AN ENGINEERING MODEL FOR INNOVATION IN THE MINING INDUSTRY

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ABSTRACT

There is no doubt that the word and concept of "innovation" is over-used today. Most reported innovation is merely incremental improvement and "business as usual". While incremental improvement is important, true innovation is transformational or business disruptive and requires a driving force of great need for the innovation to occur ("necessity is the mother of invention"). For the mining industry these driving forces have historically been forced upon us from external factors e.g., government regulation, societal and environmental pressures, low grades or "dirty ore-bodies" etc. While we recognise the need for innovation, we often find it difficult to get traction as an internal motivation is required when often there is no apparent need to do anything … "right now".

To help focus on the key parameters of innovation and especially the key requirement of driving force it may help to think about innovation as an analogy to heat and mass transfer e.g., heat transfer = h x A x ΔT or rate of mass transfer = k_L x a x (c*-c)

That is ……. innovation rate transfer, $r_i = k_i \times A_i \times \Delta St_i$

With:-

r_i: Innovation rate transfer is defined as the speed at which innovation adds value to a business.

ΔSt_i: For innovation driving force ΔSt_i this could be defined as ("future state position") – ("current state position"). Like heat and/or mass transfer, innovation cannot occur without a driving force. A key role for management is to define the vision and driving force for innovation and anticipate or drive towards desirable future states.

ki : An equivalent of the heat and/or mass transfer co-efficient in "doing innovation". There must also be sufficient "agitators" or effective agents of change within an organisation to make change happen. A low ki means slow progress, however often organisations can become too focussed on ki without clearly defining the ΔSti and throw "resources at innovation, hoping for the best.

Ai: Ai could be thought of as the extent to which the innovation could be applied across a business.

These factors and the interrelationships between them are explored further especially the key driving force ΔSti.

Keywords

innovation, gold

INTRODUCTION

The word "innovation" is over-used today. Most reported innovation is merely incremental improvement or "business as usual" and while important, true innovation is transformational or business disruptive and requires a driving force of great need for the innovation to occur (hence the old saying "necessity is the mother of invention").

The mining industry is well-known for being very conservative and major disruptive change occurs very slowly. Sometimes change is forced upon us by the orebodies themselves e.g., lower grades, "dirtier" or deeper and sometimes by environmental regulation and/or by societal pressure - the "licence to operate". Unfortunately, we are mainly reactive, and we rarely anticipate major change before it is upon us!

Historically the great mining companies of the world became "great" based upon the discovery and development of large, high-grade, and near-surface orebodies. Exploration for these "Elephant Class" orebodies continues all over the world however there is no doubt, they are becoming rarer. The deposits we do discover today are generally deep, low grade and with a high cost to develop and operate. Faced with such difficult orebodies there appears to be a strong need for innovative disruptive technologies throughout the entire mining value chain - just to stay profitable.

While staying profitable is essential, perhaps the <u>future</u> great mining companies of the world will become "great" by applying breakthrough innovations? Applying transformational innovative technologies to difficult orebodies rather than relying on the discovery of large and easy to develop high-grade orebodies would be a major change indeed.

Could this happen? Maybe. But with our history of slow innovation adoption, it does not bode well.

So, what actually prevents us developing and applying transformational innovations to current, let alone future orebodies?

Put simply, true innovation is hard work, really hard work. To quote Thomas Edison, "genius is 1% inspiration and 99% perspiration". Once a breakthrough has been made it is still often extremely difficult to get traction within a mining organisation especially if there is not an immediately obvious "burning bridge".

To help transformational and innovative technologies get traction this paper explores the use of a model for innovation. An <u>Innovation Equation</u> is proposed that uses a mass and heat transfer analogy to breakdown the key components of innovation. Perhaps this will allow additional structure for focussed innovative thinking, planning, and for the implementation of new and disruptive technologies?

HISTORICAL INNOVATION

In the long distant past, major mining companies supported large internal R&D departments and they were, at least partially, responsible for the development of transformational and innovative ideas and technologies. However, most, if not all, of these internal groups are long gone, unable to survive the short-term focus of cost cutting by non-technical management in a very cyclical industry.

Importantly and at the same time in Australia (and in other parts of the world?) taxpayer funded R&D at universities and institutions like CSIRO also suffered major funding cutbacks. The government directive is to seek more industry funding. The impact has been profound.

So, who is "doing" innovation today in the mining industry?

Faced with a "business improvement" focus and no internal support structures like R&D departments, laboratories etc, it is generally small groups of key individuals within mining companies that provide the drive for innovation. To move forward we have been forced to develop new mechanisms. For example collaboration, in a variety of formats, is gaining traction as a way of sharing cost and risk. These collaborations will often include universities, other research institutions and METS organisations for example – all trying to share risk and cost.

While the concept of collaboration is not new the use has grown significantly and in new and inventive ways like for example digital "open-sourcing" of challenges and opportunities and the use of public "brain-storming" type events.

A MODEL FOR INNOVATION - AN INNOVATION EQUATION

All businesses want to be "innovative" and they want any new technologies to make an immediate impact on the "bottom line". In the eyes of management there is little value making a significant discovery if it cannot be used and used quickly - otherwise it is seen as an "academic" curiosity. This is understandable to some extent. However, not well understood by non-technical managers is that the development and implementation of new technologies can be long and costly, even when working collaboratively.

So how do we maintain the focus of an organisation when a new technology can take years or even decades to develop and implement? This is especially an issue in the modern western business world when the average tenure of a CEO is five to seven years. By the time a truly disruptive technology is developed and implemented several versions of executive management may have "come and gone" in the meantime. Each iteration needs to "buy-in" to the vision developed by others which can often be a major issue.

It is possible to create focus when developing and implementing new technologies over many "generations" of management, but there must be absolute clarity of vision as well as dedicated and sufficient resources.

What exactly is the problem are we trying to solve or opportunity we are trying to exploit and what is the driving force for change? Clear problem or opportunity definition is critical.

Hence for innovation to proceed and proceed quickly we need three key features:

1. There must be a clear and large driving force for change. The driving force could be financial or reducing risk profile perhaps. There must be significant incentive for transformational and disruptive change.

2. Can the innovation be widely applied across a business? Disruptive technologies are fundamentally disruptive due to their wide application.

3. There must be ample effective resources assigned to develop and implement change. The greater the resources assigned the quicker innovation is created and deployed.

These features appear familiar to engineers. Similar to the well-known heat and mass transfer relationships shown in (Eqn 1) and (Eqn 2) shown below :-

Rate of heat transfer, $q = h \times A \times \Delta T$ (Eqn 1)

Rate of mass transfer, $j = k_L \times a \times (c^* - c)$) (Eqn 2)

Perhaps it is possible to use a heat and mass transfer analogy to help define the value of a new technology? Can it also help structure our approach to implementing an innovation as quickly as possible by breaking up "innovation" into its key mass and heat transfer analogue features allowing focus on the "rate limiting" components.

