Monday, August 17, 2020

HALLGARTEN & COMPANY

Sector Review

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Hafnium Review

Awaiting the Nuclear Renaissance

The Hafnium Wannabes

	Strategy	Ticker	Market Cap	Project	Country
Developers					
Australian Strategic Materials	Hold	ASM.ax	AUD$128mn	Dubbo	Australia
Leading Edge	Hold	LEM.v	CAD$21.9mn	Norra Karr	Sweden
Search Minerals	Avoid	SMY.v	CAD$9.3mn	Foxtrot	Canada
Texas Mineral Resources	Avoid	TMRC	US$123mn	Round Top	USA

Hafnium Review

Awaiting the Nuclear Renaissance

- + Hafnium (Hf) has become a metal that is discussed more often, principally as a by-product credit by developers of Rare Earth deposits where it appears as an accessory mineral
- + Hf is joined at the hip with Zirconium and there is little prospect of developing one without the other, fortunately there is good demand for Zr at current times
- + The burgeoning construction of nuclear power stations in China promises stronger demand for Hf from its uses in such facilities
- + The production of HF is currently dominated by the US and France, with China having limited influence (thus far)
- ✘ The Hafnium price has been bouncing along the bottom for years with little sign of recuperation on the horizon
- ✘ Two projects that have cited Hafnium resources, DZP and Silver Fox, are burdened by massive capex (the former) and little prospect of getting to production (the latter)
- ✘ Financing of projects remains very difficult and almost inevitably requires a committed offtaker

The Highest of High Tech Usages

The metal we shall look at here is obscure even compared to others we have covered in recent times. There are no primary mines and its uses are either in super-alloys or nuclear plants. It has no public pricing mechanism (i.e. traded in a market) and the USGS does not even dare to venture which countries the production comes from and how much that production might be. This puts Hafnium in the "more obscure than Scandium" category, which is a dark place indeed.

Rather bizarrely Hafnium takes its name for the Latin name of Copenhagen, which considering that the ancient Romans never got as far as Denmark gives it one of the strangest etymologies in the Periodic Table.

The rationale for visiting the metal though is not mere information but that Hafnium promises to be more on the radar in the future because it makes up a small part of volumes from the Dubbo Zirconia Project (DZP) of Australian Strategic Materials. In the absence of any other apparent producers of size, that might make the DZP the heavyweight in the Hafnium space going forward.

What is it?

Hafnium is a chemical element with symbol Hf and atomic number 72. In appearance it is a lustrous, silvery gray, metal. Hafnium is estimated to make up about 5.8 ppm of the Earth's upper crust by mass.

Zirconium and hafnium are both refractory lithophile elements that have nearly identical charge, ionic radii, and ionic potentials. As a result, their geochemical behavior is generally similar. Hafnium is found in zirconium minerals, hence the presence together at projects such as Australian Strategic Materials' Dubbo Zirconia Project (DZP). The notable physical difference between these metals is their density, with zirconium having about one-half the density of hafnium. The metal has one of the highest melting point alloys known to man.

The most notable nuclear properties of Hafnium are its high thermal neutron-capture cross-section and that the nuclei of several different hafnium isotopes readily absorb two or more neutrons apiece. In contrast with this, zirconium is practically transparent to thermal neutrons, and it is commonly used for the metal components of nuclear reactors – especially the claddings of their nuclear fuel rods.

Hafnium reacts in air to form a protective film that inhibits further corrosion. The metal is not readily attacked by acids but can be oxidized with halogens or it can be burnt in air.

