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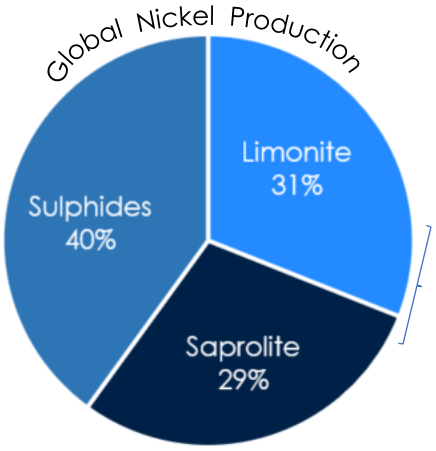
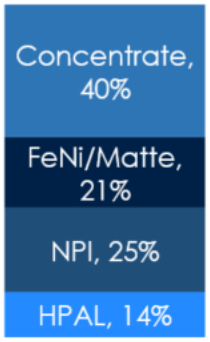


HPAL: Upping The Pressure



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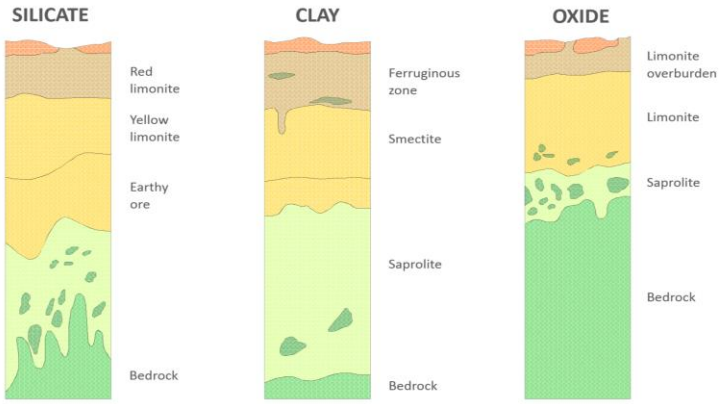
Introduction

- **To my mind there is a disconnect between the EV-inspired optimism that has led to renewed interest in nickel laterite projects processing via HPAL (e.g. CLQ, MLX), and the reality of building and operating them.**
- There is no doubt that the dawning of the EV market will significantly benefit nickel (sulphate) producers - it has for example already significantly lowered by-product unit costs by sharply increasing cobalt prices. However the revival of interest in HPAL needs to be tempered by the experience of past and present operations.
- Similar to our Gold POX review last year, this presentation reviews the experience of all global HPAL nickel operations as well some of the project developers.

- **Key points:**
- 1. **HPAL works, but it's challenging and capital intensity is high.** Autoclave pressure averages ~1,600kPa higher than in POX (+54%), with temperatures +37°C (+17%). Capex averages US$49k/t Ni.
- 2. **Nameplate capacity is often not achieved, and never consistently.** Failures include the likes of Bulong, Murrin Murrin, Goro etc.
- 3. **Ramp-up projections are often unrealistic.** On average projects only achieve 80% by year four resulting in substantially higher costs and capital requirements. In contrast CLQ expects to be >80% in year two.
- 4. **Cobalt is a potential HPAL game-changer.** While in ferronickel or matte smelting the cobalt credit is lost, recoveries via HPAL are excellent and it has already significantly lowered opex.

Nickel Laterites

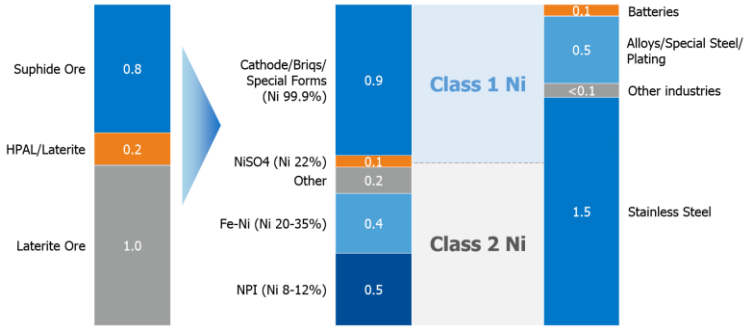
- Over the last 15 years the emergence of NPI has seen supply from laterites grow from ~40% to ~65% and this trend is set to continue – Norilsk sees 550kt of new laterite supply between 2016-2025 vs. a drop of 50kt from sulphides. Most of this growth is expected to be NPI and FeNi.
- **Deposit Formation:** Laterites are formed by weathering of olivine-rich ultramafic rocks, resulting in nickel accumulation (and typically an associated cobalt enrichment) in the lateritic weathering profile. Mineralisation is generally hosted in two horizons, saprolite (generally 1.0-2.5% Ni, high Mg, low Fe, low Co) and limonite (0.8-1.5% Ni, low Mg, high Fe, high Co). For example looking at typical laterite profiles:



- Laterite weathering generally requires a tropical, humid environment, and thus the majority of deposits are confined to the equatorial belt, dominated by Indonesia, the Philippines, the Caribbean and New Caledonia. Resources outside this belt (e.g. in Australia, Brazil, Madagascar etc) are generally much older.
- Oxide and silicate deposits are the most prevalent with clay deposits representing ~10% of resources. However outside of strip ratios etc, **the key factor in all deposits are the proportions of iron, magnesium and silica**, as they largely determine the preferred processing route.

Class I vs. Class II Nickel

- Though clearly in its infancy, the growth in importance of battery demand should not be understated, particularly as battery chemistry becomes increasingly nickel weighted.
- GMR currently forecasts EV demand exceeding 100ktpa in 2022, so still small in a >2Mtpa nickel market. However strip out the >70% of existing nickel supply which is unsuitable for EVs and **it seems increasingly clear we will see a bifurcation of nickel pricing.**
- Looking at the current split between Class I and Class II products:

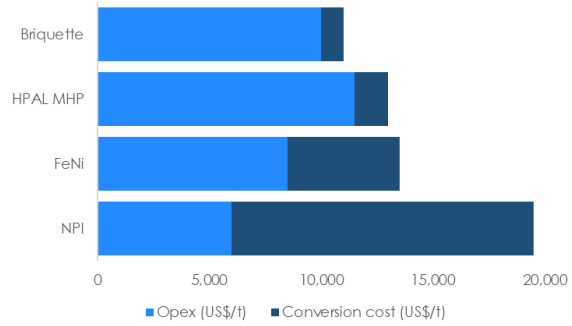


Source – Norilsk

Battery grade nickel increasingly demands nickel sulphate and in the absence of expensive conversion costs that means **>70% of nickel supply is unsuitable for EVs.**

In terms of laterite production, **HPAL is the only established option for nickel sulphate.**

- As the chart below illustrates, it is prohibitive to convert Class II nickel into sulphate. As a result we are going to see increasing substitution of existing Class I production, plus potentially more HPAL.