And of course, as engineers we like to have equations!

Hence the **Innovation Equation** proposed is shown below in Equation 3 :-

rate of innovation transfer, $r_i = k_i \times A_i \times \Delta St_i$ (Eqn 3)

Where:-

r_i: Rate of innovation transfer: Defined as the speed at which innovation value is created and employed into a business (or industry). Value could be in terms of incremental cash flow or rate of NPV increase (rate of growth) or rate at which risk is reduced. It is rate based. We want innovative, transformational, and disruptive change to add value as quickly as possible.

ΔSt_i: Innovation Driving Force: This is defined as the difference between what a possible future state (St) could look like, compared with the current state or ["future state position"] – ["current state position"]. The future and current states could be expressed in total cash generated, NPV or risk profile for example.

A key role for mining boards and executive management is to define the future technology vision – the future "state". What do we want our businesses to look like and what is the role of technology in those visions? This is key to defining the driving force for innovation and it is much better to do this before being forced to by regulation or by poor orebodies. Leadership within our mining companies is critically important and the horizon must be looking forward 10, 20 and even 50 years into the future. Where do we want our businesses to be positioned? Can we define a future where we are more profitable and/or run a lower risk profile than our competitors?

Importantly it is also critical that there is a clear understanding of global trends and to "see" future limitations and opportunities for our businesses e.g., climate change, renewable energy and the cost of power, artificial intelligence, robotics, environmental limitations, and the on-going nationalisation of mining (in some jurisdictions) are just a few examples.

For heat and mass transfer the driving force describes the fundamental problem at hand – e.g., how to heat or cool something (at some rate) or how to cause a desired chemical/physical reaction to occur quickly. A large driving force generally means a smaller heat exchanger or a smaller reactor. This of course leads to lower costs for the same rate of transfer. For heat and mass transfer the driving force is self-evident but the driving force for innovation or disruptive/transformational change is not so easy to quantify. However, like heat and mass transfer, without a major driving force disruptive innovative change cannot happen or it happens slowly. Most truly disruptive technologies inherently have large driving forces which can often come from outside the business for example recent changes to tailings disposal standards and regulations based on societal expectations.

Sometimes it can be as simple as defining a clear "what if ….". For example, what if we could extract metals from the ground with minimal or no disturbance to the earth at low cost (i.e., hard rock in-situ recovery)

Mapping out the future states for a business is a key management activity and it must be done frequently as the pace of disruptive global trends and external change quickens. This is much more than the usual five-year business planning cycle this is about setting long-term technology targets and clearly defining future states to force rapid transformational change within a business.

A_i: The Innovation Transfer Extent. Defined as the extent to which the innovation can be applied across a business or perhaps an entire industry.

In heat transfer, this is easy to understand e.g., the surface area of a heat exchanger for example.

For innovation there has to be an application for new technology otherwise it is just academic curiosity. New technologies develop much quicker when there is an orebody to apply it to. Some would argue that without a target orebody or application innovation will not happen at all.

Transformational or disruptive technology is only disruptive if it has wide commercial application.

A_i could be the number of sites within a business to which a new technology could be applied for example.

k_i : The innovation transfer co-efficient. This is equivalent to the familiar heat and/or mass transfer co-efficient. There must be sufficient "action" (turbulence) or activity to create and develop disruptive and transformational change. There must be effective "agents of change" within an organisation to make change happen. There must be money and other resources applied.

The innovation transfer co-efficient can also be thought of as the resources or "horsepower" applied. These resources could be intellectual manpower, money, physical facilities like laboratories and equipment or the way a technology is developed e.g., by use of collaboration. However, having a large and dedicated "innovation department" and unlimited resources doesn't necessarily mean a technology is developed quickly. The need or driving force must also be significant and there must be an orebody, site or prospect needing the innovation for application.

A low k_i will mean slow progress even if the driving force is high.

Interestingly many organisations can become too focussed on k_i without clearly defining the ΔS_{ti} and throw resources at innovation - almost hoping for the best. This can lead to waste and sometimes to a perception that innovation "doesn't work for us".

Negative Influences on the Rate of Innovation Transfer

Implementing innovative technologies is hard work and there are many pitfalls in the implementation journey as shown in the Figure 1 below (Ref 8). A key role for management responsible in implementing new technologies is to guide them through the pitfalls. This is hard work, requiring significant effort.

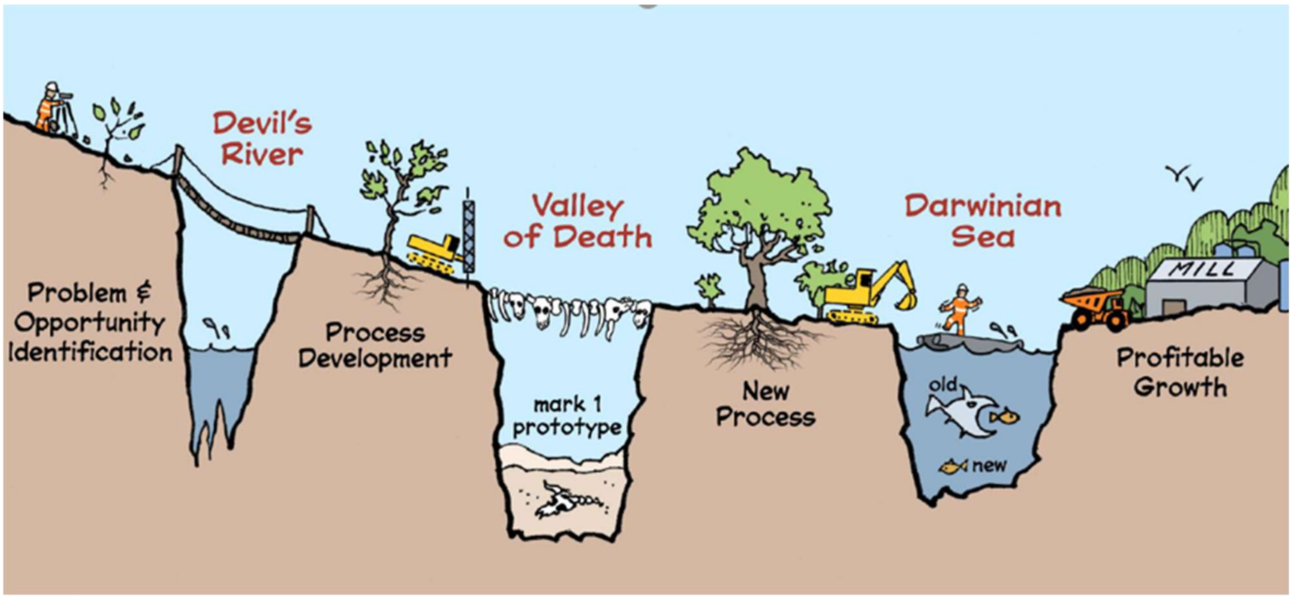


Figure 1 : The Perilous Innovation Journey

In addition, if internal politics and bureaucracy reigns supreme, then innovation is easily stifled. Organisations can simply become too large with too many management levels. It should be of no surprise that smaller companies are often more agile and more innovative.