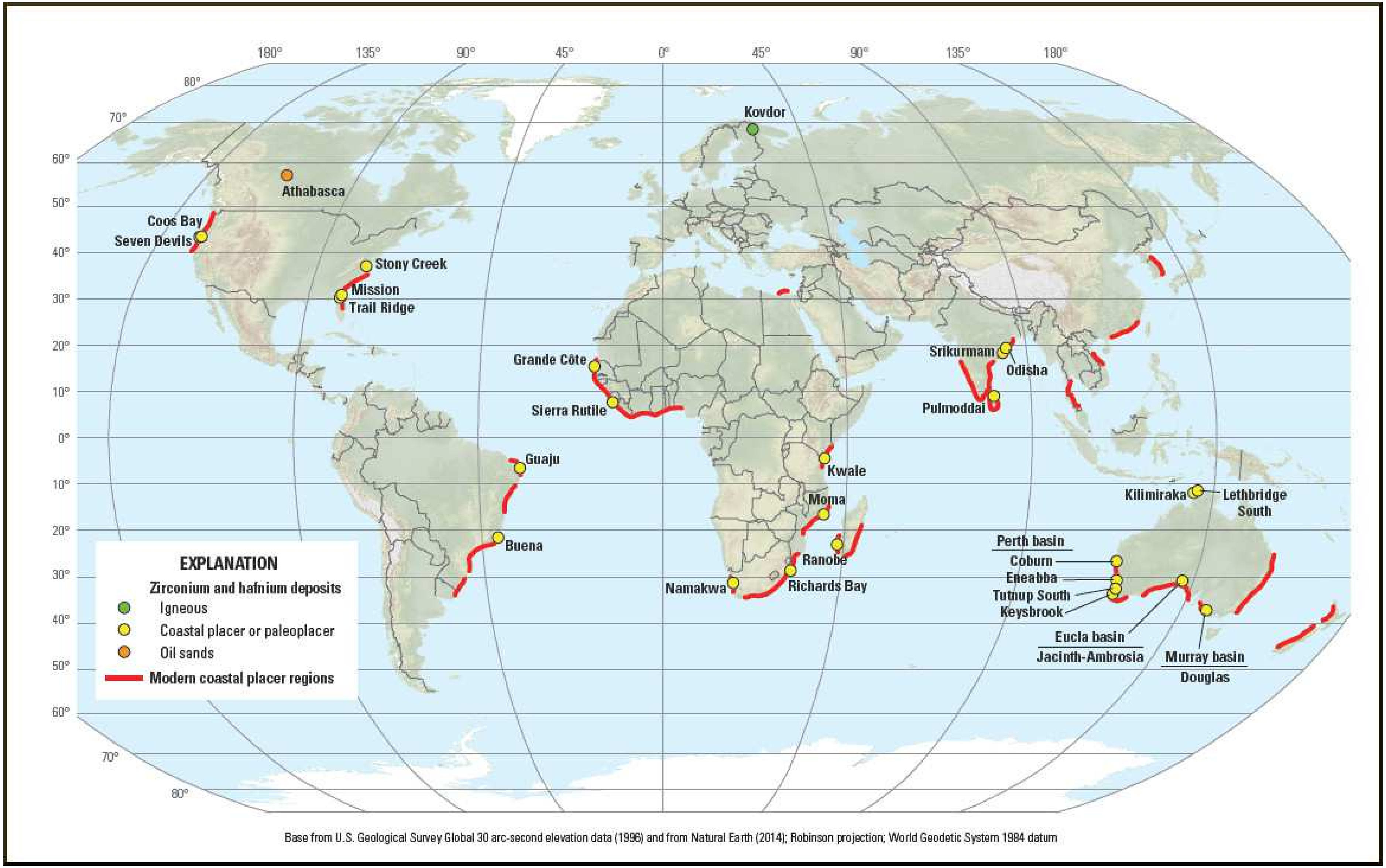
Uses

The most high profile usage is in the nuclear industry as Hafnium's large neutron capture cross-section makes it a good material for neutron absorption in control rods in nuclear power plants.

Hafnium is also used in filaments and electrodes. Some superalloys used for special applications contain hafnium in combination with niobium, titanium, or tungsten. It is also used in alloys with iron, titanium, niobium, tantalum, and other metals. Small additions of hafnium increase the adherence of protective oxide scales on nickel-based alloys and improve the corrosion resistance. An alloy used for liquid rocket thruster nozzles, for example the main engine of the Apollo Lunar Modules in the 1960s, was composed of 89% niobium, 10% hafnium and 1% titanium.

More than 80% of Hafnium is used for superalloys, plasma cutting equipment and nuclear control rods, with aerospace and gas turbine technologies forecast to substantially increase demand. Hafnium metal is presently valued at around $800 per kg with a total market approaching 100 tonnes per year.

Zirconium is a good nuclear fuel-rod cladding metal, with the desirable properties of a very low neutron capture cross-section and good chemical stability at high temperatures. However, because of hafnium's neutron-absorbing properties, hafnium impurities in zirconium would cause it to be far less useful for nuclear-reactor applications. Thus, a nearly complete separation of zirconium and hafnium is necessary for their use in nuclear power. The production of hafnium-free zirconium is the main source for hafnium.