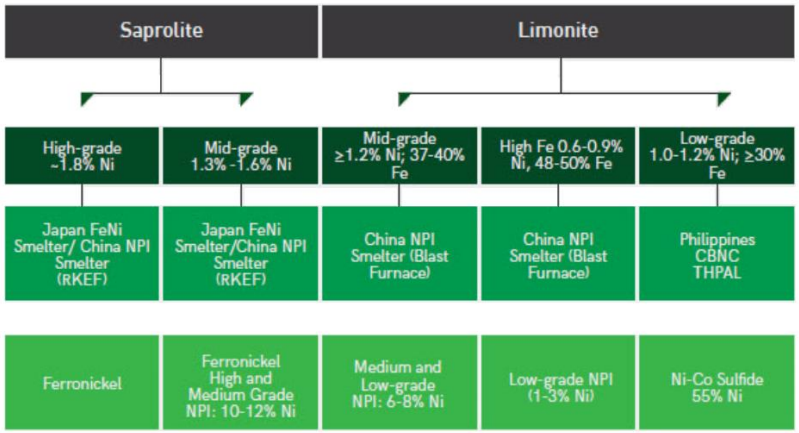


Source – GMR, adapted from Norilsk

The cheapest supplier to the EV market will be from existing briquette production – For example **BHP is looking at producing up to 200ktpa nickel sulphate at Nickel West.** However when HPAL gets it right costs are comparable, and better than FeNi when current cobalt by-product credits are included.

Laterite Processing Options

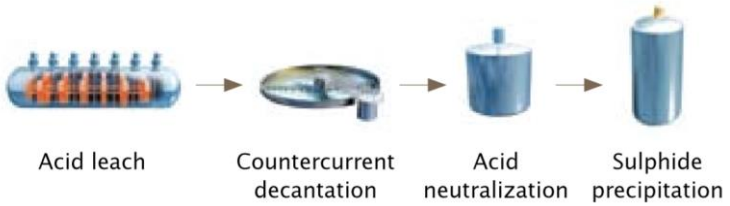
- Compared to the typical sulphide flowsheet nickel laterite processing is more varied. Around 80% is processed pyrometallurgically, and much of that is offshore after selling DSO. ~44% is produced as Nickel Pig Iron, ~36% as Ferronickel, with the balance mostly Briquette or Hydroxide. In summary:
- **Nickel Pig Iron:** Historically, there was little/no market for DSO limonite ore, nor for low grade saprolite. However since the development of the Chinese NPI market in 2005 DSO imports have skyrocketed for use in blast furnaces – E.g. Philippine's exports have gone from 4Mt in 2008 to 30Mt in 2017. Indonesian exports have also resumed (now annualising ~7Mtpa). Current NPI production accounts for ~580kt of global nickel supply (~28%) and it is still growing. Though an inferior product, NPI has imposed a price ceiling on nickel.
- **Ferro-Nickel**: Higher grade saprolite ores are generally exported to Japanese FeNi smelters, though some medium grade ore is also processed in Chinese NPI smelters (RKEF). Ore is blended to achieve the right SiO_2/MgO ratio, typically 1.5-2.5, with the end product destined for use in stainless steel. Though cost competitive, recoveries of cobalt are generally poor and it is not suitable for most limonite ores.
- Looking at the options through the lens of Nickel Asia who process a variety of laterites in the Philippines:



- **Hydrometallurgical?** As is the case for Nickel Asia (CBNC and THPAL), HPAL has typically been reserved for low-grade limonite deposits.

High Pressure Acid Leaching

- **HPAL is the most widely adopted technology for processing lower grade limonite ores**, particularly given the Caron process is no longer seen as economic.
- It represents >10% of global nickel supply and given the growing demand for nickel sulphate (and cobalt), its share is expected to increase in the future.
- Though the back-end of plants differ based on what product is recovered, the core of all operations is generally the same, namely:



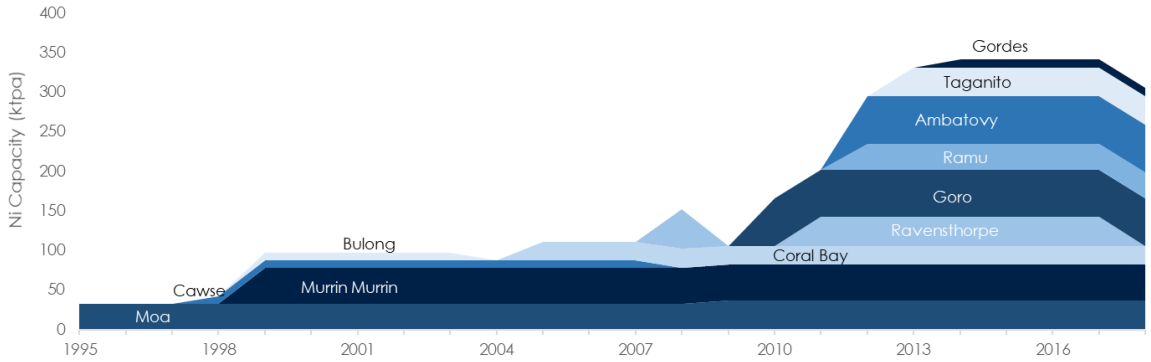
- Slurry is reacted with sulphuric acid in the autoclave to leach nickel and cobalt, on average at 255°C and 4,500kPa, +17% and +54% respectively vs. POX. The CCD wash then separates out the residue (mostly iron oxide), before acid neutralisation and sulphide precipitation.
- Aside from nickel grades the main consideration in HPAL is the amount of acid consuming agents in the autoclave feed, with sulphuric acid representing the biggest component of opex. Leaving aside iron (which reprecipitates as hematite, regenerating acid), the principle acid consuming elements are **magnesium** and **aluminium**. In general:
- Acid consumption (kg/t) = 55 + 36.1(Mg) + 28.8(Al), or on average 260-400kg/t at existing operations.
- This equation dictates why you want an autoclave feed which is generally sub 5% Mg, largely precluding saprolite feeds.
- **Alternatives?** Direct Nickel continues to be investigated, though solutions are highly corrosive, as is the case with chloride leaching. Others remain niche - Heap Leaching is reliant on low iron content, Atmospheric Leaching (and EPAL) requires more sulphuric acid and costs are not dissimilar to HPAL.

