



White Paper

SCANDIUM

A review of the element, its characteristics, and current and emerging commercial applications

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Element Description (Sc)

In 1879 a Swedish chemist Lars Fredrik Nilsson was looking for rare earth elements in the minerals euxenite and gadolinite when he discovered erbium and ytterbium; scandium was later separated from the ytterbium. While Mendeleev predicted an element (“ekaboron”) in scandium’s location on his periodic chart in the late 1860’s, Nilsson was credited with the actual discovery of scandium. At that time these minerals had only been found in Scandinavia, and the element was named after the region.

Scandium is a soft, silvery-white metallic element with an atomic number 21, and is technically a light transition metal. It does exhibit some characteristics that are similar to the rare-earth elements (lanthanides), and is often classified as a member of the REE group, along with yttrium. The smaller size of scandium’s ion allows it to react chemically with elements like aluminum, magnesium and zirconium. Scandium is not particularly rare---its occurrence in crustal rocks is around 22 ppm. This makes scandium generally more abundant than lead, mercury, and precious metals, and about the same as cobalt. Despite this fairly common, albeit dispersed occurrence, scandium rarely concentrates in nature. It does not selectively combine with the common ore-forming anions, so time and geologic forces only rarely form scandium concentrations over 100 ppm.

Scandium exists in nature in its oxide form, and tarnishes to pink or yellow. It is very difficult to reduce to its pure elemental state. In fact, it was not isolated in pure form until 1937 and the first pound of pure elemental scandium metal was not produced until 1960. Scandium in oxide form is referred to as scandia, or of course scandium oxide, and the chemical formula is Sc_2O_3 .

Geology

Scandium is widely dispersed in the lithosphere and forms solid solutions in over 100 minerals, most commonly as a trace constituent of ferromagnesian minerals.

- Concentrations in these minerals (amphibole-hornblende, pyroxene, and biotite) typically range from 5 to 100 parts per million equivalent Sc_2O_3 .
- These minerals commonly occur in igneous rocks, basalt and gabbro.

Enrichment of scandium also occurs in rare-earth minerals, wolframite, columbite, cassiterite, beryl, garnet, muscovite, and the aluminum phosphate minerals.

Table 1 - Minerals Containing Elemental Scandium

Bazzite	$Be_3(Sc,Al)_2Si_6O_{18}$
Cascandite	$Ca(Sc,Fe^{++})Si_3O_8(OH)$
Jervisite	$(Na,Ca,Fe^{++})(Sc,Mg,Fe^{++})Si_2O_6$
Juonniite	$CaMgSc(PO_4)_2(OH) \cdot 4(H_2O)$,
Kolbeckite	$ScPO_4 \cdot 2(H_2O)$
Magbasite	$KBa(Al,Sc)(Mg,Fe^{++})_6Si_6O_2OF_2$
Pretulite	$ScPO_4$
Scandiobabingtonite	$Ca_2(Fe^{++},Mn)ScSi_5O_{14}(OH)$
Thortveitite	$(Sc,Y)_2Si_2O_7$
Titanowodginite	$Mn^{++}(Ti,Ta,Sc)_2O_8$
Heftetjernite	$ScTaO_4$

The known, independent, scandium mineral deposits are generally insignificant in size and grade, with certain notable exceptions in some of the lateritic clay resources found in Australia. Sedimentary deposition can form large scandium resources, as can placer depositions, particularly if they contain euxenite, monazite or zircon. Scandium can be found in much higher concentrations in thortveitite, euxenite, and gadolinite. These minerals tend to be found in pegmatite formations, and are rare.

Most of today's scandium production tends to come as a byproduct of the leaching activity associated with production of other metals, minerals, or rare earths, specifically U, Th, Al, W, Sn, Ta, P and REE's. Some scandium production has also been generated from the scandium-yttrium silicate mineral, thortveitite. The principal Sc-producing countries today are China, Russia, Ukraine, and Kazakhstan.

In the US, the fluorite tailings from the Crystal Mountain deposit near Darby, MT., are known to contain thortveitite and associated scandium-enriched minerals. Smaller scandium resources are contained in tungsten, molybdenum, and titanium minerals from the Climax molybdenum deposit in Colorado. Other lower grade domestic resources are present in ores of aluminum, cobalt, iron, molybdenum, nickel, phosphate, tantalum, tin, titanium, zinc, and zirconium. Process residues from certain historic tungsten operations in the United States also contain significant amounts of scandium.