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Moma
Ranobe
Namakwa
Richards Bay
Srikurmam
Odisha
Pulmoddai
Kilimiraka
Lethbridge South
Perth basin
Coburn
Eneabba
Tutnup South
Keysbrook
Eucla basin
Jacinth-Ambrosia
Murray basin
Douglas
EXPLANATION
Zirconium and hafnium deposits
Igneous
Coastal placer or paleoplacer
Oil sands
Modern coastal placer regions
Base from U.S. Geological Survey Global 30 arc-second elevation data (1996) and from Natural Earth (2014); Robinson projection; World Geodetic System 1984 datum

Sources

Zirconium and hafnium ore minerals are all primarily formed by crystallization from magma.

A major source of zircon (and hence hafnium) ores is heavy mineral sands ore deposits (mainly Australia and South Africa), pegmatites (particularly in Brazil and Malawi) and carbonatite intrusions (the Kola peninsula in Russia). The behaviors of zirconium and hafnium in the environment are very similar to one another in that most zirconium- and hafnium-bearing minerals have limited solubility and reactivity.

The main ore mineral for both elements is zircon ($ZrSiO_4$), which typically has a zirconium to hafnium (Zr:Hf) ratio of 50:1. Baddeleyite (ZrO_2) is a less common but commercially important mineral that contains both zirconium and hafnium, but in a ratio of approximately 73:1. The heavy mineral sands ore deposits of the titanium ores, ilmenite and rutile, yield most of the mined zirconium, and therefore also most of the hafnium.

The most likely new source of Hafnium is trachyte tuffs containing rare zircon-hafnium silicates eudialyte or armstrongite, as at the DZP.

Hafnium reserves have been infamously estimated to last under 10 years by one source if the world population increases and demand grows. In reality, since hafnium occurs with zirconium, hafnium can always be a byproduct of zirconium extraction to the extent that the low demand requires.

Processing

The chemical properties of hafnium and zirconium are nearly identical, which makes the two difficult to separate. After zirconium was chosen as material for nuclear reactor programs in the 1940s, a separation method was developed. These liquid-liquid extraction processes with a wide variety of solvents are still used for the production of hafnium. About half of all hafnium metal manufactured is produced as a by-product of zirconium refining. The end product of the separation is hafnium(IV) chloride.

There are several processes for the extraction of Zirconium and hafnium metals. The Kroll process involves reduction of zirconium oxychloride by magnesium metal in an inert atmosphere. The resulting metal contains a mixture of zirconium and up to 2% hafnium and is used for non-nuclear applications in corrosive environments and in specialty alloys. The van Arkel-de Boer/crystal bar process (e.g. gaseous diffusion of tetraiodide on W bar). This process was the first industrial process for the commercial production of pure ductile metallic zirconium. It is used in the production of small quantities of ultra-pure titanium and zirconium. It primarily involves the formation of the metal iodides and their subsequent decomposition to yield pure metal. This process was superseded commercially by the Kroll process. Having said that, many Hf metal producers, such as Allegheny Technologies, Framatome, TVEL, and the Chinese, still use the van Arkel-de Boer method.

Nanoscale Powders, for instance, has successfully made Hf metal via Na reduction of $HfCl_4$.

For nuclear-grade applications, the metals must be separated because of their different neutron absorption characteristics.

Demand

Currently, the United States of America and France are the major hafnium producing countries with a combined share of more than 85% of the global production. This can be explained by the increasing demand from applications such as aerospace and submarines as global security threats have intensified. Hafnium is essential for aerospace applications, such as space rocket engines and heat-resistant hafnium-niobium alloys.

Following strong growth in the global commercial aerospace industry during 2018, the industry has since declined due to production issues in particular aircraft models. However, the industry is expected to recover moving forward as long-term demand for commercial aerospace vehicles remains optimistic with approximately 40,000 vehicles to be produced over the next 20 years. However, some of these predictions may have been too optimistic in light of the economic damage caused by the current virus crisis.

Hafnium at the DZP

While the original pitch of ASM (or Alkane as it then was) was the Zirconia potential of Dubbo, the Rare Earth boom then brought to the fore the added “juice” of REE revenue streams. Then other metals started being encountered in commercial grades and we styled it as the deposit that had “something for everyone”.

When we did that we did not expect the massively obscure (even by REE standards) metal Hafnium to go from a twinkle in the eye to a potential major revenue contributor. The company, encouraged by significant market interest, began work on a process pathway to recover hafnium as an additional product for the DZP.

Resource estimates were produced that included the Hafnium element of the deposit.

