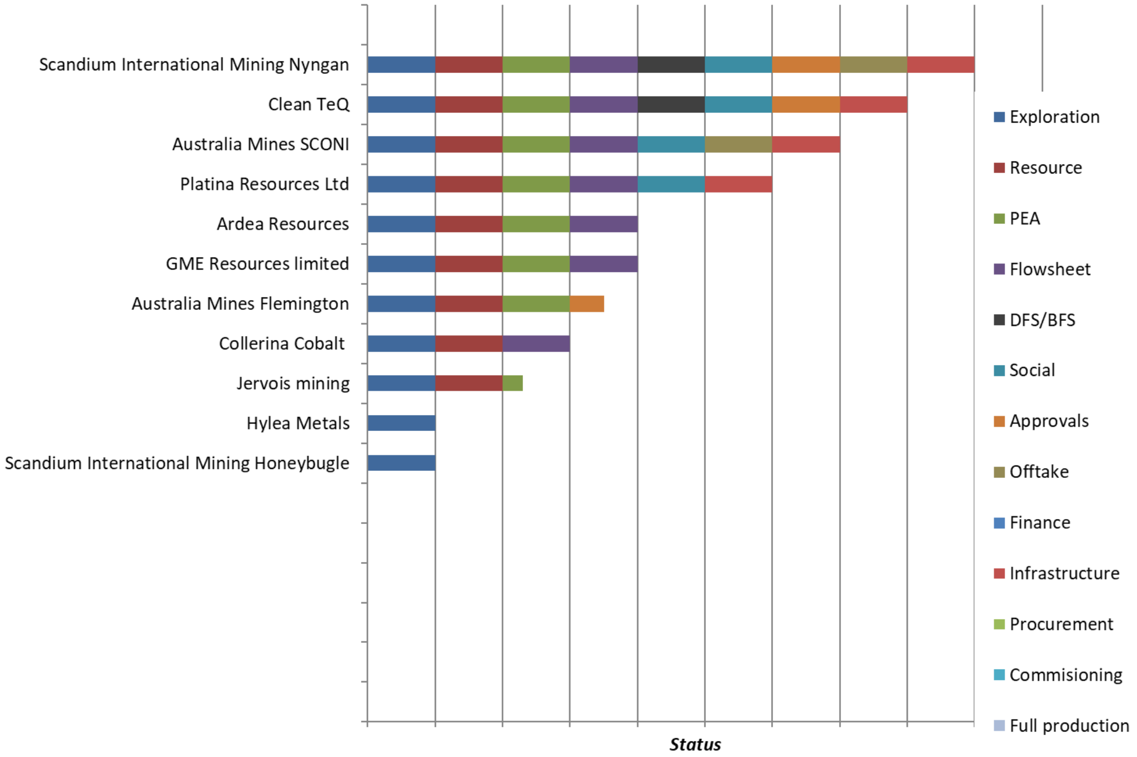
- Primary Sc high grade deposits (grades of 400-500ppm Sc)
  - Nyngan (Scandium International)
  - Owendale (Platina)

- By-product from nickel laterite mined for Ni and or cobalt
  - Sunrise -(Clean TeQ) (Ni-Co)
  - SCONI/Greenvale -(Australia Mines)
  - Goongarrie – (Ardea) (Ni-Co)
  - Tiger’s Creek – (Hylea) (Co-Ni-Pt)
  - Flemington- (Jervois Mining)

- High grades lead to operating costs potentially ~half that of existing Chinese producers

Source CM

Status of new Australian projects



- Many projects
- Different stages of development

Source CM

Other proposed supply

- REE/U by-product
  - Texas Rare Earth Resources - Round Top, Texas, USA
  - Pele Mountain Resources - Eco Ridge, Ontario, Canada
  - Galileo Resources - Glenover in South Africa.
  - Lakeside Mineral - Misery Lake, Quebec, Canada
  - Kumir Uranium Rare earth deposit in Gorny Altai
- Aluminium of Greece - Grecian red mud
- TiO_2 pigment acid waste by-product
  - SCALE in the EU - Tronox
  - Saraf Agencies - Ganjam district of the State of Odisha, India 2.4 tpa
- Nickel laterite
  - Expansion of THPAL to 14 tpa $3-$4 million capex
  - Meta Nikel Kobalt – Gördes, Turkey
- Niobium by-product
  - NioCorp – Elk Creek, Nebraska, USA
  - Imperial Mining – Crater Lake, Quebec, Canada