Foreign resources are known in Australia, China, Kazakhstan, Madagascar, Norway, Russia, and Ukraine. Resources in Australia are contained in nickel and cobalt resources in New South Wales. China's resources are in tin, tungsten, and iron deposits in Jiangxi, Guangxi, Guangdong, Fujian, and Zhejiang Provinces, and is currently produced at Bayan Obo, the REE deposit in Inner Mongolia. Resources in Russia and Kazakhstan are found in certain uranium-bearing deposits, and on the Kola Peninsula in apatites. In the Ukraine, scandium was previously recovered as a byproduct of iron ore processing at Zheltye Voda. Scandium in Madagascar and Norway is typically found in pegmatite formations containing thortveitite.

One other potentially significant scandium resource is the red mud tailings from the Bayer process, employed in bauxite processing into alumina. Red mud tailings typically contain 50-110 ppm Sc, but certain locations show concentrations of 150 ppm, depending on the ore type and precise process route. The processes that essentially double the original concentration of scandium (typically 30-50 ppm) also concentrate numerous other metals, specifically iron, aluminum and titanium, which are energy and process intensive to separate from scandium. Consequently, scandium recovery from these environmental legacy residues can be problematic, both as to environmental issues and cost.

General Scandium Applications

Principal uses for scandium are in solid oxide fuel cells (SOFC's), high-strength aluminum alloys, high-intensity metal halide lamps, electronics, and laser research.

- **Solid Oxide Fuel Cells (SOFC's)** – Scandia can substitute for yttria as a stabilizing agent for the solid electrolyte (typically zirconia) in the fuel cell. The substitution allows reactions to occur at lower temperatures, extending the life of the components and increasing the power density of the unit.
- **Metallurgy** - Scandium readily alloys with aluminum and modifies the grain structure of the combined metal, dramatically increasing strength without sacrificing corrosion resistance, while offering enhanced weldability---something typically lost in the alloying process of high performance aluminum alloys.
- **Ceramics** - The addition of about 20% scandium carbide to titanium carbide results in a doubling of the hardness of the mixed Ti-Sc carbide, to about 50 GPa, second only to diamonds in hardness.

- **Electronics** - Scandium is used in the preparation of the laser material $Gd_3Sc_2Ga_3O_{12}$, gadolinium scandium gallium garnet (GSGG). This garnet when doped with both Cr and Nd ions is said to be 3 1/2 times as efficient as the widely used Nd doped yttrium aluminum garnet laser. Ferrites and garnets containing scandium are used primarily in switches in computers. These magnetically controlled switches work by undulating light passing through the garnet and microwave equipment.
- **Lighting** – Scandium is used in mercury vapor high-intensity lights to create natural light. Scandium has a broad emission spectrum that generates a ‘daylight’ effect desirable for camera lighting, movie and television studio lights.
- **Phosphorus/Displays** - Scandium compounds have application as a host for phosphorus or as the activator ion in TV or computer monitors. Sc_2O_3 and $ScVO_4$ are typical host materials, while $ZnCdS_2$, activated with a mixture of silver and scandium, creates a red, luminescent phosphorus suitable for use in television displays. The current cost of scandium typically dictates the use of other materials in these applications.

One good ‘pointer’ for future scandium applications is the current usage of yttrium. Yttrium oxide (yttria) has a world supply/demand figure of about 11,000 tonnes and was again included on the critical metals list by the US DOE (2011). The US DOD put yttrium on its shortfall list in 2013, recommending stockpiling. Yttria is used as a dopant for other metals where extreme heat resistance is required, and its electrical conductivity makes it useful in SOFC’s and other applications. It is also a catalyst in chemical refining, and is used as a phosphor in energy-efficient lighting systems. Scandium has much better electrical conductivity than yttrium, is a superb heat-treating (and strengthening) dopant, and has known application in high performance lighting. While scandia is ~100 times the cost of yttria, scandia’s superior physical properties and attributes can outweigh the cost disadvantage in many applications. At this time, yttria has clear commercial acceptance over scandia in numerous applications because it is available in quantity (China supplies 90% globally).