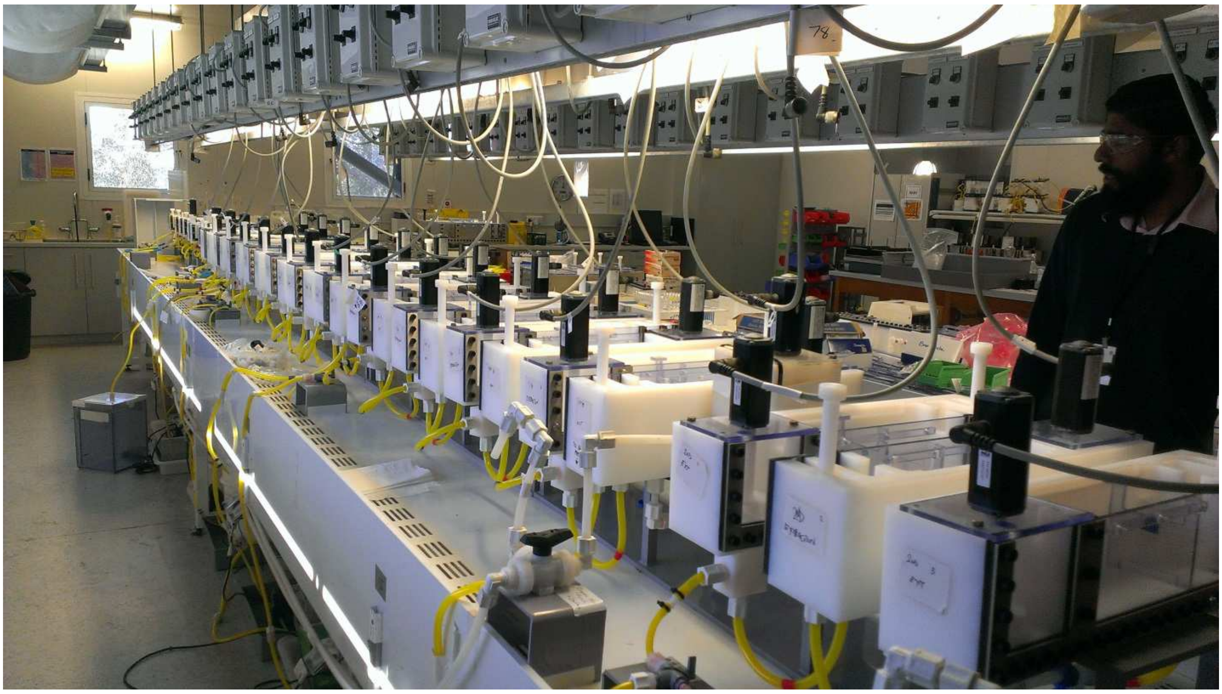
Dubbo Project – Mineral Resources

Resource Category	Tonnes (Mt)	ZrO_2 (%)	HfO_2 (%)	Nb_2O_5 (%)	Ta_2O_5 (%)	Y_2O_3 (%)	TREO* (%)
Measured	42.81	1.89	0.04	0.45	0.03	0.14	0.74
Inferred	32.37	1.90	0.04	0.44	0.03	0.14	0.74
Total	75.18	1.89	0.04	0.44	0.03	0.14	0.74

*TREO% is the sum of all rare earth oxides excluding ZrO_2, HfO_2, Nb_2O_5, Ta_2O_5, Y_2O_3

The company then went ahead with separation work to piloting level by the ANSTO labs in Sydney. In 2015, ASM developed a process pathway to recover hafnium (which always occurs with zirconium in nature) from the zirconium circuit, working with ANSTO to produce hafnium products via the DPP.

Previously, the flow sheet incorporated recovery of zirconium, niobium and rare earth products only. The inclusion of a hafnium circuit has had little impact on the overall flow sheet; however, the removal of hafnium (along with other impurities) from the zirconium stream has resulted in higher-purity zirconium products with potential for higher revenues from this product stream. .



The improvement consisted of the addition of a scrub circuit into the zirconium solvent extraction process, to remove the Hafnium for subsequent refining to produce a saleable hafnium product. This addition was made by the company's team outside of the FEED scope after further research with ANSTO.

The Process

Dubbo is somewhat of a test-case for all REE-focussed deposits who wish to also harvest their REE component. Therefore it is worth belabouring the point on the process required.

ASM's extraction process begins with dry ground ore being mixed with concentrated sulphuric acid and roasted to form sulphated solids.