Source CM

Hardener supply: Players and Prices

- Hardener can be up to 20% Sc but is usually 2% (nominal)
- Process routes
  - Aluminothermic reaction between Sc_2O_3 and aluminium >850°C -- $Sc_2O_3 + 2Al = 2Sc + Al_2O_3$
  - Add to aluminium Hall Heroult electrolysis cells (Chinese work)
  - Scandium chloride reaction with aluminium (CSIRO patent)
  - Scandium fluoride – HF route (Russian work)
  - Scandium fluoride - sodium ammonium scandium fluoride route (META Nikel Kobalt)

- Prices highly variable: if scandia $1,000/kg -- Hardener(2%) at cost is ~$40/kg but prices up to $350/kg seen
- However, prices of hardener have followed price of scandia downward
- Current Chinese prices $40-$150/kg
- Poor quality AlSc less than nominal 2% as low as 1%Sc

- Players – Intermix-Met in Russia, KB Affillips, AMG, Chinese producers

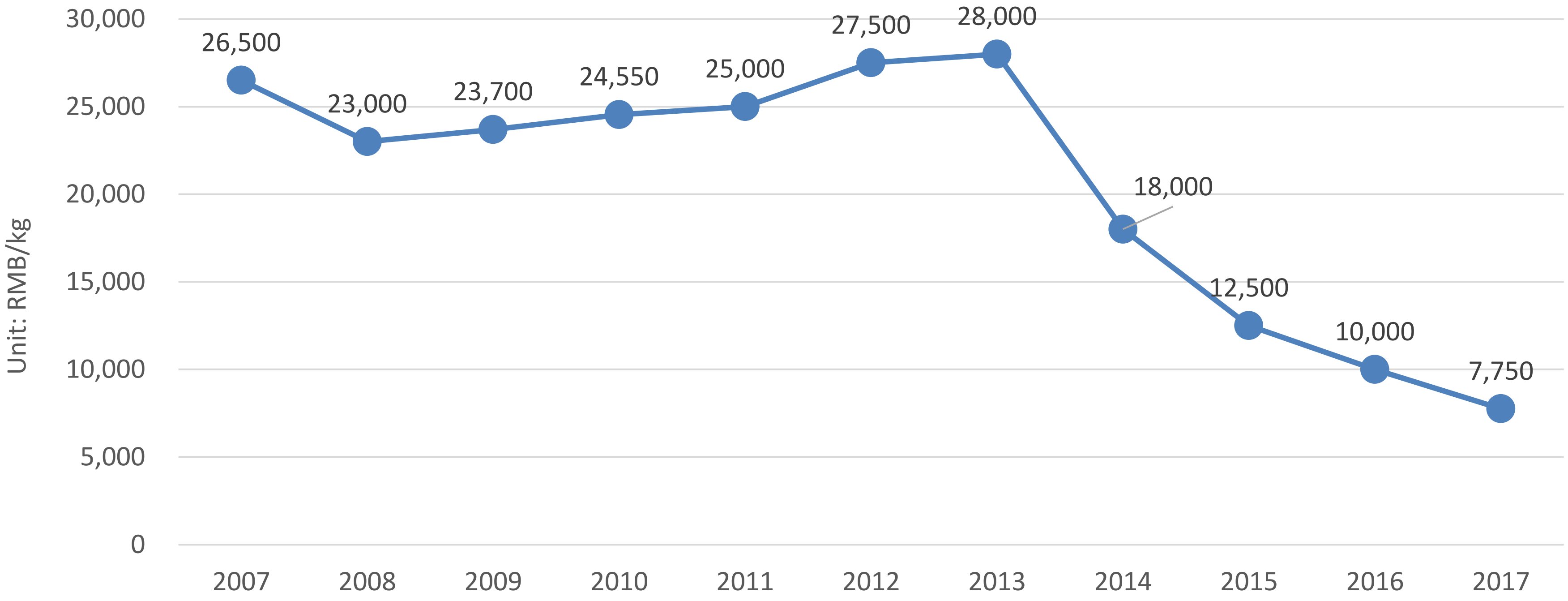
Source CM

Which scandium product?