Historic Production of Scandium

Scandium production was a small scale enterprise, from discovery of the element through the 1970’s. In the late 1950’s, the Kawecki Chemical Company in the US pursued scandium mineralization in phosphate bearing material associated with a variscite mine in Utah (Little Green Monster), but refining the material proved difficult. At about this same time, Russian metallurgists were also actively searching for and experimenting with scandium. Russian scandium production began in the Cold War, specifically at the Nova Mine, near the town of Zhovti Vody, in the Ukraine. The Nova mine was a deep (1,000 meters) underground polymetallic resource, primarily iron ore, but it also contained scandium, uranium and other radioactive minerals. The scandium resource was estimated to be 7.9 M tonnes grading 105 ppm scandium, and the mine was believed to be the only primary scandium mine in operation in the world. The Russians produced scandium oxide from this source, specifically applied to lightweight, high performance AlMgLi-Sc materials for their advanced MIG fighter jets. During this time, Russian know-how on scandium was tightly held as a proprietary military secret.

At the end of the Cold War, a US specialty metals company called Ashurst Technologies (‘Ashurst’) formed a JV with Eastern Ore Dressing Kombinat (VostGOK) and the I.N. Frantsevich Institute for Problems of Materials Science to control the Nova mine. Ashurst retained an effective 35% interest in the mine, along with an off-take agreement on all of the scandium products produced. Scandium was recovered and refined at VostGOK’s facilities, and a 2% Sc-Al master alloy was also produced for sale globally by Ashurst.

Ashurst became over-extended financially during 1996, either due to issues with the mine and its partners, or with other gold exploration ventures, which were also prominent in its market announcements. While 1996 was a success for Ashurst in a marketing sense regarding scandia, it was the last year the company issued an annual report. The Company sold about 2 tonnes of 2% master alloy during 1996, and a similar amount in the first 5 months of 1997, records were not filed after Q2 1997, and the company ceased trading thereafter.

Ashurst's growth plans underway at this time were also very interesting. The Company had secured rights to purchase an additional 20 tonnes of master alloy from a Russian source, with exclusive rights to market outside of Russia. The Company also committed to a capital program to substantially expand the capacity of the VostGOK master alloy facility from 60 tonnes p.a. to 650 tonnes p.a. It is estimated that Ashurst sold 10-20 tonnes of master alloy in total, over 18-24 months.

The Nova mine actually continued producing for approximately 5 more years, but a labor strike in 2002 closed the mine, and it became flooded with groundwater. In 2003, after attempts to reopen the facility, the mine was permanently closed, and due to environmental issues, it will likely never be reopened.

Stockpiles of scandium oxide and scandium master alloy remain in Russia, having been formed in the Cold War era. These stockpiles are rumored to be dwindling, but continue to be offered for sale in the market today. The Russian military also continues to purchase master alloy material from these stockpiles.

The Bayan Obo rare earth (Nb/REE/Fe) mine complex in Inner Mongolia, China represents the other significant source of scandium production today, although it is not known what the scandia production rate is from this deposit. The deposit is large (18 km x 4 km), and extremely complex, with deposition, mineralization, metamorphism and intrusions occurring over a suspected four different metallogenic periods. The deposit exhibits over 190 known mineral species, and can also produce both scandium and thorium. The various ore types at the deposit have different scandium contents, ranging from 40 ppm to 169 ppm. Higher scandium contents are observed in REE tailings, where grades can reach 250 ppm.

Current Scandium Production

Using government data to understand critical materials supply chains can be challenging. Data is often collected over different time intervals, and the data capture is not detailed enough to support a good view of the minor metals, REE and specialty metals markets.

- The USGS publishes a Minerals Commodity Summary on scandium, and it is of some value in determining true market volumes or prices. The most current USGS published price estimate for scandium oxide (2013) is US\$5,000/kg for 99.99% grade, with considerably lower pricing estimates for lesser purities. Small quantities generally command higher prices on the internet. Global trade volumes are defined as 'very small', less than 10,000 kg (10 tonnes).
- The US Department of Commerce (DOC) publishes imports and exports on a product basis, but the data is based on North American Industry Classification System codes. Rare earth mining does not have its own figures and is instead a subset of "all other metal ore mining."
- The International Trade Commission (ITC) provides international trade statistics, along with U.S. import and export statistics, but this database does not provide trade information specific to individual REEs and compounds (except for cerium).

Various independent authors quote global market scandia volumes of 2-10 tonnes per year. EMC believes the current (2014) market supply is at least 15 tonnes per year. This estimate is based on

discussions with potential customers, the level of metals trader activity and interest, and the fact that certain scandium consumers are believed to be sourcing their own scandium through small controlled recovery operations. This estimate doesn't consider scandium contained in master alloy currently being sold from Russian stockpiles.

