Bluejay Mining Technical Report:

Assessment of Titanium Slag production complex in Greenland within the Dundas Ilmenite Project

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Content:

Frontispiece: The uplifted ilmenite-bearing beaches at Moriusaq along the south-coast of the Steensby Land Peninsula, 80 km south of Qaanaaq. The abandoned settlement Moriusaq is seen at the coastal stretch before the small tombola.

1 Background for titanium slag production

Titanium slag is one of the main feedstock types for TiO_2 pigment producers. Titanium slag is produced by converting ilmenite (at 45% to 55% TiO_2) to a titanium-rich material ('titanium slag' at 75% to 85% TiO_2) using a high temperature metallurgical process. Titanium slag can be used as feedstock through the so-called sulphate process or by the chloride process to produce TiO_2 pigment.

Production of titanium slag from ilmenite is a bulk-material process that needs large quantities of ilmenite. Worldwide, the process is only done at one facility in Canada, three facilities in South Africa, one facility in Norway, and at some smaller facilities in China and Vietnam. A new facility has been built in Saudi Arabia by a new operator, but this is currently undergoing significant modification due to problems with the technology employed.

2 Description of the titanium slag processing

Several million tonnes of titanium-slag are produced annually for the manufacture of TiO_2 pigment. The production process is complex requiring high temperatures to keep the slag fluid and careful furnace control to prevent vessel damage by the corrosive slag.

The upgrade of the TiO_2 content (to produce titanium slag) is done by ilmenite being reduced in an electric arc furnace (smelter) in a high temperature metallurgical process to produce titanium slag and pig iron. The furnaces are very large industrial processing facilities operating at temperatures of 1,600 to 1,800°C. The process is highly energy intensive; individual furnaces are typically rated at 40-70MW, and total energy usage is in excess of 2000 kWh/tonne of slag, depending on ilmenite composition.

The slag produced is highly aggressive towards the furnace refractories. For this reason, control of the thermal balance is essential, with the furnace being operated to form a protective frozen layer of material along the side and end walls of the furnace. The furnaces are operated continuously with a relatively constant inventory of slag and iron being maintained, with tapping of the slag and iron being done intermittently.

The slag leaves the furnace at a temperature of approximately 1700°C and is tapped into large moulds. It is then cooled, crushed, screened and sized in a slag processing plant to produce a titanium slag product for sale to TiO_2 pigment producers. Chloride slag can have a TiO_2 content of 85-90 percent, while sulphate slag can have a TiO_2 content between 78-86 percent. The undersized material from chloride slag ("slag fines") is too small for the chloride process, and as a consequence must be used in the sulphate process. Around 10 to 20% of chloride titanium slag produced therefore ends up in the sulphate process. A simplified flowsheet of ilmenite smelting is shown in Figure 1.

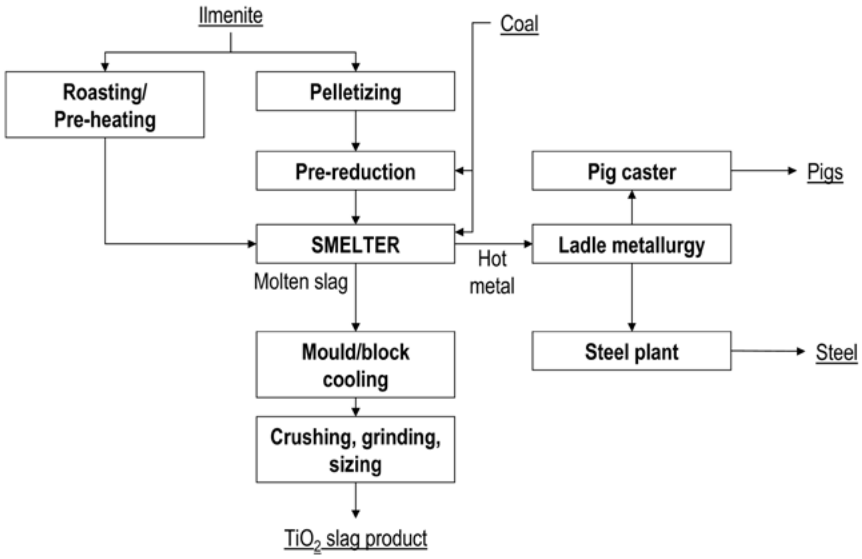

Figure 1 *Simplified flowsheet of ilmenite smelting (Filippou and Hudon, 2009)* [1].

3 Production of titanium slag in Greenland

In the following is the requirements and estimated costs reviewed for a titanium slag production complex in Greenland at the Dundas Ilmenite Project in Northwest Greenland. Both needed production complexes, support facilities, related infrastructure and operational raw materials input (energy/fuel, reductant material, chemicals) are considered.

According to Murty *et al.* (2007)[2], in addition to ilmenite as a source of the titanium, the additional 'key cost drivers' for the production of titanium slag are electrical power, reductant, electrodes and water. Murty *et al.* (2007) add *"Titania* [titanium] *slag production facilities are typically located close to the source of ilmenite (to minimise transport costs) and in a location with low cost electric power. All current producers are located in areas where power can be purchased at no more than 3 US cents per kWh"*.

Samal *et al.* (2010) identified the contribution of various items to the production cost of slag, with the ilmenite excepted. This is shown in Figure 2; this confirms that more than half the costs are made up of the items identified by Murty *et al.* (2007). The primary costs for a titanium slag identified in this study are: Energy (23%), Electrodes (17%), Reductant (coal, 15%), Chemicals (e.g. gasses, acid, alkalizes 14%), Maintenance (14%), Operating Labour (14%), Other (3%).

The study by Samal *et al.* (2010) are based on smelters that are based in already industrialized regions close to support and service infrastructure, does not take into account infrastructure such as accommodation or arctic harbour facilities – nor does it take into account the larger inventory of spare parts and operating equipment that also need to be present for an operation at an arctic remote

[1] Filippou, D. and Hudon, G. (2009). Iron removal and recovery in the titanium dioxide feedstock and pigment industries. The Journal of The Minerals, Metals & Materials Society, Vol.61, pp. 36-42.

