SOVEREIGN CONSULTING INC.
AN ENVIRONMENTAL SERVICES FIRM

# A Short History of Pyrite and Acid Rock Drainage: An Engineer's Perspective of ARD

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Golden, Colorado

- Pyrite history, mineralogy & microbiology
- Testing procedures
- ARD Tetrahedron review
- Best Management Practices overview
- Engineering considerations

# Acid Rock Drainage

# A Little History and Background…

- Pyrite's name comes from the Greek, *pyrites lithos*, "the stone which strikes fire"
- Iron sulfide ($FeS_2$) – "fool's gold"
- The crystals form in the Isometric System; cubes, octahedrons, pyritohedrons and combinations of these and other forms
- It also may be found in radiating disks, hair-like crystals, concretions, and massive lumps in sulphide ore deposits
- Pyrite sometimes also contains small amounts of cobalt, nickel, silver or gold as well as selenium (replaces sulfur)
- Other metals can replace the iron (e.g., copper) but then it's no longer pyrite…
- Most abundant of all sulfide minerals and occurs in all kinds of rocks (sedimentary, metamorphic, igneous).

# How and where does pyrite form?

**Telethermal/biological (Sedimentary Environments)**

- Organic deep ocean sediments (marine shale)
- Coal swamps (sulfate-reducing biochemical reactors too)
- Roll front uranium deposits

**Epithermal/biological and abiotic (Igneous Environments)**

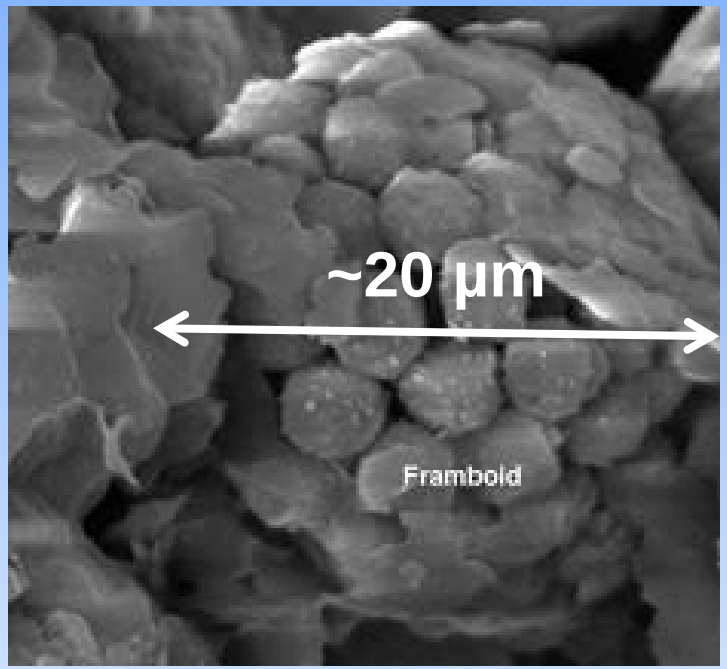
- Hot springs
- Alteration zones near igneous intrusions

**Mesothermal/Hypothermal / abiotic (Igneous & Metamorphic Environments)**

- Black smoker hydrothermal vents on seafloor
- Igneous intrusions

# Common Pyrite Forms

- Framboidal

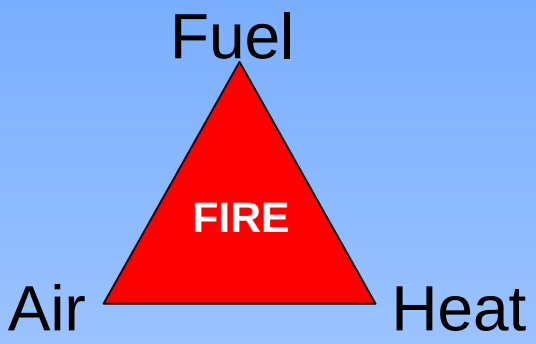



- Crystalline

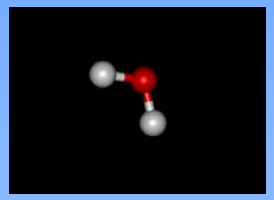
**Ref: GARD Guide**

*Mother Nature has been making pyrite for quite a while but it's only been recently in geologic time that it's become a problem…*