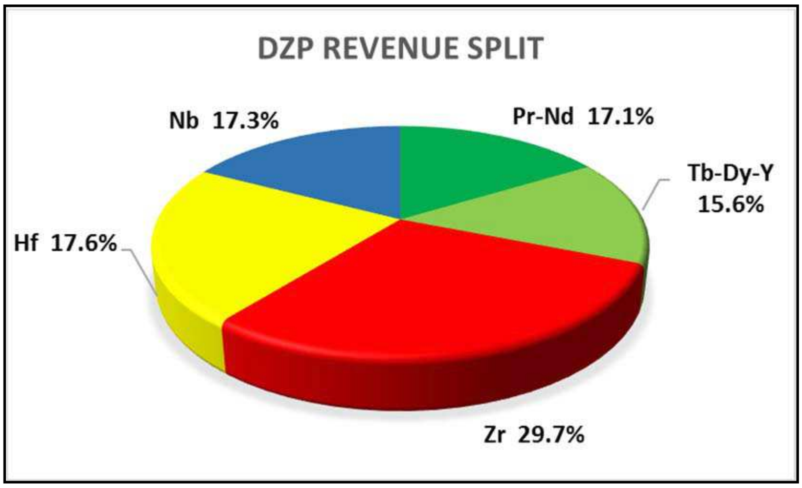
These solids are cooled and mixed with chilled water in a leach tank, where the sulphate species formed during the sulphation process (including zirconium, hafnium, niobium and rare earths, along with impurities of iron, aluminium and zinc) are leached into solution.

After a nominal time of leaching, the leach slurry is passed through the counter current decantation (CCD) circuit to wash and separate the solids into two liquors: one that comprises the majority of the

Light REEs, and a second bearing zirconium/hafnium/niobium/Heavy REEs.

The LREE liquor passes directly from the CCD circuit to the LREE recovery circuit. The remaining liquor passes through several stages of a solvent extraction (SX) circuit, which separates the other metals in solution (zirconium/hafnium, niobium and HREEs):

- Zirconium/hafnium (combined) is recovered from the loaded strip liquor in the first SX stage
- The raffinate from the first SX cycle is heated to recover a crude niobium-tantalum precipitate, which is then further refined to produce the final niobium product
- Following niobium recovery, the main process liquor stream is cooled and contacted in the SX plant by the circulated organic flow to recover residual zirconium (zirconium scavenging)
- The remaining process liquor (mainly HREE concentrate) is combined with the LREE concentrates and pumped to a REE SX separation process, which produces final separated REEs in oxide form
- After recovery and purification, some of the zirconium stream passes through a hafnium removal circuit. Both zirconium and hafnium then enter product finishing and packing circuits