[2] Murty, C.V.G.K., Upadhyay, R. and Asokan, S., 2007: Electro Smelting of Ilmenite for Production of TiO2 Slag - Potential of India as a Global Player, XI International Conference on Innovations in the Ferro Alloy Industry (INFACON XI), Das and Sunderesan, pp. 823-836, Indian Ferro Alloy Producers' Association, , Macmillan India, Delhi, 18-21 Feb. 2007

location. The study are furthermore not taking environmental measures (waste and water treatment plants) nor does it take account research programs that need to be conducted to establish the optimal smelting conditions or the international down-stream customer chain (offtakers of titanium slag) that need to be setup and supported by the organisation.

In the following sections each of the primary cost components identified by Samal *et al.* (2010) be reviewed and estimated for a titanium slag production in Greenland.

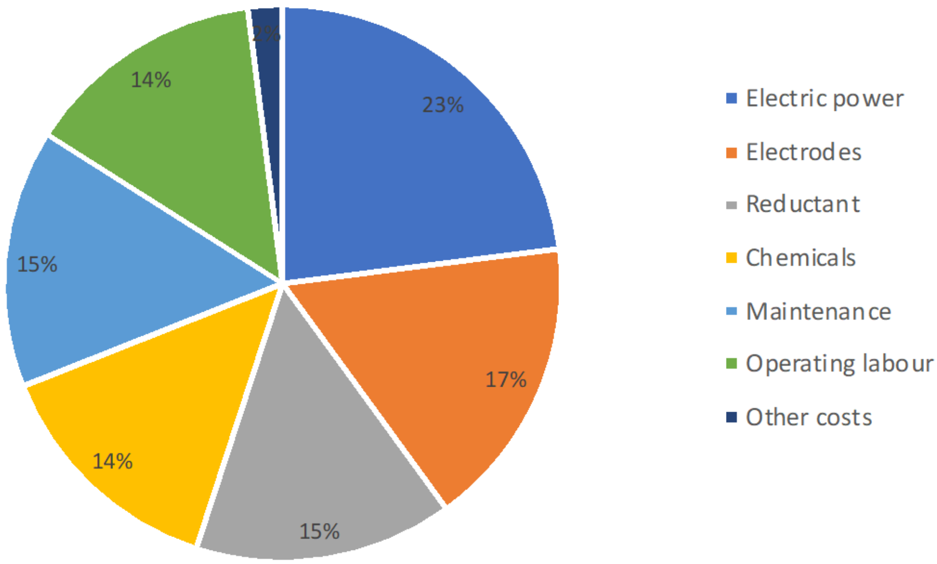

Figure 2 *Share of production costs for slag using a 48% TiO2 ilmenite (Samal et al., 2010).*

As a benchmark for an alternative titanium slag production facility in Greenland is the operation at the Sorel-Tracy Metallurgical Complex in Quebec, Canada, by Rio Tinto Fer et Titane (Rio Tinto Iron & Titanium) used[3]. The complete titanium slag and by-product production complex at Sorel-Tracy consist of a pre-ore treatment plant, a smelter plant (electric furnace), an upgraded slag (UGS) plant, a metal powder plant and a steel plant. The metal powder and steel plants make use of a part of the pig iron that are produced as a by-product to produce down-stream end-user products (iron powder that are used by e.g. the automotive industry for the manufacture of high precision parts and steel products in the form square or round billets in different length that are designed according to specific client needs and applications).

For the benchmarking of an alternative titanium slag production in Greenland will the pig iron by-product production not be consider further processed on-site in Greenland; but rather shipped to off takers of such a product. The considered complex in Greenland will also be scaled down to meet the current level of production envisaged by the current mining and processing scenario at Dundas – presented in the developed pre-feasibility study and social impact assessment for the Dundas Ilmenite Project.

[3] See e.g. Rio Tinto Fer et Titane, 2010 '60 Years of History 1950 – 2010' https://www.riotinto.com/documents/RTFT_SD_2010_FR.pdf and https://www.riotinto.com/canada/rtft

3.1 Energy – power plant

Using a figure of 1,160 kWh per ton of ilmenite (Murty et al, 2007) being processed for the production of titanium slag, smelting of all Dundas Premium ilmenite requires 435,000 MWh annually, or a power requirement of 10.4m MW/day.

There are two issues for consideration for this if a smelting was to be undertaken in Greenland: electricity cost and availability of a reliable electricity source with enough capacity.

Murty *et al* (2007)[2] provide electricity costs for the main smelting countries (Table 1). As can be seen the cost in Greenland is significantly higher, by a factor of 10x, adding a significant amount to the manufacturing cost (Nukissiorfiit, 2019)[4].

Table 1 *Cost of electricity for ilmenite smelting in countries with such facilities in operation (from Murty et al., 2007)*[2] *7 added with information on cost of electricity in 2019 in Greenland*[4]*.*

Country	US$ cents/kWh
Canada	< or = 3
Norway	< 2
South Africa	2.2
Greenland	25

Murty *et al.* (2007)[2] quote the power cost in South Africa as 44 US$ per ton of titanium slag with the electricity price in Table 1 (using a figure of 1.160 kWh/ton ilmenite); on the same basis the cost in Greenland would be of the order of US$ 500 which is clearly not practical. The cited study is from 2007. Development in electricity prices have been evaluated using publicly available data. In South Africa, current prices (2018) are around double to triple that shown in Table 1) and it appears that large-scale users within the mining and processing industry pay around one half of the standard industrial tariff. However, using a 2018 data, the South Africa cost would be 88 US$/ton to 126 US$/ton slag, it is still much below Greenland prices. The data for provinces in Canada has also been validated through public and personal communication with representatives in Canada; the price in Quebec is currently US$ cents <3 whereas in Alberta it is close to two times that cost.