HPAL Operations

Operation	Start-End	Design Production	Processing	Plant	HPAL	Autoclaves	Temp	Pressure	Diameter	Length	Ni	Acid	GMR Score
Moa	1959	37ktpa Ni, 3.7ktpa Co	Limonite	HPAL	3.4Mtpa	4	255°C	4,500kPa	3.0m	15.2m	1.30%	260kg/t	10/10
Murrin Murrin	1999	45ktpa Ni, 3.0ktpa Co	Smectite/Blend	HPAL	4.0Mtpa	4	255°C	4,450kPa	5.0m	35.0m	1.24%	400kg/t	7/10
Cawse	1998-08	9ktpa Ni, 2.0kt Co	Limonite	HPAL	0.5Mtpa	1	250°C	4,500kPa	4.6m	27.0m	1.69%	375kg/t	6/10
Bulong	1999-03	10ktpa Ni, 0.9ktpa Co	Smectite	HPAL	0.6Mtpa	1	250°C	4,000kPa	4.6m	28.6m	1.70%	518kg/t	3/10
Coral Bay	2005	24ktpa Ni, 1.9ktpa Co	Limonite	HPAL	2.4Mtpa	2	245°C	4,450kPa	4.7m	N/A	1.26%	N/A	9/10
Ravensthorpe	2007-17	36ktpa Ni, 1.3ktpa Co	Lim/Saprolite	EPAL	2.0Mtpa	2	250°C	4,500kPa	4.6m	24.1m	1.65%	332kg/t	5/10
Goro	2010	60ktpa Ni, 4.5ktpa Co	Lim/Saprolite	HPAL	4.0Mtpa	3	270°C	5,600kPa	4.3m	30.0m	1.50%	355kg/t	5/10
Ambatovy	2012	60ktpa Ni, 5.6ktpa Co	Limonite	HPAL	6.1Mtpa	5	260°C	N/A	5.2m	37.0m	1.13%		6/10
Ramu	2012	33ktpa Ni, 3.3ktpa Co	Lim/Saprolite	HPAL	3.4Mtpa	3	255°C	4,200kPa	5.1m	34.0m	1.15%	260kg/t	8/10
Taganito	2013	36ktpa Ni, 2.6ktpa Co	Limonite	HPAL	3.4Mtpa	2	245°C	4,450kPa	5.7m	36.1m	1.25%	N/A	8/10
Gördes	2014	10ktpa Ni, 0.8ktpa Co	Limonite	HPAL	1.4Mtpa	1	255°C	4,600kPa	5.2m	27.0m	N/A	N/A	?
Avg. POX (Gold)	N/A	N/A	N/A	POX	3.8Mtpa	2.7	217°C	2,907kPa	N/A	N/A	N/A	N/A	9/10

Source – GMR

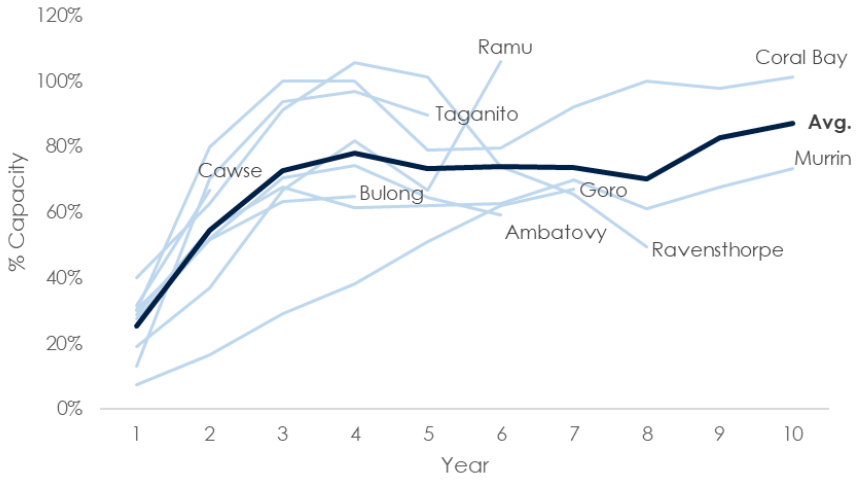
- At an average score of below 7/10 it's fair to say the history of HPAL isn't littered with successes. Despite recoveries being achieved as expected, capex and opex blow-outs, slow ramp-ups and a depressed nickel (and cobalt) market have contributed to most operations struggling to operate profitably.
- **Looking at capacity over time:**



Source – GMR.

Ramp-Up Risks

- **On average it takes ~4 years to achieve 80% of nameplate production capacity**, much longer than typical ramp-ups at POX plants. In addition design capacity is often never achieved.
- **HPAL plant ramp-ups over time:**

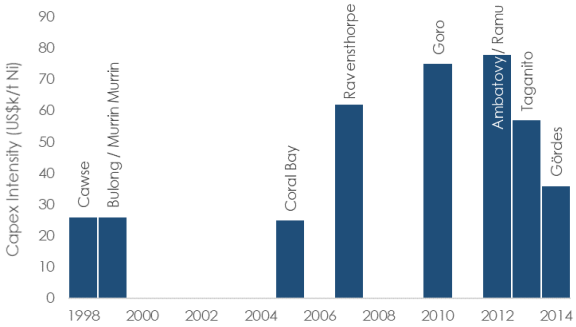


Source – GMR. Excludes Moa & Gördes.

- Clearly a protracted ramp-up has a significant knock-on effect on capital requirements. For example while Ambatovy was built for US$5.5B, it has required a further ~US$1.7B of working capital during its ramp-up.
- Notable failures include Bulong, Goro and Murrin Murrin. In addition though Ravensthorpe achieved First Quantum's revised capacity on restart (if only temporarily), it never met BHP/Comet's original design rate.

Capex & Opex

- **Capex:** Average capital intensity has been US$49k/t, though ranging from US$16k/t to US$92k/t. However this is spread across over nearly two decades and ignores plant complexity (e.g. briquette vs. MHP).



Source – GMR. Excludes working capital requirements. Multi project years are unweighted averages.