It is also no surprise that the innovation "arm" of a company is sometimes split away from the parent company such as Glencore Technology or Outotec.

A somewhat "tongue-in-cheek" equation for this effect is $r = f(n^m)$ where r = internal resistance to new ideas, n = number of employees and m = number of management levels. From the author's experience over several decades, this relationship is unfortunately quite accurate with the number of management levels between innovation leaders and the CEO/Board important.

Anything and everything we can do to reduce the number of low-value-add workflow steps within an organisation will inevitably lead to faster progress.

APPLYING THE INNOVATION EQUATION TO THE GOLD INDUSTRY

Use of the Innovation Equation is explored further in several key gold industry examples.

Example 1: Non-Cyanide Lixiviants : *a tough nut to crack as cyanidation is the Bayer Process of gold processing*

How long have we, as an industry, been talking about non-cyanide lixiviants? We seem to be making only limited progress. Non-cyanide treatment has been discussed in many forums including here at ALTA on numerous occasions. There is a very large number of academic papers dedicated to non-cyanide lixiviants and numerous processes have been developed. Some have been patented.

Applying our new **Innovation Equation**.

rate of innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (Eqn 3)

ΔSt_i:

Future State: A "safe" cyanide free technology that is ~50% cheaper than cyanide

The current driving force for non-cyanide use is in most circumstances low. If a cyanide licence can be obtained, then it is used. No alterative process can compete with cyanide based on cost alone.

Hence, perhaps the focus for researchers should be on reducing the capital and operating cost of alternative lixiviant ore processing. If it is cheaper, it will be adopted.

A good analogy is the explosive growth in the use of small roof-top photo-voltaic (PV) cells by homeowners all over the world. People are perhaps not so much interested in "saving the planet"; the power is simply cheaper.

However sometimes the driving force can be large if cyanide cannot be used for metallurgical reasons e.g., the thiosulphate process of Barrick.

Sometimes the difference between developing a gold mine using a non-cyanide lixiviant or not developing the mine at all can create a clear driving force. However, these are not common factors and without a clear cost benefit non-cyanide lixiviants will probably continue to struggle to gain traction.

Cyanide is still relatively cheap, and the technology widely understood. But will this always be the case? Is there a future where the application of alternatives lixiviants is required? Will more metallurgically demanding orebodies make cyanide alternatives viable?

Also, no incumbent technology necessarily “stands still”. For example, development work on recycling of cyanide continues. If the cyanide leach process can be completely closed and there is no discharge to the environment will cyanide have an extended future? This would especially be the case if the cost of recycling is less than the cost of detoxification.

The future state is uncertain with no clear consensus in industry, academia, or government.

It should be noted however that the cost of cyanide treatment is increasing, especially with the use of very expensive cyanide destruction processes to comply with the Cyanide Code or other specific regulations so perhaps the cost gap is narrowing?

ΔSt_i appears low for now.

k_i: For non-cyanide lixiviants then interestingly k_i is quite high relative to the many other issues/opportunities in our industry. There have been numerous processes developed and studied over many decades and a lot of money has been spent investigating alternatives.

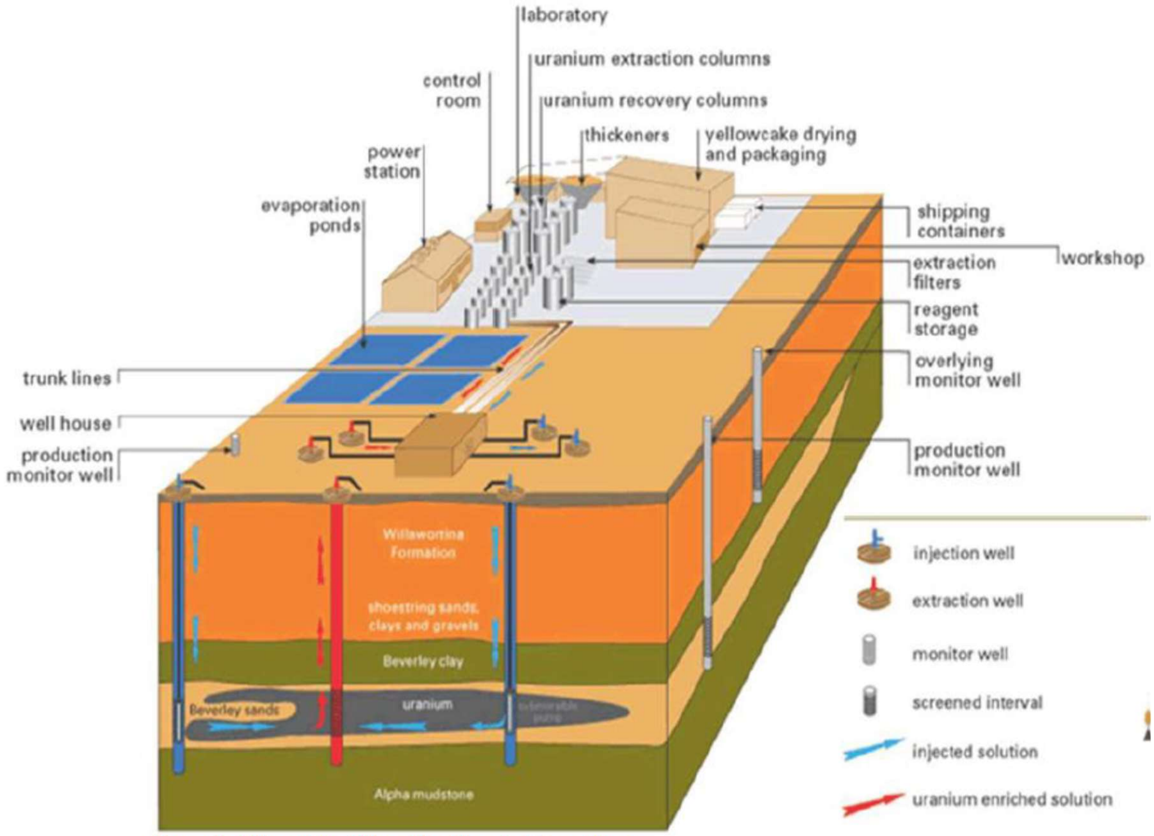
However, the focus should be on producing a cheap cyanide alternative. This would create much more activity.

A_i: Despite restrictions in some jurisdictions, cyanide continues to be widely used and widely applied to new projects.

A_i appears low and for now, the “king” reigns.