Regarding the potential energy use and availability in Greenland. The production of titanium slag requires industrial sized electric arc furnaces each rated between 40-70 MW. To put this into perspective the largest power production in Greenland currently takes place at the hydro power plant 'Buksefjorden' near Nuuk. The plant's current capacity is 45 MW and according to the Government of Greenland it was valued at DKK 1.73 billion in 2017 [5]. The total capacity of the current five hydro power plants in Greenland is 91.3 MW, which is similar to the energy needs of approximately two electric arc furnaces designed for reducing ilmenite.

4 From www.nukissiorfiit.gl/kundeservice/priser/ [Greenland data August 2019: 1.65kr/kWh]

5 'Sektorplan for Energi- og Vandforsyning', Government of Greenland, 2017, https://www.nukissiorfiit.gl/wp-content/uploads/2018/07/Sektorplan-for-energi-og-vandforsyning-DA.pdf

Currently, all the potential sites for hydro power plants in Greenland are in South- and West Greenland and none are located in the area around Qaanaaq[6]. Also, options for hydro power at Dundas have been evaluated and found not to be present.

As there is no local supply in the mine site area, the current electricity supply for the Dundas mine is included as part of the site infrastructure cost. It comprises four diesel generators, one to supply power to the dry magnetic processing plant, accommodation complex and product storage, the others will provide power to the wet gravity separation processing plant and adjacent infrastructure. It would not be practical to use a similar approach for energy supply to a smelter because the power required is orders of magnitude greater and the import of the volume of fuel required would not be possible either logistically or economically. Consequently, the smelter would need to be sited elsewhere in Greenland closer to a suitable source of electrical power and infrastructure.

Furthermore, building a hydro power plant is a complex multi-long project and alternative types of power plants could be relevant to consider. One of the alternatives could be a power plant using heavy fuel oil (HFO). Such a fuel plant with a power output around 80 MW came at a value of approximately DKK 1 billion in 2017[7] (equal to around US$ 150M). The highly polluting heavy fuel oil have been banned by the Government of Greenland as a fuel in Arctic shipping[8]. The current setup at Dundas is to use the more expensive Arctic Diesel for the power generation. In addition to this, additional costs may arise due to the special conditions and requirements in Greenland and the Arctic environment. An 80 MW power plant would, based on the pre-feasibility study for the current mining and processing scenario at Dundas, consume an estimate of 13.7 million litres of diesel. This would amount a yearly cost of around at least US$ 8M. This fuel costs will be inflated much more by the arctic conditions, high transportation costs and a large storage facility as fuel must be stored during the 7-8 months with no shipping access due to sea-ice.

Other sources of renewable energy (solar power or wind power) will only be able to provide a minor input to the operation and not be able to produce the 40-70 MW needed for a titanium slag production facility.

In addition to the power supply, infrastructure for transporting the energy at or to the mining site must be established. The cost associated with the operation and maintenance of power supply and supply infrastructure is not assessed here.

The above, focus merely on energy need for the smelter plant. This is the primary facility in a complete production chain for titanium slag. However, ore pre-treatment plant and up-graded slag plant facilities have not been considered in this review of energy need as it is beyond the scope of the present study to investigate these in details, as the smelter constitute the central chain in the production and therefor is prerequisite for the remaining part of the production chain. If the other production facilities were to be taking into consideration, would the energy consumption, and associated cost both for construction and operation of a power plant, increase dramatically and probably be 2 times that of a smelter.

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[6] 'Sektorplan for Energi- og Vandforsyning', Government of Greenland, 2017, https://www.nukissiorfiit.gl/wp-content/uploads/2018/07/Sektorplan-for-energi-og-vandforsyning-DA.pdf

[7] Example of such a plant built in Mali can be found at https://www.ifu.dk/news/nyt-hoejeffektivt-kraftvaerk-oeger-elforsygning-i-mali/ and https://www.bwsc.com/Files/Files/PDF/Brochures/Turnkey%20contractor/BWSC_Independent-power-producer_10-0202.pdf

[8] See e.g. news at Eye On Arctic https://www.rcinet.ca/eye-on-the-arctic/2018/09/18/greenland-arctic-heavy-fuel-oil-ban-shipping-navigation-pollution-ocean/

3.2 Smelter plant – electrodes, reductant

The expected annual production of ilmenite at the proposed mining site is 440,000 tonnes per annum. For Dundas ilmenite, the available Premium ilmenite should permit the production of around 200,000 tons per year of titanium slag at an assumed TiO_2 content of 85%. Such a production could be done in a single smelter; although running a single smelter also provide risks to an production.

Using an existing smelter, for which development was started in 2011 and completed in 2014 by the company Cristal[9] as a benchmark (see also description of this smelter further below) and inflating cost to 2020 with an additional allowance for winterisation at a Greenland location the estimated capital cost is US$ 400M, or at the current exchange rate DKK 2.70 billion[10].

Furthermore, the estimated cost of the smelter does not include supply and support infrastructure. It would also have a significant impact on revenue generation as the construction period for the smelter will be significantly longer than the construction period for the remaining and current planned mining infrastructure. It will be extremely difficult to sell the Premium ilmenite if it was only going to be available until the smelter was operational, for example five years after the beginning of mining.

Outside of China, there has been limited investment in the construction of ilmenite smelters in the last 20 years. Table 2 shows the location and size of existing ilmenite smelters.