- **Opex:** Most producers do not report unit costs (especially during ramp-up), but Moa is the lowest with a US$2.35/lb cash cost in 2017, driven in part by low acid consumption. To highlight a few operations – US$/lb Ni cash costs (net):

	2012	2013	2014	2015	2016	2017
Moa	4.94	5.52	4.99	3.88	3.42	2.35
Ambatovy	-	-	7.04	4.83	4.27	3.83
Goro	-	-	-	9.28	5.65	4.56

- **Cobalt:** The impact of the recent price rise should not be understated. Stripping out the cobalt by-product credit:

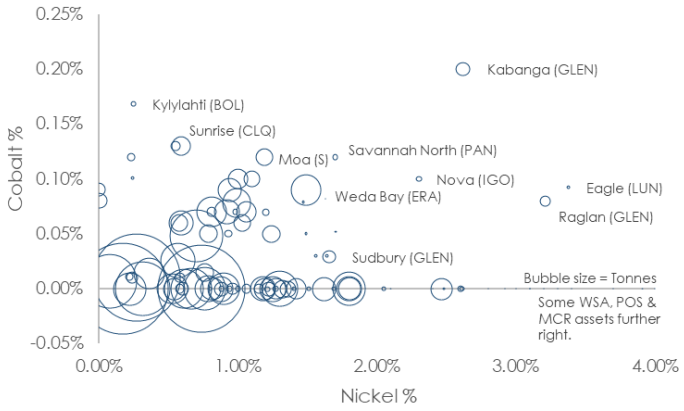
	2012	2013	2014	2015	2016	2017
Moa - Mining, Processing & Refining	6.55	6.56	6.24	5.15	4.63	4.80
Cobalt by-products	-1.41	-1.21	-1.34	-1.36	-1.26	**-2.90**
Ambatovy - Mining, Processing & Refining	-	-	7.82	5.49	4.89	6.01
Cobalt by-products	-	-	-0.87	-1.09	-0.82	**-2.35**

HPAL & Cobalt

- As the previous slide illustrated, the rise in cobalt prices has significantly reduced HPAL by-product costs, a benefit which non-HPAL laterite operations do not feel (e.g. most pyrometallurgical process routes lose all the cobalt). That means **if we are in a sustained bull market for cobalt, then the HPAL cost base has been fundamentally lowered.**
- Many projects are already reacting to this – For example we've seen a number of HPAL developers re-work their resource estimate based on a cobalt cut-off. For example:

		Before			After			
Ticker	**Project**	**Tonnes (kt)**	**Ni**	**Co**	**Tonnes (kt)**	**Ni**	**Co**	**Cut-off change**
ARL	**Kalgoorlie**	797,600	0.70%	0.05%	64,400	0.77%	0.13%	From 0.5% Ni to 0.08% Co
CLQ	**Sunrise**	109,000	0.65%	0.10%	101,000	0.59%	0.13%	From 0.6% NiEq to 0.06% Co
MLX	**Wingellina**	182,560	0.92%	0.07%	85,900	?	0.11%	From 0.5% Ni to 0.05% Co
PGM	**Owendale**	33,700	0.11%	0.06%	17,600	0.23%	0.12%	From 300ppm Sc to 0.08% Co

- **But they remain nickel projects:** As it stands a tonne of cobalt is worth 6x a tonne of nickel, but the average HPAL operation produces 12x as much nickel as cobalt. While operations will no doubt increasingly emphasize cobalt production, at the end of the day these remain nickel projects.
- Looking at nickel resources globally (including the majority that don't report cobalt grades):



Source – GMR.

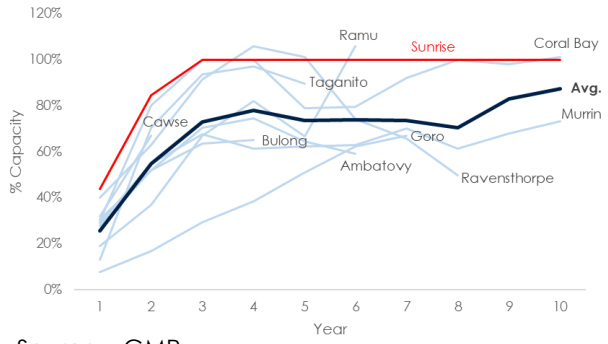
Cobalt Streams? A number of producers have reportedly been considering selling a stream, for example Vale is reportedly looking at selling a US$500M stream at Voisey's Bay.

Critiquing CleanTeq et al.

- Understandably HPAL's high capex and opex has discouraged many developers who instead seek alternative processing options. For example **Mindoro's** Agata switched to a DSO development and **Eramet's** Weda Bay to a pyrometallurgical option (from AL).
- Those remaining include the likes of Vermelho, Pomalaa, Owendale and San Felipe. However of all the developers **Clean Teq's** Sunrise project has attracted the most interest. Comparing it to a few Aussie peers:

Projects	Nameplate Production	HPAL Capacity	Autoclaves	Capex	Intensity	Ni	MgO	Al_2O_3	Acid	Resource
Sunrise	19ktpa Ni, 3.2ktpa Co	2.5Mtpa	2	US$0.8B	US$41k/t	0.80%	<1.0%	2.50%	240-290kg/t	101Mt at 0.59% Ni, 0.13% Co
Wingellina	40ktpa Ni, 3.0ktpa Co	4.3Mtpa	3	US$2.0B	US$50k/t	1.05%	1.52%	5.63%	270kg/t	183Mt at 0.92% Ni, 0.07% Co
Sconi	5ktpa Ni, 0.7ktpa Co	0.8Mtpa	1	-	-	0.81%	-	-	-	89Mt at 0.58% Ni, 0.06% Co
Goongarrie	15ktpa Ni, 2.0ktpa Co	1.5Mtpa	1	-	-	0.77%	-	-	-	64Mt at 0.77% Ni, 0.13% Co

- **Capex:** At US$41k/t CLQ capex seems too low to us, even though it excludes a number of supporting infrastructure costs (gas pipeline, fleet etc). US$1.2-1.5B is where expect it to end up based on historical averages. Arguably more important however is clarity on their working capital assumption.
- **Opex:** CLQ forecasts US$3.48/lb, which if you compare it to 2016 operating costs elsewhere (i.e. stripping out the cobalt impact), it would be the lowest cost HPAL project globally. That seems highly unlikely to me. Acid consumption is going to be low, in-line with the likes of Moa and Ramu, but expected nickel grades are much lower than anything currently in operation (0.8% vs. an average of 1.4%).
- **Ramp-Up:**



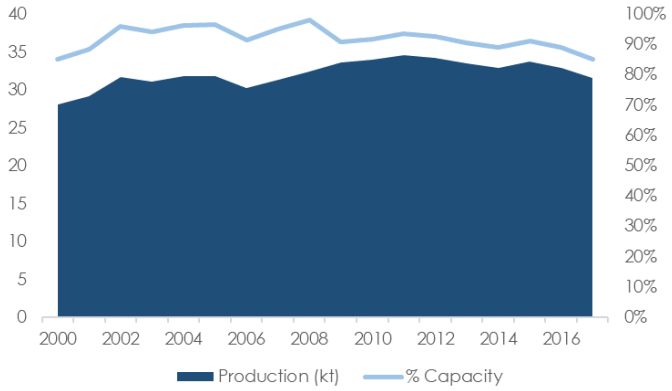
Source – GMR.