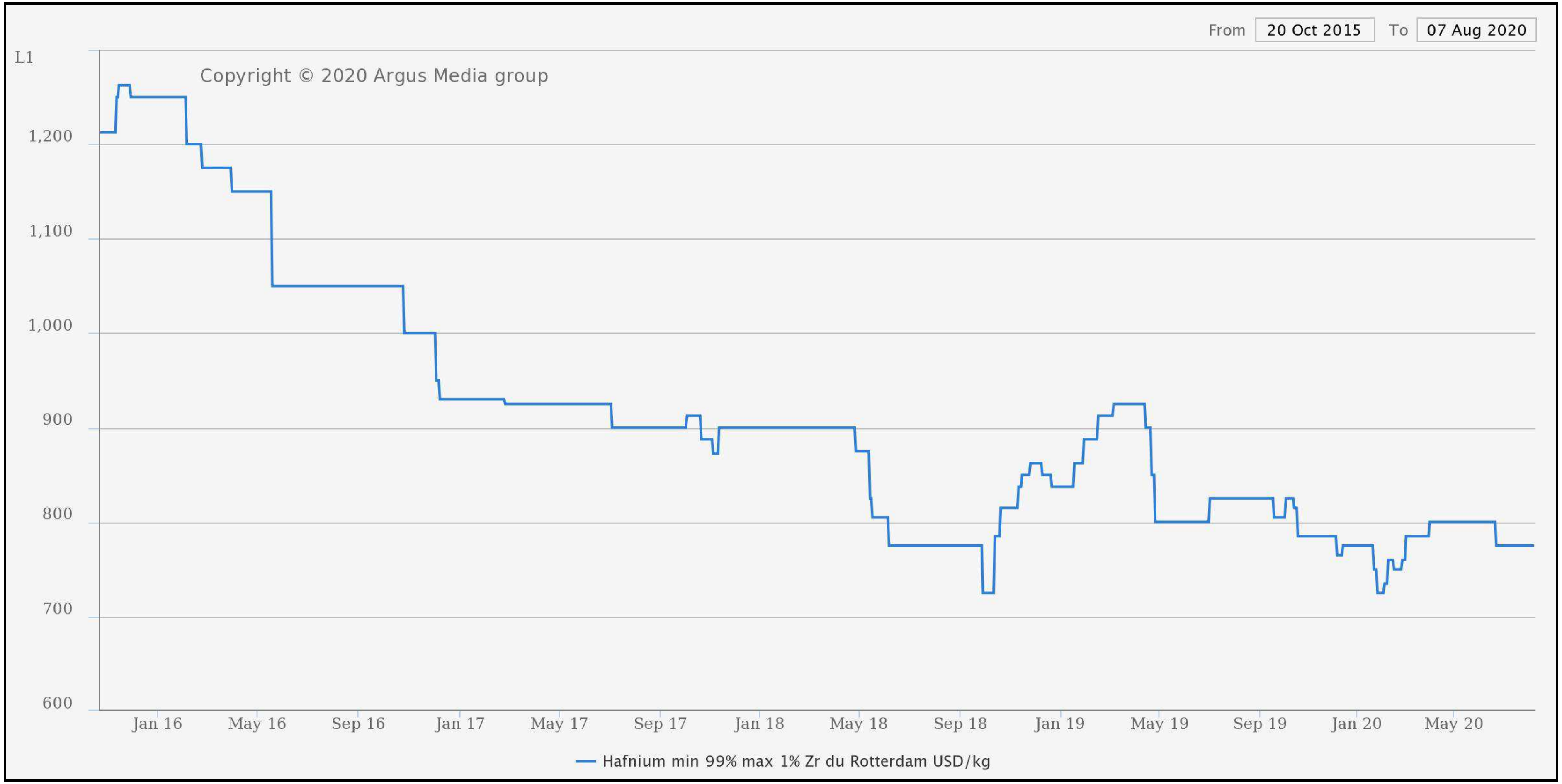
Needless to say this is a complex process.

Economics

ASM's thinking was that, with an assumed recovery of 50% and 200 tpa of 95% grade HfO_2 production (with prices for the metal being around US$1,000 to $1,200 per kg - but using $500 for 2020 in the model) then revenues should be of the order of US$100mn per annum from Hafnium alone. This would amount to around 18% of expected revenues, so a non-insignificant co-product contribution. Dubbo is targeting production of ~200 tpa Hf, but to be "conservative" given the market size, they only factor annual sales of ~50 tpa.

The preliminary capital and operating estimates of the inclusion of the Hafnium circuit into the final plant design suggest its incorporation would add significant value to the project.

It's worth noting though that the FEED study came with a hefty capex of AUD$1.3bn. The most poignant question is whether the sizable capex is ultimately a deal-killer for Dubbo.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Hafnium Pricing

The previous page shows the progress in the price in recent years. To our knowledge only Argus Metals provides professional pricing for Hf, and have only done so since 2015. Asian Metal used to also provide a HF metal price quote, but discontinued this several years ago. Before that pricing was on the "eye of newt, toe of frog" basis.

Some care to use Alibaba pricing (including in one shocking example in a PEA). Good luck to them.

In the old days, Hf basically was a pricing duopoly between then Areva (now Framatome) and ATI Wah Chang. However, when Westinghouse/Toshiba gave in to Beijing's demand in 2007 to give them Zr/Hf separation and production technology as a condition for selling four of their AP1000 nuclear reactors into China, the genie was out of the bottle several years later. Ironically, in 2006, BNFL sold Westinghouse Electric to Toshiba. Westinghouse owned Western Zirconium near Ogden, UT, where the Zr/Hf processing was done.

Chinese Hf metal provided a ceiling for spot prices, although now, given the growing anti-Chinese sentiment in the US, as well as import tariffs, Chinese sales into the US have essentially disappeared.

Search Minerals – Non-Disruptive

In the past we have covered Search Minerals (TSX-V:SMY) in a positive light but drifted away from it as it failed to make up its mind which part of its territory it was developing, or even if it was developing any part. Even worse the company appears to be subject to a creeping no-premium takeover from a noxious Swiss private equity fund, which ultimately is a road to nowhere.