***Table 2** Existing ilmenite smelters world-wide outside of China during the last 70 years.*

Company	Country	Location	First production	Capacity ktpa	Number of furnaces	Power MW	Sulphate/ Chloride titanium slag
RTIT	Canada	Sorel, Quebec	1950	1200	9	50-70 AC	Both
RTIT	South Africa	Richards Bay	1977	1000	4	70 AC	Chloride
Tronox	South Africa	Namakwa	1994	160	2	25-35 DC	Chloride
Tronox	South Africa	KwaZulu-Natal	2001	220	2	36 DC	Chloride
Eramet	Norway	Tyssedal	1987	220	1	40 AC	Chloride

The most significant recent investment in an ilmenite smelter facility was made by Cristal (now Tronox), at that time one of the larger global TiO_2 producers, in 2011 at a site in Saudi Arabia. The capital cost was given as $550M for a design capacity of US$ 500,000 tons per year of chloride slag in two furnaces (Adams, 2019). Construction started in 2011 and was completed in 2014. However, significant issues have been experienced through commissioning and attempts to bring a furnace online were ended in 2018[11] to allow significant modifications to be made to the equipment. Operations are now scheduled to restart in 2020. The experience is an example of the challenges associated with the design and operation of a titanium slag smelter. All operators of smelter plants have experienced issues bringing online new facilities or in restarting furnaces after refurbishment.[12]

[9] Adams, R. (2019) TiO2 Worldwide Update, Year: 2019, Vol.27, no.1.
[10] Information from Dundas Titianium
[11] See for example news at Fastmarkets IM at https://www.indmin.com/Article/3841697/Technical-issue-at-Cristals-Saudi-slag-project-to-keep-high-grade-titanium-feedstocks-tight-in-2019.html

Aside from energy as a raw material, the smelting of ilmenite would also require a large tonnage of reductant in the form of 'coal'. Murty (2012) provide a norm of 0.14 kg reductant per ton of ilmenite for reductant. This means that the titanium slag processing of 440.000 tons of ilmenite at Dundas would need in excess of 60.000 tons per year of reductant.

Anthracite coal, high quality metallurgical coal, is the preferred reductant because it has a low total ash content, usually below 10 weight percent, together with low CaO and S. The quality of this material is crucial to the composition of the slag because any impurities, such as SiO_2 and Al_2O_3 report to the final product lowering the TiO_2 content and reducing the value. The anthracite would need to be imported from an international location to the smelter site in Greenland by sea as no know local source of metallurgical high-quality anthracite coal is available in Greenland. Currently the Rio Tinto Iron & Titanium operation in Sorel-Tracy Metallurgical Complex is getting their reductant, anthracite coal, from Russia.

The average price per ton of anthracite coal stated by the U.S. Energy Information Administration for 2017 was US$ 93.17[13]. However, as the anthracite coal have to be had high-quality metallurgical properties will the price per ton more likely approach that of coal coke (bituminous coal) which in 2017 had an average price of US$ 122. This would mean that the reductant coal would amount a yearly cost of between US$ 5.6M to 7.3M.

As also indicated by the U.S. Energy Information Administration, long-distance shipments of coal means that the cost of transportation easily can be more than the cost of the coal itself. As the coal for Dundas would have to be shipped in arctic waters by polar-class ice-enforced bulk-carrier ships will the transport cost probably be even higher. The 60.000 tons reductant coal will amount to two handy-max size bulk carriers. Assuming a shipping price of between US$ 80 to 110 per tons of high-quality anthracite the yearly shipping cost will amount between US$4.8M to 6.6M.

In total the reductant alone, will amount yearly between US$ 10.4M to 13.9M.

In addition to this, the reductant must be stored in heated storage facilities during the cold weather period (7-8 months) so that the material is not freezing. Based on the current pre-feasibility study for the mining and infrastructure scenario consider for Dundas will a winterised storage facility cost in the order of US$ 3-4M for the reductant alone.

Also, large and continued research programs are needed to assess the quality of the reductant material to optimize and produce the highest quality titanium slag. Not only will this be a yearly cost, the study also needs to be initiated before commencing production as the most suitable source must be identified. An estimated cost of such a research program including industrial scale testing prior to commencing production is estimated to cost between US$ 3M to 5M.

3.3 Upgrade slag plant - chemicals

Because of the increased need for higher grade titanium feedstocks for TiO_2 pigment production is an upgrade plant facilities, in which titanium slag is being purified (upgraded to a higher titanium content) needed to complete titanium slag production chain and meet the requirements by off-takers of titanium slag, part of the complex that Rio Tinto Fer et Titane in Quebec. A similar upgrade plant facility

[13] EIA U.S. Energy Information Administration anthracite average price per ton 2017 https://www.eia.gov/energyexplained/coal/prices-and-outlook.php

is included for completeness in the possible scenario for a titanium slag production complex at Dundas. However, the upgrade plant facility at Rio Tinto Fer et Titane in Quebec is unique and it is very unlikely that such a facility would be technical, operational and economic feasible for a production at Dundas.

The purification (upgrade) treatment in the upgrade plant facility consists of removing impurities from the slag by a hydrometallurgical process by acid leaching. The preferred leaching agent is hydrocholoric (HCl) acid. The HCl acid is highly corrosive and a difficult material to handle. Furthermore, pressure leaching with HCl acid is complicated operation. The technology of upgrading titanium slag is highly specialised and much of the technologies and industrial research are not accessible due to proprietary rights. Rio Tinto Fer et Titane's titanium slag upgrade plant, the USG Plant, was constructed in 1997. It's a unique plant worldwide with a patented process that increases the TiO_2 content of slag from 80% to around 95% which is currently sold under the registered trademark USG™ slag. The laboratory and pre-pilot phases were done over a five-year period and two-years of fine-tuning of the pilot plant was needed before the plant was ready for commercial production. The cost of construction the USG plant at Sorel-Tracy was US$ 350M in 1997[14] (which with inflation would equal around US$ 460M today). The initial full production capacity was 200,000 tonnes. This would be like the input of 'Premium' ilmenite from Dundas. Ninety-eight percent (98%) of the HCl acid is reported to be regenerated in by the plant, however, a variety of exotic materials, like graphite and fluorinated polymers, are reported to be used to adapt the equipment to our special process operating conditions, including the use of high-pressure hydrochloric acid at very high temperatures.

As the upgrade of titanium slag from a production in Greenland would be depended on an extensive research program and subsequent pilot-scale testing and fine-tuning is the exact need, properties and hereby also cost of HCl acid or other chemicals needed for the hydrometallurgical process by acid leaching impossible to estimate within the scope of the current study.