My main critique of CLQ is their ramp-up projection: 44% in year one and 84% in year two appears optimistic, and this assumption dictates expected working capital requirements.

Reviewing HPAL Operations

Moa (50% Sherritt, 50% Cuba)

- **History:** Moa was the world's first HPAL plant and it has been running continuously since 1961. Current capacity is 37ktpa Ni, with refining operations in Alberta producing nickel and cobalt in briquette form. An expansion to 49ktpa was abandoned in 2008. Lowest cost HPAL asset globally apparently.
- **Ore-type:** Mining is focused on the economically viable zone, known as the LB ('limonita balance'), defined as where nickel exceeds 1% and iron exceeds 35%. Below the limonite layer (which is generally 3-6m thick), nickel grades are also high in the underlying saprolite, but magnesium grades are also much higher. Moa Nickel, which only has rights to mine limonite, has completed mining in parts of its concessions, leaving the now-exposed saprolite available to mining by other companies (who are looking at starting a ferronickel process). The Camarioca Norte and Sur ores typically average 1.5-1.7% Mg and 6.4-7.5% SiO2, which is higher than ores historically processed at Moa. There is also a product blend of 2% Mg and 4% Mg limonite/saprolite.
- **Plant Capacity:** 3.4Mtpa for 37ktpa Ni as briquettes.
- **Capex:** N/A.
- **Autoclaves:** Four (arranged vertically). Operating conditions 255°C and 4,500kPa.
- **Operating History:**

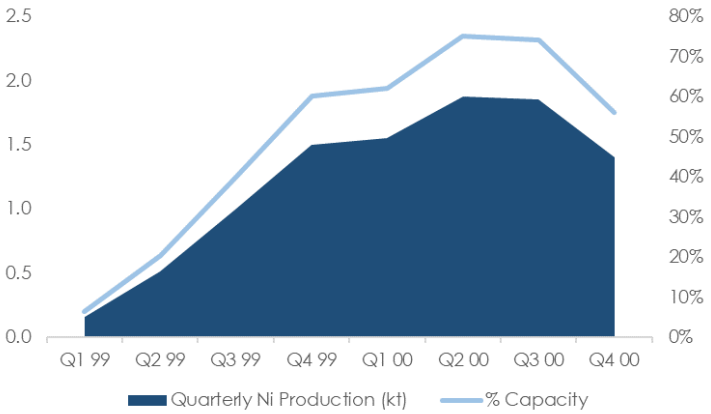


Source – GMR.

- **Key Takeaway:** The first HPAL operation, it continues to be the cost benchmark for all others.

Cawse (100% Wingstar)

- **History:** Centaur brought the Cawse project into production in late 1998 and while a relatively successful initial ramp-up, debt and mounting losses saw the company collapse in 2001. OM Group acquired the project in 2002, then Norilsk acquired OM Group's nickel assets in 2007. In 2008 the operation was closed, then in 2014 Wingstar acquired it.
- **Ore-type:** Though there is some smectite (nontronite), the bulk of resources is hosted in limonite clays which typically occur within 10-15m of surface and are 20-40m thick. Nickel is contained in a fine fraction, allowing the barren coarser silica to be screened out prior to leaching. This allowed Cawse to upgrade the ore by 30-50%. Reserves pre-commissioning were 30.3Mt at 1.0% Ni and 0.06% Co.
- **Plant Capacity:** 0.5Mtpa for 9ktpa Ni as cathode (though OMG later closed the SX-EQ and produced a precipitate). An expansion to 4Mtpa (45ktpa Ni) was initially considered in partnership with Anaconda. Considered the last of the three second generation plants.
- **Capex:** US$234M for 9ktpa (US$26k/t).
- **Autoclaves:** One. Operating conditions 250°C and 4,500kPa. Diameter 4.6m, length 27.0m.
- **Operating History:**

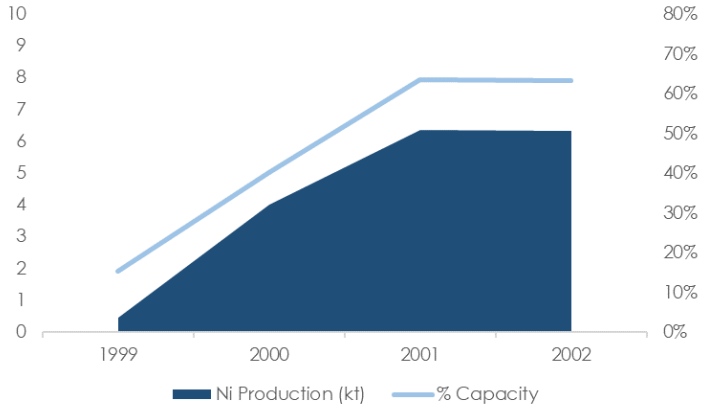


- **Key Takeaway:** Fairly successful, but too small to capitalise on it.

Source – GMR. Note operating statistics were not reported under OM/Norilsk ownership.

Bulong (100% Wingstar)

- **History:** In 1998 Preston Resources acquired the West Australian Bulong project off Resolute for A$319M. Production commenced in 1999 but ramp-up challenges, acid supply issues and mounting losses precipitated a collapse, with the project eventually shut-down in 2003. LionOre acquired the project in 2004, aiming to convert it into an Activox plant capable of processing 40ktpa Ni. However they were taken out by Norilsk in 2007 and in 2014 Wingstar acquired the (still closed) project, now called Avalon.
- **Ore-type:** Nickel and cobalt mineralisation is predominantly associated with smectite clays (nontronite), typically 20-30m thick. Ore is high in magnesium, with acid consumption the highest of all HPAL plants at >500kg/t. Prior to commencing production reserves were 41Mt at 1.14% Ni, 0.09% Co.
- **Plant Capacity:** 0.54Mtpa producing 10ktpa Ni as cathode (~99.8% Ni). Stage II was to see an expansion to 2.4Mtpa. The plant is considered the first of the second generation PAL projects, and it adopted the most innovative downstream process of the three second generation projects (sequential direct SX for Co & Ni, with final recovery of each by EW).
- **Capex:** ~US$160M for 10ktpa Ni (US$16k/t).
- **Autoclaves:** One. Operating conditions 250°C and 4,000kPa. Diameter, 4.6m, length 28.6m.
- **Operating History:**

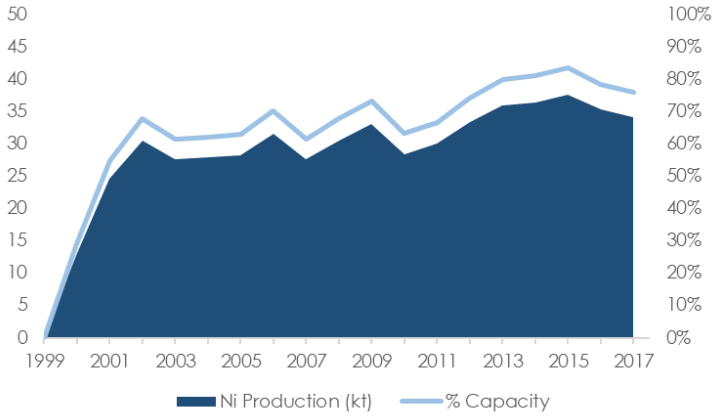


- **Key Takeaway:** A technical failure. Acid challenges, gypsum precipitation and mounting losses saw the project closed early.