# Acid Rock Drainage Tetrahedron



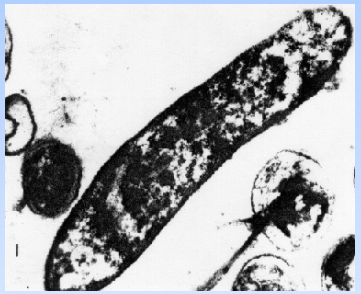

**Water**



**Oxidizer**

**(Air, $Fe^{+3}$)**

**ARD**



**Bacteria**

# Acid Base Accounting

## Static Testing

- Paste pH
- Acid-Generation Potential
- % Sulfur (pyritic & total sulfur)
- Neutralization Potential

# Acid Base Accounting

- Humidity Cells

- Column Tests

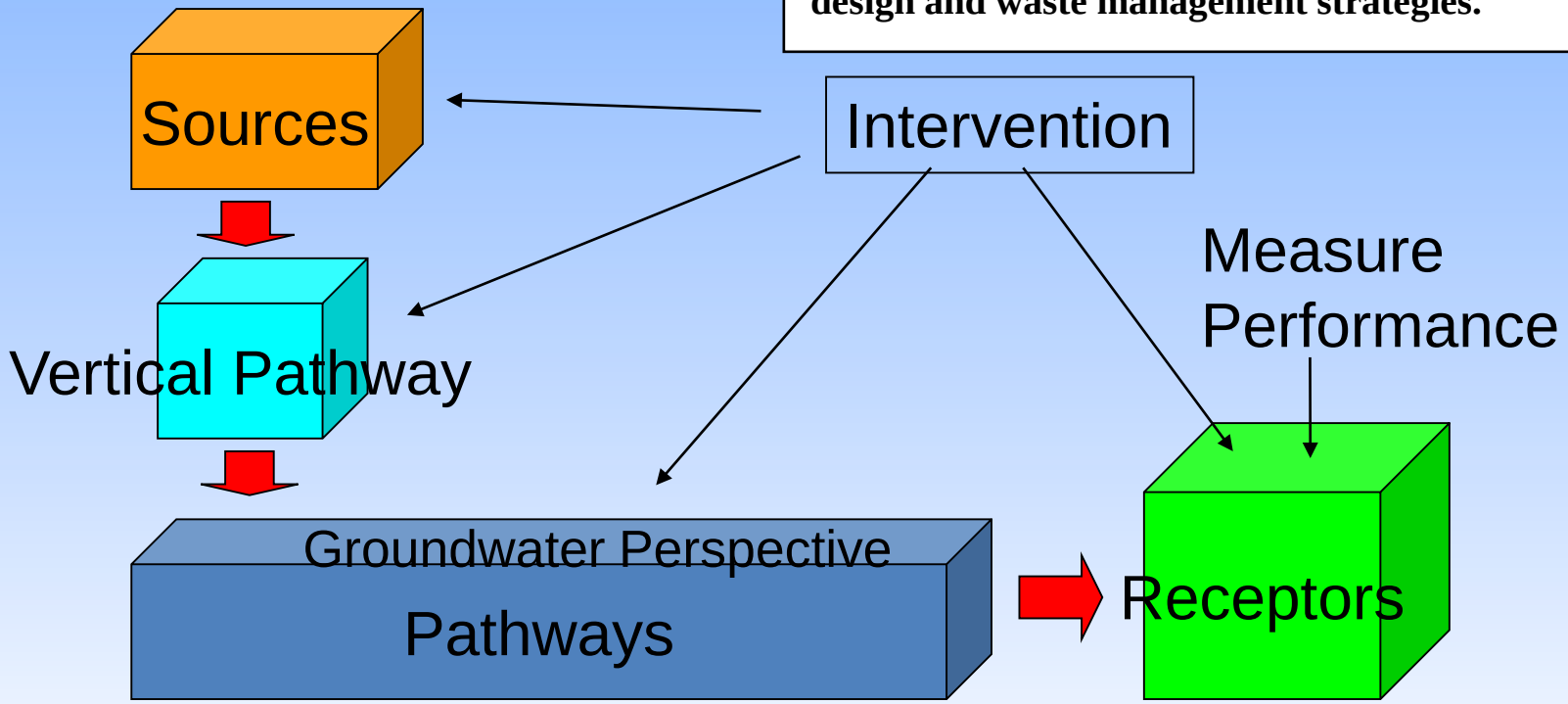
Tests rarely address potential remedies to ARD at a given site; sure, they predict that ARD will be a problem but…