Example 2: Hard-rock In-situ Recovery (ISR): mining end-game

It is interesting that ISR has gained some traction in recent years including being part of the ALTA conference suite. ISR technology has of course been widely applied to the recovery of uranium when geology is favourable as shown in the Figure 2 below. However, application to hard rock is not commercially practiced at this stage.



Beverley Uranium Mine, Heathgate Resources Environmental Impact Statement

Figure 2 : Uranium In-Situ Leaching

The main challenges for hard-rock ISR are creating access, lixiviant and redox chemistry and solution containment.

Applying the **Innovation Equation**

rate of Innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (Eqn 3)

ΔSt_i:

Future State: No traditional mining, minimal surface land disturbance, no tailings with Capex and Opex costs < 50% of conventional mining and processing

The driving force for hard-rock ISR is theoretically large and increasing year after year as high-grade and relatively shallow deposits are mined out. Orebodies will become “stranded” without a viable means for economic recovery.

While there is some environmental and societal “kudos” from not physically mining the main advantage has to come from the lower cost of making metal. Applying conventional technologies to deep low-grade deposits is very expensive.

In the 2018 ALTA ISR conference the author presented some hypothetical “what if” numbers for an example hard-rock ISR for recovery of copper (Ref (1)). In that presentation the key assumptions made were that capex cost is 30% and opex 40% of conventional mining technology costs. Then for an equivalent 30 Mtpa copper concentrator the NPV increased from negative USD 1.8 bn to positive USD 3.3 bn. Based on these “what if” assumptions the economic driving force ΔSt_i is indeed significant.

A concept was also presented called Resource ISR whereby the entire orebody or large parts of the orebody is leached at the same time. This ensures a continuous high metal production rate despite a low rate of metal leaching. This is of course a very different approach to that adopted in existing ISR operations. Furthermore, is it possible to use the drill holes used to define the resource (and later reserve) and not incur the additional and very considerable cost of drilling? Figure 3 below shows an example of resource definition drilling holes - could they be retrofitted for leaching?

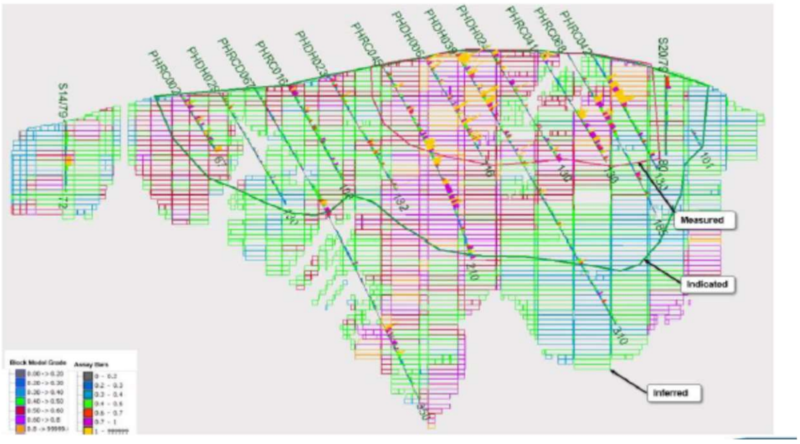


Figure 3 : Example of Resource Definition Drill Holes

The potentially highly attractive future state of hard-rock ISR simply cannot be ignored. Work in this area is expected to intensify and accelerate. Those organisations that can apply this technology first will have a significant advantage to their competitors – for a period at least.

ΔSt_i is high.

k_i: For hard-rock ISR, k_i is low but slowly increasing. There is some increasing interest amongst mining companies and researchers. Despite the huge potential driving force, the technology is perhaps seen as too difficult or too far into the future?

Significantly more resources are required if we want future success. Large scale collaboration inside and outside the mining industry is needed.

A_i: Historically with deposits near surface and high grade then conventional mining and processing technologies were used. However, the deposits being discovered today and into the future will be mainly low-grade, deep, and generally metallurgically difficult.

Hence A_i for hard-rock ISR is moderate but increasing rapidly.

Low-grade and deep deposits which will be simply uneconomic using current technologies if major breakthroughs do not occur.

Example 3 : "Dry" Tailings Disposal: *doing the* ***right*** *thing*

After numerous tailings storage facilities (TSF) failures over many years, some even leading to fatalities, it is clear we must change.

The images shown in Figure 4 below of the catastrophic failure of Feijao Dam 1, Brumadinho, Brazil, January 25, 2019, are disturbing to say the least (Ref (2)). While this particular failure is not gold related our issues are similar.

Figure 4 : Moments after the failure of Feijao Dam 1, Brumadinho (Ref (2))

Quickly disappearing are the days of storing large amounts of dilute tailings in huge earthen dams and that can only be rehabilitated at great cost. “Dry tailings” appears to be the future.

“Dry” tailings can refer to filtered tailings or paste thickened tailings mixed with mining waste. As well as lower risk, dry tailings storage often leads to water recovery and re-use as well.

Applying the **Innovation Equation**

rate of Innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (3)

ΔSt_i:

Future State: Very low risk tailings disposal at ~ USD 1.00/t waste deposited

The driving force for “dry tailings” is very high. It could be argued this is driven by community, governmental, environmental, and societal pressure in general.

Many mining companies are seeing this future state and are actively working towards it.

ΔSt_i is high.

k_i : For “dry” disposal k_i is large and increasing rapidly. Numerous equipment companies have risen to the challenge of supplying equipment that can cost-effectively de-water tailings. Geotechnical understanding is also rapidly improving. Most major mining companies are getting behind the change to “dry” tailings and numerous facilities are already in operation. Innovation focus is now shifting to reducing the cost of “dry” tailings disposal and there are many fascinating technologies emerging in this space.

Standards and protocols for tailings disposal are being created and adopted.

Community expectations are high.

A_i: More and more sites for “dry” disposal are being considered. Communities and governments are favouring “dry” and safe disposal.

A_i is high and increasing rapidly.

Example 4: Ultra Low Specific Energy Metal Recovery via Preconcentration, Early Waste Rejection and Low Energy Comminution: *stop grinding gangue*

As grades in gold mining drop (as in most metalliferous mining) margins are reducing and upfront capital costs for new mines are increasing almost directly in proportion to grade. Shown in Figure 5 below (Ref (3)) are Australian mined gold grades over time.