3.4 Maintenance & Services

It is outside of the scope of the present study to detail maintenance requirements for a titanium slag production facility in Greenland. For the the Sorel-Tracy Metallurgical Complex operated in Quebec, Canada, by Rio Tinto Fer et Titane, it is reported that the expenditures in 2017 was US$ 338M[15] with US$ 100M spend on local procurement for goods and services. Considering that the complex is operating 9 furnaces; this would mean a total expenditure level per furnace would be around US$ 37.6M; and that the local goods and services would amount US$ 11.1M. The Sorel-Tracy Metallurgical Complex is in an already industrialized and populated area; the above figures will be many times higher considering a remote location operation under arctic conditions.

3.5 Waste and wastewater treatment plant

For the titanium slag processing is process water needed in the ore preparation plant, the smelter furnace plant and in the case that an upgrade slag plant is part of the complex, also process water in such a facility. In 2016, the Sorel-Tracy Metallurgical Complex in Quebec, operated by Rio Tinto Fer et Titane, reported a used of 46.1 million cubic metres of water. It is estimated that an operation at Dundas will use between 5 to 10 million cubic metres of water (the Sorel-Tracy Metallurgical Complex

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[14] RTFT https://www.riotinto.com/canada/rtft/ugs-plant-celebrates-its-20th-birthday-23872.aspx
[15] RTFT https://www.riotinto.com/documents/RT_RTFT_2017_SD_report_en.pdf

have 9 furnaces; there would only be the need of one at Dundas, however, water for a ore preparation plant and the upgrade slag plant would also need to be taken into account).

In 1991-1994, the Sorel-Tracy Complex in Quebec installed a water treatment plant for the industrial wastewater from ore preparation and the smelter furnaces. This is done to remove suspended solids in the wastewater before it is lead back into the St. Lawrence river. Rio Tinto Fer et Titane spend CND$ 33M in 1991-1994[16] on the wastewater treatment plant; considering inflation this amount would be CDN$ 51M today (equal to US$ 38M). As a titanium slag processing at Dundas only will use on furnace will the cost drop and it is estimated that a wastewater treatment plant would cost in the order of US$ 4-6M.

3.6 Labour

To illustrates the number of jobs at producers of titanium slag, Rio Tinto Fer et Titane at Sorel-Tracy Metallurgical Complex in Canada, employs more than 1,400 people[17]. At the complex nine furnaces are installed that is approximately 150 employees/furnace. The expected annual production of ilmenite at the proposed mining site is 440,000 tonnes per annum. This amount of ilmenite could be handled by a single furnace and approximately 150 employees if the estimated labour-requirement per furnace from the Sorel-Tracy Complex is assumed. If an average tax revenue per employee similar to the estimate for the rest of the mining site is assumed the annual income tax revenue for 150 employees is estimated at US$ 3.4M per annum.

3.7 General cost level in Arctic – the Arctic Factor

The general capital and operation cost level in the arctic have been studied and assessed by US Department of Defense (2010)[18] and for and northern arctic Canada by The Mining Association of Canada (2014)[19, 20].

The Mining Association of Canada finds that capital costs (CAPEX) for northern operations (remote northern/arctic Canada) compared to southern operations is about double for gold mines and 2.5 times higher for base metal mines. The US Department of Defense in their research state that: “Construction in the Arctic costs, as a rule of thumb, three to five times more than comparable infrastructure in lower latitudes.” It should be noted, that the capital costs that are assessed here are related to basic infrastructure and not highly complex industrialised complexes.

The Mining Association of Canada also assess the operating cost for northern projects and state that these are 30-60% higher than for projects at more southern latitude.

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[16] Published by authority of the Minister of the Environment©, Minister of Supply and Services Canada 1996, Catalogue No. En 153-6/28-1996E http://planstlaurent.qc.ca/fileadmin/publications/diverses/protection/028_a.pdf

[17] RTFT: https://www.riotinto.com/canada/rtft/locations-15134.aspx

[18] US Department of Defense – Report to Congress on Arctic Operations and the Northwest Passage https://archive.defense.gov/pubs/pdfs/Tab_A_Arctic_Report_Public.pdf

[19] The Mining Association of Canada – Levelling The Playing Field https://www.pdac.ca/docs/default-source/priorities/securities/levelling-the-playing-field---final.pdf?sfvrsn=8b46a798_2

[20] The Mining Association of Canada - Quantifying the Cost Differential of Mineral Development in Northern Canada: Grounding the Next Step Forward. Presentation by Brendan Marshall, Director, Economic Affairs, The Mining Association of Canada, 2014 Nunavut Mining Symposium https://static1.squarespace.com/static/527e42c4e4b0aea5e0569d9b/t/5356c8dce4b05f484022a063/1398196444905/3+-+Marshal+Mining+Association.pdf

The above considerations about costs levels for capital expenditure and operational cost are referred to as the Arctic Factor.

3.8 Summary of estimated CAPEX and estimated OPEX associated with a titanium slag processing at Dundas

Table 1 and Table 2 summaries the estimated capital and operation costs (eCAPEX and eOPEX) associated with a titanium slag processing complex in Greenland and within the Dundas Ilmenite Project. The costs are detailed in sections 3.1 to 3.6.

The eCAPEX, without an Arctic Factor (see section 3.7), is estimated to be at least US$ 975M which converted to Danish kroner would be around DKK 6.60 billion. Applying an Arctic Factor (see section 3.7) would the estimated eCAPEX cost be US$ 1,95M to US$ 2,925M (DKK 13.19 billion to DKK 17.76 billion).

The current mining and infrastructure scenario at Dundas calculated in the pre-feasibility study is in comparison US$ 285M (DKK 1.92 billion).

The eOPEX, without an Arctic Factor (see section 3.7), is estimated to be at minimum US$ 39.5M per year which converted to Danish kroner would be around DKK 267M per year. Applying an Arctic Factor (see section 3.7) would the eOPEX cost be US$ 46.9M to US$60.1 M per year (DKK 317.1M to DKK 406.3M per year).