The results don't provide me with any useful design data. This needs to change…

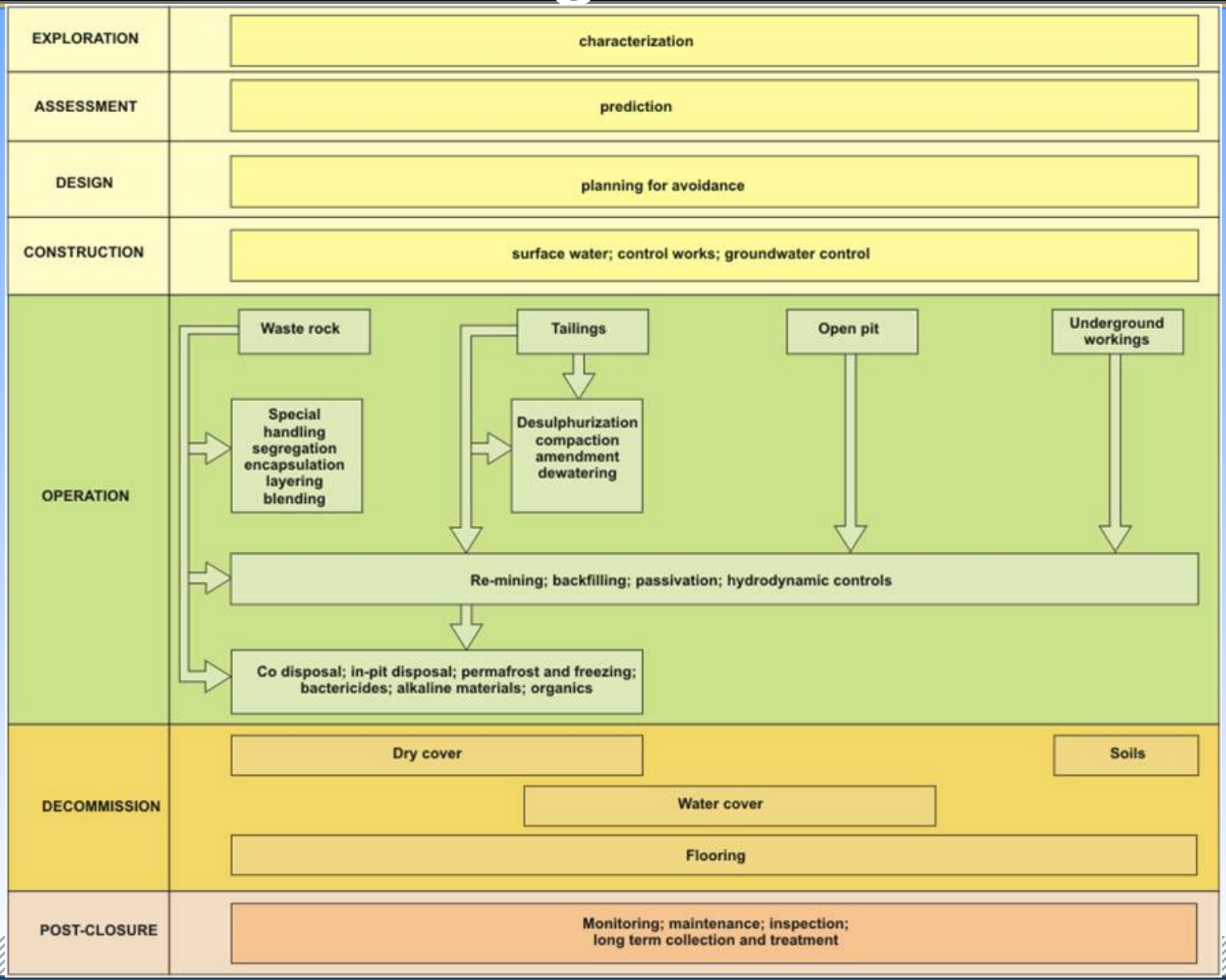
# Overview of Best Practice Methods

**REF: GARD Guide 2010**
***www.gardguide.com***

**Early avoidance of ARD problems is a <u>best practice</u> technique that may be achieved through integrating results of characterization and prediction, described in Chapters 4 and 5, along with mine planning, design and waste management strategies.**