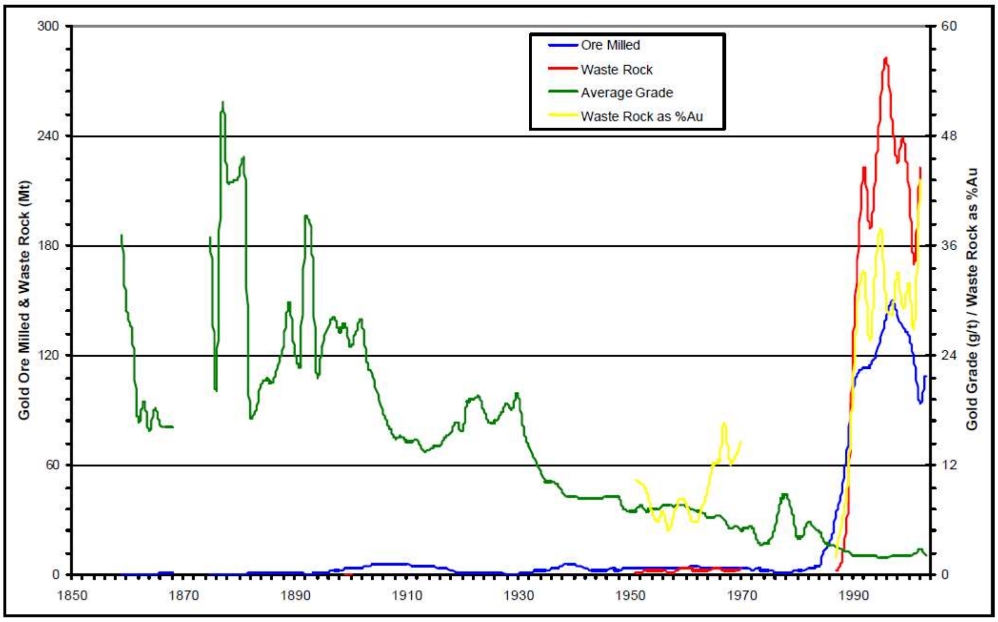


Figure 5 : Decline in mined gold grades in Australia from Ref (3)

There is reasonable industry activity focussing on reducing comminution cost and energy usage. Some technologies being pursued are:-

- dry grinding and other low and ultra-low grinding technologies
- early coarse waste rejection (pre-concentration) e.g., ore sorting (see Figure 6 below from Ref (4)) and bulk sensing technologies
- mine-face sensing technologies e.g., "ShovelSense"

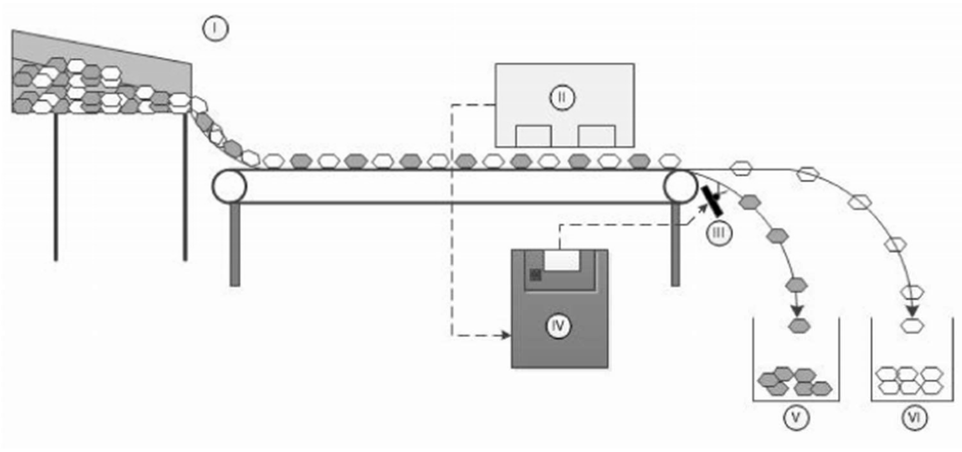


Figure 1. Belt-type sorter: (I) Material presentation by vibrating feeder and belt; (II) sensors; (III) ejection nozzle array; (IV) central processing unit (CPU); (V) drop fraction; and (VI) ejected fraction.

Figure 6 : Typical Ore Sorter from Ref (4)

Most of the energy used in a mine is used to crush and grind ore to a fine particle size. At lower and lower grades, a huge amount of energy is used to grind gangue for separation to occur. In addition, global drivers like carbon dioxide induced Climate Change and the need to reduce emissions is gaining momentum putting pressure on all heavy industries including mining.

The driver for reducing the amount of energy we use per tonne of metal produced is large. Disruptive innovations in this area are emerging quickly.

Applying the **Innovation Equation**.

rate of Innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (3)

ΔSt_i:

Future State: Overall comminution costs ~ 50-70% cheaper (per ounce of gold produced) than conventional technologies

The driving force for ultra-low energy metal recovery is high. And it is not just $/ounce of gold produced or tCO_2/tonne ore processed. Lower specific water usage and co-deposition of coarse waste/rejects for safer and lower cost tailings disposal are also drivers.

ΔSt_i is large and increasing rapidly

ki: For ultra-low energy metal recovery the activity and resources being applied is increasing slowly. Use of current technologies like ore sorting is advancing at a rapid pace. Emerging technologies like advanced sensing technologies at the mine face is gaining traction.

Dry grinding is gaining attention and while some of the equipment technologies are not new, applying to metalliferous mining is potentially disruptive.

In addition, low energy flotation technologies are emerging and developing rapidly

Numerous researchers are engaged and being supported in this innovation ecosystem.

However, it seems the full extent of the problem has not yet dawned on many mining companies and k_i appears moderate at best.

Ai: Use of ultra-low energy metal recovery technologies applies to most if not all mining operations around the world. Disruptive technologies in this space have the potential for significant market penetration and adoption.

Hence Ai is inherently large.

Example 5: Enhanced Heap and Dump Leaching: *make the old new again but "supercharged"*

These are old technologies that could, with some breakthroughs ("supercharging"), allow low-grade deposits to be viable. In many ways they are in-between the aspirational hard-rock ISR and conventional comminution separation circuits.

For gold it has historically been a popular technology however recovery is typically poor. A typical heap leach installation is shown below in Figure 7.

