Metal Mine Tailings Management Workshop
Iqaluit, Nunavut
February 9 & 10th, 2006

On Land or Underwater Disposal of Mine Waste

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Presentation Outline

- Acid generation control strategy
- Cover technologies
- Dry covers - case history and performance
- Permafrost encapsulation
- Water and ice covers - case history and performance
- Disposal in natural water bodies
- Saturated cover concept

Sulphide Oxidation Process

Sulphide oxidation

- Acid generating processes:

$$FeS_2 + (15/4)\ O_2 + (7/2)\ H_2O = Fe(OH)_3 + 2SO_4^{-2} + 4H^+$$

- Non acid generating processes:

$$ZnS + 2O_2 = Zn^{+2} + SO_4^{-2}$$

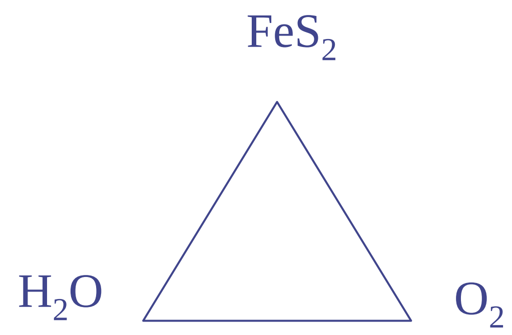
Other oxidation processes

- Ammonia oxidation

$$NH_4^+ + 2O_2 = NO_3^- + H_2O + 2H^+$$

Sulphide Oxidation - Control Strategy

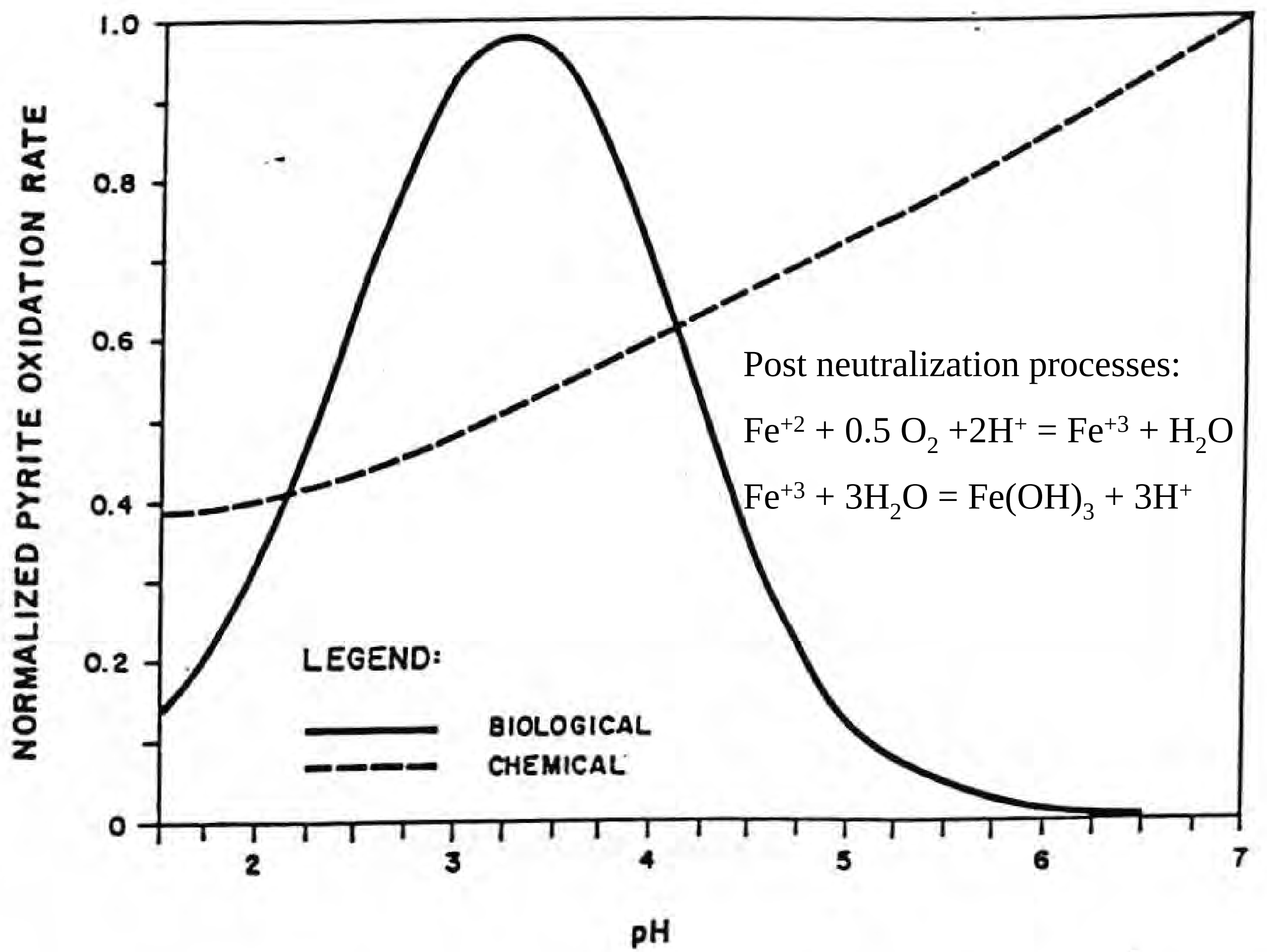
- Sulphide minerals, oxygen and water - key ingredients of sulphide oxidation/acid generation problem
- Perpetual collection and treatment strategy unsuitable for long-term management
- Prevention and control measures - best strategy for long-term management:
  - Removal of sulphide minerals - uneconomical
  - Exclusion of air, and hence oxygen – dry and wet covers
  - Exclusion of water or both – dry covers
  - Natural material like till, clay and synthetic liners - oxygen and water limiting
  - Water covers - oxygen limiting



Sulphide Oxidation - Control Strategy

- Chemical control technologies:
  - Reaction kinetics
    - pH control
    - Temperature control
  - Surface coatings and passivation
    - Coal tar and asphalt emulsion coatings
    - Sintering and vitrification
    - Silicate bonding
- Electrochemical and galvanic control

Pyrite Oxidation Vs. pH

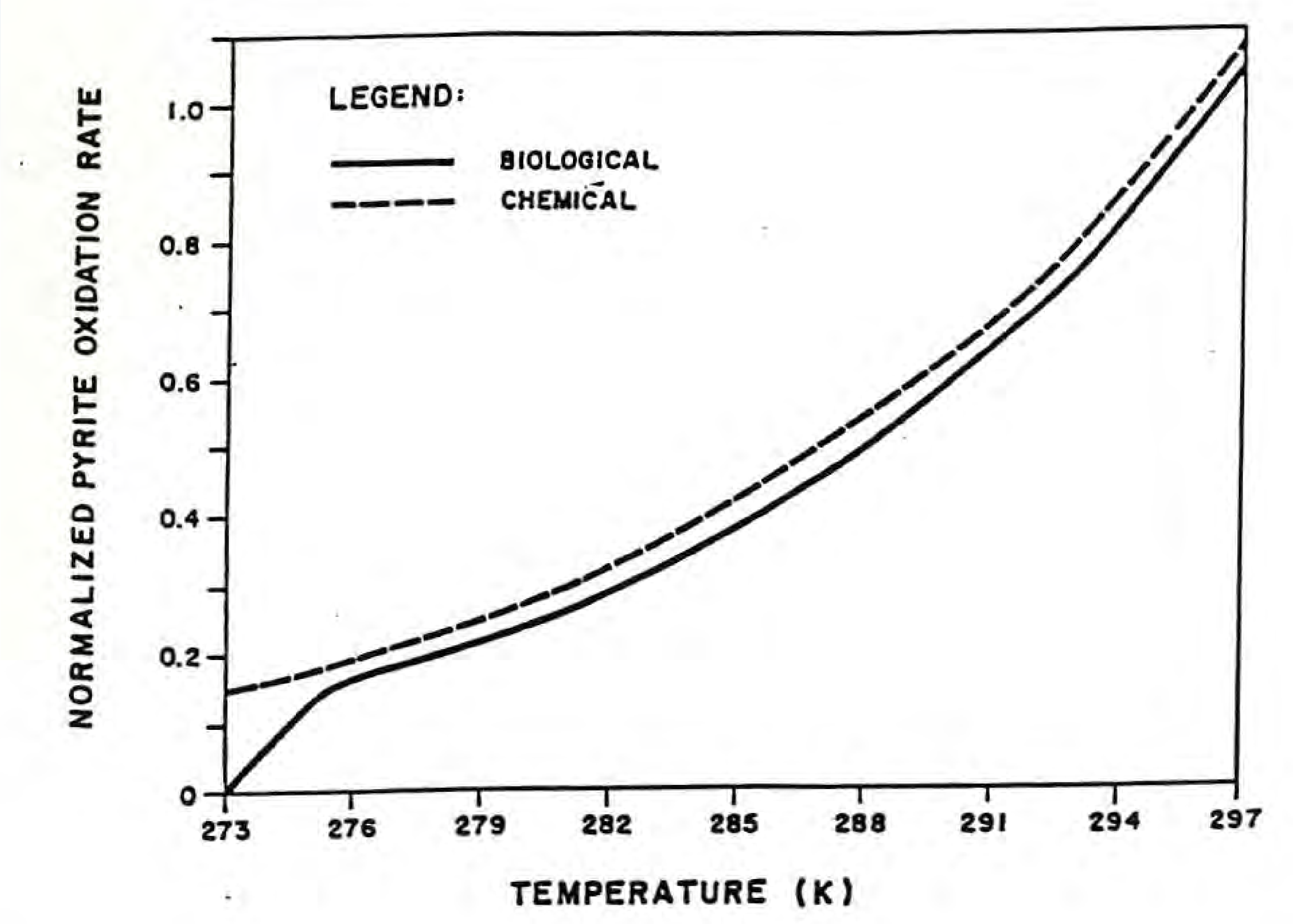


Post neutralization processes:

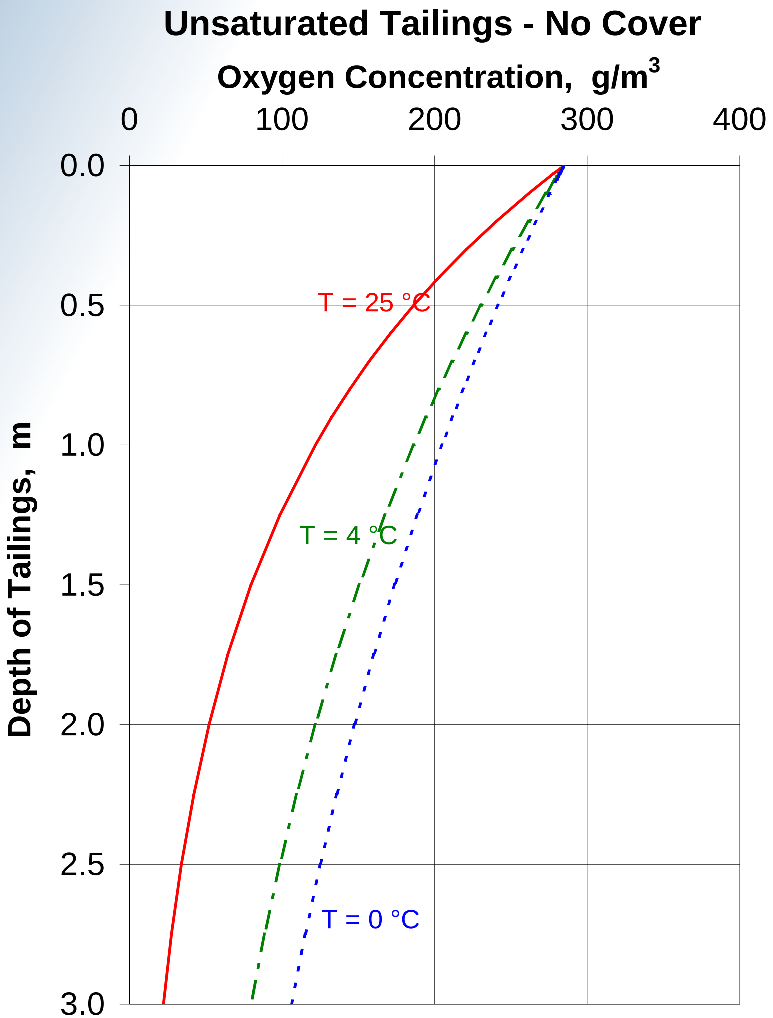
$Fe^{+2} + 0.5\ O_2 + 2H^+ = Fe^{+3} + H_2O$