Source – GMR.

Murrin Murrin (100% Glencore)

- **History:** Built by Anaconda (Forrest), the Murrin Murrin plant in Western Australia had a fairly tortuous commissioning leading eventually to Anaconda's debt restructure and recapitalisation, plus a rebranding to Minara. Production has never achieved 45ktpa Ni nameplate capacity and an initial plan to expand the operation to 115ktpa was dropped early on. Glencore acquired full ownership in 2011.
- **Ore-type:** Highest nickel and cobalt enrichment is within a smectite zone, consistently predominantly of smectite clay mineralogically dominated by nontronite. Some grade is also carried in saprolite and to a lesser extent limonite, with the plant treating a blended feed. Reserves have recently been more than halved to 104Mt at 1.05% Ni, 0.08% Co, from 2016's 238Mt at 0.94% Ni, 0.06% Co. This was driven primarily by a 'comprehensive re-optimisation of the ore body and mine plan'.
- **Plant Capacity:** Designed for 4.0Mtpa, 45ktpa Ni, capacity was de-rated to 40ktpa with nickel produced as briquettes. The plant is the largest of the second generational HPAL projects.
- **Capex:** US$1.3B. That's US$29k/t at design capacity, or more like US$33k/t of de-rated capacity.
- **Autoclaves:** Four operating at 255°C, 4,450kPa. Diameter 4.3m, length 37.0m.
- **Operating History:**

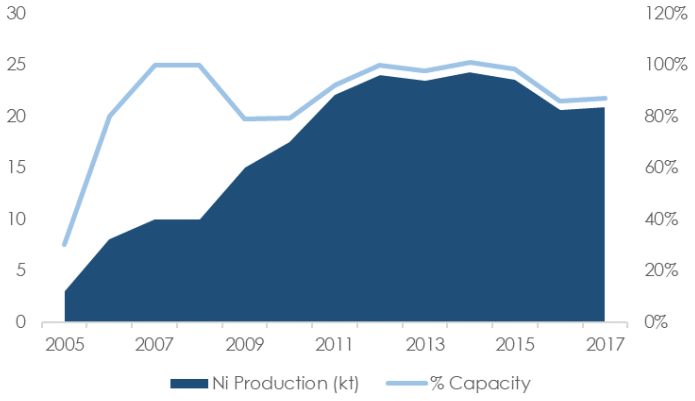


Source – GMR.

- **Key Takeaway:** It was called Murrin Murrin because they built it twice. A lesson in trying to build a plant too cheaply (Clean Teq) the lack of back-up systems, surge tanks and redundancy measures impacts to this day, despite a significant amount of work redone in its first two years. It remains challenged, as evidenced by the recent huge reserve reclassification.

Coral Bay (SMM 54%, Mitsui & Sojitz 18%, 10% Ni Asia)

- **History:** Since 1977 Nickel Asia's (60%) Rio Tuba mine in the Philippines has been mining saprolite ore, selling to FeNi smelters abroad. Lower grade limonite was stockpiled until the commissioning of the Coral Bay HPAL plant in 2005. The ramp-up was highly successful, reaching design rates within 15 months.
- **Ore-type:** Limonite, fed from Nickel Asia's Rio Tuba mine. Limonite reserves at Rio Tuba are 48.1Mt at 1.08% Ni, 35.7% Ni. Saprolite reserves are 19.8Mt at 1.51% Ni, 13.9% Fe. There are two limonite streams – Low grade Ni (1.0-1.2% Ni) is sent to the HPAL plant, while a high Fe feed (0.6-0.9% Ni, 48-50% Fe) is exported to be made into low grade NPI/PI.
- **Plant Capacity:** Originally 10ktpa, capacity was more than doubled in 2009 and now stands at 24ktpa Ni in the form of a mixed sulfide product containing 55-60% Ni. This is shipped to SMM's refineries to produce nickel sulfate. Cawse was the first of the third generation plants.
- **Capex:** US$0.2B for the initial 10ktpa (US$20k/t), US$0.3B for later 10ktpa expansion (US$31k/t), ex. a refinery.
- **Autoclaves:** Two. Diameter 4.7m. Operating conditions 245°C and 4,450kPa.
- **Operating History:**

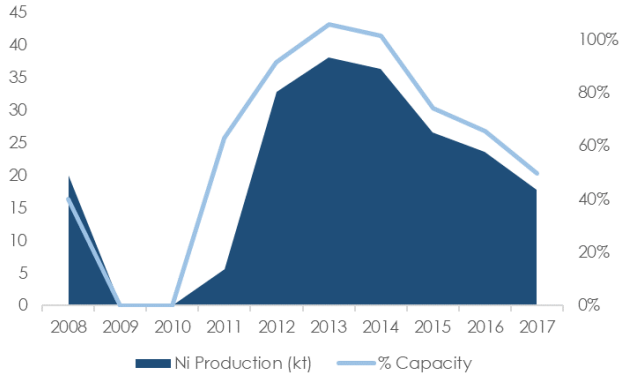


Source – GMR.

- **Key Takeaway:** The first operation to really succeed since Moa, it has been used as a template for future projects (e.g. Taganito).