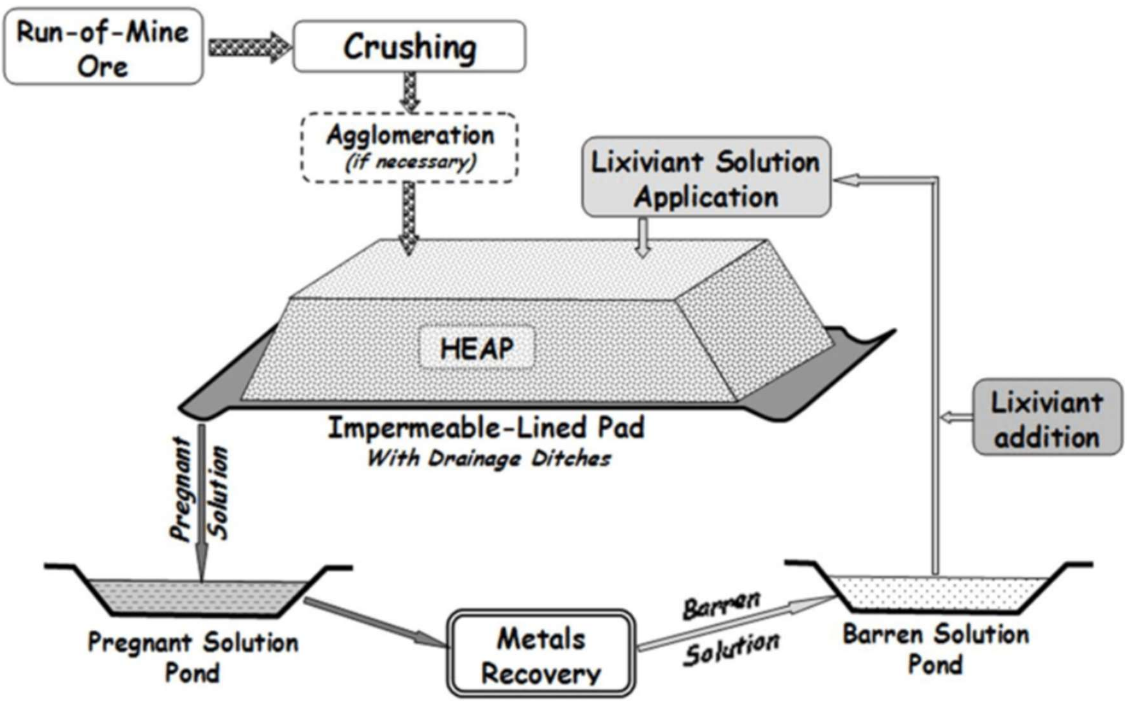


Figure 7 : Typical Heap Leach Flowsheet

"What if" …… we could treat all ores at <u>high recovery</u> and <u>low cost</u> in heap leaching? Can the technology be transformed?

Applying the **Innovation Equation**.

rate of innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (3)

ΔSt_i:

Future State: Heap or dump leaching of ores at high recovery and low cost in all environments

The driving force for "supercharged" heap and dump leaching is high. Since only crushing is used (or simply mining in the case of dump leaching) then less energy with lower CO_2/tonne of metal is attractive. No fine tailings are generated with less water required.

Could heap and dump leaching be perceived as a relatively "green" technology?

"What if" ….. instead of 50-70% gold recoveries we could achieve 90-95% recoveries in heap leaching - rapidly?

"What if" ….. refractory low-grade ores could also be treated in heap and dump leaching without expensive pre-treatment?

There is a strong driving force for disruptive innovation in heap/dump leaching.

k_i: The resources being applied in this ecosystem appears relatively low. Perhaps it is seen as "old tech" or that there is a perception that not much can be changed? In terms of the technologies used to move, stack and irrigate ore this may be true but innovative technologies to enhance overall recovery and the rate of recovery are being investigated by several groups.

Low metal recoveries are often tolerated due to the low cost of processing on low-grade ores. However, with additional research and clever engineering design can recoveries be increased?

Can heap leaching be applied to ROM grade ores with rapid metal extraction at high recoveries?

In addition, research, and practical experience into use of the technologies in extremely cold and high rainfall locations is continuing to further expand potential applications.

k_i is currently low but with more intensity and research this technology could be very attractive and even transformational.

A_i: Heap and dump leaching is used widely but has been historically limited to low-grade free-milling ores, moderate rainfall, flat terrain, and moderate temperature locations. There is now wider application into arctic and sub-artic areas.

A_i would appear to be moderate but increasing.

Example 6: Low Grade Gold-Copper Ores: *can copper (and other) by-products support low gold grade ores?*

Low-grade primary gold ores may not be economic and low-grade primary copper ores may not be economic. However, can a combined low-grade gold & copper ore together be economic? While there are some operating examples of these orebodies now can additional co-products like molybdenum, cobalt and even haematite itself (assuming pure enough) make a deposit even more viable?

In many ways it appears the gold and copper industries are "merging" over time? For the gold industry, low cost free-milling gold ores are disappearing fast and often we find primary orebodies containing copper and other potential co-products. For the copper industry large high-grade copper deposits will eventually deplete and gold, silver and other co-products in lower grade copper deposits will become more important over time.

This may drive future gold industry business rationalisation well beyond the gold industry itself. Will primary copper producers looking for the gold "edge" buy out gold producers in the future? Or vice-versa.

Lots of questions.

Gold production from such ores is likely to increase over time and already a significant proportion of the worlds primary gold production is from copper concentrates. Gold associated with copper sulphides and treated via flotation, flash smelting and anode slimes metal recovery can be very cost effective. The terms for gold in concentrate can be very attractive and often the overall (effective) recovery of gold is high via a smelting pathway anyway.

Hence a typical flowsheet of the future for low-grade gold and copper ores may be the gravity-float-leach (GFL) approach

- Gravity gold if viable should always be recovered up-front.
- Flotation of a copper concentrate for associated gold recovery, even at low copper grades, may be profitable.
- Pyrite treatment for gold e.g., from flotation cleaner tail.
- Finally, the now copper and sulphide free flotation tailings can be treated by conventional cyanidation at low reagent cost.

However, there are several challenges with these flowsheets and in no particular order:-

- High arsenic copper minerals and arsenopyrite?
- Other concentrate impurities like Sb, Hg, Bi incurring penalties, blending or impurity removal processes.
- High levels of pyrite and gold loss associated with a flotation cleaner tail fraction that may be refractory
- Marketing of lower copper and sulphur grade concentrates even with high gold "credits"
- Final flotation gold tail recoveries may be low making it difficult to justify further processing

Applying the **Innovation Equation**

rate of Innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (3)

ΔSt_i:

Future State: Low-grade gold-copper ores with significant by-product credits (like copper, silver, and molybdenum) will become the new "norm"

The driving force for improved processing of primary low-grade gold-copper orebodies appears significant. For some deposits low-cost impurity removal treatments for concentrates will be needed. For others gold recovery from pyrite may be required.

As is the case for the primary copper producers the historical ability to blend copper concentrates and "smear" impurities into smelter feed and accept penalties appears to have hampered the development of impurity removal technologies for copper concentrates in general. However, as the ores get "dirtier" and smelter restrictions tighten this luxury will end.

Are we (and the copper industry) prepared to get "ahead of the game"? Since many of these issues are common with primary copper production perhaps copper and gold producers need to work together more often? Each side can provide relevant expertise.

ΔSt_i appears high

ki: What future technologies may look like is still unclear

For "dirty" concentrates the key would seem to be removing the arsenic and other impurities in a "key-hole" fashion from copper concentrates produced without oxidising sulphur and iron.

Innovative processes for gold recovery from high pyrite cleaner tailings are required.

Large multi company and multi-industry (gold and copper producers) collaboration should be pursued as technologies are complex, expensive, and time-consuming to develop.

k_i appears low but slowly increasing.