In early April 2020, results from the Silver Fox part of its portfolio (the fourth major mineralized zone in SMY's Port Hope Simpson – St. Lewis district). Trenching/channelling (4 new channels in 2019), and mapping/prospecting indicate that the surface expression of this mineralized zone is up to 8.8m wide and 650m long. This surface expression is significantly longer, but thinner, than the surface expressions of the nearby, and related, Foxtrot and Deep Fox deposits. The mineralization is similarly hosted by peralkaline volcanic rocks and contains slightly lower grades of the REE magnet materials (Nd, Pr, Tb and Dy) but significantly higher grades of Zr and Hf.

In the company's view Silver Fox exhibits high-grade Zr (Hf, Nd, Pr, Dy, Tb) mineralization ranging from 3.63 to 8.83m wide over 650m strike length;

The channel assay highlights (all true widths) included:

- FSC-19-04: 26,389 ppm Zr, 110 ppm Dy, 1494 ppm Nd, 409 ppm Pr, over 7.14m
- FSC-18-01: 28,965 ppm Zr, 96.7 ppm Dy, 1249 ppm Nd, 348 ppm Pr over 6.49m
- FSC-12-02: 25,466 ppm Zr, 89.1 ppm Dy, 1281 ppm Nd, 348 ppm Pr over 8.83m

And the Hafnium grades:

	FSC12-03	FSC12-02	FSC19-04	FSC-19-01	FSC18-01	FSC12-04
Hf (ppm)	646	599	663	826	702	676

According to management, Silver Fox contains Zr (Hf) values much higher than any other of its REE resourced or mineralized zones in SE Labrador.

The company commissioned SGS Canada (Lakefield) to conduct preliminary metallurgical testing on a channel sample from Silver Fox for recovery of a zirconium and hafnium mineral concentrate.

We cannot admit to being impressed as the grades on these samples are not very different to DZP's but at DZP that is a resource estimate, while these are just some best-of-the-best surface samples.

We refer to Search Minerals as non-disruptive as it is unlikely to move forward in the Rare Earth space and even less so in the Hf/Zr space.

Leading Edge – Left Trailing Behind

We feel for shareholders and management at Leading Edge (TSXV:LEM, OTCQB: LEMIF, Nasdaq First North: LEMSE). The company has been cobbled together out of the merger of Tasman and Flinders combining a Rare Earth and a graphite project, respectively, into one entity with a Swedish specialty minerals vibe. Conventional wisdom lauds jurisdictions that are stable and progressive. However, Sweden has proven to be a disappointment for card-carrying fans of this thesis with the company's Norra Kärr deposit having been placed in a seemingly eternal "penalty box" by the combined fury of uninformed local NGO's and their acolytes.

The Norra Kärr deposit, along with REE and zirconium, is enriched in hafnium with a reserve grade of 338 ppm hafnium oxide (HfO_2).

Norra Kärr Mineral Reserve Estimate (WAI, November 2014)

Classification	Ore Tonnes (kt)	TREO (%)	HREO (%)	% HREO in TREO	Ce_2O_3 (%)	Dy_2O_3 (%)	Er_2O_3 (%)	Eu_2O_3 (%)	Gd_2O_3 (%)	Ho_2O_3 (%)	La_2O_3 (%)	Lu_2O_3 (%)
Proved	-	-	-	-	-	-	-	-	-	-	-	-
Probable	23 571	0.592	0.314	0.531	0.124	0.0269	0.0184	0.00218	0.0196	0.00593	0.0551	0.00234
TOTAL	23 571	0.592	0.314	0.531	0.124	0.0269	0.0184	0.00218	0.0196	0.00593	0.0551	0.00234

Classification	Ore Tonnes (kt)	Nd_2O_3 (%)	Pr_2O_3 (%)	Sm_2O_3 (%)	Tb_2O_3 (%)	Tm_2O_3 (%)	Y_2O_3 (%)	Yb_2O_3 (%)	Zr (%)	U (%)	Th (%)	Hf (%)
Proved	-	-	-	-	-	-	-	-	-	-	-	-
Probable	23 571	0.0648	0.0161	0.0178	0.00396	0.00280	0.215	0.0172	1.36	0.00131	0.000663	0.0286
TOTAL	23 571	0.0648	0.0161	0.0178	0.00396	0.00280	0.215	0.0172	1.36	0.00131	0.000663	0.0286

In 2018 the company provided an update on the first of a range of research projects aimed at capturing value-added opportunities for the project. A Pre-Feasibility Study completed on Norra Kärr in 2015 identified a range of opportunities to improve project economics while reducing capital expenditure and minimizing the environmental footprint of the project.