Current Market Opportunities for Scandium

Two robust growth markets await a reliable and expanded supply of scandium. These are defined as markets that would be able to utilize 2-5 times their current consumption, if only the supply sources were there to offer scandium at prices that could be absorbed into the product. In each case, the end product is a game-changer, and the cost of the new material comes with performance offsets that pay for the higher expense. These two markets are:

1. **Solid Oxide Fuel Cells (SOFC's), and**
2. **Scandium-alloyed Aluminum alloys (Al-Sc alloys)**

Solid Oxide Fuel Cells-Explained

In general terms, a fuel cell is an electrochemical cell that converts a fuel source and an oxygen source into an electrical current, plus water, CO₂ and heat. It does this by promoting reactions between the fuel and oxidant (reactants), which are triggered by a very high temperature environment. SOFC's employ a hard ceramic material as the solid electrolyte, sandwiched between an anode and a cathode, used to separate the reactants. At temperatures of approximately 1,000 °C, two important changes occur in this system:

- The solid ceramic electrolyte becomes 'soft', selectively porous, and electrically conductive, and
- The reactant molecules in the system, kept separated by the solid electrolyte barrier, become highly 'excited'.

In this excited state, oxygen molecules pick up electrons. This causes them to take on a negative charge becoming ions. The oxygen ions are then selectively drawn through the solid conducting electrolyte separating them from the hydrogen fuel source. Once through the electrolyte barrier, the oxygen combines with hydrogen (or hydrocarbon) molecules, to form water (or CO₂) and heat. The extra electrons that enabled oxygen transport are thrown off in the combination with hydrogen. They are provided a direct return pathway to the cathode (+), generating a recurring flow of electrons which can be captured as electrical current. The reaction is exothermic, sustaining the proper high temperature reactive environment. The operation is continuous---as long as the reactants flow into the system, and the internal environment stays hot enough, the system generates current. There are no moving parts and no eroding parts, as exist in traditional batteries.

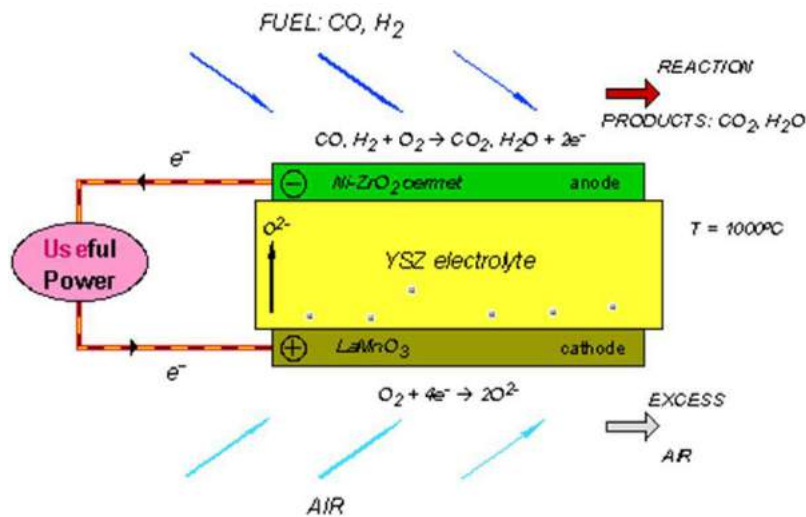
Fuel cells have been around for over a century, and were consistently employed by NASA as an electrical power supply source on spacecraft. There are a number of types of fuel cells, constructed with different architectures and different types of electrolytes, but the SOFC design is currently the clear leader. SOFC's have distinct advantages in energy efficiency, flexibility with various fuel sources, lower exotic metal content, and low pollution levels.

- **High Efficiency.** A SOFC running natural gas is approximately 60% efficient, which is about equal to the best of the combined cycle natural gas (CCGT) fired turbine generators used by public utilities. With heat recycle capability, SOFC efficiency can rise to over 85%. These efficiency levels represent

the best currently achievable—coal or gas-fired facilities without heat recycling systems are typically 35% efficient, and internal combustion engines in automobiles are 25-30% efficient (gasoline/diesel).