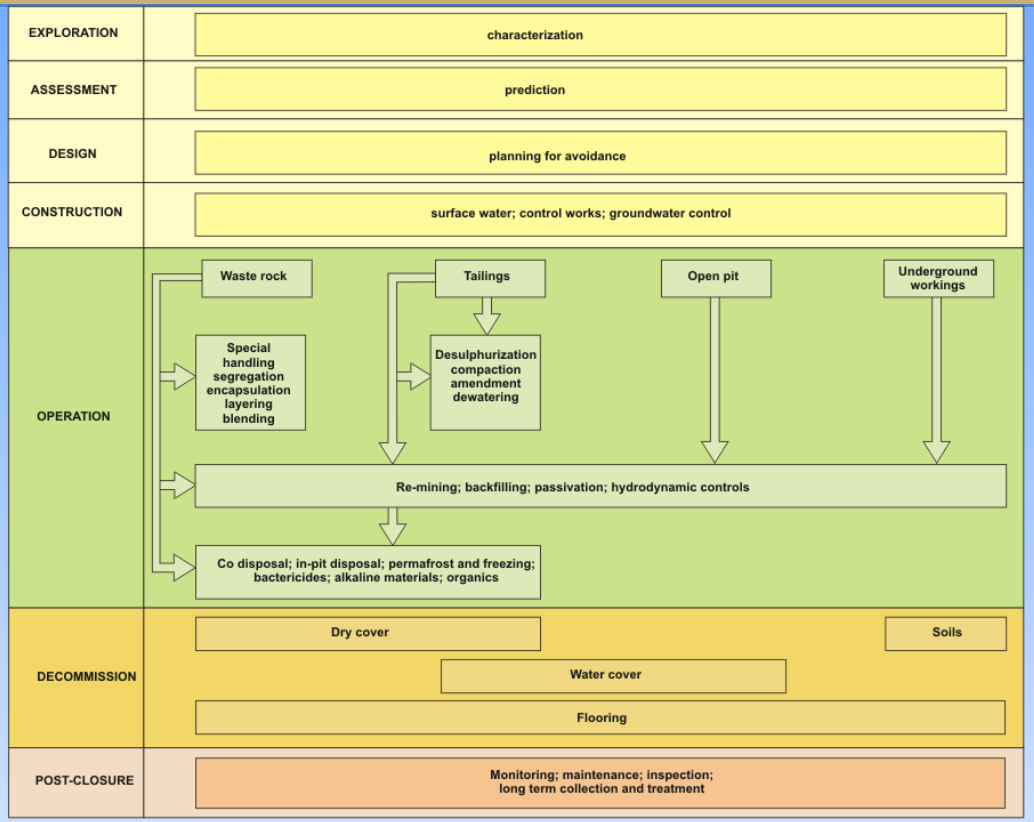
# ARD Mitigation Framework




**Ref: GARD Guide 2010**

# Best Practice Methods (1)

- Avoidance
- Special handling methods
  - Incorporate into mine plan
  - Segregation
  - Tailings desulphurization
  - Compaction and conditioning
  - Encapsulation and layering
  - Blending
  - Co-disposal
  - Permafrost and Freezing