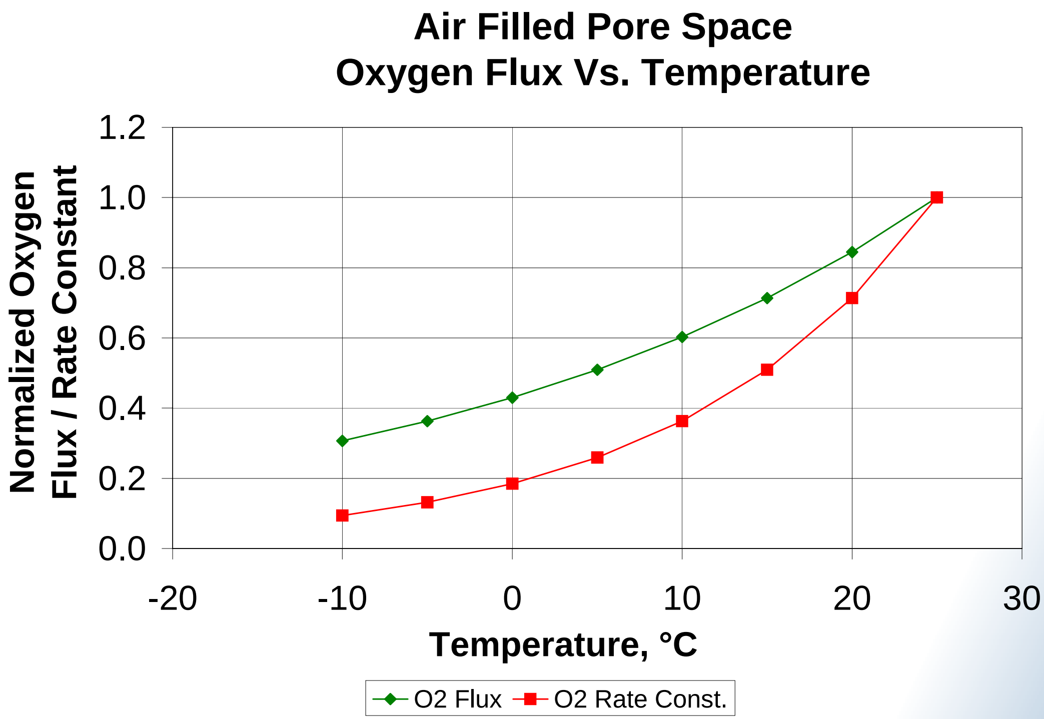
$Fe^{+3} + 3H_2O = Fe(OH)_3 + 3H^+$

Pyrite Oxidation Vs. Temperature



Oxygen Diffusion - Unsaturation Conditions

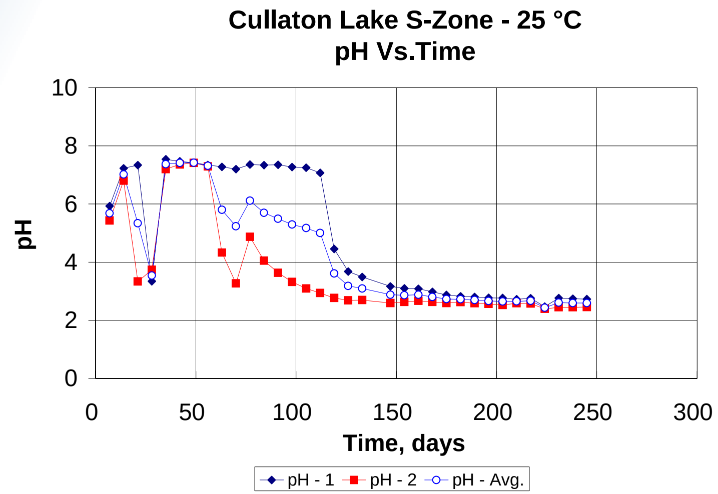


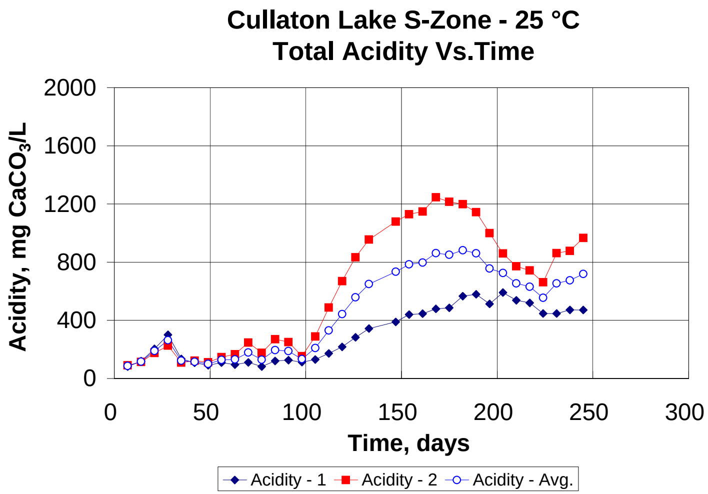


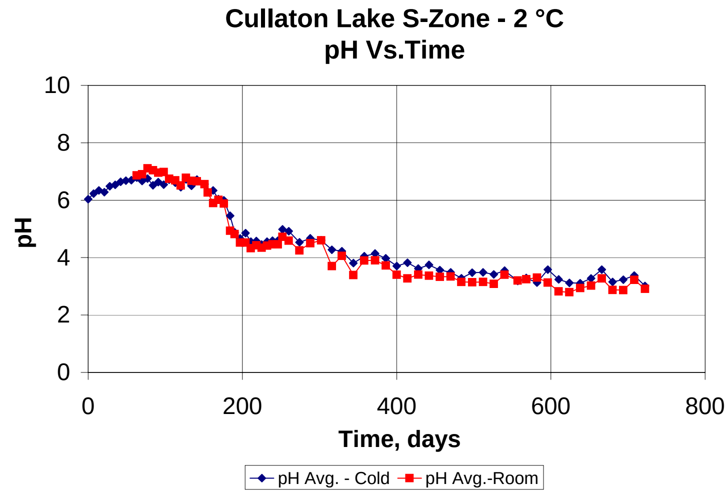
Waste Reactivity - Cold Climatic Conditions

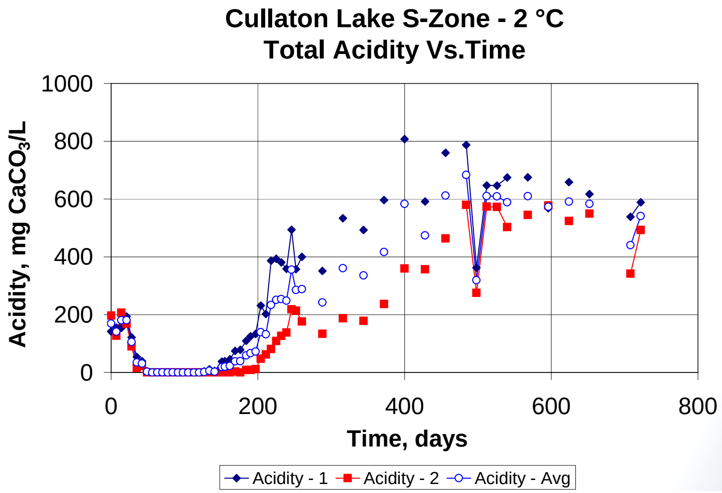
Sulphide Reactivity Vs. Temperature

Cullaton Lake S-Zone (0.4 % S, NP/AP = 0.16)









Sulphide Reactivity Vs. Temperature

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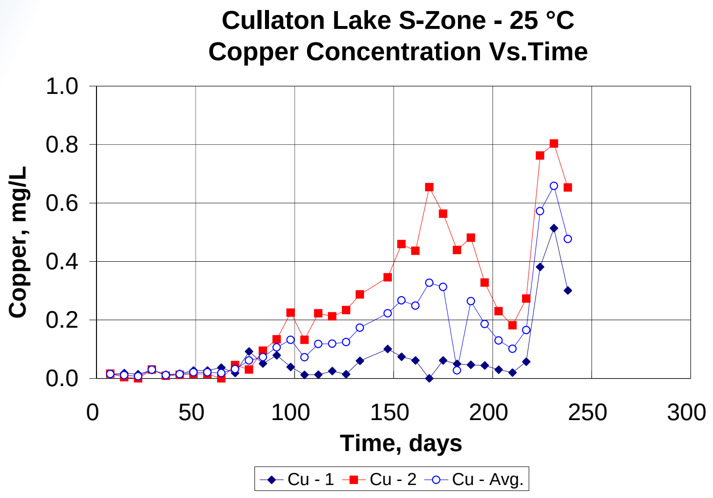
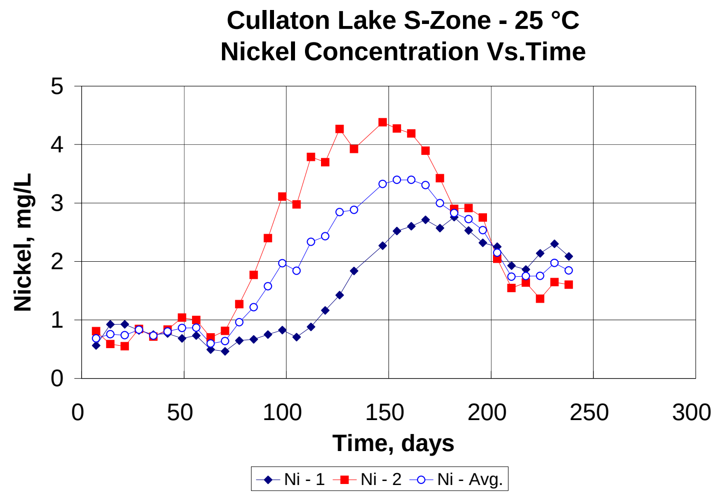
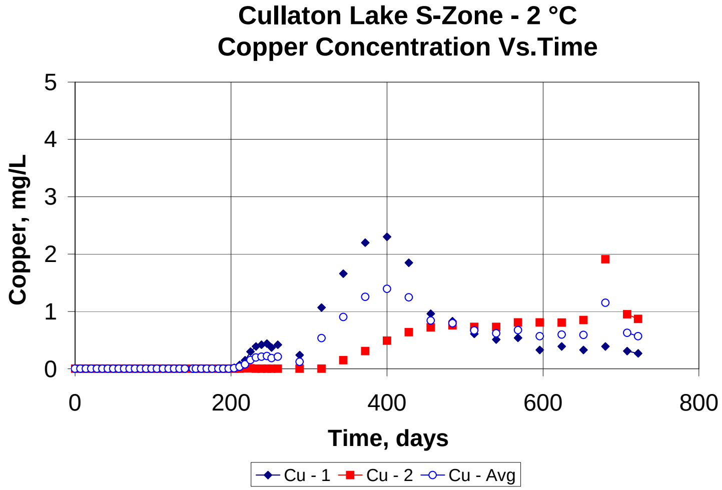
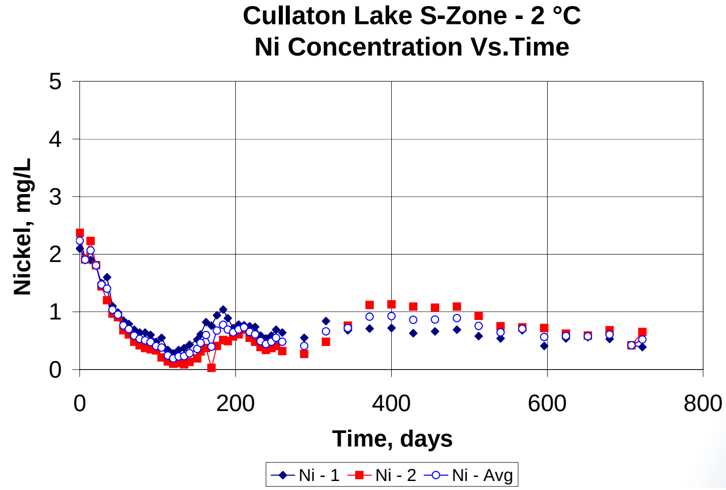








Cover Technologies for the North

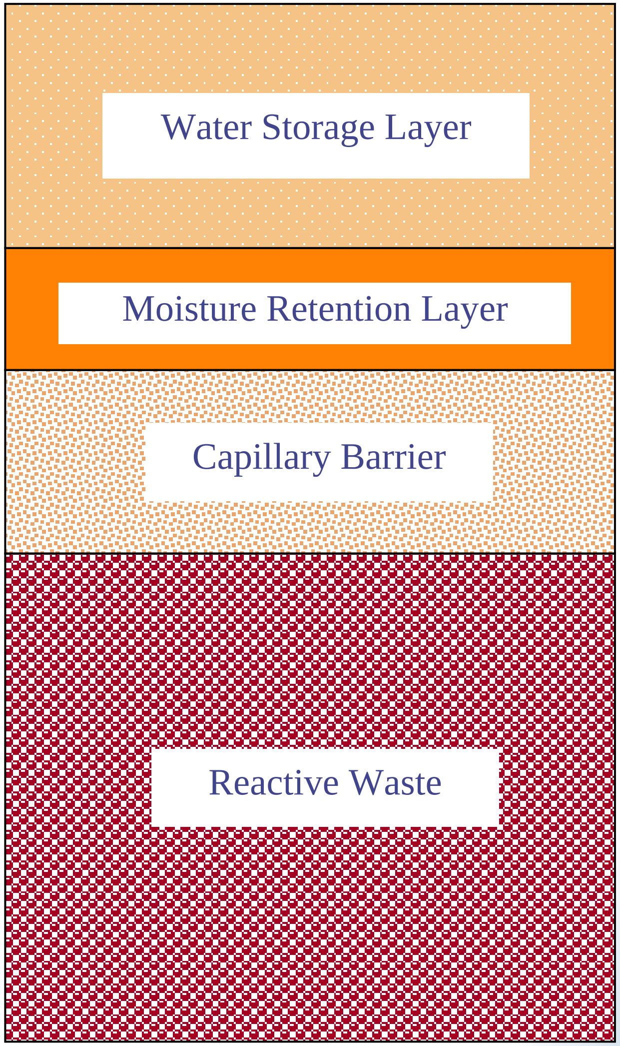
- Vegetation Cover
- Engineered Dry Covers
- Permafrost Encapsulation
- Water and Ice Covers
  - Disposal in man-made lakes
  - Disposal in natural water bodies
- Saturated Barriers

Vegetation Cover - Successes / Challenges

- Successful site remediation
- Surface stabilization, and wind and water related erosion control
- Greatly improved site aesthetics
- Acid rock drainage continues unabated
- Limited growth period and availability of native seed species in the north
- Ongoing effluent collection and treatment required on a long-term basis (perpetuity)
- Sludge collection, disposal and management required

Engineered Dry Covers

- Simple soil to composite engineered covers to limit both oxygen diffusion and moisture infiltration
- Factors affecting economic and feasibility of a cover system:
    - Site climatic conditions
    - Availability of cover materials
    - Distance to borrow sources
    - Cover and waste material properties and conditions
    - Surface topography and hydrology
    - Cost ~ $50k to $100k / ha; may be more in the north



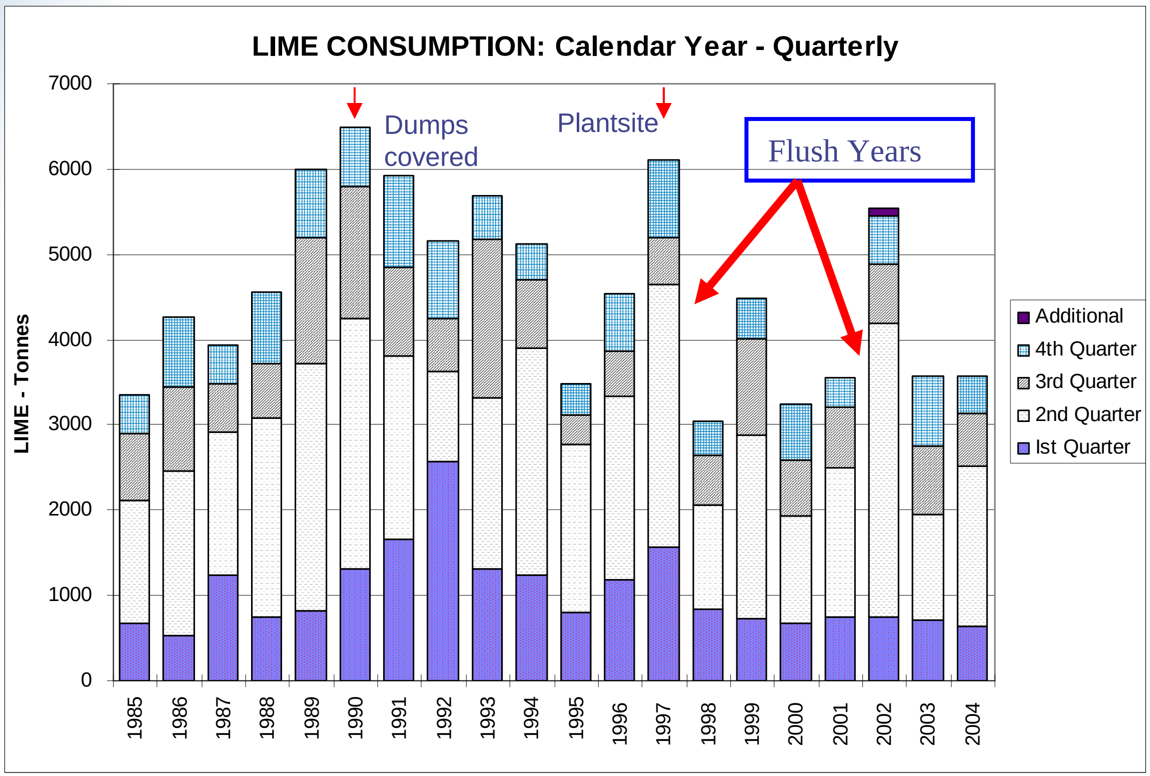
Engineered Dry Covers
Equity Silver Mine, Placer Dome

Equity Silver Mine, Placer Dome, Houston, BC

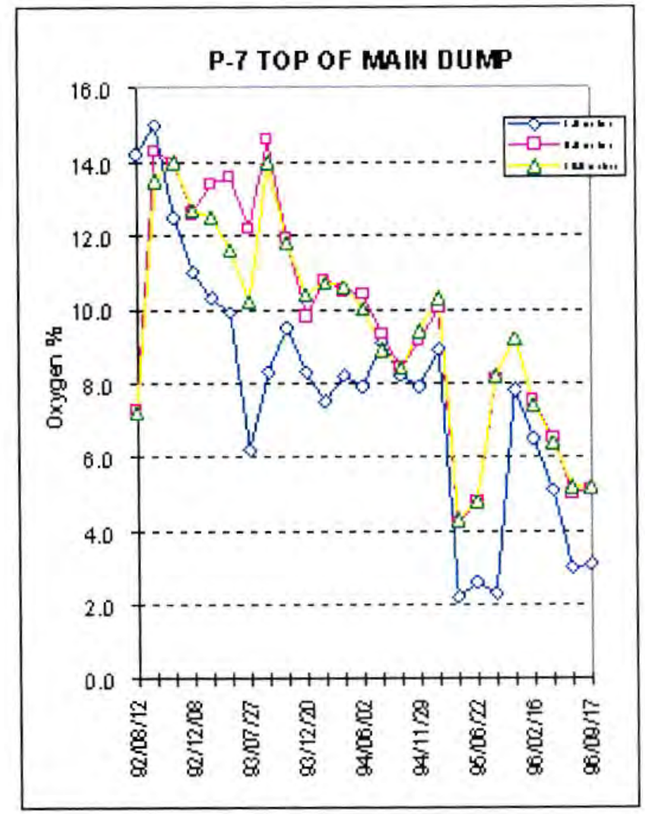
- Site located in the central BC, approximately 35 km southeast of Houston at an elevation of ~ 1300m
- Open pit and underground mining operation
- Approximately 77.4 Mt of acid generating waste rock containing ~ 2 - 5 % pyrite, placed in three separate waste rock dumps
- Engineered composite cover consisted of ~ 0.5 m compacted clay layer as moisture retaining oxygen barrier overlaid by ~ 0.3 m of un-compacted till as erosion control and vegetation growth medium
- Site remediation started in 1990 and completed in 1997
- The cover has reduced precipitation infiltration, oxygen ingress and lime consumption, but the overall treatment cost is still high
- Annual variations in precipitation continues to affect cover performance

Engineered Dry Covers
Equity Silver Mine, Placer Dome

Effluent Treatment - Annual Lime Consumption



Residual Oxygen conc.