- **Low Emissions.** SOFC's when operated with a hydrocarbon fuel source do generate CO₂, but are much cleaner processors of fuels than combustion-based systems, and are considered low emission devices.
- **Localized Power.** SOFC's represent distributed power, which means they avoid both the transmission losses and most of the distribution infrastructure of traditional utility-provided electrical service. They can be placed where power is needed, subject to a fuel source. They initially generate DC power, so are particularly suited to sites with significant DC power needs, such as Data Centers.
- **Good Fuel Flexibility.** SOFC's are also the most fuel-flexible design because of their high operating temperature. High temperature allows SOFCs to reform fuels internally, which enables the use of a variety of fuels, and avoids the cost/complexity of adding a fuel reformer. SOFC's tolerate several orders of magnitude more sulfur than other cell types, and are not poisoned by carbon monoxide (CO), which can even be used as a fuel. This property allows SOFCs to use gases made from coal.

The principle of a SOFC is shown in the following figure:



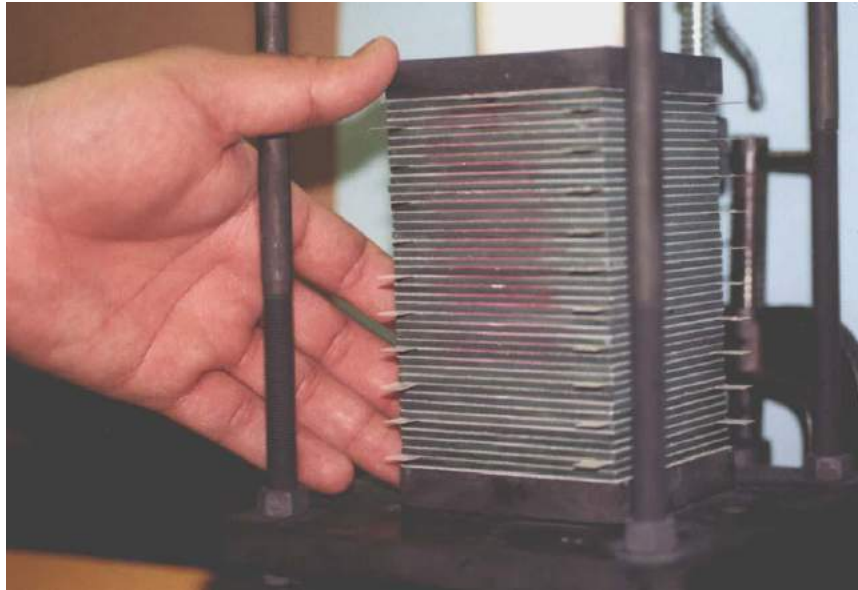
Solid Oxide Fuel Cell Chemistry

While high operating temperatures enable many of the differentiating benefits of SOFC's, they also tax the engineering and materials requirements needed for operation. Temperatures of 1,000°C create thermal fatigue in the system, rapidly oxidize metal components, and require expensive alloys and thermal shielding to retain heat and protect personnel. The solid electrolyte, typically zirconia, would never withstand this temperature without being stabilized with a metal. The stabilizing and conducting metal of choice for the electrolyte has traditionally been yttria (yttrium-stabilized zirconium, or 'YSZ'), and it is often used in the anode and cathode metal mixture as well.

Enter scandium. Scandia is a better choice as the stabilizing agent for the zirconia (ScSZ) in the solid electrolyte because it is a considerably better ionic electrical conductor than yttrium. More importantly, scandium allows the electrolyte to conduct at significantly lower temperatures (750-800°C) and in fact raises the power density of the unit at those lower temperatures. This temperature drop is very significant in that it reduces the cost of materials for thermal shielding (stainless steel, rather than exotic

alloys) and it substantially reduces the thermal stresses within the unit. High temperature, yttria-stabilized SOFC's (YSZ) typically exhibit a 2-3 year life, before requiring refurbishment/stack replacement. Scandia-stabilized SOFC's are expected to achieve +10 year commercial operating cycles—although none have been in operation that long to say for sure. The dramatic increase in service life, along with greater power outputs and savings in other exotic materials and manufacture costs makes the economics of today's leading edge SOFC's competitive with grid-supplied electrical power. Today's leading edge SOFC's contain scandium.

A SOFC 'stack' is shown below:



A 40 cell internally-manifolded SOFC stack (projected power level ~400 W)

There are over 100 companies working with, designing, or offering SOFC's today. However, the technical leader in commercial SOFC technology is Bloom Energy, a private company headquartered in Sunnyvale, California. Bloom Energy ("Bloom") makes Bloom Energy Servers in 100KW and 200KW sizes, which operate typically on natural gas, can be installed in a commercial parking lot or garden area, and will generate electricity for 9-10 cents/kwh (***Fuel Cell Maker Bloom Energy Opens The Kimono***, Business Week, February 25, 2010). These units are in service, available for customers to purchase or lease, and enjoy certain US State/Federal energy-related tax incentives that further improve their economics. Bloom's designs utilize scandium, and while scandia is currently 100 times the price of yttria, the overall operating parameter improvements are critical to the commercial competitiveness of the product. Bloom's website is an excellent place to go to learn more on commercially available SOFC's (www.BloomEnergy.com).