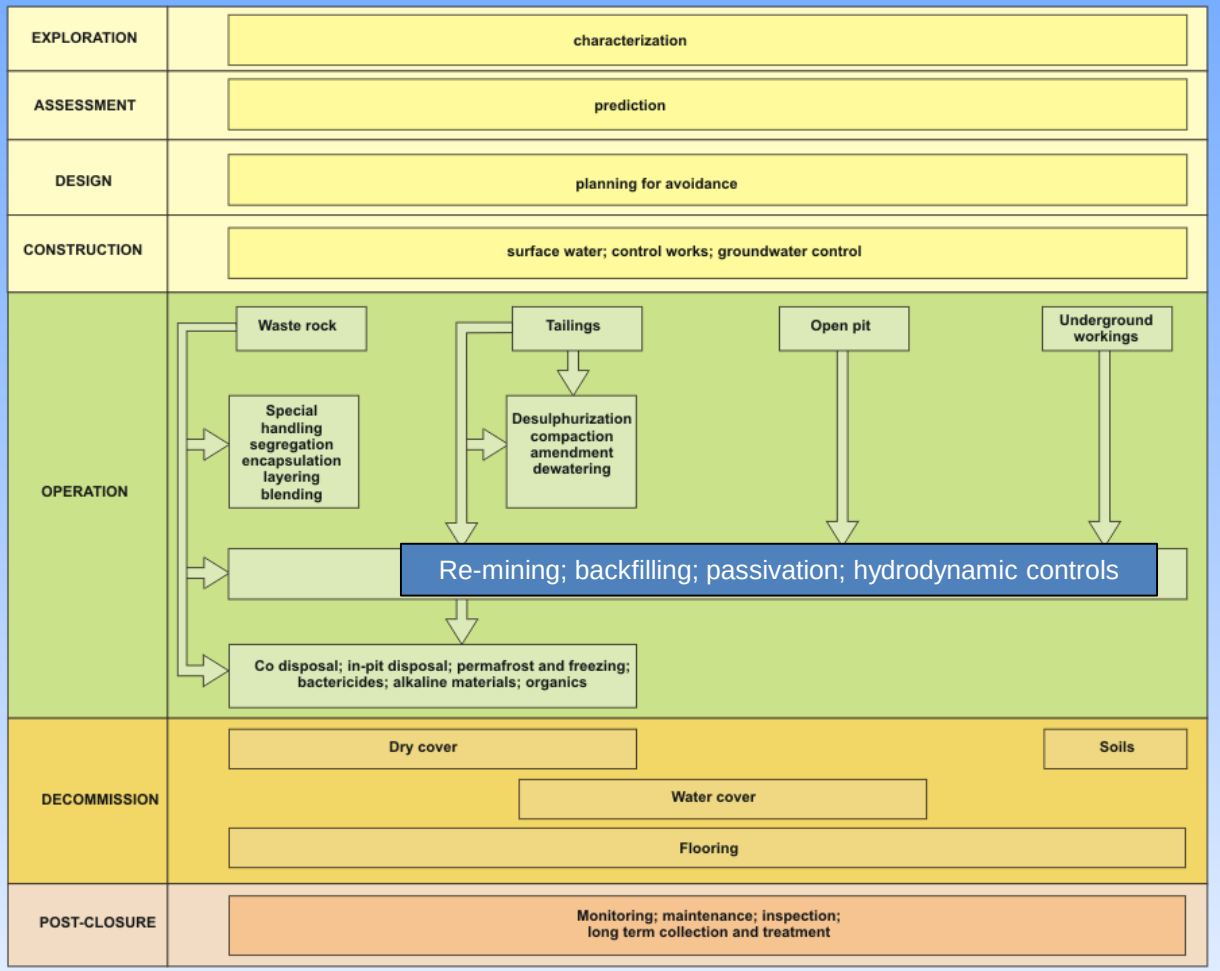



**What about *Abandoned* Mines?**

**REF: GARD Guide 2010**

# Best Practice Methods (2)

- Dry Cover Methods
  - Soil
  - Alkaline
  - Organic
  - $ynthetics
  - Gas barriers
  - Vegetation
  - Landform design
- Water Cover Methods
  - Subaqueous disposal
  - Partial water cover
  - Wetland covers
  - Attenuation
  - Stream flow regulation
  - Water recycle and reuse