- SOFC needs high purity scandia
- Scandium metal for special applications – high purity
- Aluminium industry needs scandium metal in aluminium
- If using oxide to make hardener 99.8% scandia is pure enough
- 2% Sc hardener common – higher Sc content would be preferred
- Produce a halide and master alloy at the mine site?
- AlMgSc hardener?

Source CM

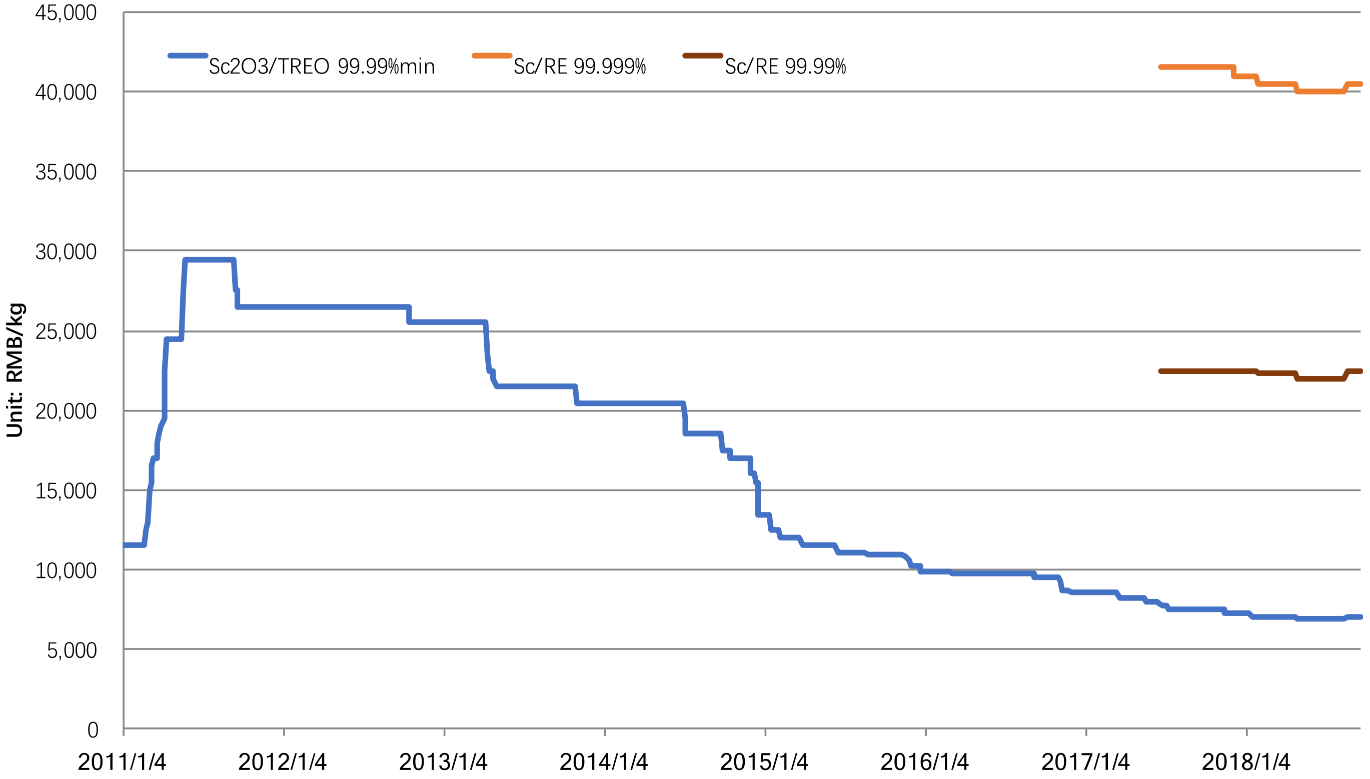
Chinese Scandia Prices 2007 to 2017



Chinese marginal producers almost at break even with current prices ~$US 1,100/kg