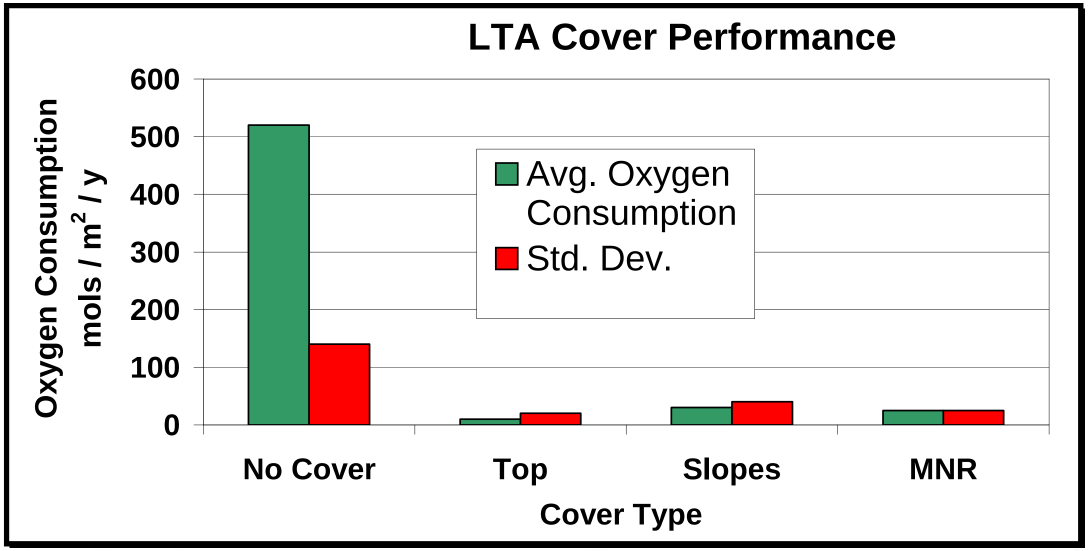


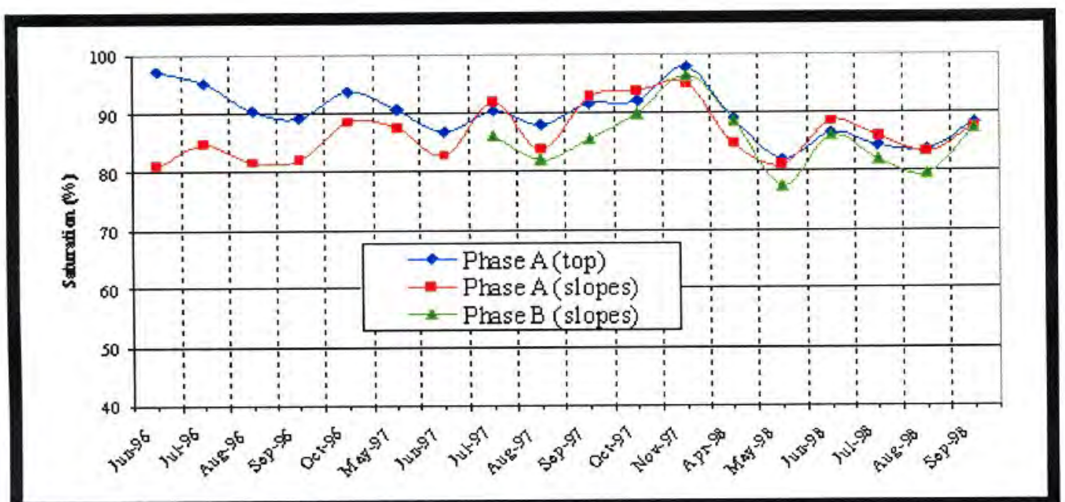
LTA, Barrick Gold

Les Terrains Aurifères (LTA) Barrick Gold, Malartic, QC

- LTA site is located approximately 8.5 km southeast of the City of of Malartic, Northern Québec
- Approximately 8 Mt of acid generating tailings placed over ~ 10 Mt of alkaline tailings covering an area of ~ 140 ha
- Alkaline tailings deposited from Malartic Goldfield Mine from 1930 to 1965, and acid generating tailings from Barrick's Bousquet Mine from 1977 to 1994
- Engineered dry cover using sand-gravel as drainage and MNR mine site alkaline tailings as oxygen barrier layers
- The designed cover has reduced tailings oxidation rate by ~ 95% and the oxygen barrier layer moisture saturation is maintained at ~ 85 %

LTA, Barrick Gold





Engineered Dry Covers – Geo-membranes
Mine Poirier, Joutel, QC

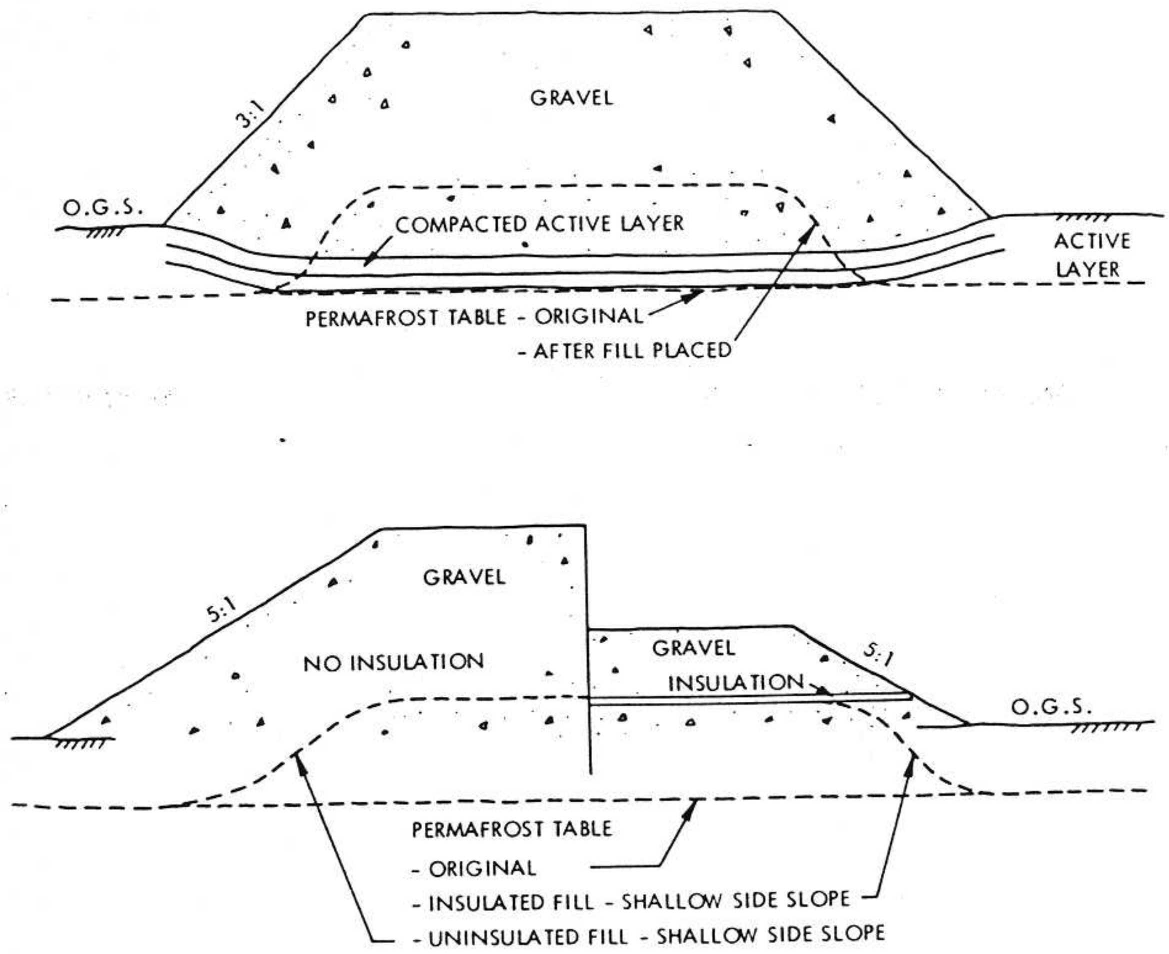
Before
Rehabilitation

After
Rehabilitation

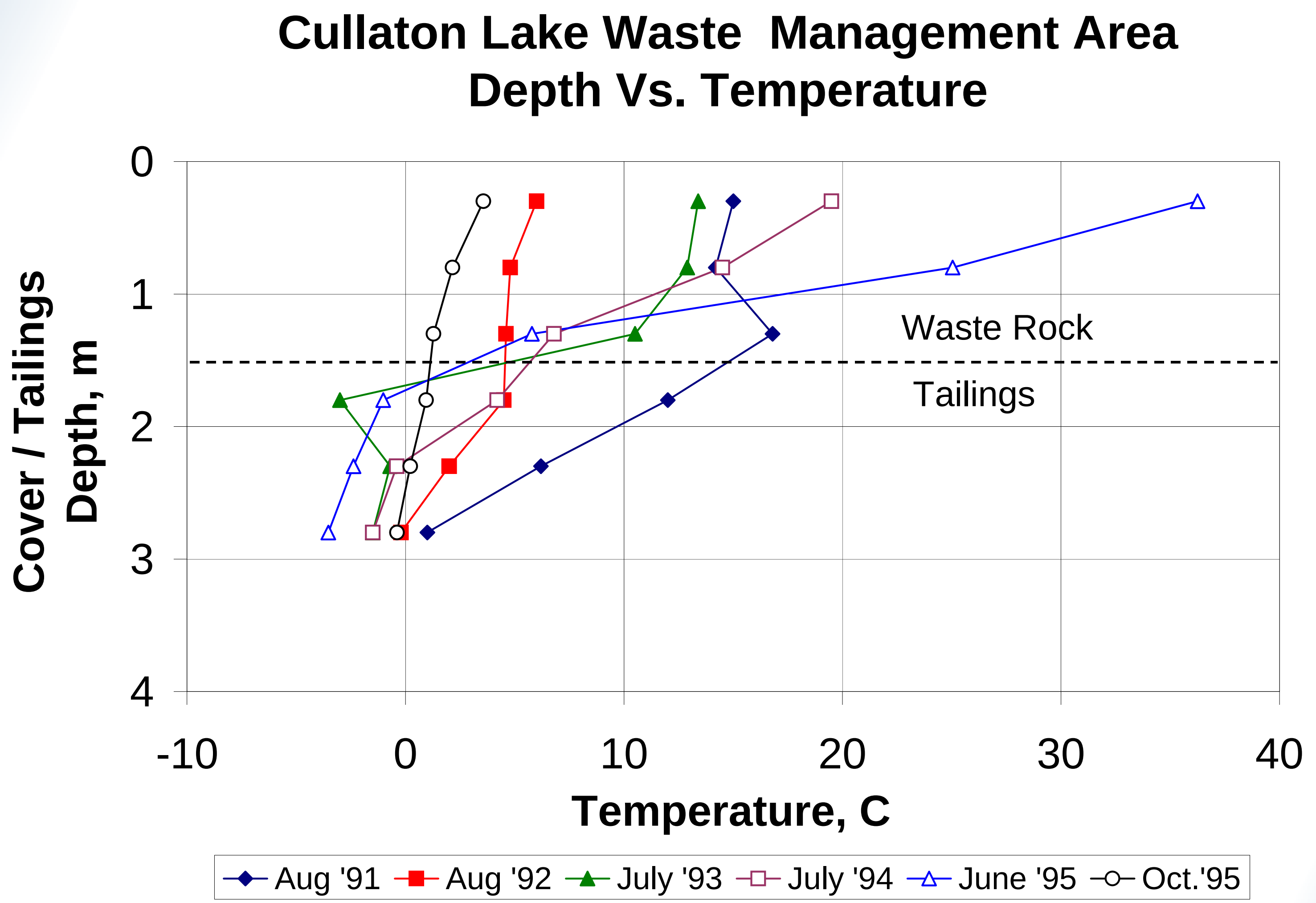
Permafrost Encapsulation

- Suitable for northern permafrost regions of continuous and/or wide spread discontinuous permafrost
- Limiting oxygen ingress, exposure depth and infiltration flow paths
- Raising of permafrost table by placement of suitable insulating surface covers
- Use of thermal siphons to promote additional freezing
- Discharge of paste / thickened tailings to promote freezing
- Alternate tailings disposal cells for freezing purposes
- Negative implications of long-term climate change

Permafrost Encapsulation



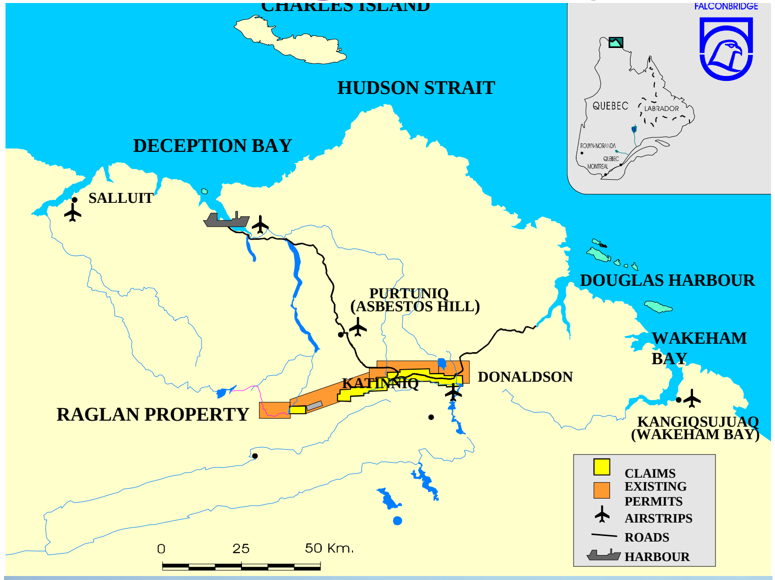
Permafrost Encapsulation - Cullaton Lake, NWT