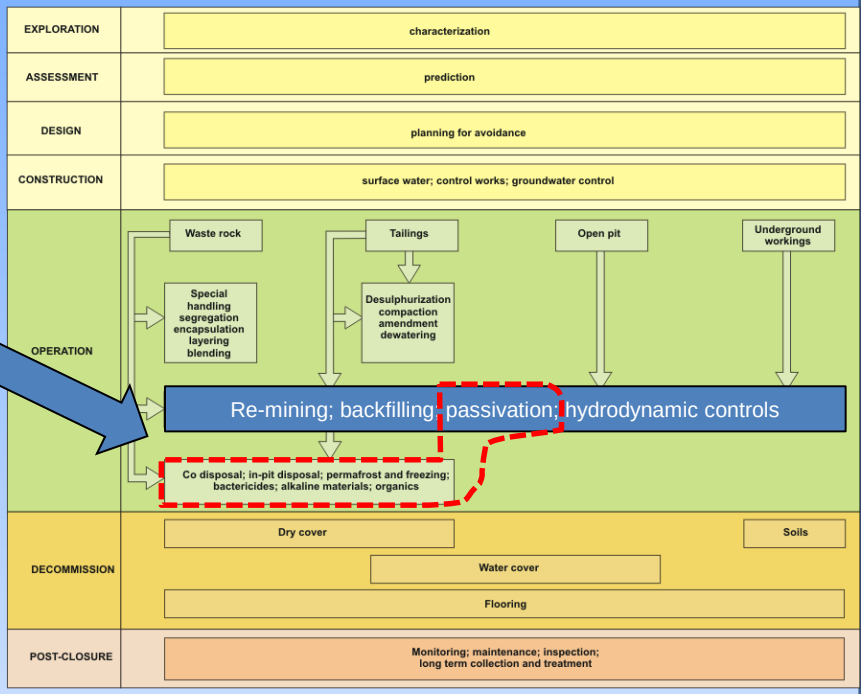



**REF: GARD Guide 2010**

# Best Practice Methods (3)

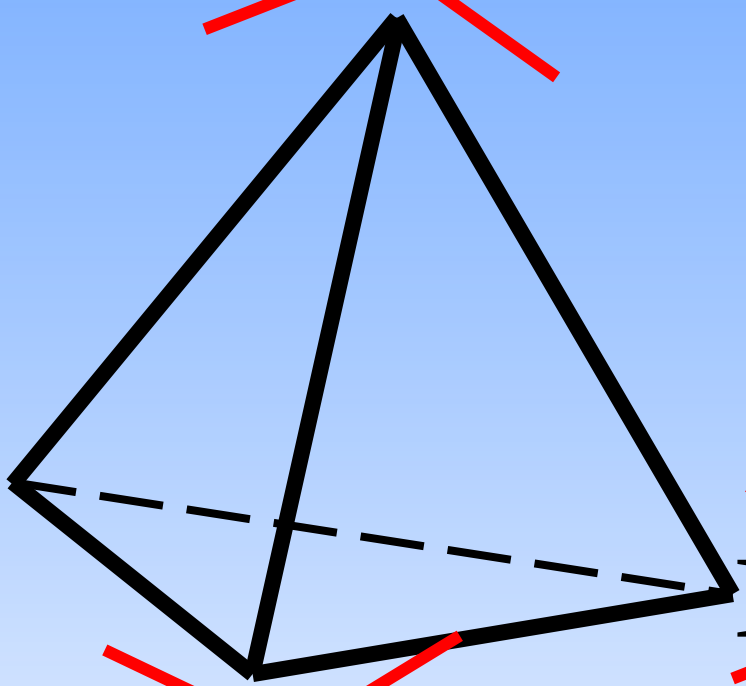
- Additions and Amendment Methods
  - Passivation
  - Alkaline materials
  - Organics
  - Bactericides
- Water Management Methods
  - Hydrogeological & Hydrodynamic Controls
  - Dewatering
  - Diversion
  - Flooding
  - Seals

???