Ai: More and more low-grade primary gold-copper deposits will be found. Cost-effective treatment technologies will have many applications.

A_i for now appears moderate.

Example 7: Cost Effective Treatment of Low Au to S (Au:S) Refractory Ores

Purely refractory gold ores are an increasingly important source of gold, and this is seen throughout all jurisdictions in the world. Typically, these refractory orebodies have relatively high Au:S ratios and even at relatively low gold grades these may be economic using flotation to upgrade both gold and sulphur content.

If gold and sulphur content is high enough in the ore, then direct treatment can economically occur. The flowsheets used in the refractory industry involve oxidation of sulphide sulphur and iron liberating gold for downstream gold recovery – most commonly via cyanidation. However, it is worth noting that just because gold is associated with sulphide sulphur does not mean the ore is necessarily refractory. Often a finer grind or a simple pre-oxidation before cyanidation is enough to get acceptable recoveries in cyanidation without an oxidative pre-treatment at all.

An example of the trend in refractory ore make-up is shown below in Figure 8 for the Russian Petropavlosk organisation (Ref(5)). This is being repeated all around the world.

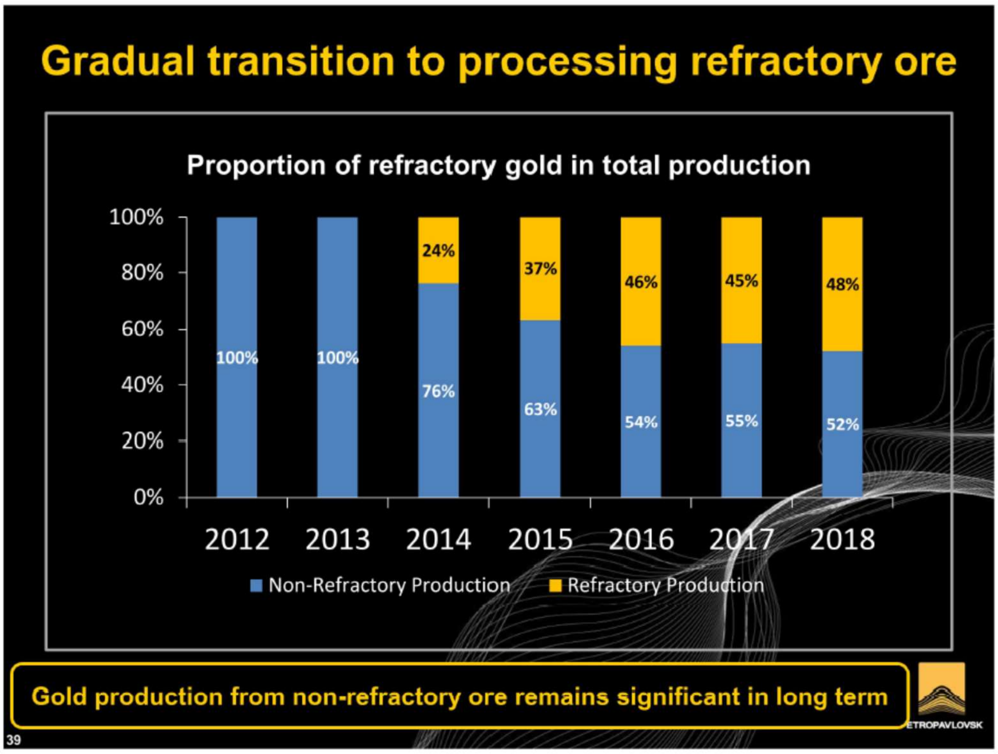


Figure 12: Petropavlovsk Gradual Transition to Refractory Ore

Figure 8 : Transition to Refractory Ore – Petropavlovsk Ref (5)

The incumbent oxidation technologies are roasting, pressure oxidation, biological oxidation and fine grinding with atmospheric ferric oxidation. They are all expensive to build and operate.

For high Au:S ratio ores then these technologies may remain profitable especially during times of high gold price but what if we are faced with truly refractory low Au:S ratio ores? Can these ores be profitable with current technologies?

For some low Au:S ores a significant fraction of the sulphide sulphur present may contain low, or no gold and hence some form of selective sulphur oxidation may make a deposit profitable – if you are lucky !!

However, micron or nano-size gold truly locked within pyrite or arsenopyrite matrices (at low-grade) is expensive to recover using known oxidation technologies. In addition, there is often arsenic, mercury and other impurities to consider which can add to costs

"What if" …. we could selectively recover gold from truly refractory ores without oxidising sulphide sulphur and iron in a "keyhole" approach with the same capital and operating cost structure as free-milling ores? This of course could also be applied to high Au:S ratio ores as well.

That would be quite a breakthrough.

Applying the **Innovation Equation**

rate of Innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (3)

ΔSt_i:

Future State: Recover gold from refractory ores (especially low Au:S ores) at a "free milling" cost

The driving force is significant.

Developing a new gold recovery process for such refractory ores is not easy. The key challenge is to avoid oxidation of iron and sulphur.

k_i: Most of the current industry activity is associated with improving the efficiency and cost base of the existing pre-oxidation processes, that is, incremental improvements. This work is valuable, but a major transformational breakthrough is required especially if low Au:S refractory ores are to be treated.

k_i is low which is a little surprising given the increasing likely dominance of these ores in the future.

Again, a large multi-company collaboration appears required.

A_i: More and more of these deposits are being found. Cost-effective "key-hole" type technologies would have many applications.

A_i is moderate but increasing

Example 8: Arsenic Disposal: *the arsenic problem is growing and it is time to be proactive*

For arsenic mobilised during treatment of high-arsenic gold-copper sulphide ores or high-arsenic refractory ores a cost effective and long-term sustainable solution for disposal is required. Arsenic waste may be in the form of oxides or sulphides from pyrometallurgical or hydrometallurgical treatment.

While low levels of arsenic can often be managed internally within a process (e.g., ferric arsenate in high temperature pressure oxidation) higher concentrations may ultimately lead to "stranded" deposits with no means of treatment. Current arsenic disposal methods involve "locking" arsenic with iron or calcium. This can be technically effective but at some cost and with unknown long-term stabilities.

Alternative sustainable approaches to managing arsenic are required. A technology that looks very promising is Dundee Sustainable Technologies (DST), "GlassLock Process" where arsenic is encapsulated in glass generating a stable product (see Figure 9 below – Ref (6)).