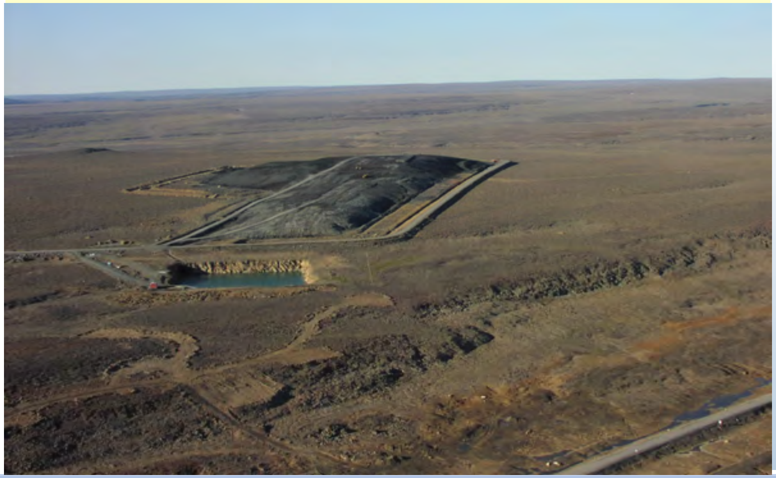


Permafrost Encapsulation – Raglan Project

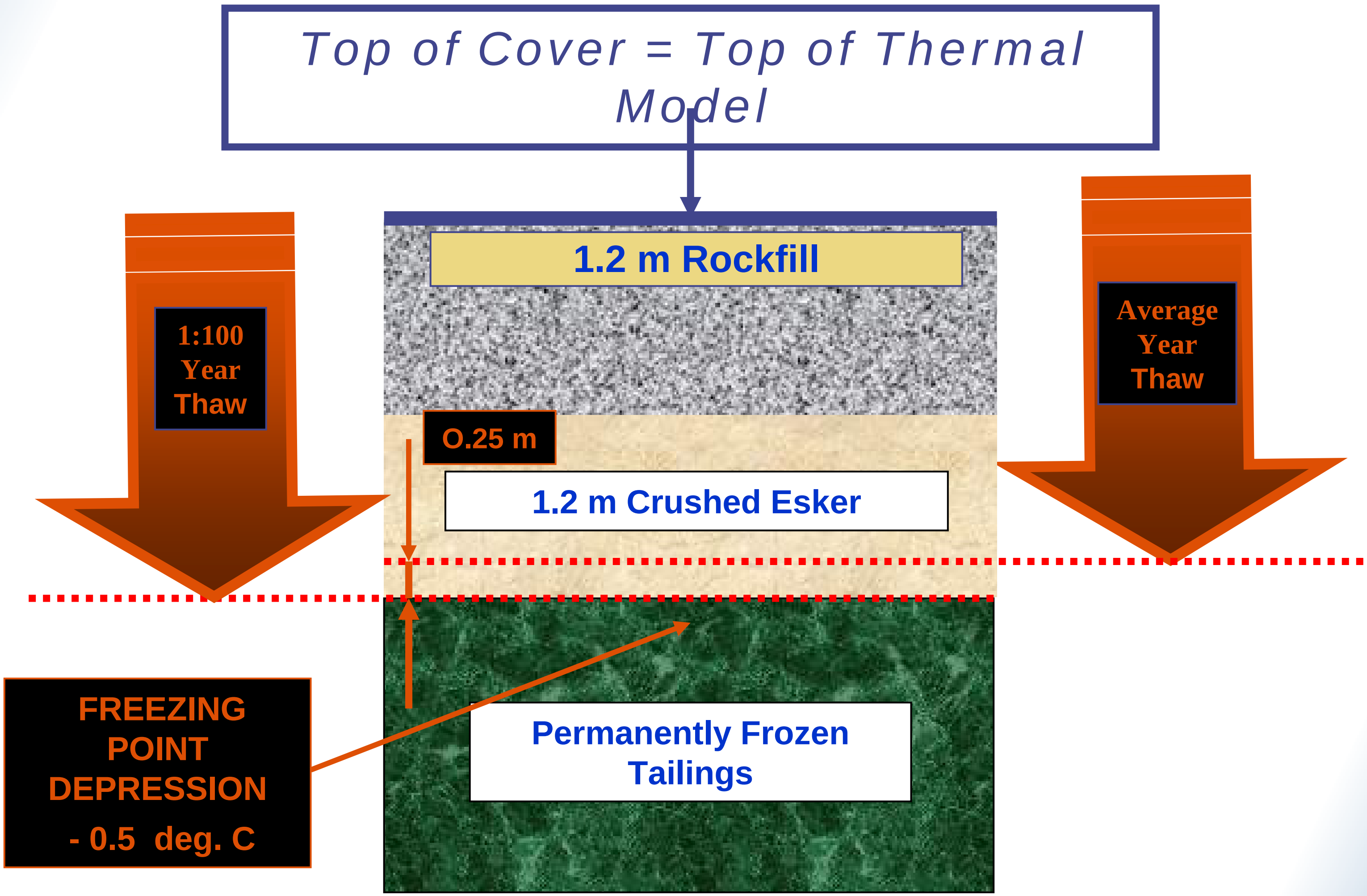
Falconbridge/INCO Raglan Project

- Permafrost encapsulation of filtered, dry tailings (85% solids)
- Cover of coarse, crushed rock and esker emulating landscape
- Locally available cover materials
- Active zone contained in the cover layer
- Design allows for global warming
- Progressive rehabilitation
- Concept to be refined based on operational experience

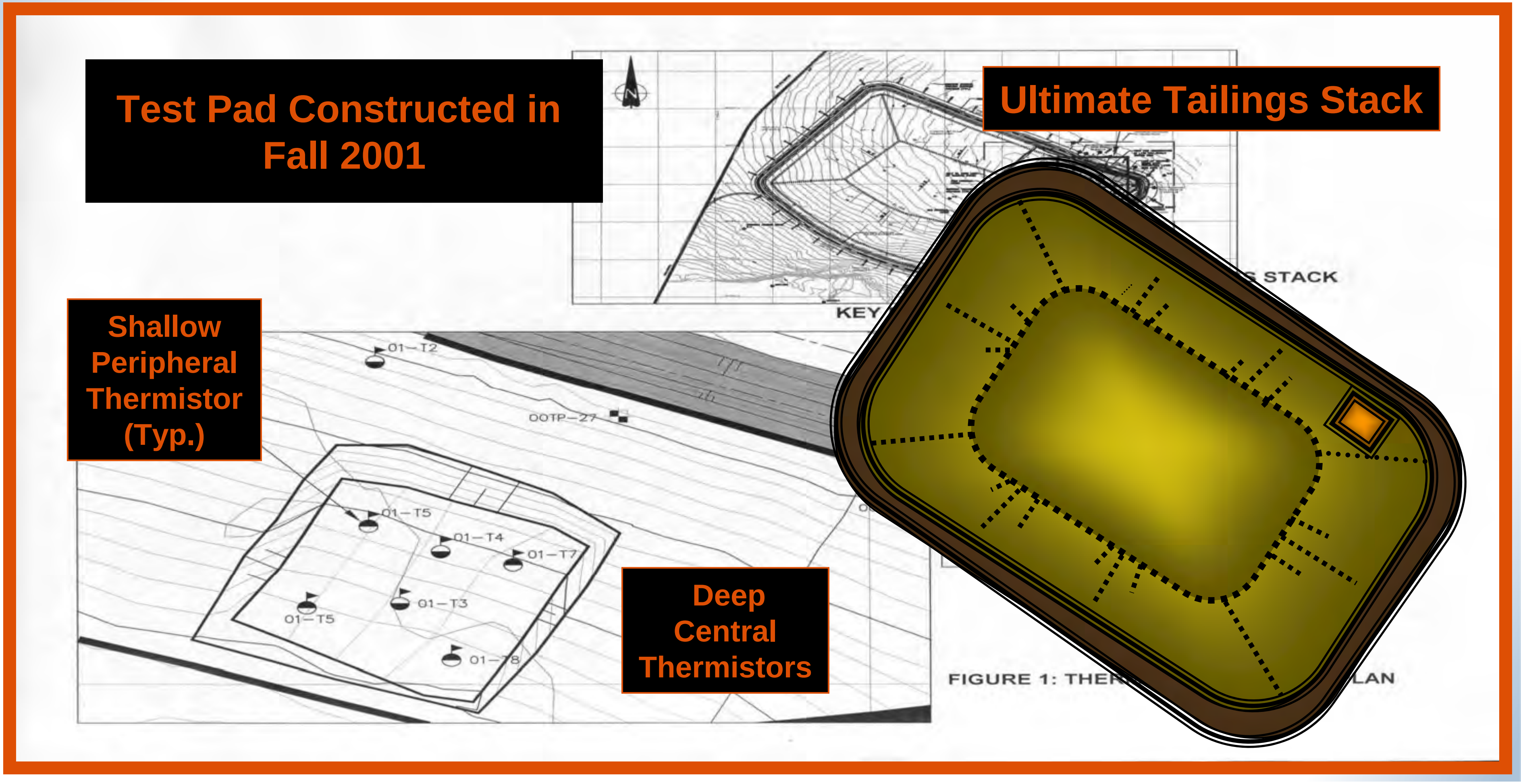




Permafrost Encapsulation – Raglan Project



Permafrost Encapsulation – Raglan Project



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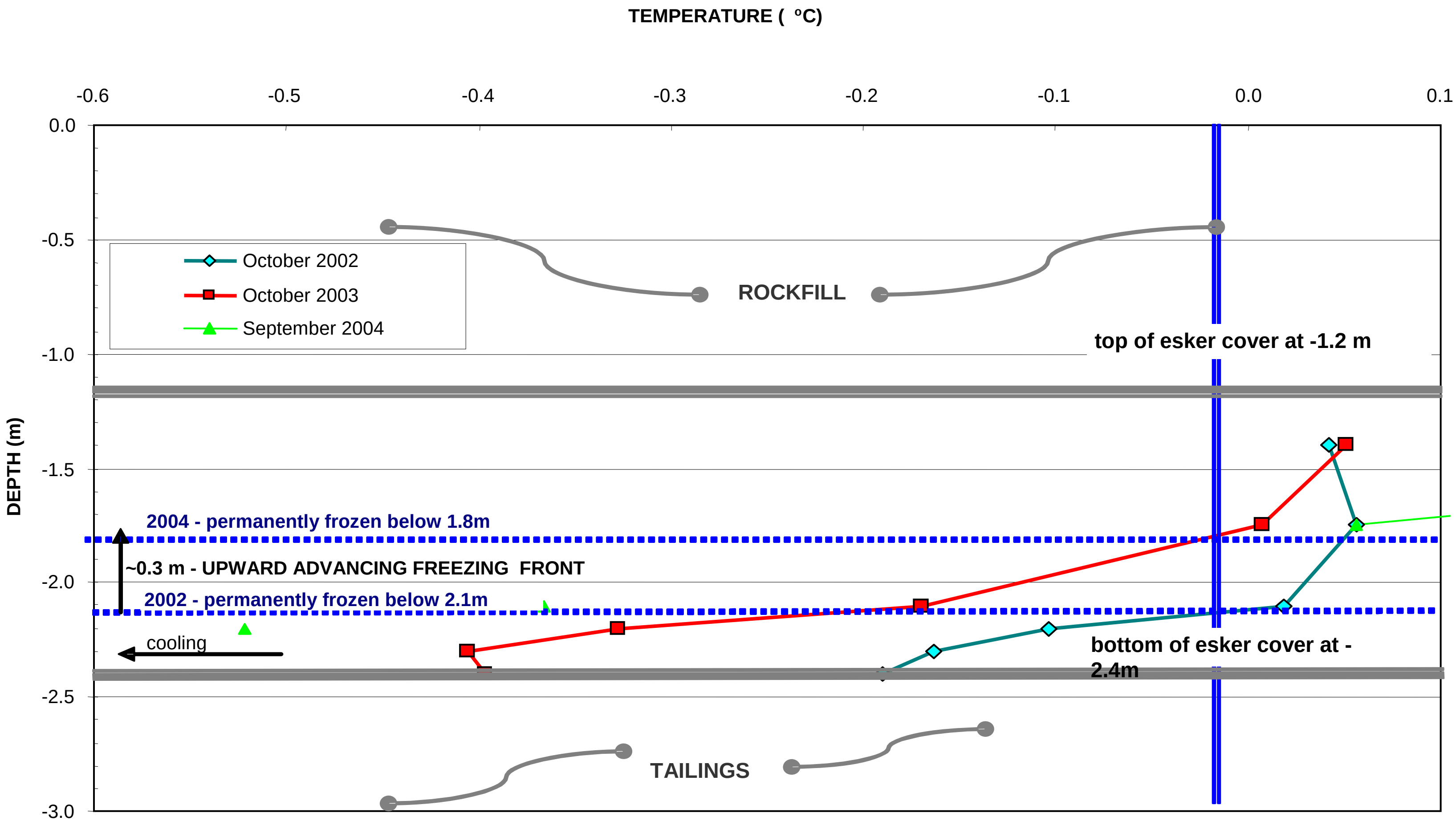


Permafrost Encapsulation – Raglan Project

- Active zone is contained within the cover
- Freezing of deeper tailings zone has advanced
- Upward advance of freezing is occurring
- Based on the modelling, reaching steady-state will take 50 + years.
- At the current time there appears to be no reason indicating that an adjustment to the cover design is necessary.
- Refinement of the cover layers can be undertaken closer to closure

Dry Covers - Summary

- Small foot print and low and to medium overall risk of catastrophic failure (depending on dam heights and water table elevation)
- Cover selection, design and placement dependent on site specific conditions
- Inclusion of local landforms conditions in overall cover design
- Local availability of cover materials is prerequisite
- Most engineered dry cover sites are still at experimental stages and no integrated, long-term performance record is available

Dry Covers - Summary

- Implications of freeze-thaw heaving, ice lens formation, differential thermal or mechanical deformations and winter desiccation on cover integrity in the north are yet to be fully evaluated
- Longevity of membrane covers at persistently low temperatures, specifically thermal shrinkage/stretching and cracking, is yet to be established
- Progressive reclamation may not be always possible and the waste may be partially exposed during the operating phase
- Permafrost encapsulation is very promising for the north, however, its applicability is most impacted by the global warming trend

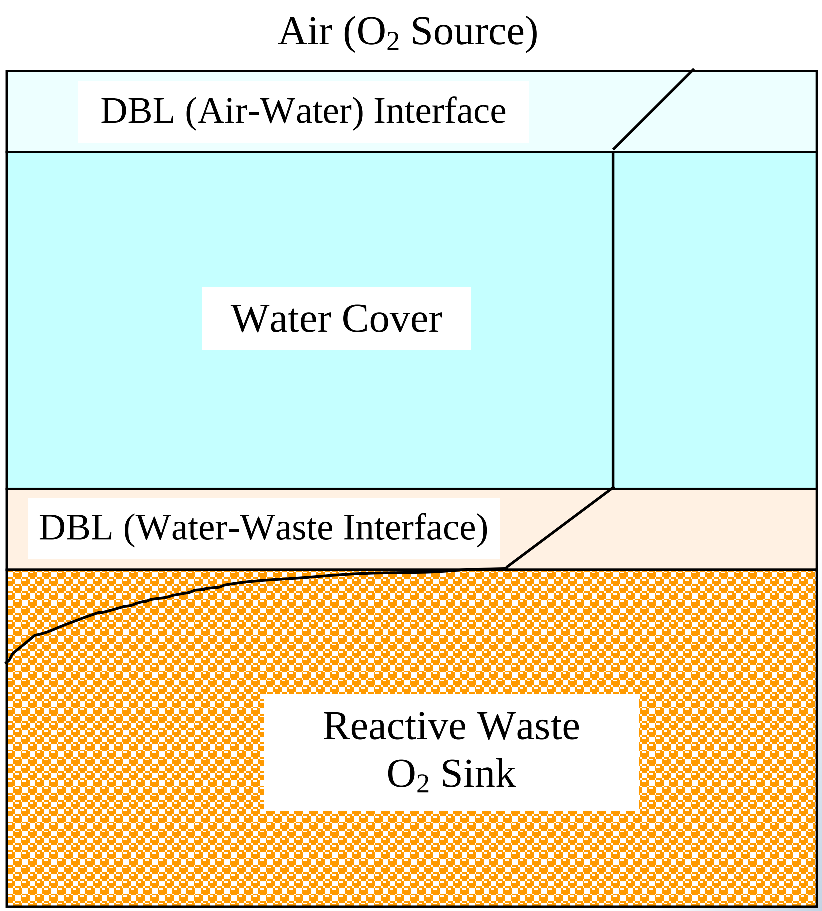
Water/Ice Covers - Advantages

- Natural and most economical cover
- Suitable climatic and topographic conditions required
- Low oxygen solubility and diffusivity in comparison to air
- Reduced reactivity at low temperatures