Table 3 *Estimated capital expenditure (eCAPEX) for titanium slag processing facilities and related infrastructure.*

Titanium slag processing complex in Greenland – estimated CAPEX				
Item	**Cost at international location**	**Cost at remote arctic location**	**Item comment**	**Inconvenience associated with item**
Energy – Power Plant	$150M	$300-450M	Diesel-based power plant; hydropower is not possible at Dundas.	No availability of cheap reliable power; no hydro-power potential; diesel transport and heavy increase in environmental/emission impact.
Fuel Storage	$11M	$11M	Based on CAPEX cost of infrastructure scenario in current PFS for Dundas.	Fuel storage needs to be 4 times the current PFS for Dundas; large areal footprint.
Smelter Plant	$400M	$800-1,200M		Heavy investment; winterization; harsh conditions for maintaining a constant industrial production, large areal footprint, heavy increase in environmental/emission impact. Reductant & chemicals need to be shipped to site and stored. No transport of product 7-8 months per year because of sea-ice. Complete customer-chain need to be established. Furthermore, the harsh environment could cause a risk for shutdowns of the smelter plant; this is a high risk for the processing since the smelter plant once on-line need to be continuously feed.
Upgrade Slag Plant	$350M	$920-1,380M		Heavy investment; winterization; harsh conditions for maintaining a constant industrial production, large areal footprint, heavy increase in environmental/emission impact. Reductant & chemicals need to be shipped to site and stored. No transport of product 7-8 months per year because of sea-ice. Complete customer-chain need to be established.
Feed and Product Storage	$15M	$15M	Based on CAPEX cost of infrastructure scenario in current PFS for Dundas.	Large areal footprint, harsh conditions for storage, increase in environmental impact.
Water Treatment	$4-6M	$8-18M		Harsh climate conditions for water treatment; large areal footprint.
Sludge Disposal Site	$4M	$8-12M		Harsh climate conditions for water treatment; large areal footprint; closure and remediation work complicated.
Accommodation, Workshops, Office & Support Infrastructure	$26M	$26M	Based on CAPEX cost of infrastructure scenario in current PFS for Dundas.	Harsh climate conditions; winterization. All facilities need to be established in remote location/on-site.
Initial Research Program for titanium slag processing at Dundas	$5-10M	$5-10M	Research Program for the development/pilot plant testing and optimization of Dundas titanium slag processing.	High uncertainty associated with research programs because of proprietary rights to existing technologies and know-how.
Total estimated CAPEX	**US$ 972M**	**US$ 2,093 - 3,122M**		

Table 4 *Estimated operational expenditure (eOPEX) for titanium slag processing facilities and related infrastructure*

Titanium slag processing complex in Greenland – estimated OPEX				
Item	**Cost at international location**	**Cost at remote arctic location**	**Item comment**	**Inconvenience associated with item**
Energy - diesel	$8M	$10.4-12.8M		No availability of cheap reliable power; no hydro-power potential; diesel transport and heavy increase in environmental/emission impact.
Electrodes	Currently not possible to estimated	Currently not possible to estimated	Before an initial research program have been undertaken is it not possible to provide an estimate on the cost associated with the number and wear on the electrodes.	Not detailed.
Reductant	$5.6M - 7.3M	$7.3-11.7M		Storage for coal need to winterised.
Chemicals	Currently not possible to estimated	Currently not possible to estimated	Before an initial research program have been undertaken is it not possible to provide an estimate on the cost associated use of chemicals in the complex.	Uncertainties related to the chemical processing under harsh cold climate conditions.
Maintenance & Services	$11.1M	$14.4-17.8M		The remote location means that there is a high risk of longer shutdowns in case of technical issues as it takes longer time to transport specialised technicians to the site.
Spare Parts	$3 - 5M	$3 - 5M	Based on OPEX cost in current PFS for Dundas.	A large inventory of spare parts needs to be established because of the remoteness and the inaccessible nature of the site 7-8 months per year.
Labour	$3.4M	$3.4M	Based on OPEX cost in current PFS for Dundas.	Expensive highly skilled experts must be sourced international and not in Greenland.
Camp	$1.5M	$1.5M	Based on OPEX cost in current PFS for Dundas.	
Flights	$3.4M	$3.4M	Based on OPEX cost in current PFS for Dundas.	
Resupply vessel	$1M	$1M	Based on OPEX cost in current PFS for Dundas.	Remote location only accessible by ship 4-5 months a year.
IT & Communication, Training & Recruitment, Insurance, SSHEQ Greenland G&A	$1.5	$1.5M	Based on OPEX cost in current PFS for Dundas.	
Customer relation chain/market & off-site office	Currently not possible to estimated	Currently not possible to estimated	Before an initial market research and detail planning have been undertaken is it not possible to provide an estimate on the cost associated with building the customer relation program.	Uncertain whether it is possible to introduce new titanium slag material into a customer chain that are very closed and many time deals with much larger producers of titanium slag.
Continuous research and monitoring program for titanium slag processing at Dundas incl. laboratories	$1-2M	$1-2M	Research Program for the development/pilot plant testing and optimization of Dundas titanium slag processing.	
Total estimated OPEX	**min. US$ 39.5M**	**US$ 46.9M - 60.1M**		

3.9 Additional considerations

Some of other additional considerations, which also have been considered, but where it is outside the scope of the current study to provide a complete assessment, are summaries in Table 3 and shortly described in the following.