Aluminum-Scandium Alloys (Al-Sc)

In general, it is possible to modify and improve aluminum or titanium base materials by alloying them with scandium, typically by additions of up to 2% scandium (by weight). When scandium and aluminum metal are combined in a molten state, these two elements can be made to solidify in a number of different intermetallic phases, depending on the cooling temperature selected, and the Al-Sc ratio present. The most desirable of those phases (dispersoids) is as Al_3Sc , which holds scandium in

thermodynamic equilibrium with aluminum, and is the form that exhibits the most dramatic effects on the microstructure and properties of the resultant aluminum alloy material, which we will refer to as Al-Sc alloy. The key changes are:

- **Grain Refinement** – Scandium promotes (during so called heterogeneous nucleation) the formation of small, evenly shaped (equiaxed) grains in the alloy melt, which is a desirable characteristic. As a molten alloy metal mixture cools and solidifies, smaller evenly shaped grains are able to better fill the cavities created by the shrinking solidified metal. This creates increased strength by avoiding shrinkage porosity, and also reduces the tendency for hot cracking, which shows up in high temperature environments or as a result of welding. This grain refinement markedly improves both weldability and weld strength.
- **Superplasticity** – This characteristic is defined as a substance's ability to bend under stresses that would normally cause a fracture, and is typically achieved at half of the absolute melting point. Fine grained aluminum base material structure and stabilization of that grain boundary structure by the Al_3Sc dispersoids is believed to cause this trait, which is highly useful in a manufacturing context. This allows alloy material to be heated and formed under high stress into more complex shapes without creating a narrowing or pinching which would otherwise lead to early fracture.
- **Precipitation Hardening** – This is somewhat the opposite of the superplasticity characteristic, in that very fine and evenly distributed coherent Al_3Sc phases, can give significant hardness increases to the alloy. These phases can be precipitated from a so-called supersaturated Al-matrix by moderate heat treatments of 250-350° C. All high performance (aerospace) aluminum alloys which display a strength value higher than 300 MPa (43 ksi) rely on precipitation hardening. This characteristic is particularly useful because the addition of scandium to certain Al-alloys (like 5XXX Al-Mg), that are otherwise not heat treatable, makes them respond to this beneficial annealing technique. Compared to other alloying elements, scandium is the most efficient precipitation hardener for aluminum base materials.

Beyond these micro-structure changes that occur when scandium alloys with aluminum, there are two other important and very practical application characteristics that emerge:

- **Corrosion Resistance** - The addition of scandium to aluminum alloys makes them highly corrosion resistant. Aluminum resists corrosion by rapidly forming a thin oxidized layer which tends to halt further degradation, but salty environments can attack and destroy aluminum quickly. Typical aluminum alloying and hardening techniques tend to further reduce corrosion resistance. Scandium's dramatic positive effect on corrosion resistance, in concert with increasing strength, is highly unusual and useful.
- **Weldability** - Aluminum is weldable, as are many aluminum alloys, depending on their alloying components, and use of advanced welding technologies. With alloys however, the heat-affected zone at the weld site, particularly the frontier zone of the weld itself, tends to be weaker than the alloy base material---often by 50% or more. Some of this loss in strength can be regained by subsequent heat treatments, depending on the alloy specifics. Certain Al-Sc alloys weld with no appreciable loss in strength. This characteristic is extremely valuable, due to the flow-on effects of lower cost manufacturing options in designing and assembling aluminum alloy parts and structures.

There are several steps to the manufacture of Al-Sc alloys. First, the scandium oxide needs to be procured, which is the most significant problem today. The oxide grade is important but not critical: grades of 95% or better are suitable. Al-Sc master alloy typically has 2% Sc content, considerably above the first eutectic state, so most of the scandium is actually not fully dissolved in its inter-metallic form of

Al₃Sc, as it is in the final product. The 2% master alloy is then used to precisely dose larger batches of molten aluminum, along with other desired alloying metals, to produce various aluminum alloys. Master alloy producers are typically smaller specialist companies who market a variety of master alloy products to the major aluminum smelters.