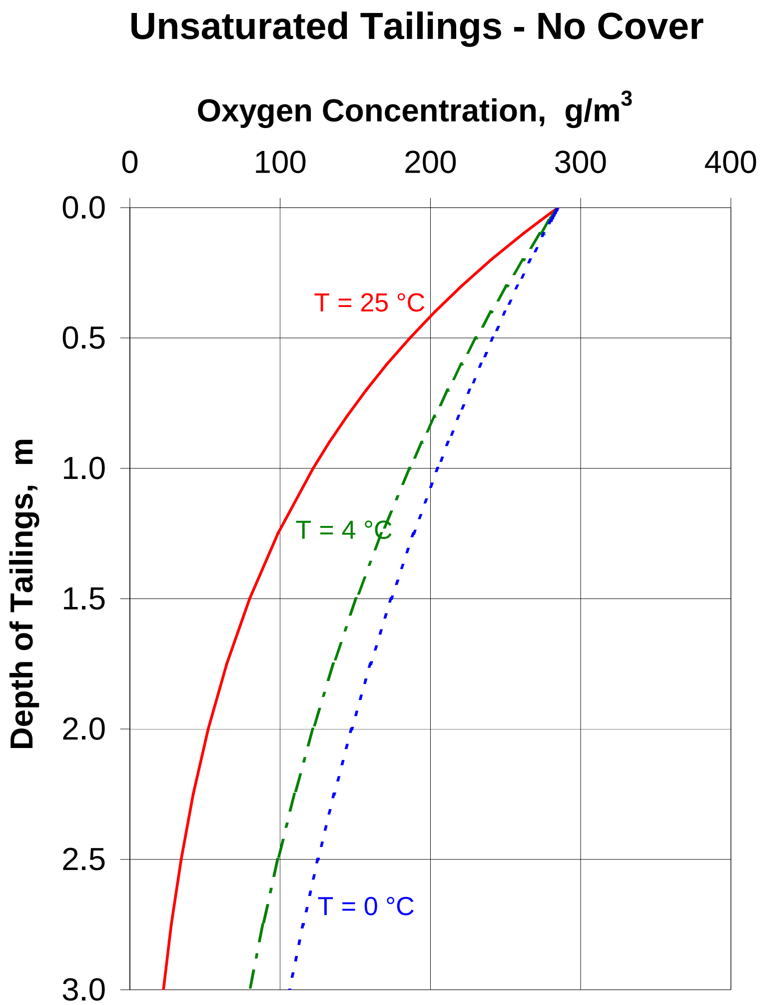
Oxygen Parameters	Water	Air	Ratio water/air
Solubility	8.6 mg/L @ 25 °C	285 mg/L (21.5% v/v)	0.03
Diffusivity	2×10^{-9} m^2/s	1.82×10^{-5} m^2/s	1.11×10^{-4}

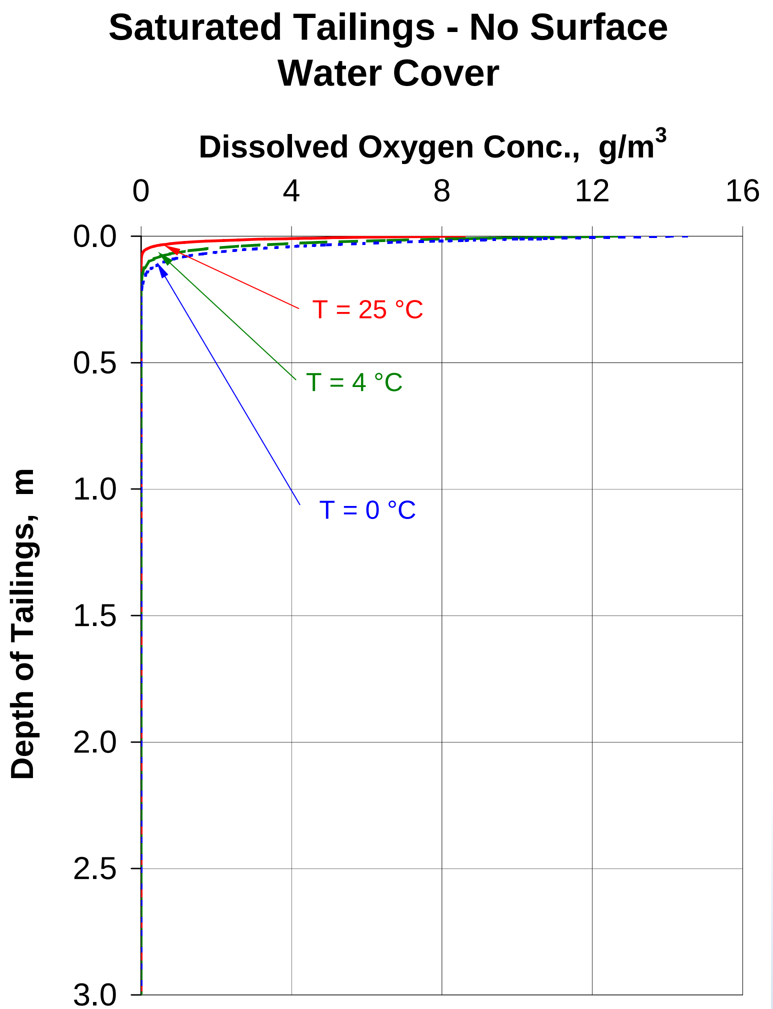
Water and Ice Covers

- Water covers - oxygen limiting
- Diffusion barrier to both oxygen in the water cover and contaminants in the submerged waste
- Development of Diffusion Barriers Layers (DBL) at the water-waste and water-air interfaces
- Stagnant and well mixed water cover conditions
- Ice cover contributes to poor mixing and stagnation
- Ice scouring

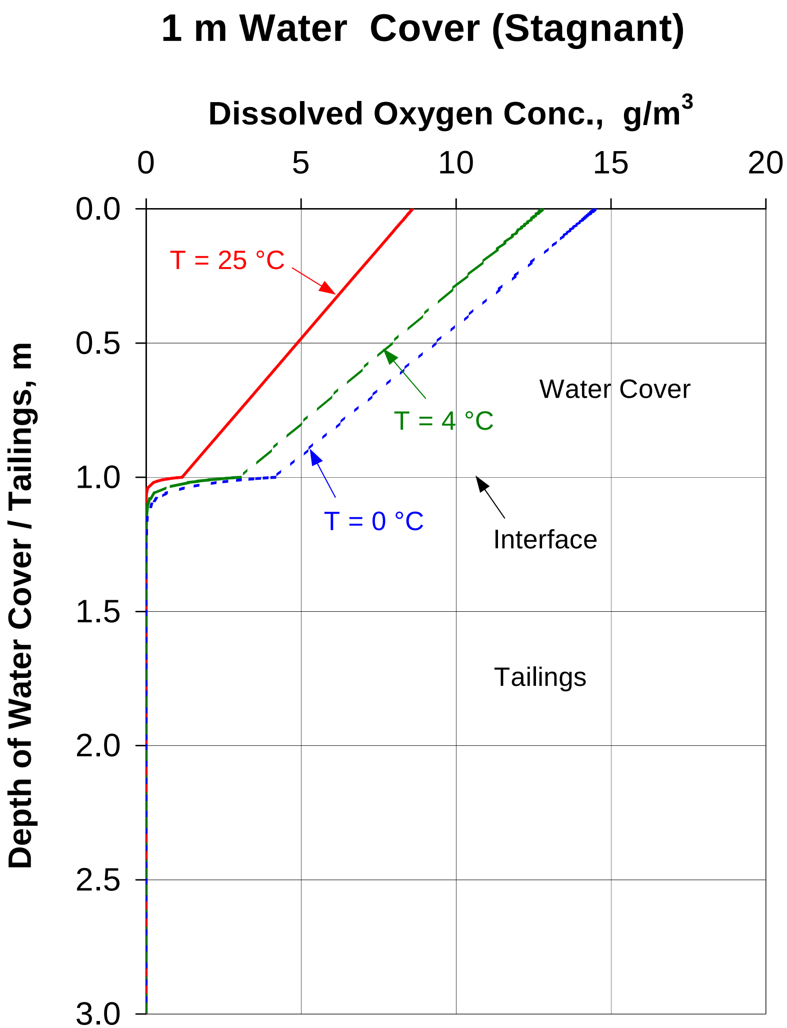


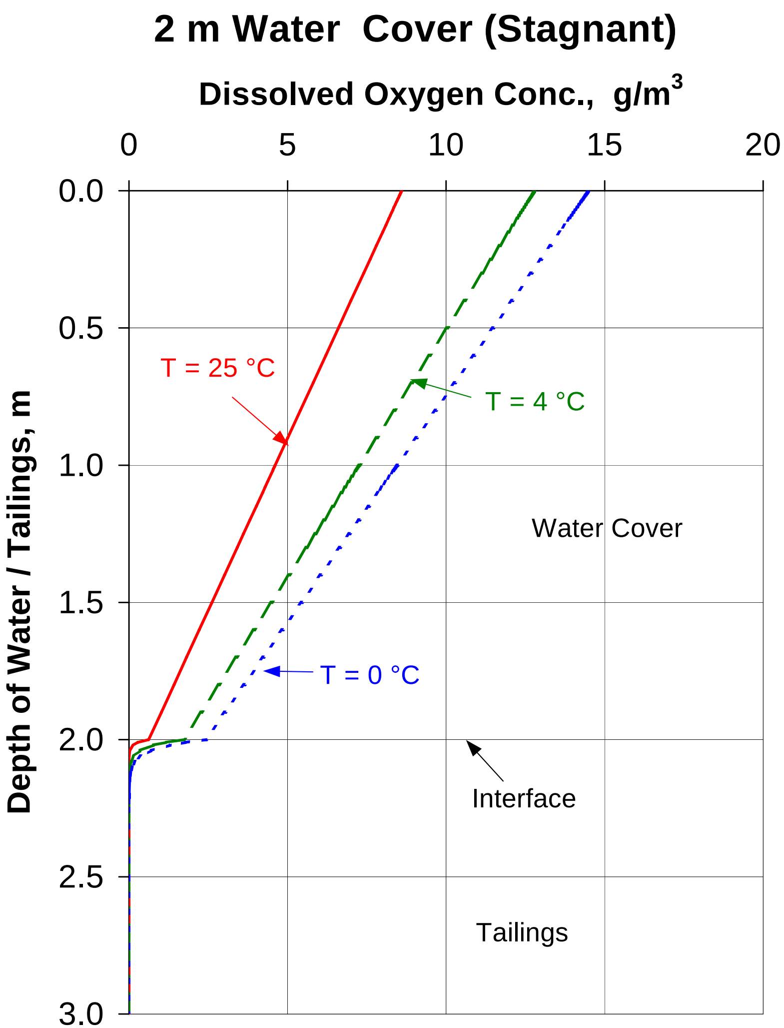
Water Cover - Oxygen Diffusion Profiles





Stagnant Water Cover - Oxygen Diffusion Profiles

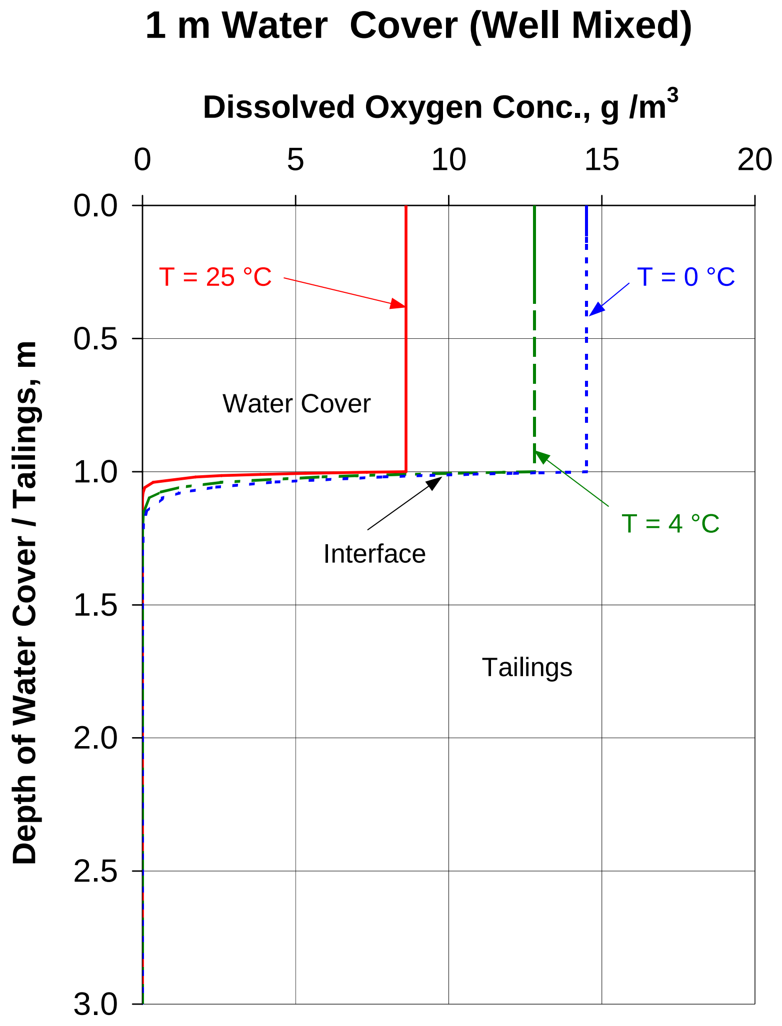




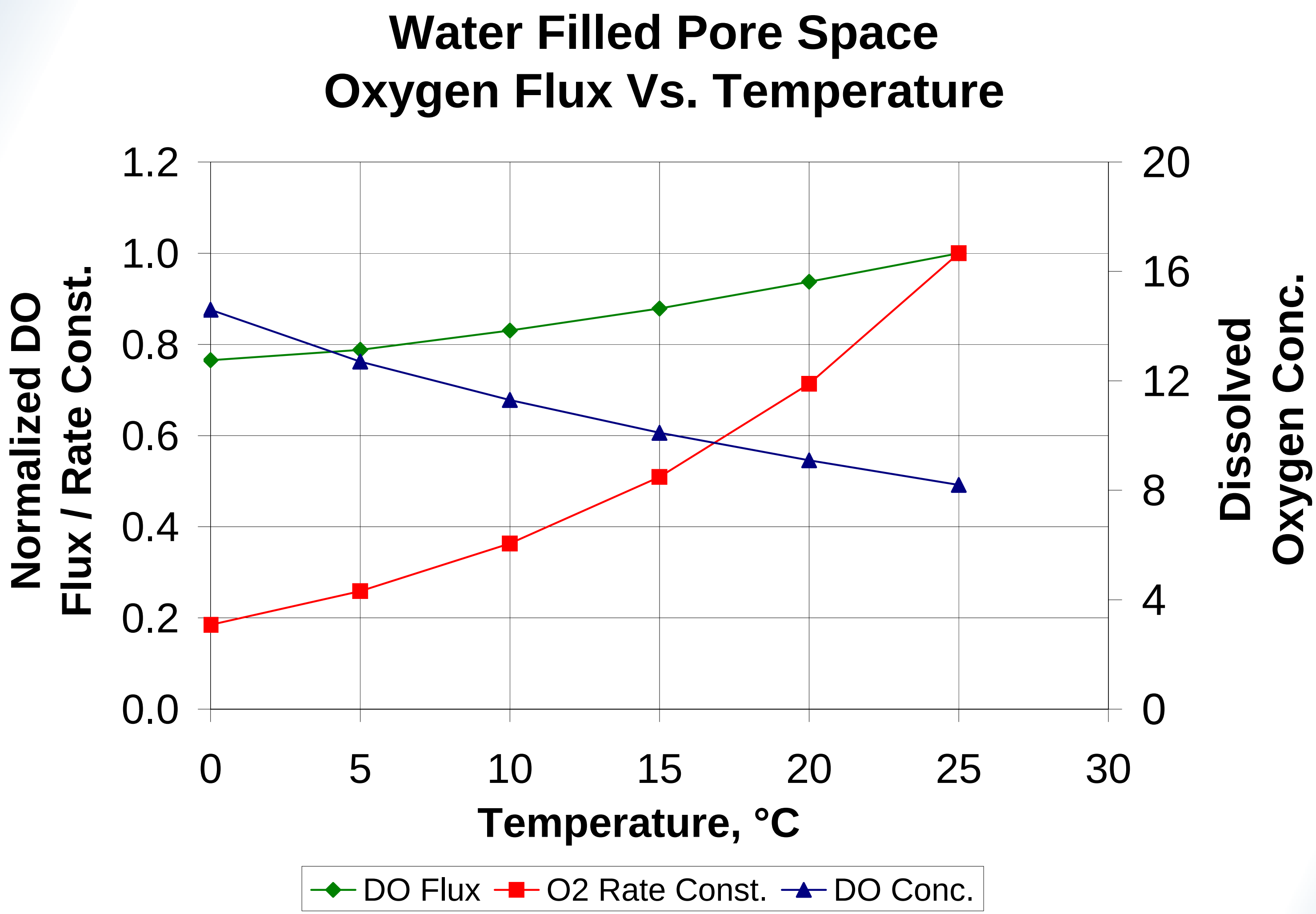
Well Mixed Water Cover - Oxygen Diffusion Profiles