Table 5 *Additional Considerations, Inconvenience & Potential Impact on Project & Greenland Additional Considerations, Inconvenience & Potential Impact on Project & Greenland.*

Titanium slag processing complex Dundas/in Greenland		
Consideration	**Inconvenience**	**Potential impact on the Dundas Ilmenite Project & Greenland**
Harsh cold arctic climate	Uncertainties about complex and delicate processing under the cold climate conditions, risk of unwanted shutdowns. Simple processing and mining is not associated with the same issues.	Operational uncertainties and risk when dealing with highly and delicate complex operations; full production not achieved; safety and critical failures on esp. smelter plant furnace. Simple processing and mining is not associated with the same issues. The Dundas Ilmenite Project will not be feasible; hard to get financing for the project.
Toxic residual material handling	Storage facilities for toxic residual material handling need to be established due to no shipping access for 7-8 month a year – no facility for handling it in Greenland.	Risk associated with storage and handling of toxic material on-site. Environmental risk for Greenland.
Environmental impact	Impact atmospheric, physical and living environment will be increase. Closure plans at the end of the production; no production after resources is used.	Environmental impact too high for the project to be executable. Greenland's CO_2 emission will be increased with 44%. Remediation will be very complex.
Specialised workforce	No access to local specialised workforce; no know-how/experience in Greenland with metallurgical processing.	A high number of expensive employees with specialised skills and experience must be sourced outside of Greenland
Enlarged areal footprint	Obstruct access to reserve/resource of the ilmenite (applies if the smelter is at Dundas).	Decrease in mine-life; less production; economics in the project uncertain; hard to attract investments to the project. Greenland will not utilise its resources fully.
Know-how & Protected Technologies	Protected technologies and know-how not readily available.	Large expensive research programs with uncertainties need to be undertaken; timeframe will be dramatically extended for the project before it can commence design and production
Ilmenite for blending	Need to be bought and shipped to site from international locations.	Very expensive; project not feasible. The Dundas Ilmenite Project will not be feasible meaning that the Greenlandic society will miss an opportunity for new income and activities.
Access to market, Target market & Business model	Customer-relations to international down-stream off-takers of titanium slag need to be established. Pig-iron ore customer relation must be established. Production will cease after use of local resources.	Adding additional down-stream value chains to the operation make the marketing and handling more complex – and will take considerable longer time to setup.
Size and type of project vs. community/social impact	The size and type/characteristics of including the titanium slag processing facility in the Dundas Ilmenite Project will dramatically increase the size/impact. Furthermore, a large industrial complex in the high north of Greenland would likewise change the characteristics and the dynamics with the local community, the Greenlandic and international society.	Greater pressure on public services and local community/culture. The project will no longer represent a natural "organic" development and growth. Pressure from international society considering the environmental impact from a large-scale project in Arctic north.

3.9.1 Harsh cold arctic climate

The cold climate at Dundas for 7-8 months a year provide a very high risk for complex and delicate metallurgical and industrial processing. A titanium slag smelting plant, as well as the upgrade slag plant, need to be operated continuously when on-line. The process and the facilities are not suited for frequent shutdown/start-up; not only because of the process and operation itself but also because of the safety risks associated with shutdown/start-up. It is foreseen that the harsh cold climate could pose a risk for such unwanted shutdowns/start-ups. The currently planned mining and processing of the ilmenite-bearing sand at Dundas is a much more simple and low-techology operation which can be undertaken under the harsh climate.

3.9.2 Toxic residual material handling

Hazardous residual materials mainly consist of waste oils, acetone as well as mud and oily wastewater produced in the complex need to be disposed in facilities suitable for this. Such toxic material would be needed to transport to an international location since there are no facilities that can handle these in Greenland. Furthermore, acid reservoirs and retention basins at the upgrade slag plant need to be established – which under the cold climate conditions are difficult and associated with higher risks.

3.9.3 Environmental impact

As the energy consumption is very high and because smelting process itself produce gasses will the greenhouse gas emission, especially CO_2, be very high if a titanium slag processing facility was established at Dundas, or elsewhere in Greenland, especially if diesel is used for power generation.

For the Sorel-Tracy Metallurgical Complex in Canada, which, notable, get their electricity from hydropower, was the emission in 2010[21] 1.26M tons of CO_2 (with 88% originating from the Ore-treatment Plant, the Smelter Plant and the Upgrade Slag Plant). A simple downscaling to the size of a possible titanium slag facility at Dundas (with one smelter furnaces instead of 9 at Sorel-Tracy) would mean that the processing alone at Dundas would produce 112,000 tons of CO_2.

It is estimate that the power plant needed for titanium slag processing at Dundas 13.7M litres of fuel yearly. Using an emission factor for Diesel Fuel Arctic (DFA) of 72.97 kg CO_2-emissions/GJ and a density of 0.8 kg/l, a total of 34,330 tons CO_2 emissions per year is estimated for the power plant that are needed for a titanium slag facility at Dundas. This would mean that the CO_2 emission would be increased from 85,700 tons CO_2[22] to 232,030 tons CO_2 in total. The annual CO_2 emissions from energy production in Greenland were 523,963 tonnes in 2015[23]. Consequently, the titanium slag production including the current mining and processing scenario at Dundas would increase Greenland's CO_2 emission by 44% (without the titanium slag facility at Dundas is the increase 14%[22]).

Beside the increased emission would the impact on physical and living environment also be increased.

3.9.4 Specialised workforce

Available local workforce for titanium slag production at Dundas is limited/non existing and many of the more technical skills associated with metallurgical and industrial/chemical processing are currently not present. It is estimated that at least 150 employees would be needed if the titanium slag processing facilities was established. For many of these employees will the level of education and the

[21] RTFT https://www.riotinto.com/documents/RTFT_SD_2010_FR.pdf

[22] Bluejay Mining Plc Dundas Ilmenite Project Environmental Impact Assessment 2019

[23] Grønlands Statistic 2019 www.stat.gl

expertise-level be much higher than the currently planned mining and more simple processing (gravity and magnetic separation) at Dundas.

3.9.5 Enlarged areal footprint

Footprint of a titanium-slag production facility at Dundas would is extensive; probably 2-3 times bigger than the current footprint. The large footprint of a titanium-slag production at Dundas would increase the environmental impact dramatically. Also, as the areal extent of a large permanent titanium-slag production facility would be needed to be built on-top of the ilmenite orebody would this remove resources from the project which would decrease the mining life and the economics in the project.