Ravensthorpe (100% First Quantum)

- **History:** Originally developed by BHP for US$2.1B, first nickel was produced in Oct 2007. However following a little over 12-months of operations (~20kt Ni production), losses had amounted to US$678M (including Yabulu), driven primarily by a failure to reach nameplate capacity. C&M was instigated in Jan 2009 with FM then acquiring for US$340M in Feb 2010. It took 18-months and a further US$380M to restart, with the focus on a redesign of comminution and beneficiation areas. Operations restarted end 2011 (initially profitably), but after racking up losses of US$167M from 2015 closure was re-instigated in Oct 2017.
- **Ore-type:** Around 2/3^{rds} of laterite mineralisation is hosted in goethite/limonite, with nickel predominately associated with very fine-grained iron hydroxide minerals. The balance of mineralisation is within the upper levels of saprolite, bounded by a MgCa discontinuity. Reserves are low-grade at 199.4Mt at 0.6% Ni, 0.03%, with the low grade offset by significant beneficiation which almost doubles the leach grade.
- **Plant Capacity:** Originally 50ktpa, FM redesigned to 36ktpa, processing 3.5Mtpa via EPAL (2.0Mtpa PAL, 1.5Mtpa AL). Limonite is treated via PAL, saprolite via AL (though ~10% of saprolite can be treated via PAL, stretched to 25% when the AL tank failure occurred), with nickel produced as MHP.
- **Capex:** Originally US$2.1B for 50ktpa (US$42k/t), then US$2.5B for 36ktpa (US$69/t).
- **Autoclaves:** Two operating at 250°C, 4,500kPa. Diameter 4.6m, length 24.1m.
- **Operating History:**

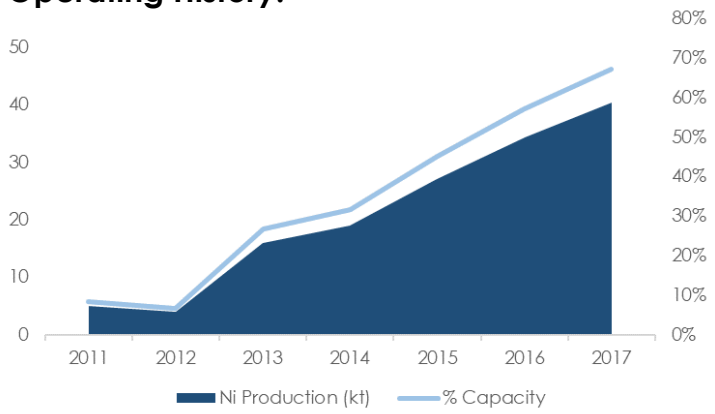


Source – GMR.

- **Key Takeaway:** BHP were alleged to have refused a higher bid by Murrin Murrin on the fear they could successfully restart it, and sold it for a lower price to First Quantum who were - surprisingly - technically successful.

Goro (95% Vale, 5% New Caledonia)

- **History:** Vale acquired the New Caledonian project as part of its 2006 Inco acquisition. Typical of the time capex costs ballooned prior to first production in 2008 and the project has struggled to reach nameplate capacity(triggering a clause that allowed SMM/Mitsui to put their stake back to Vale in 2016/17). The operation lost US$1.4B between 2014-16, with Vale subsequently seeking to sell down its stake in late 2017. There are currently no stated reserves, with Vale reclassifying 2014's 122Mt at 1.42% Ni to resources citing the fact that they were/are no longer economically viable.
- **Ore-type:** Very fine-grained limonite accounts for the bulk of resources at ~65%, with goethite the predominant mineral. It typically grades ~1.4% Ni, ~0.12% Co, ~0.8% MgO, ~5.6% Al_2O_3 and ~49% Fe. Some saprolite is processed alongside limonite despite much higher MgO levels – over 30% in places. Typical saprolite grades are ~2.1% Ni, ~0.10% Co, ~18% MgO, ~2.2% Al_2O_3 and ~18.6% Fe. Given the higher saprolite MgO there is a maximum acid to ore ratio (originally 0.37).
- **Plant Capacity:** 4Mtpa of both limonite and saprolite, producing 60ktpa as nickel oxide (~78% Ni).
- **Capex:** US$4.5B for 60ktpa (US$75k/t), up from an original US$1.5B.
- **Autoclaves:** Three. Operating conditions 270°C and 5,600kPa – Much higher pressure than peers.
- **Operating History:**

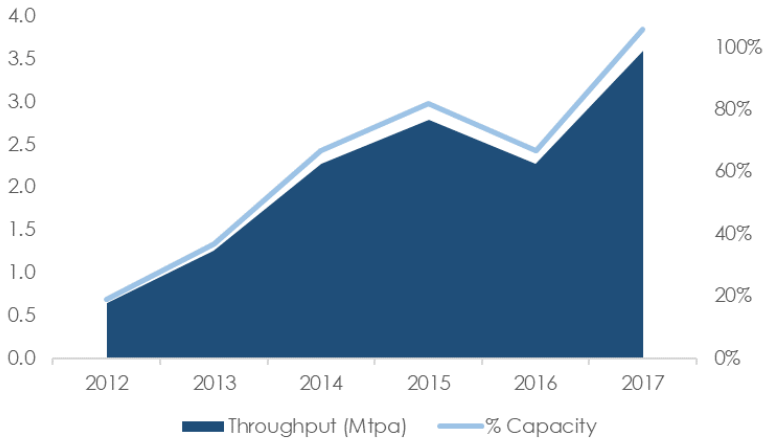


Source – GMR.

- **Key Takeaway:** One of the failures. The ramp-up has taken a huge amount of time, incurring significant losses. GMR estimates that since Inco started work on the project some US$10B has been spent to date, in today's dollars.

Ramu (8.6% Highlands, 6.4% PNG, MCC 85%)

- **History:** The Ramu HPAL operation is located in the Madang province of PNG. Discovered in 1962, Highlands took over management in 1992. Metallurgical Corp of China (MCC) joined the project in 2005, with construction completed in 2012.
- **Ore-type:** Limonite hosts the bulk of nickel and cobalt resources, averaging ~7.5m thickness and typically grading 1.6% Ni, 0.38% Mg. Mineralisation is primarily goethite, with garnierite occurring in minor quantities within saprolite. Some saprolite is also mined, with the enriched saprolite layer ~2.0m thick and typically 2.9% Ni. Reserves stand at 49Mt at 1.0% Ni, 0.1% Co.
- **Plant Capacity:** 3.4Mtpa for 33ktpa Ni as MHP.
- **Capex:** US$2.1B for 33ktpa Ni (US$64k/t).
- **Autoclaves:** Three operating at 255°C and 4,200kPa. 5.1m diameter, 34.0m length.
- **Operating History:**

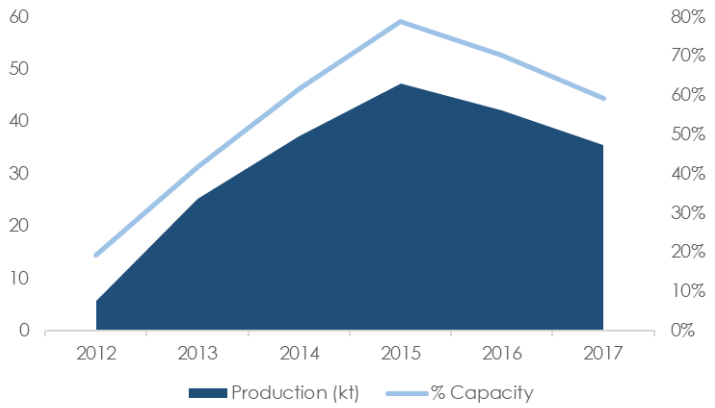


- **Key Takeaway:** Though a lengthy ramp-up, the project has successfully reached design capacity.