1 m well mixed surface water cover

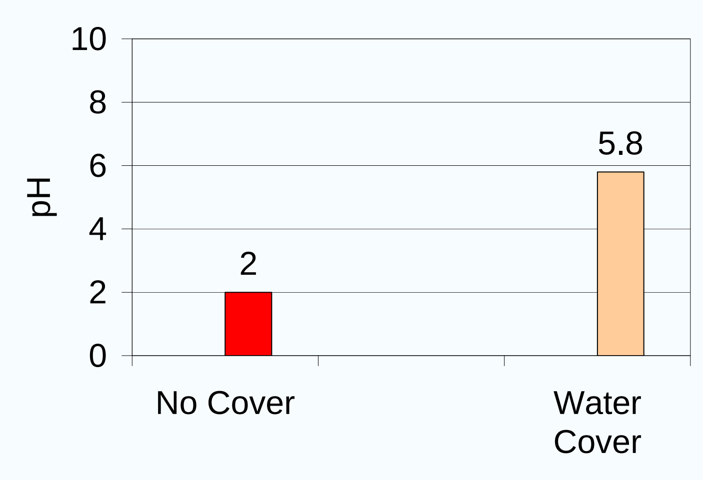
- Oxygen limiting cover
- Oxygen transfer/diffusion controlled by a Diffusion Boundary Layer (DBL) at the waste-water interface
- No impact of water cover depth unless stagnant water column
- Bulk oxidation of unsaturated waste reduced to a very shallow zone surface oxidation under water cover conditions

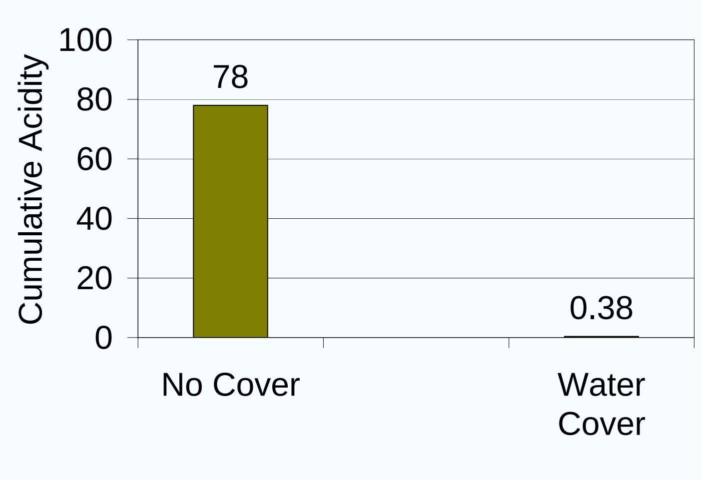


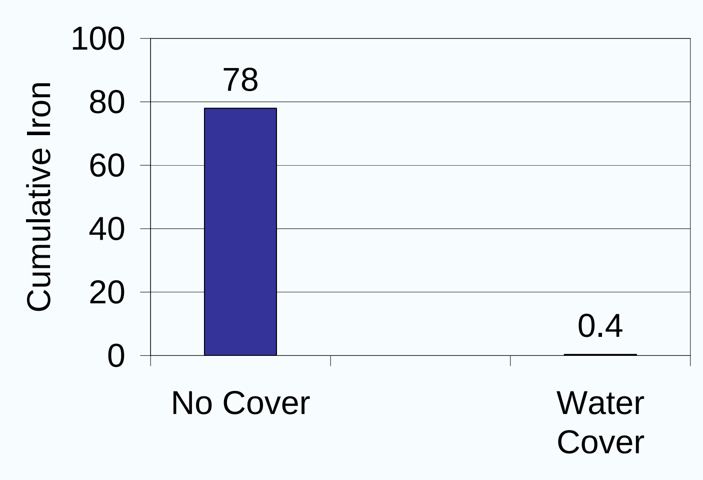
Water Cover - Temperature Effects



Performance of Water Covers - Laboratory Studies







	Control No Cover	Water Cover
Acidity	100	0.48
Total Iron	100	0.51

Performance of Water Covers - Field Sites (Man-made)

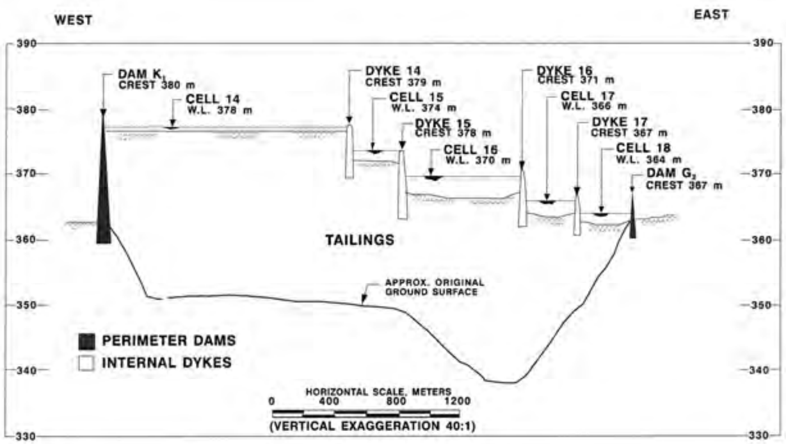
- Four study sites: Denison, Panel, Quirke and Stanleigh Tailings Management Areas (TMAs) located at Elliot Lake, Ontario, Canada
- Low ore grade (~0.1% U) and uranium market conditions led to mine closer in early to mid 1990s
- Highly acid generating pyritic uranium tailings containing 5-10% pyrite; NNP = -100 to -150 kg $CaCO_3$/tonne
- Acid-leach milling process, very small to nil available alkalinity
- Extensive field sites having in-situ shallow water covers of minimum 1 m depth; site rehabilitation during 1992 to 1999
- All sites on care and maintenance

Water Cover Sites - Denison TMA

- Mine operation from 1957 to 1992
- 63 M tonnes of acid generating pyritic U tailings; 5-7% pyrite
- Two tailings management areas (TMA-1 and TMA-2); combined area 290 ha; separate single elevation water covers
- Decommissioning activities 1993 to 1996; impervious containment dams; reinforcement 1993; designed precipitation run-off facilities
- Tailings dredged; single elevation water cover provided and maintained by natural run-off from containment area catchment basin
- In situ lime addition and periodic effluent treatment

Water Cover Sites - Quirke TMA

- Mine operation from 1956 to 1961, and from 1968 to 1990
- 42 M tonnes acid generating U tailings and 4 M tonnes waste rock
- TMA 192 ha, ~ 15 m elevation difference along the site
- Rehabilitation and decommissioning 1992 to 1995; five hydraulically interconnected internal dykes and cells provide a terraced configuration;
- Single elevation water cover in each cell
- Water cover maintained by gravity flow from an upstream Gravel Pit Lake
- Lime incorporation in the tailings substrate and periodical addition to maintain neutral conditions in WC



Vegetated Sites – Nordic/Lacnor TMAs

- Mine operations from 1957 to 1968 and from 1957 to 1960
- 14.7 M tonnes of acid generating uranium tailings in two TMAs having a combined area of 131 ha; ~ 5-7% pyrite
- Successful revegetation of tailings for past 25 yrs
- Dams and facilities upgraded in 1998-99
- Sites on care and maintenance basis; effluent collected and treated continuously

Site Characteristics

- Acid generating pyritic uranium tailings; 5-10% pyrite, NNP -100 to -150 kg $CaCO_3$/tonne
- Major components: quartz 75%, muscovite 10-12%, potassium feldspar 5-10%; minor sericite, plagioclase, chlorite and calcite
- Particle size 50% less than 75 µm
- Acid-leach milling process, neutralization of tailings prior to discharge; gypsum-metal hydroxide containing neutralization sludge

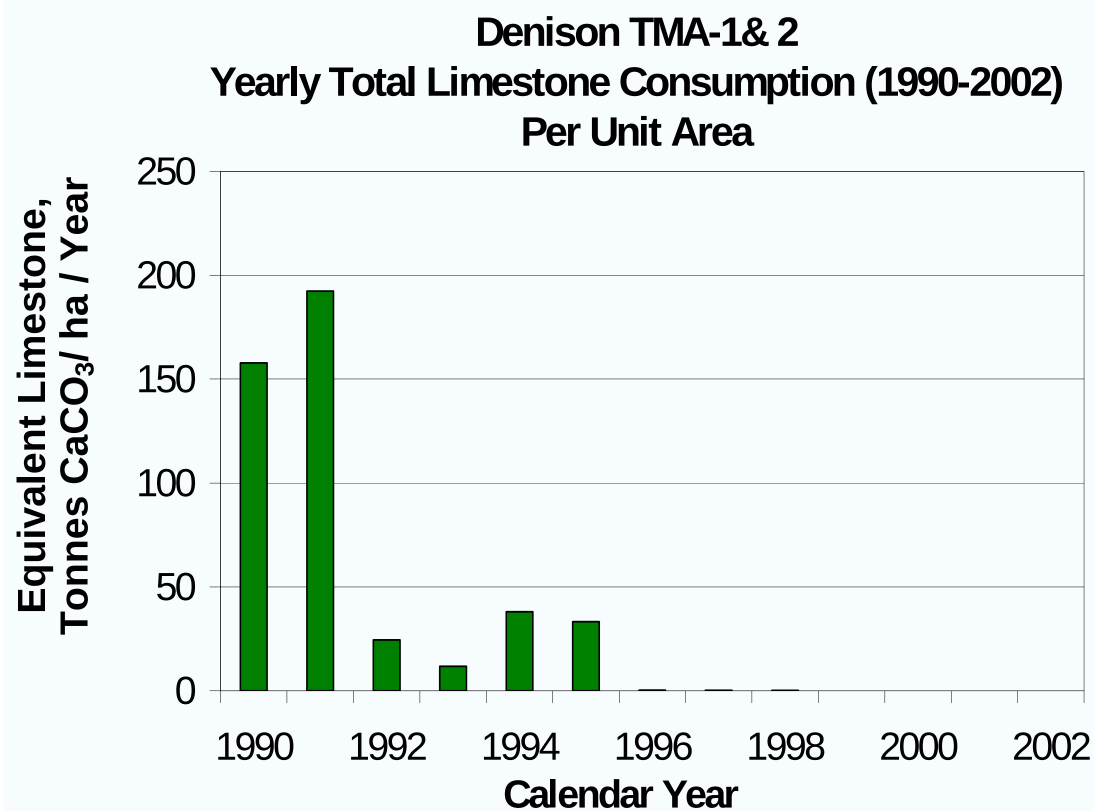
Site	Total Amount of Tailings (M tonnes)	Total Surface Area (ha)	Year of Complete Submersion
Denison	63	271	1996
Quirke	46	192	1995
Panel	16	123	1993
Spanish-American	0.5	51	1994
Stanleigh	19.8	411	2002
Nordic & Lacnor	14.7	131	-

Performance of Water Covers

- Analysis of yearly water cover data on alkali additions to the water cover and at the effluent treatment plant
- Comparison based on yearly equivalent limestone addition per unit area for water cover and vegetated sites

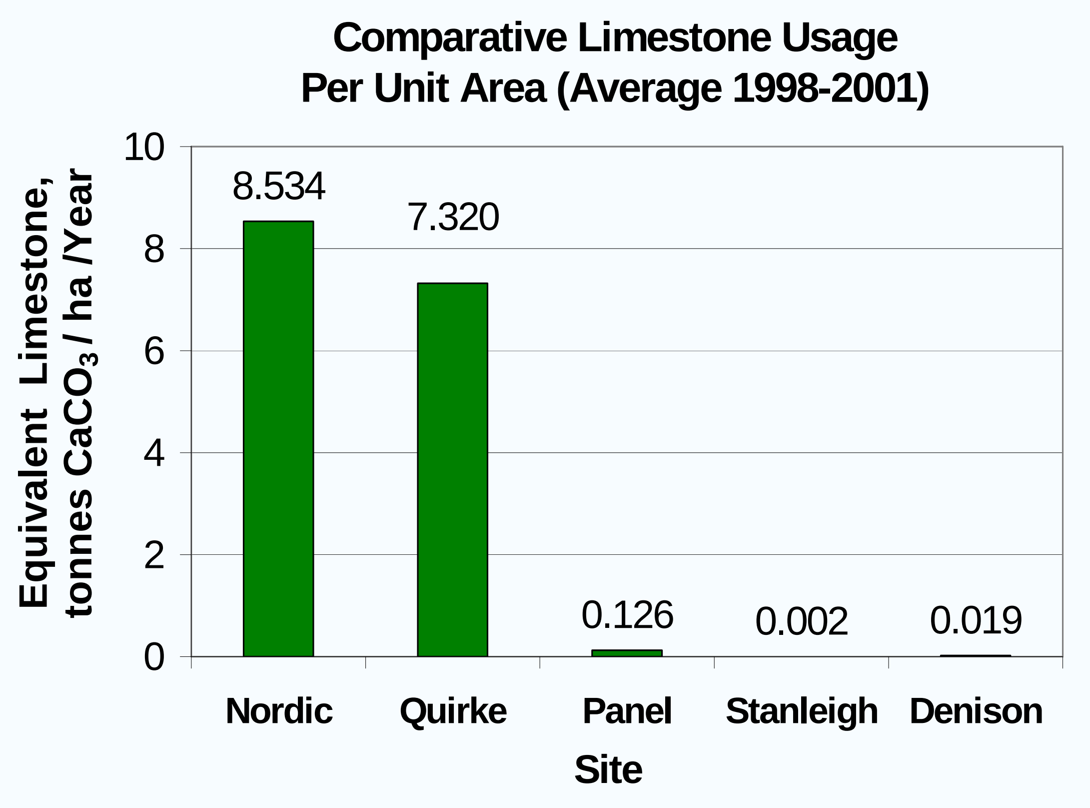
Performance of Water Covers - Denison TMA