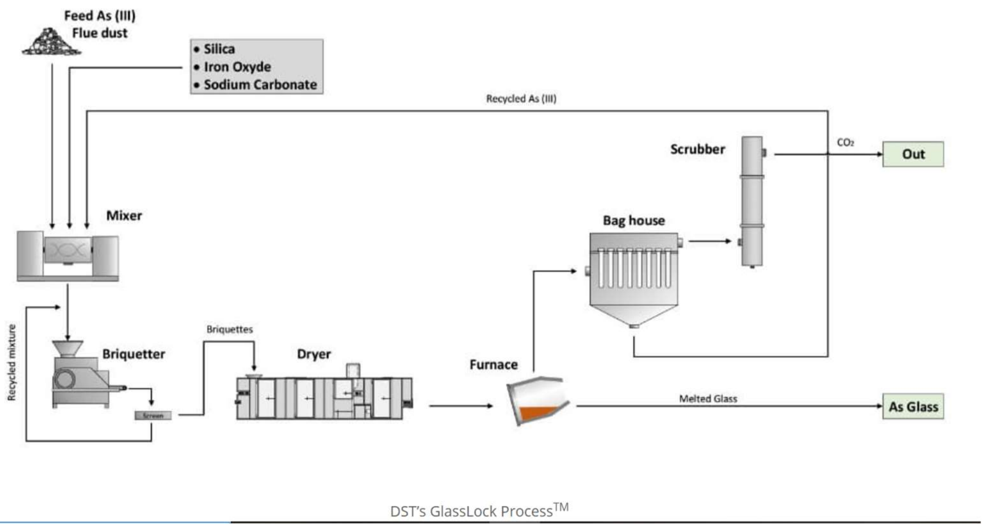


Figure 9 : GlassLock Process (Ref (6))

"What if …. we could dispose of arsenic (and other toxic impurities) at low cost with a significantly better environmental outcome?"

Applying the **Innovation Equation**

rate of Innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (3)

ΔSt_i:

Future State: Sustainable disposal of metallurgically mobilised arsenic

The driving force for an innovative arsenic disposal solution appears significant. How many orebodies and projects are currently being by-passed because they are deemed "too hard"? Our exploration colleagues know that treatment is difficult, and we may be missing opportunities at the discovery stage …. "the mets can't handle this stuff!"

ΔSt_i appears high

k_i: There has been significant academic research over many years investigating the stabilisation of arsenic.

While there are isolated groups, like DST, developing truly innovative solutions the innovation ecosystem in this area appears small.

Given the challenges associated with copper recovery from enargite and gold recovery from arsenopyrite there seems to be a growing need for new arsenic management tools. Again, perhaps more collaboration between gold and copper companies on solving the "arsenic problem" seems sensible. Of course, other metal commodities have similar issues, and the collaboration could go well beyond gold and copper.

Apart from a few selected organisations the k_i appears moderate for the industry overall.

A_i: Deposits of gold-copper and refractory ores containing high levels of arsenic will become much more of a focus in the future.

Example 9 – Cost effective, rapid, real-time gold deportment analysis: *where exactly is the gold in tailings?"*

This may seem like an odd example in an innovation context but how many gold producers actually know where their gold losses in solid tailings are deported in real-time? Most often even the total gold loss is not quantified for many hours or days. This represents of course a lost opportunity for recovery correction.

Diagnostic leaching and other tools do give some insight but often weeks or even months after the sample was taken. While this is interesting and useful data, total gold loss and a breakdown via deportment of gold loss in real-time would be very valuable. Even quantified gold deportment within a day would be useful.

"What if" …. we could quantify gold deportment within in our solid tailings in real time (or near real time)

Applying the **Innovation Equation**.

rate of Innovation transfer $r_i = k_i \times A_i \times \Delta St_i$ (3)

ΔSt_i:

Future State: Quantify solids gold deportment losses in process plants in real-time

The driving force for real-time solids gold deportment analysis appears to be significant.

k_i: There are a number of groups investigating alternatives to fire-assay for process control. However, it seems unlikely that fire-assay will be replaced soon especially for metallurgical accounting purposes.

Total gold at low concentrations is not easy to measure on-line. However there has been some developments like Metso:Outotec's Courier 6GL on-line gold analyser shown below in Figure 10. A minimum detection limit of 0.2 g/t is claimed (Ref (7)). While this is useful there is still no information on how the gold loss is deported in tailings. But a step in the right direction at least.

Figure 10 : Outotec Courier 6GL

The k_i is low for the industry overall.

A_i: This is a technology that could be potentially used in any gold operation and hence A_i is large.

SUMMARY

Table 1 below summarises the examples explored. This is an industry wide perspective and application to a particular company or organisation may lead to different priorities. The Innovation Equation is used in a semi-quantitative manner only at this stage with descriptors of Low, Moderate or High applied to the parameters of the equation.

Some suggested actions are nominated to help speed up the process of applying innovation.

While it may be possible to use the equation with $ values this is left for future investigation.

Table 1 : Application of Innovation Equation - Summary Table

Example	Issue/Opportunity	Desired Future State	Driving Force ΔSti	Innovation Transfer Co-efficient ki	Innovation Transfer Extent Ai	Innovation Transfer Rate ri	Action Required
1	Non-cyanide Gold Recovery	Low cost non-cyanide technology	Low	High but wrong focus?	Low	Low	Focus research & development on reducing non-cyanide cost structure
2	Hard-rock In-situ Metal Recovery	No mining. Very low capex and opex	Very high	Very Low	Moderate	Low	Huge opportunity. Additional resources required. Global scale collaboration?
3	"Dry" Tailings	Very low risk talings disposal at moderate cost	High	High	High	High	Maintain the "rage"!
4	Ultra-Low Energy Comminution	Energy costs and hence GHG's < 30% of current	High	Moderate	High	Moderate	A few selected groups working in this area. Is greater collaboration required?
5	Enhanced Heap & Dump leaching	Tank leach type recoveries at low cost	High	Low	Moderate	Low	Step change in recoveries required
6	Treat Low Grade and "Dirty" Au and Cu Ores	Exploit high Cu credits to offset lower gold grades. Impurities like As/Bi/Sb the issue	High	Low	Moderate	Low	Additional focus on copper concentrate impurity removal processes required.
7	Enhanced Refractory Gold	"Free-milling" recovery and cost structure for refractory ores	High	Very Low	Moderate	Low	Tough problem but potentially huge implications. Large scale collaboration alsmost certainly required.
8	Arsenic Stabilisation	Safe and sustainable long-term arsenic stability at moderate cost	High	Moderate	Moderate	Moderate	Technologes exist and some emerging. Application and demonstation required.
9	Real-Time Tailings Gold Solids Analysis	Real-time analysis for enhanced gold recovery	High	Low	High	Low	Major industry collaboration required. Impotant to include METS and other organisations

CONCLUSIONS

An Innovation Equation is presented and used to examine, by example, nine innovation opportunities in the gold industry. Clear definition of the problem or opportunity is key.

The equation may allow organisations to focus on the key aspects of transformational and disruptive innovation with the key objective to speed up adding value to a business from innovation in general.

The author predicts that whichever companies can rapidly implement transformational and disruptive innovation will become the "great" mining companies of the future.

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