Source – GMR.

Ambatovy (12% Sherritt, 48% Sumitomo, 40% Kores)

- **History:** Discovered in 1960, modern history begins with Dynatec acquiring full control of the project from Phelps Dodge in 2005, then partnering with Sumitomo and Kores in 2006. In 2007 Sherritt became operator of the project acquiring Dynatec for US$1.7B, with construction starting shortly afterwards. First nickel was produced in 2012, and in 2017 ownership was restructured with Sherritt reducing its stake by 28% in return for eliminating US$1.3B of debt from its balance sheet.
- **Ore-type:** Limonite constitutes more than 90% of the economic grade of nickel mineralisation, typically with iron concentrations of 40-50%, predominantly in goethite. Reserves are 180.9Mt at 0.83% Ni, 0.08% Co.
- **Plant Capacity:** 6.0Mtpa, producing 60ktpa Ni, 5.6ktpa Co in the form of briquettes.
- **Capex:** US$5.5B for 60ktpa (US$92k/t), excluding ~US$1.7B of additional working capital during ramp-up.
- **Autoclaves:** Five operating at 260°C. Diameter 5.2m, length 37.0m. Volume 870m^3.
- **Operating History:**

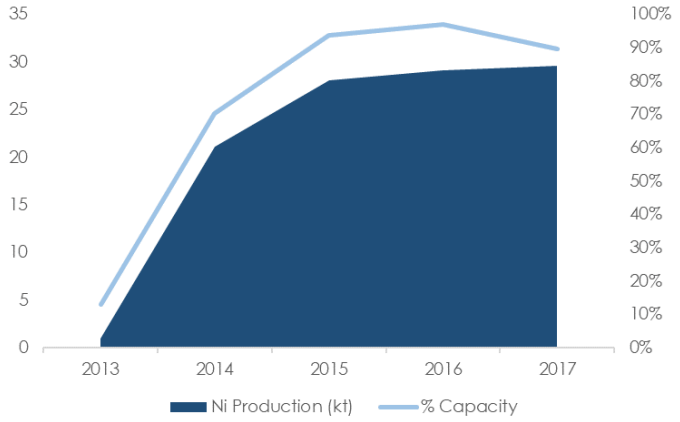


Source – GMR.

- **Key Takeaway:** Despite their renowned expertise in nickel technology and some clever financial engineering around the project, Ambatovy came close to bankrupting Sherritt, proving how difficult HPAL can be.

Taganito (75% SMM, 15% Mitsui, 10% Ni Asia)

- **History:** Similar to Coral Bay (Rio Tuba), the mine at Taganito in the Philippines operated long in advance of the HPAL plant. Since 1987 higher grade saprolite ore has been mined and exported to FeNi smelters, with lower grade limonite stockpiled. The decision to build the HPAL plant to process this material reflects the success of Coral Bay, and despite experiencing delays during construction and a typical capex overrun, since commissioning in late 2013 Taganito has been one of the more successful HPAL operations.
- **Ore-type:** Owned and operated by Nickel Asia (65%), the Taganito nickel mine has limonite reserves of 129.4Mt at 1.06% Ni, 46.1% Fe. Saprolite reserves are 57.2Mt at 1.49% Ni, 9.8% Fe. There are two limonite streams – Low grade (1.0-1.2% Ni) is sent to the HPAL plant, while a high Fe feed (0.6-0.9% Ni, 48-50% Fe) is exported to be made into low grade NPI/PI.
- **Plant Capacity:** Originally 30ktpa, the plant was expanded in 2017 to 36ktpa Ni in the form of a mixed sulfide product containing 55-60% Ni. This is shipped to SMM's refineries to produce nickel sulfate.
- **Capex:** US$1.7B (up from US$1.3B) for 30ktpa (US$57k/t), ex. a refinery.
- **Autoclaves:** Two operating at 245°C and 4,450kPa. Diameter 5.7m, length 36.1m. Volume 1,008m^3.
- **Operating History:**



Source – GMR.

- **Key Takeaway:** One of the few successes, SMM has been able to replicate its experience at Coral Bay.

Gördes (50% Zorlu, 50% GSR)

- **History:** Owned by the Turkish conglomerate Zorlu Holding (and mining subsidiary Meta Nikel), Gordes is a laterite deposit in Turkey. Production commenced in 2014.
- **Ore-type:** Most of the nickel is contained in limonite with higher Fe grades and low MgO. The lower saprolite zone is less well developed. Reserves are reportedly 300kt of contained nickel, though grades are not publicised.
- **Plant Capacity:** 1.4Mtpa (10ktpa Ni) as MHP. A doubling of capacity was planned in Stage II, but with the recent GSR deal capacity is now expected to be increased to 40ktpa.
- **Capex:** US$360M (US$36k/t). Including Stage II capex is expected to total US$860M.
- **Autoclaves:** One operating at 255°C, 4,600kPa. Diameter 5.2m, length 27.0m.
- **Operating History:**

- **Key Takeaway:** Last month Zorlu signed a deal with **GSR Capital**, the Chinese private equity firm, where GSR will invest US$4.5B by 2023 building a 25k MW battery plant for use in EVs and energy storage, plus partnering with Meta Nikel. This is the same PE firm which last year acquired Nissan's battery business for US$1B, and who have also been eyeing a 20% stake in SQM.

Conclusion

- As EV/battery demand continues to grow greater amounts of nickel sulphate are going to be required. In the near-medium term that demand will be met from existing Class I producers like BHP, but growing deficits are going to require new sources in the future.
- Given the increasing scarcity of large, high-quality sulphide deposits, that means further development of nickel laterites.
- For Class I nickel that means new HPAL projects, with stainless steel demand continuing to be well supplied by FeNi and NPI producers.
- HPAL clearly has a mixed track-record, but when working well operations are cost competitive, particularly given the recent run in cobalt prices.
- However the failures cannot be overlooked, and developers need to be more realistic about expected ramp-up targets, lest the sins of the past be repeated.

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