Leading Edge Materials had partnered with a research team lead by Professor Julien Leclaire at the *Institut de Chimie et Biochimie Moléculaires et Supramoléculaires* (ICBMS) in Lyon, France to investigate the extraction and separation of hafnium and zirconium from a process material previously considered to be waste. Professor Leclaire had worked extensively on highly selective extraction systems that apply carbon dioxide to form reversible extractive agents, with a focus on REEs in both primary and waste materials.

The initial six-month research alliance was partially funded by Leading Edge Materials, which gave the company the exclusive rights to apply the intellectual property (IP) developed within two years of project completion. If research is not ongoing within the two-year period, rights to use the IP shall return to ICBMS.

Prior to this though, in February 2016, the Supreme Administrative Court of Sweden cancelled the company’s mining lease for the Norra Kärr project. The court ruled that the lease, first granted in May 2013 by the Swedish Mining Inspectorate, was not adequately supported by environmental studies. The license reverted to an exploration license, which the predecessor firm, Tasman, first secured in August 2009. The company applied extensions of the exploration license.

So whatever aspirations that the company held to make a difference in the Hafnium space have necessarily been put on hold. However, the ICBMS project post-dated the disappointing turn of events signalling that the company was determined to soldier on. The trouble is that this is not a primary Hf, or even Zr, project so will not move forward if regulators still give the REE aspects the thumbs-down.

Complications

Further muddying the waters are projects that purport to be pretenders in the race to produce Hf (e.g. USARE's Round Top) that stand as much chance as the proverbial Snowflake in the Underworld.

It is important to remember that Zr metal (at ~5-7,000 tpa depending upon where in nuclear cycle) is a small fraction of Zr chemicals (significantly more than one million tpa of Zircon) and Hf metal (at under 100 tpa, including oxide) is a small fraction of Zr metal.

For those strategically inclined, similarly to Rare Earths, the focus should not be on raw material sources *per se*, but on downstream processing capabilities (including extraction and separation).

Moreover, given that Hf's primary application is as alloy additive in 2nd and 3rd generation Ni-based superalloys for turbine blades (where its use in power generation is traditionally bigger than in jet engines), it is evident that current and medium term demand is somewhat muted.

In one recent PEA (which was riddled with egregious pricing errors/*faux pas*) the Hf oxide price point used was $864/kg from Alibaba (ergo possibly not understanding the difference between hafnia and metal). The result was to overstate the project's annual projected Hf revenues by well over US$10 million. Oops….

Also, similarly to Rare Earths, we should not put too much stock in eudialyte-based mineralisations (e.g. Norra Karr) as a potential Zr/Hf source, given better alternatives.

Risks

The potential risks are:

- ✘ That Hafnium prices remain in the doldrums
- ✘ Ongoing tough financing conditions
- ✘ Nuclear revival in the West does not occur
- ✘ Supply imbalance from too many players coming on-stream

REE prices are still captive to Chinese whims. It is REE prices that will ultimately make these potential Hf projects work, or not. Hf is just along for the ride. If REE prices do not deliver, then Hf will stay in the ground. As we can see from the DZP FEED study, if the various parts of the pricing mix can fire together then even low Hf prices will make a meaningful contribution to revenues and the bottom-line.

Financing conditions will dictate whether Dubbo or Round Top move forward. Search is blighted by its choice or partner while Norra Karr still wrestles with jurisdictional issues.

The supply imbalance is not likely to be caused by "too many" suppliers but might be prompted by just one new player being added to the mix. This remains difficult to estimate though as the nuclear energy factor may/should provide heightened demand.

Conclusion

Let us quote the USGS: "World primary hafnium production data are not available. Although Hafnium occurs with zirconium in the minerals zircon and baddeleyite, quantitative estimates of hafnium reserves are not available".

In Hafnium we have a metal that is truly off the radar but be that as it may with prices in a range that reached as high as US$2,000 per kilo in the first half of the past decade, at those levels it was definitely something obscure that was worth handling. The much lower price that has reigned in the last few years makes pursuit of Hf, a less attractive prospect.

Rightly Australian Strategic wisely used a much lower price in their models, than the prevailing market price of several years ago, because when they begin production they will be effectively cracking open the shell of this mysteriously traded mineral and exposing it to the glare of daylight which usually results in pricing being less smoke and mirrors. And higher volumes usually mean lower prices, at least in the short-term.

That said, the Hafnium component of the DZP mix is going to be a significant one and one that most pundits had not figured into their calculations. Hafnium may be “niche” but it’s a niche that ASM hopes to dominate.

The other wannabes are either non-starters or delusional.

Important disclosures

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