Year	Total $CaCO_3$ Equivalent (tonnes/year)	Total $CaCO_3$ Equivalent (tonnes/ha/year)
1990	42,779	157.858
1991	52,119	192.320
1992	6,636	24.487
1993	3,201	11.813
1994	10,288	37.963
1995	9,024	33.300
1996	74	0.275
1997	59	0.218
1998	18	0.065
1999	1	0.002
2000	1	0.002
2001	2	0.006
2002	0.16	0.001

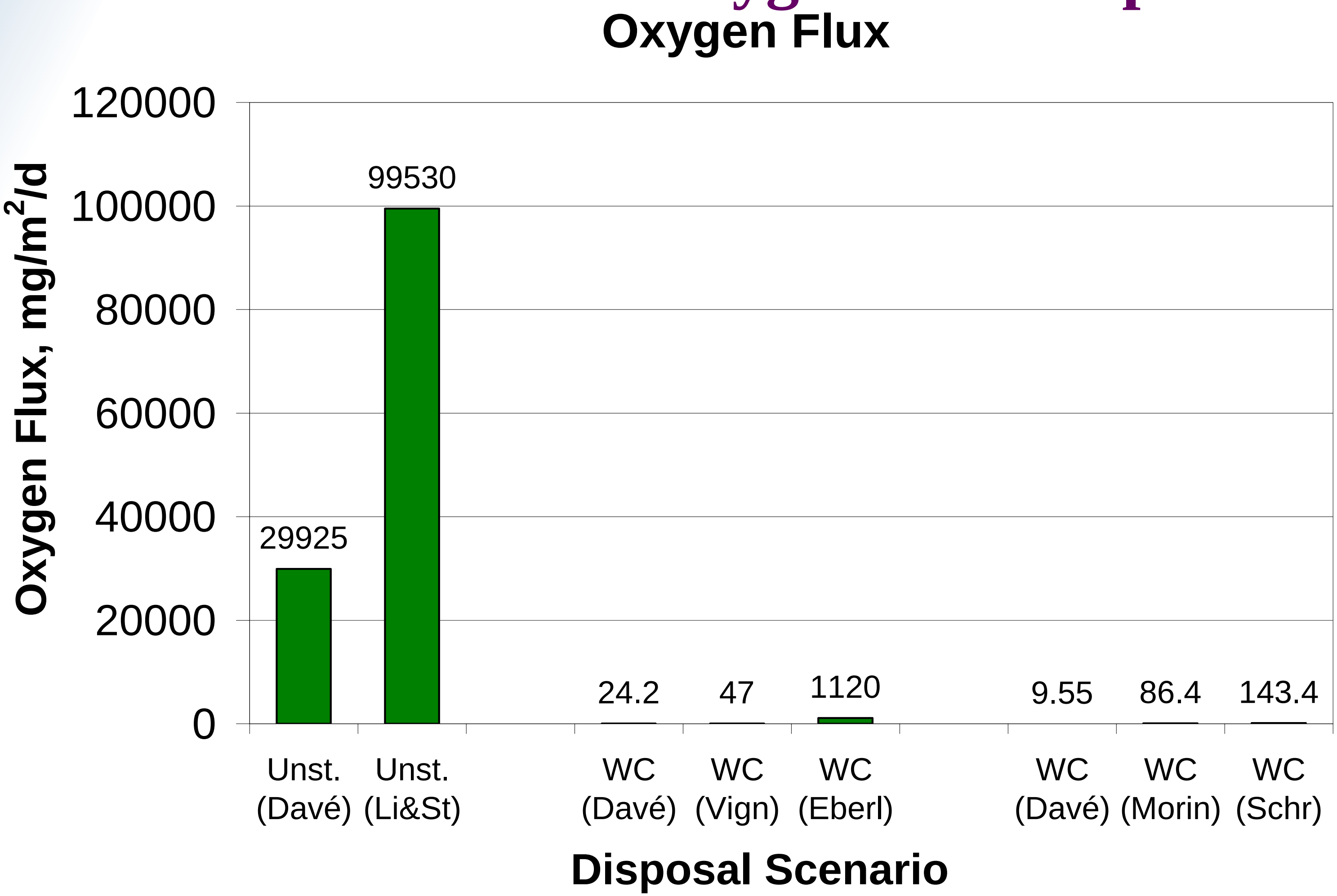


Performance of Water Covers
Water Cover / Revegetated TMAs

Site	Total $CaCO_3$ Equivalent (tonnes/year)	Total $CaCO_3$ Equivalent (tonnes/ha/year)
Denison	5.07	0.019
Quirke	1405.40	7.320
Panel	15.54	0.126
Stanleigh	0.68	0.002
Nordic	1117.91	8.534



Performance of Water Covers
Water Cover / Oxygen Consumption

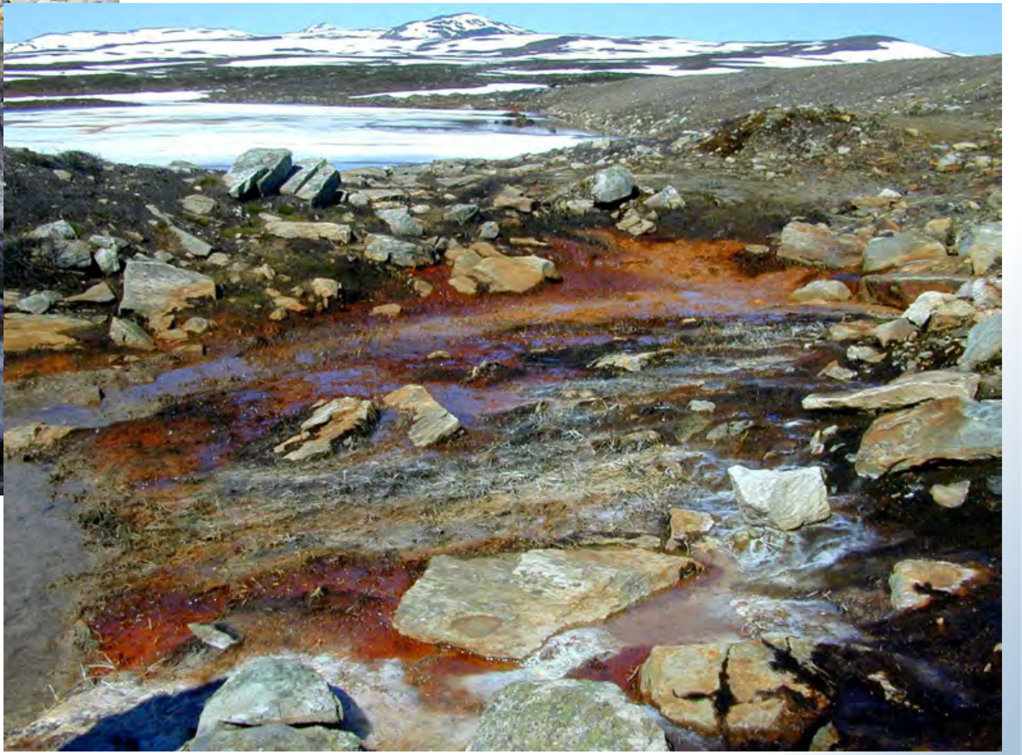


Stekenjokk Mine, Sweden

- Site located 800 m above sea level, ~ 65° latitude, in the Lapland mountains in northwestern Sweden
- 4.4 M tonnes of pyritic tailings, ~ 20 % S as pyrite, 0.64 % Zn and 0.19 % Cu
- Site decommissioned with water cover since 1991
- Frequency of very high wind conditions
- Incorporation of waste rock breakwaters; sand cover on tailings in the shallow water cover area
- Acceptable surface water quality; no treatment required

Stakenjokk Mine, Sweden

Stakenjokk Mine, Sweden

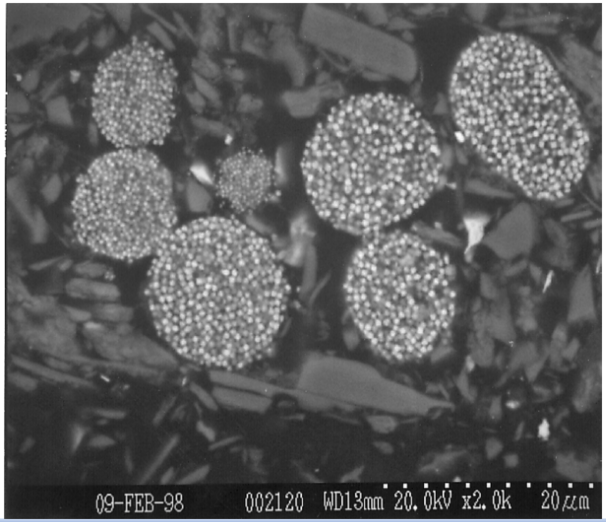


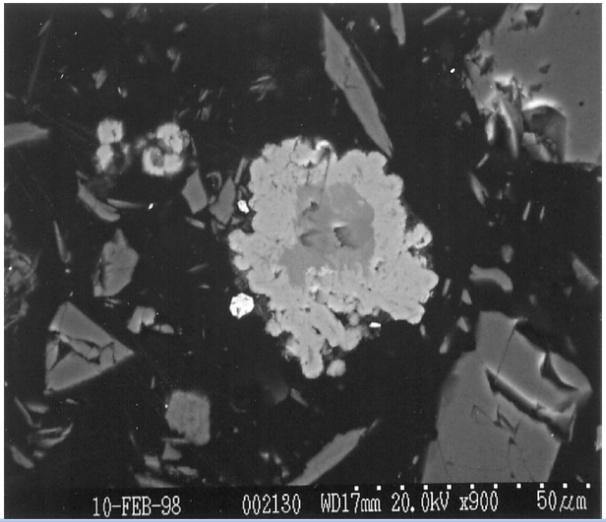
Water Covers Performance Summary

- Field sites performing well as per design specification; water cover maintained at near neutral pH conditions
- Acid generation rate at Denison TMA has reduced to less than 0.03% and 0.15% of pre-water cover operating and during site rehabilitation
- In comparison to the revegetated Nordic/Lacnor site, acid generation rates at Denison, Panel and Stanleigh TMAs have decreased to less than 1.6%
- Flushing of the previously generated acidity and oxidation reaction products at the Quirke TMA are resulting in its high alkali demand comparable to that at Nordic TMA

Water Covers on Reactive Tailings

Framboidal pyrite





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Water Covers – Permafrost Regions

- Application limited to suitable climatic conditions
- Thawing of permafrost below tailings impoundment; increased flow paths
- Stability of permafrost dam cores
- Ice dams and jamming
- Wave action and ice sloshing; wave breakers may be required
- Long-term integrity of containment structures and the associated high risk factor
- Limited biological activity and organic matter production
- In pit or below grade disposal

Summary Water Covers – Man-made Lakes

- Suitable for both existing and new waste management sites
- Design for closure for new sites; waste oxidation could be minimized
- Integration of local topography and biota
- Water quality could be maintained in-situ to meet discharge standards; downstream treatment could be minimized
- Designed for maximum probable precipitation events and extreme draught conditions
- Incorporation of minimum water cover depth and/or wave breakers to control wind-wave induced erosion
- Medium to high risk associated with the long-term maintenance of water retention dams and flow structures; large footprint in case of catastrophic failure
- Impact of global warming on water cover depth and retention

In Lake or Submarine Disposal

Selected Underwater Disposal Sites

Lakes:

- Buttle Lake BC, Westmin
- Benson Lake BC, Cominco
- Mandy Lake, MB, HBMS
- Anderson Lake, MB, HBMS
- Garrow Lake, NWT
- Lake Superior, MAN, US, Coastal Bay, Reserve Mining

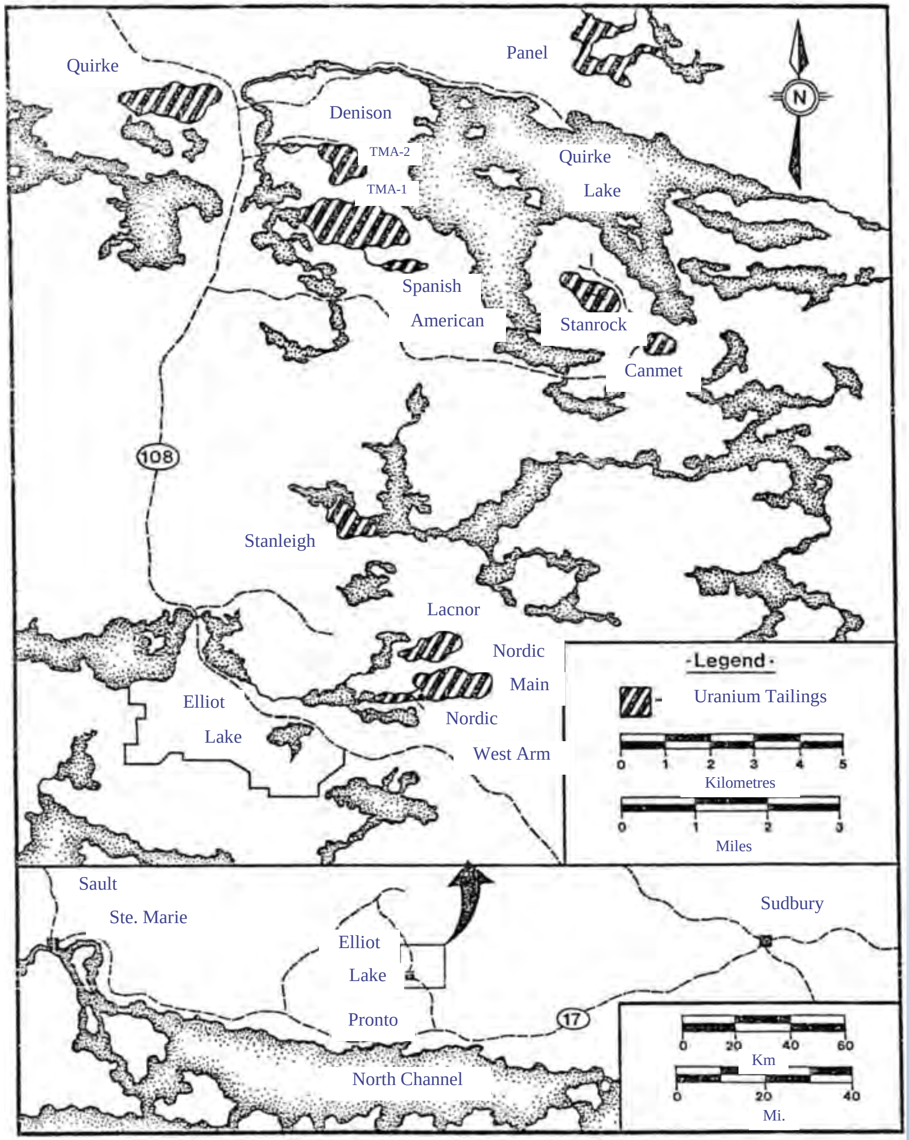
Submarine Disposal:

- Vancouver Island, BC, Fjord, Island Copper
- Alice Arm, BC, Fjord, Amax
- Tilt Cove, Bay Verte, NFLD
- Jorden River, BC, Coastal Bay, Sunro Mine