The science of advanced aluminum alloy manufacture is highly technical, and beyond the limits of this discussion. However, a couple more points are important to register, in terms of scandium's potential to deliver a new, valued, high performance aluminum alloy to market:

- **A little bit of scandium makes a big difference.** It doesn't take much scandium mixed with aluminum to generate significant material improvements; as little as 0.10 - 0.15 wt-% Sc has dramatic effects, but more scandium tends to generate additional benefits, depending on the alloy processing route selected.
- **Higher scandium contents deliver more benefits.** Scandium's natural solubility in aluminum is about 0.4% (known as the first eutectic state), but the introduction of other alloy materials in combination with scandium, along with rapid-solidification techniques (like melt-spinning, powder atomization, and permanent mold casting technologies), can hold considerably higher concentrations of scandium properly in solid solution, enabling additional precipitation hardening by nano-sized Al₃Sc dispersoids.
- **The technology of raising scandium content in alloys is advancing.** The achievable amount of scandium in solid solution depends directly on the rapid solidification technology: the faster the solidification can be made to happen, the more scandium is taken up in the aluminum crystal lattice structure. As a general rule, 0.1 wt-% of Sc will provide about 50 MPa (8.5 ksi) of strength gain. Therefore 1.0 wt-% Sc can generate an additional 500 MPa (72.5 ksi) of tensile strength, and theoretically 2.0 wt-% could deliver an incredible 1,000 MPa (145 ksi) improvement. This strength level for an aluminum alloy would match that of a very high strength steel!
- **Al-Sc alloys also exhibit much higher heat working tolerances.** Scandium raises the working heat range (due to micro structure stability) of aluminum by a factor of two, suggesting Al-Sc alloys could be employed in temperature environments of 350 -400°C, which is appreciably higher than possible with other aluminum alloys.

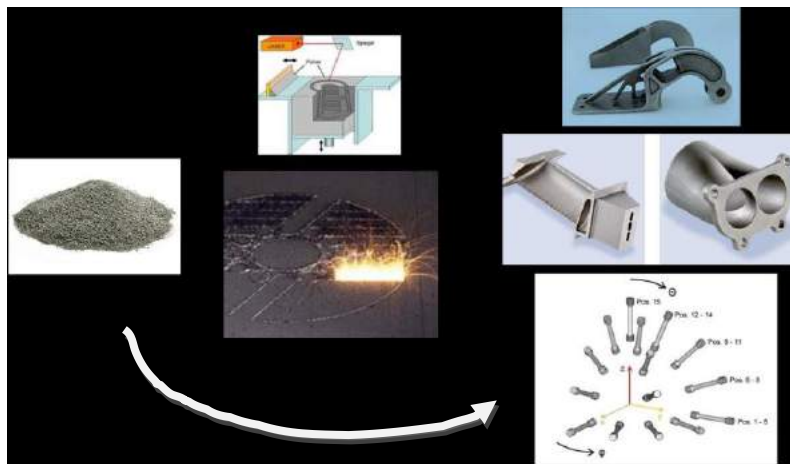
Ultimately it is these strength improvements that engineers are seeking with the addition of scandium to aluminum alloys. Certain alloys show major strength improvement with solution heat treatment or other forms of hot or cold rolling, while others are not treatable in this manner. It is interesting to note that scandium's strengthening improvement tends to be much larger (percentage-speaking) in the non-heat treatable alloys. Alloys that respond to strengthening procedures do also show further improvement by scandium additions, but those improvements are somewhat less dramatic.

The four strongest aluminum alloy families today are the 2XXX, 5XXX, 7XXX, and Al-Li configurations, with the 2XXX and 7XXX families used today in commercial aircraft structural components, and the AlCu,Mg-Li type reserved more for military, aerospace and extreme duty applications. The 5XXX group is used in auto and marine products, and is has been certified for certain aircraft applications.

- The 2XXX alloy group is heat-treatable and is mainly alloyed with Cu & Mg. This is a medium strength alloy, with good toughness and a tensile strength ranging from 350 – 500 MPa.
- The 7XXX alloy group is also heat treatable and is mainly alloyed with Zn, Mg & Cu. This is a very high strength alloy with tensile strength up to 700 MPa, but lower toughness (notch strength). Extruded profiles can reach or exceed 800 Mpa.
- Both the 2XXX and 7XXX alloy groups are prone to corrosion and have densities ~2.8 g/cm³ or higher.