Source cre.net

Asia Metals Scandia prices

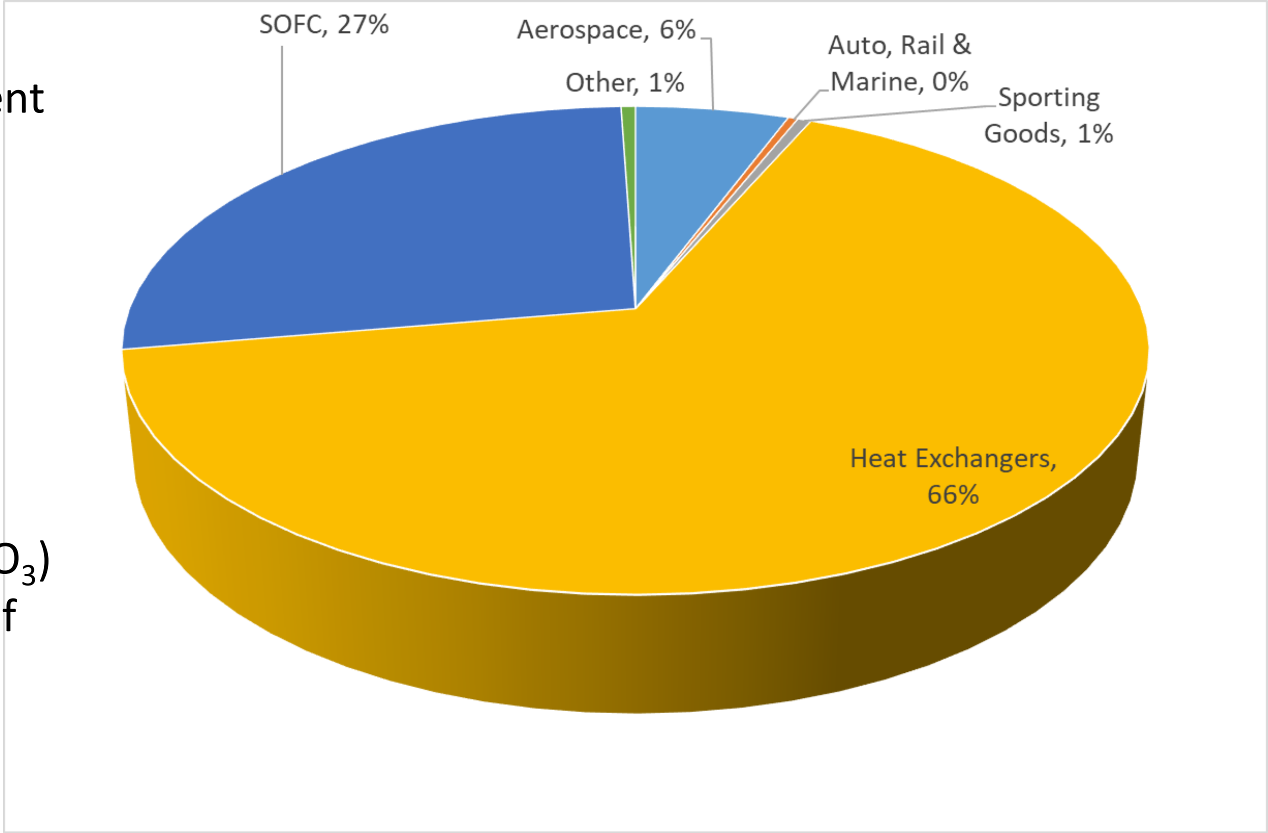


Scandium demand by 2028

Demand driven by HEX demand and to a lesser extent SOFC and AlSc aerospace demand

Potential for total global demand >500tpa by 2028

Expect HEX demand to be >>180tpa Sc (300 tpa as Sc_2O_3) by 2028 and make up 60% of the market



Where to now for Sc?

- Attitude of aluminium industry crucial
- A balanced price point needed for adoption of AlSc alloys and return on investment for new supply
- Market still well over capacity in the mid term (Chinese capacity to overhang)
- Market approaches balanced by 2028 but never undersupplied in the outlook period
- Higher cost Chinese producers to compete against new lower cost capacity in the mid-term

Source CM