3.9.6 Know-how & Protected Technologies

Although the basic process and technologies involved in production of titanium slag is available, these needs to be modified and accustomed to a production with the ilmenite at Dundas. This is heavily depending on large and time-consuming research programs and know-how that are developed during an initiated production. Those experiences and fine-tuned technologies that exists are mostly under the proprietary rights and protection of existing titanium slag producers. Large research program with large uncertainties and risks associated need to be undertaken prior to commence the design and construction of a titanium slag processing facility at Dundas.

3.9.7 Ilmenite for blending

In many cases can the optimal quality of titanium slag products only be achieved through blending of ilmenite from different sources. If this is also the case for a titanium slag production at Dundas would ilmenite from other mines international need to be bought and shipped to the site during the 4-5 months ice-free window and be store for all year production. The international likely locations will be in Africa, India or Australia. In case that ilmenite is not bought in for optimizing the value of the product would the produced titanium slag have a lower value than what is possible.

3.9.8 Access to market, Target Market & Business Model

In the case that a titanium slag production was initiated at Dundas would an offtake customer base for the produced titanium slag and a supply chain operation need to be established. However, establishing and maintaining this is a large undertaking. Titanium slag is not sold through an open metal exchange it is normally bought direct offtake agreements with customers. Furthermore, customers are often tight up to existing agreements and long relationships between titanium slag producers and TiO_2 manufactures exists and it is not easy to enter the chain. Furthermore, the limited shipping window at Dundas would mean that an all-year delivery of titanium slag to TiO_2 manufacturers which is unwanted by these. This is less of a problem for the titanium slag producers as they make use of large quantities in their smelting process and can stockpile the ilmenite concentrate.

In addition; pig-iron will be produced as a by-product from the slag production. This needs to be shipped and customer-relation/offtaker chain also need to be established for this.

The target market for a slag produced at Dundas will be titanium chloride slag. However, in the manufacture of chloride slag, a proportion of the slag production will be too small in particle size, so will need to be sold as sulphate slag. Furthermore, a portion of the ilmenite (Standard) that are produced at Dundas is not suitable for chloride slag (because of its content of Mg and Ca). This would leave a number of options: I) sell the ilmenite for the sulphate process in China (low profit margin because of shipping cost); II) campaign production of sulphate slag (this would have to be kept separate from the slag fines noted above; they are different products); III) import ilmenite (see also section 3.9.7) from another source that could be blended with the Standard to make chloride slag (added cost and complexity).

3.9.9 Size and type of project

The large size and complexity of the project if including a titanium slag production complex will increase the pressure on public services, the local and regional community as well as national. The project will need to be carried out as a 'Large Scale' project in Greenland. The stress on the community will also be increased since more foreign workers and experts needs to be included in the project and since the communities are not allowed to develop through a natural "organic" development; the mining operation and "plain" processing currently planned at Dundas represent a simple and well-suited operation for the level of an emerging resource sector in Greenland; introducing a titanium slag production complex into the project at Dundas will represent an 'unnatural' development and will not match the level of an emerging mining/industrial sector in Greenland.

3.10 Conclusion

As illustrated above, the processing of ilmenite is highly complex. It requires either smelting at very high temperatures utilizing proprietary technology or the import and use of chemicals (such as sulphuric acid or chlorine), reductants and potentially also ilmenite from other sources, in a complex multi-stage process.

In brief, the production of titanium slag on site in Greenland would require building a new power plant of considerable size due to the capacity requirements of the electric arc furnaces. Meeting the power demand through a hydro power plant does not seem feasible as no potential sites have been identified near the mining area. Building a power plant based on fossil fuels may be possible but the fuel costs will be significant and will cause this to be economical not feasible – as well as leading to a very large environmental footprint, e.g. through an CO_2 emission that will be increased with more than 30%. Pre-ore treatment plant, upgrade slag plant and wastewater treatment plant as well as increased support infrastructure will furthermore increase the capital expenditure CAPEX.

Without the titanium slag production complex at Dundas the CAPEX amounts to US$ 242M (converted to Danish kroner 1,7 billion DKK).

A titanium production complex is estimated to amount an estimated CAPEX of US$ 972M. This is on its own nearly 4 times the currently planned CAPEX for the project. The estimated CAPEX of US$ 972M of the titanium slag production complex converted to Danish kroner would be around DKK 6.56 billion. It should be noted, that the US$ 972M is without an Arctic Factor (see section 3.7). Applying an Arctic Factor (see section 3.7) would the estimated eCAPEX cost be US$ 2,093M to 3,122M (DKK 14.13 billion to DKK 21.1 billion).

Adding the titanium slag production complex to the currently planned mining and processing scenario project the total CAPEX will raise from US$ 242M to US$ 1,214M (without the Arctic Factor for the titanium slag production complex taken into) which is a five-fold increase of the total capital expenditure for the project. If the Arctic Factor on capital expenditure is taken into account (see section 3.7) will the total CAPEX for the project amount between US$ 2.335 billion to US$ 3.364 billion.

It is highly unlikely that the project with the titanium slag production complex will be able to be financed with that high CAPEX, especially considering that production capacity for ilmenite conversion into titanium slag is available at other plants globally.

Introduction and accessibility to market for titanium slag would be difficult to establish and uncertain due to the location of the project as titanium slag only will be delivered to customers will be limited by the ice-free shipping window during the summer period. The business model of producing titanium slag at Dundas is therefore very uncertain and it will therefore not be possible to raise the required capital to include this.

Furthermore, including a titanium slag production complex at Dundas increase the overall environmental impact dramatically and will put greater pressure on public services and local community/culture.

Finally, the timeline to get to full usage of all the Premium ilmenite to make titanium slag in a complex at Dundas could be up to 10 years given no research, design, technical development or feasibility has even been initiated yet. Experience from other project international also signify also the complex nature of titanium slag operation and the uncertainties associated with these. Taking this, together with a potential malfunction business model for titanium slag produced at Dundas, the uncertainty availability of cheap power at Dundas, the high environmental and social impact, provide no real option other than to ship ilmenite to an international located existing titanium slag production complex.

The conclusion is consequently, that it from an economical, technically, operationally and market perspective is not feasible to include a titanium slag production complex at Dundas.