- The 5XXX alloy group is not heat treatable, and is mainly alloyed with Mg. This is generally a lower strength alloy, showing a tensile strength of 120 Mpa. Here, the addition of scandium to the alloy mix enables a strong strength push, making the material stronger than the 2XXX alloy, while retaining good corrosion resistance, and showing a lower density of about 2.65 g/cm.
- The Al-Li group does show improvement with scandium additions but they are not particularly significant.

Principal research work has been conducted worldwide on aluminum alloys over the last 3 decades, at various laboratory and research institute levels. At the industry level, the EADS Group (Airbus Industries, Eurocopter, ASTRIUM, etc.) in particular is pushing the boundary for Al-Sc alloys, developing new alloy applications for future air transportation requirements and challenges. EADS has patents utilizing rapid-solidification methods (melt-spinning or selective laser melting), that can hold scandium in an alloy in concentrations that exceed 1.0 wt-% Sc. Their Scalmalloy® material concept enables different products (“profiles”) with up to 1.4% scandium content (plus Al-Mg-Zr). These are really ultra-high performance 5XXX alloys, currently achieving tensile strength scores as high as 700 Mpa. Because of the weldability factor, ScalmalloyRP® is also suitable for use in state-of-the-art additive layer manufacturing (ALM) systems. ALM is a new manufacturing technique which generates, or “prints” a 3-D digital CAD model shape, layer by layer, directly into a fully built-up metallic part. This metal application technique offers the ability to produce precise and complex metal shapes with absolute minimum material losses, efficiently minimizing completed part costs with relatively high cost materials.



Direct digital manufacturing or additive layer manufacturing by laser melting of powder

These material technology efforts demonstrate dramatic improvements in strength and quality for future applications for scandium-modified aluminum alloys. The combined strength increases, corrosion resistance, and weldability, plus a unique fit to additive layer manufacturing (ALM) procedures have the potential to change the way many products and parts that are made from aluminum are designed and assembled. The flow-on manufacturing cost implications, the weight savings potential, and the longevity implications all feed back into the choice of the material for the application. The aluminum alloy industry is ready and waiting for substantial, reliable, and reasonably priced sources of scandium to be available in the market.

Market Pricing

There is no organized buy/sell market for scandium today. Scandium oxide (and metal) is not traded on a metals exchange, and there are no terminal or futures markets where buyers and sellers can fix an official price. Scandium product sells between private parties at undisclosed prices. Quotes for oxide product are influenced by product quality, volumes, availability, source, and of course demand. There are a number of internet-based traders offering scandium material for sale, but amounts on offer are generally small. The HEFA Rare Earth website is one of those sources that appears directly connected to a producer, Baotou HEFA Rare Earth, located in Baotou, China, sourcing products from the Bayan Obo mine in Inner Mongolia, China.

Scandium oxide prices are also influenced by quality, with 99.9% or higher grades representing the top quality, required for electrical applications, but not for alloy applications. The nature of the contaminants also matters---some are more problematic than others in specific applications. Radioactive elements, or metals that interfere with electrical applications in the case of SOFC's, are particular problems. Quality discounts have greatly diminished lately, due to the current tight supply for any grade of oxide product, and the scarcity of the highest grade material.

Pure scandium metal is sometimes also available, but it is extremely scarce and expensive.

The 2014 USGS published price for scandium oxide (for 2013) is \$5,000/kg, at 99.99% grade, slightly higher than for this grade in 2012. The price for 99.9% scandia in 2011 and 2012 was \$3,700/kg, with no price published for this grade for 2013. The USGS published price now more accurately reflects actual trader offered prices, than pricing quoted prior to 2011. Availability is often an issue at any price, and quantities are small---from grams to 10 kg amounts. Large quantity (tonnes) pricing is not available, and no long term sales contracts are known to exist.

The 2014 USGS published price for aluminum-scandium master alloy (2% scandium) in 2013 is \$170/kg, somewhat lower than the \$220/kg price figure published for 2012.

Any significant user of scandium today would be required to produce product themselves, or contract for product to be produced from controlled stockpiles or industrial waste stream sources. Large volumes of scandia consumption are technically feasible in the future, with evident demand in several divergent markets and applications. That said, current quoted prices for scandia from the USGS or other sources remain much too high to enable widespread commercial adoption of scandium, in metals/alloy applications in particular. In order to see the various markets commit to larger scale scandia consumption, customers will look to see reliable supply sources, multiple supply sources, and cheaper scandia product than is available in today's marketplace.