In Lake Disposal

Quirke Lake Disposal Case

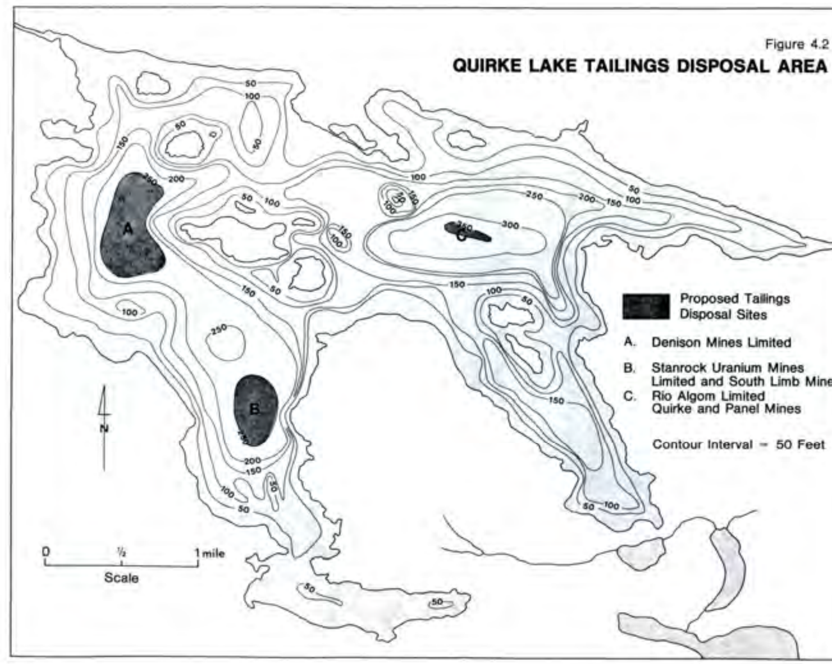
- Expansion of Uranium mines: mid to late 1970s
- Poor lake water quality: low pH, and high acidity, TDS and Ra-226 conc., low biological productivity
- Extensive tailings impoundments along the lake perimeter
- Long-lived radionuclides, $T_{1/2}$ Ra (~1600 y), Th-230 (~80,000 y)
- Impervious dam requirements
- Maintenance of waste management facilities for 10,000 to 100,00 years
- Suitable site to contain all existing and future tailings



In Lake Disposal

Quirke Lake Attributes

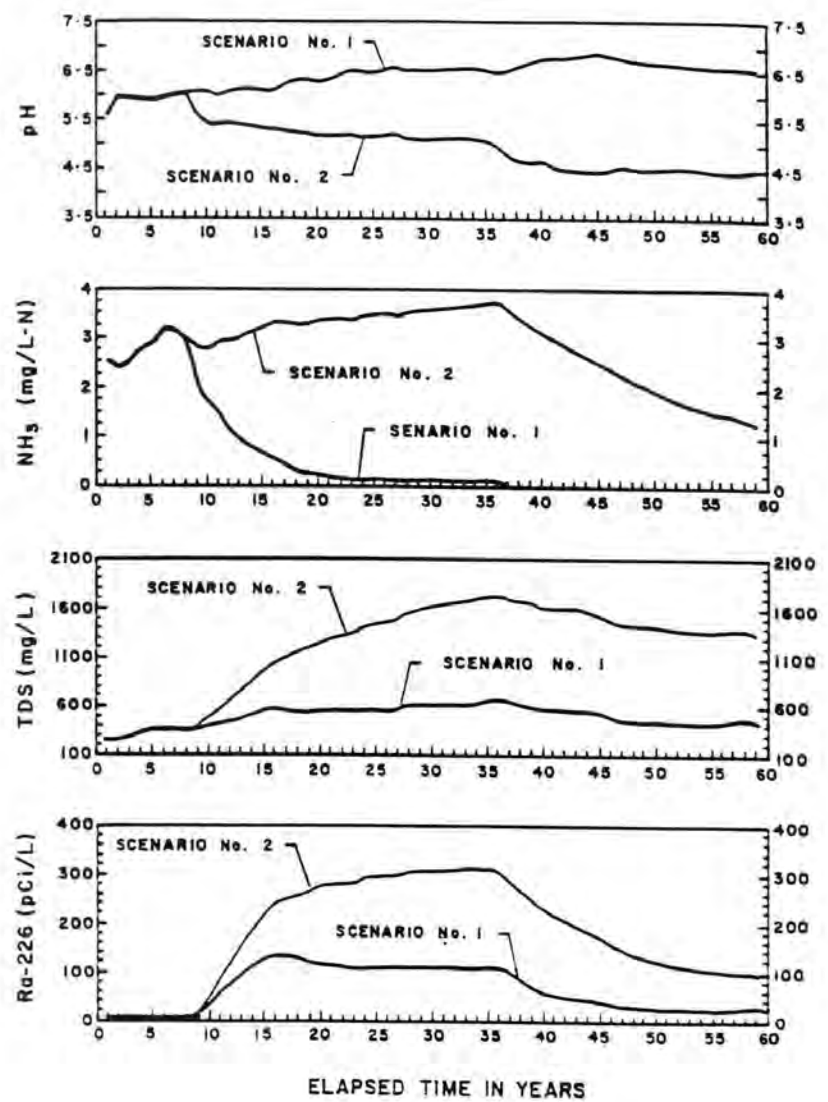
- Largest lake in the Serpent River watershed
- Area 2097 ha, volume 803 x 10^6 m^3, watershed area 162 km^2 (16,200 ha),
- Mean depth 38.7 m, maximum depth 104 m
- Average annual run-off flow ~ 5500 L/s, hydraulic residence time 4.4 y
- Three deep-water locations to accommodate all U tailings in the Elliot Lake area with a minimum water depth of ~ 30 m



In Lake Disposal

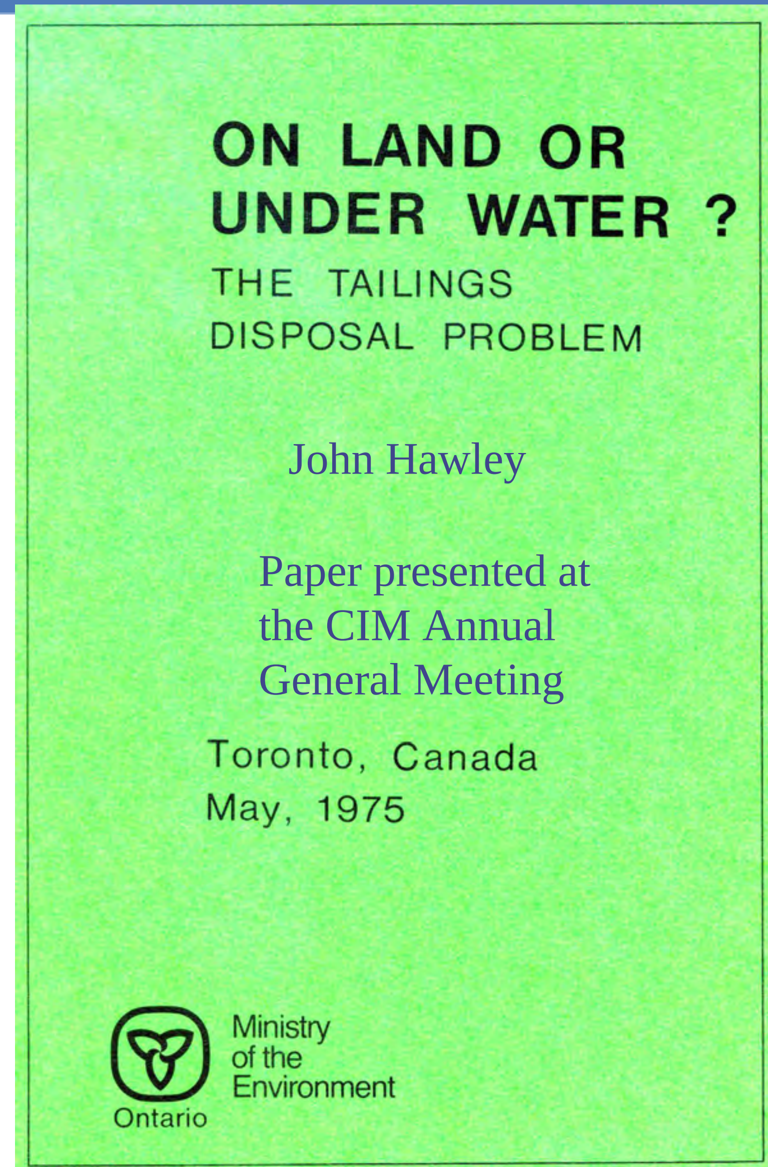
Quirke Lake Disposal

- Long-term geotechnical stability of U mine tailings facilities
- Control of acid generation, dust and radon exhalation problems
- Water quality to deteriorate for 30 y or more
- Major impact on area fisheries
- Ongoing treatment of lake discharge for NH_4, NO_3 and Ra
- Major diversions of incoming fresh water
- Costly to implement, estimated total capital cost ~ $ 160 million (1977 Dollars)



On Land or Underwater Disposal ?

- No regulatory support for underwater disposal in natural lake basins (over my dead body)
- Underwater water disposal (deep water cover) facilities offer minimal opportunities for environmental control
- In most cases, both the liquid and solid phases of the tailings slurry remain uncontrolled
- In a dry land based disposal system maximum environmental control under a given set of conditions is possible



ON LAND OR UNDER WATER ?

THE TAILINGS DISPOSAL PROBLEM

John Hawley

Paper presented at the CIM Annual General Meeting

Toronto, Canada

May, 1975

Ontario

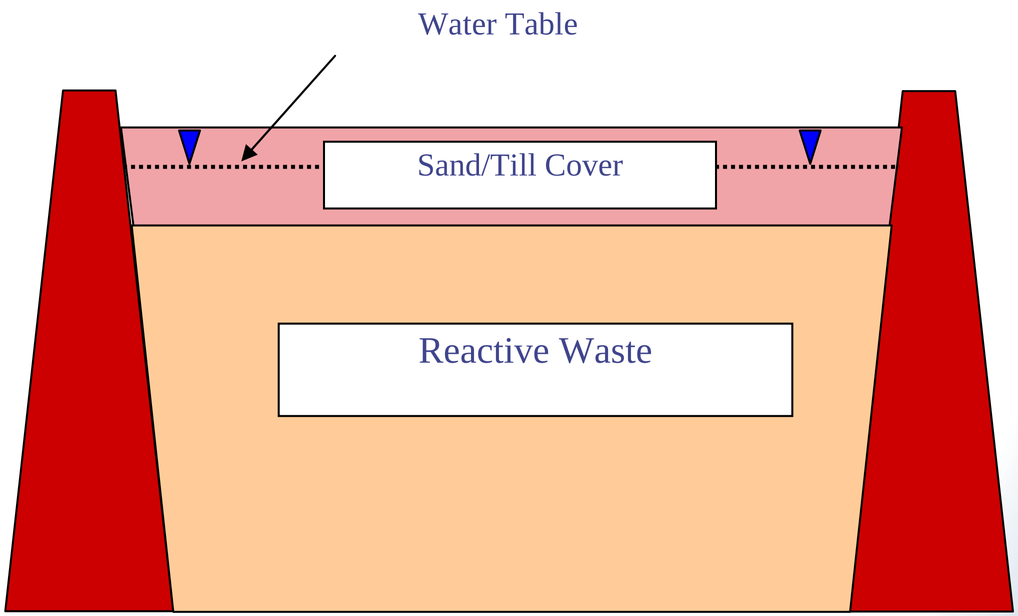
Ministry of the Environment

Disposal in Natural Water Bodies

- Minimal or no risk of catastrophic failure
- Most suitable for long-term geotechnical and chemical stability
- Suitable for small headwater or isolated water bodies
- Economically attractive and predictable technology
- Least impacted by climate change
- Water body is sacrificed during the operating phase; habitat compensation may be required
- Special ministerial permission is required and local stakeholders concurrence may be necessary
- Post operational site recovery is relatively quick, but the original habitat and biodiversity may be permanently impacted

Elevated Water Table / Saturated Cover Concept

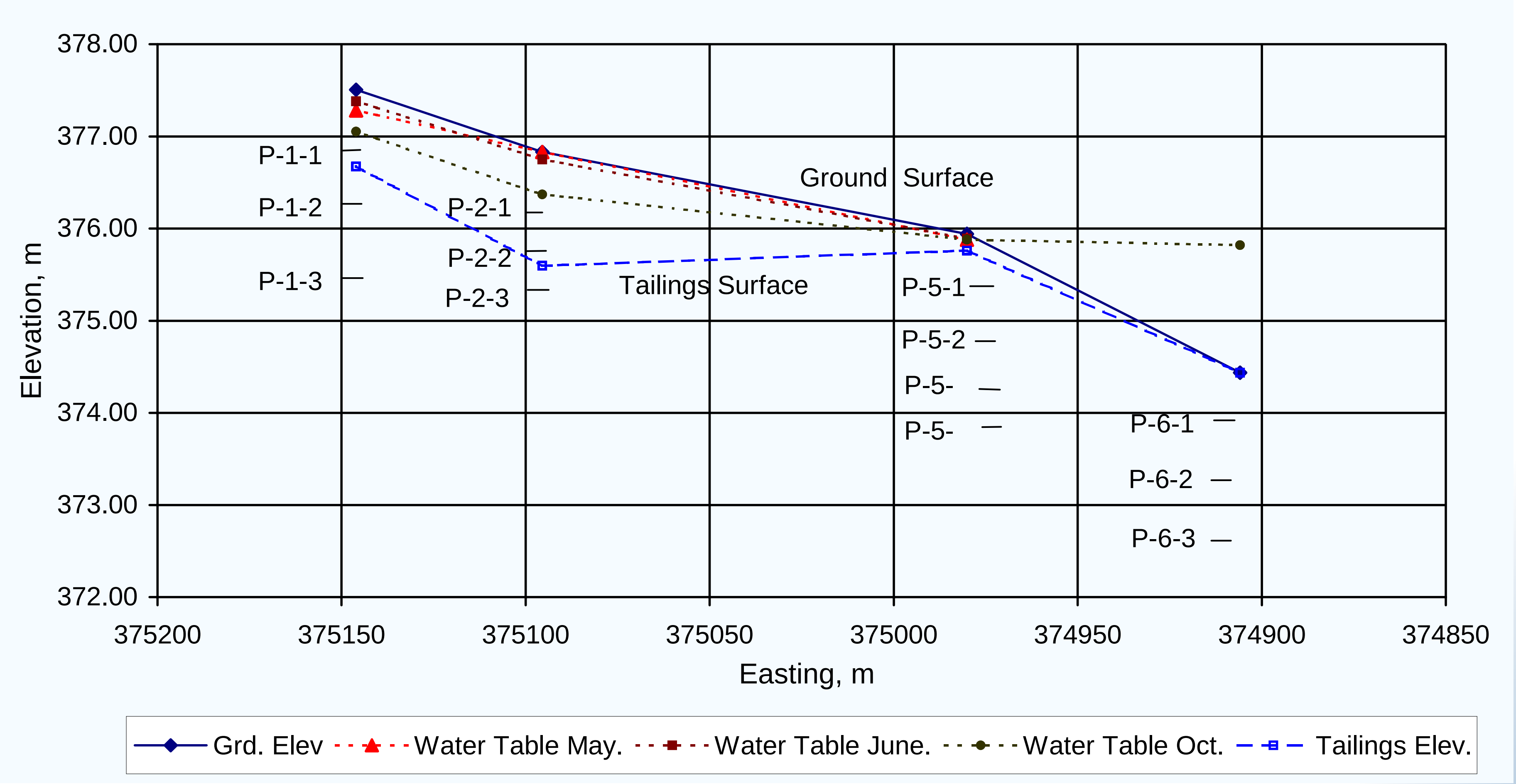
- Placement of sand/till or other non-reactive tailings surface cover, ~ 0.3 – 0.5 m in thickness
- Raising of water table to or above the tailings/waste surface
- Same advantage as a free surface water cover
- Increased impoundment dams stability, no free water surface required
- Ice erosion and scouring minimized
- Surface stability through native vegetation; may be impacted by differential snow depth and freezing
- Proposed by Lupin mine; full-scale investigations are required



Lower Williams Lake – Before Rehabilitation

Lower Williams Lake – After Rehabilitation

Lower Williams Lake – Hydrology



Summary

- Availability of suitable and site specific waste management technologies
- Permafrost encapsulation, water and ice covers and wet barriers offer unique opportunities for the north
- Low maintenance closure and walk away options are desirable over long-term perpetual treatment


Thank You!
http://envirolab.nrcan.gc.ca