**How to implement at abandoned mines?**

# Acid Rock Drainage Tetrahedron



Water

Oxidizer

(Air, $Fe^{+3}$)

Bacteria

Pyrite

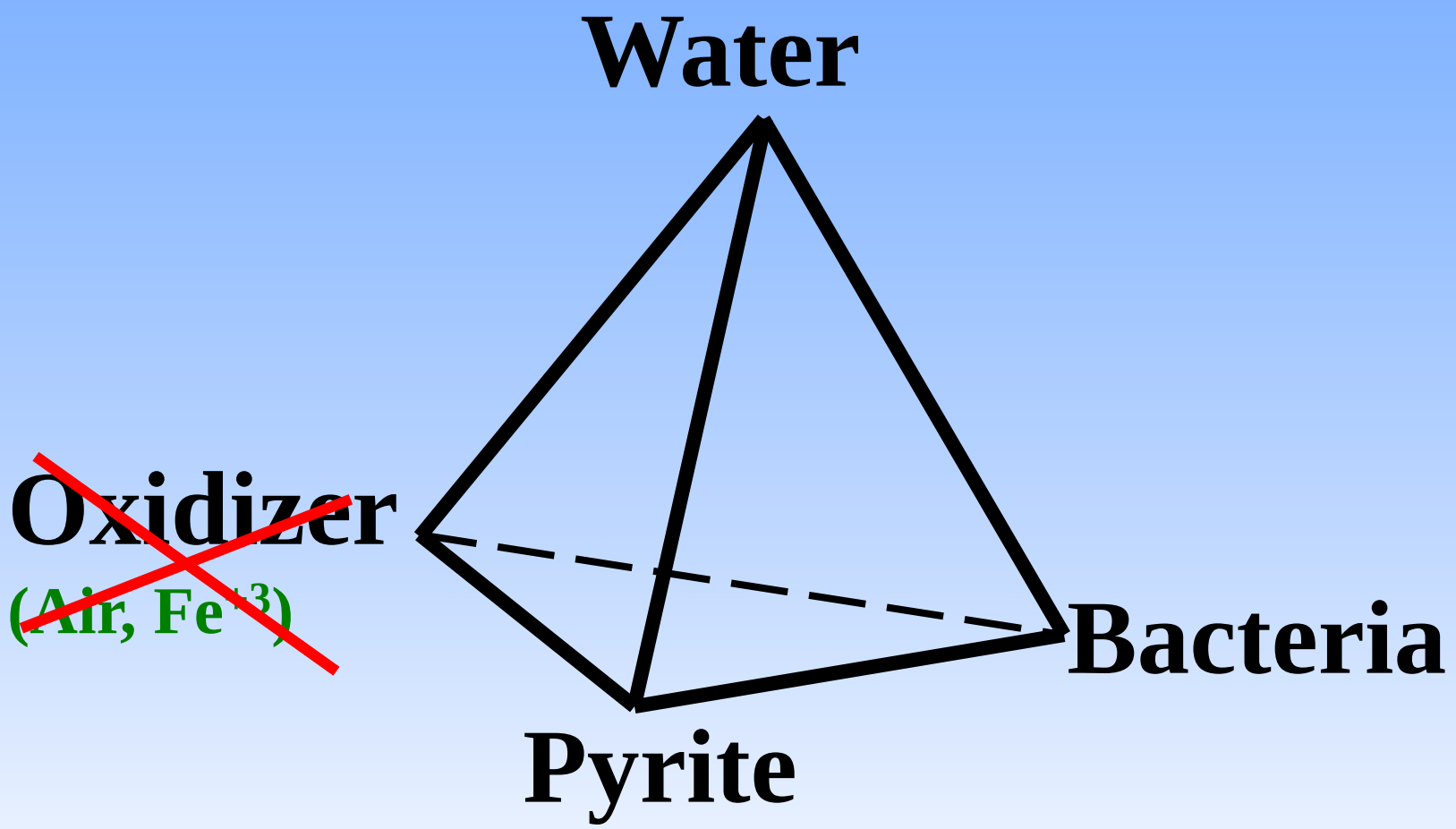
DO NOTHING = **PERPETUAL TREATMENT**

DO SOMETHING (anything) = **PATHWAY TO WALK-AWAY**

# Prevention/Source Control Summary

- Wet Encapsulation (submergence: adit plugs/pit flooding) - **keep air/oxygen out**
- Passivation additives (alkaline, organic, other) **change pyrite surface chemistry**
- Bactericides (sodium lauryl sulfate, etc.) **kill bugs & slow ARD kinetics x $10^{-6}$**
- Dry Encapsulation (covers or caps) - **keep water out**

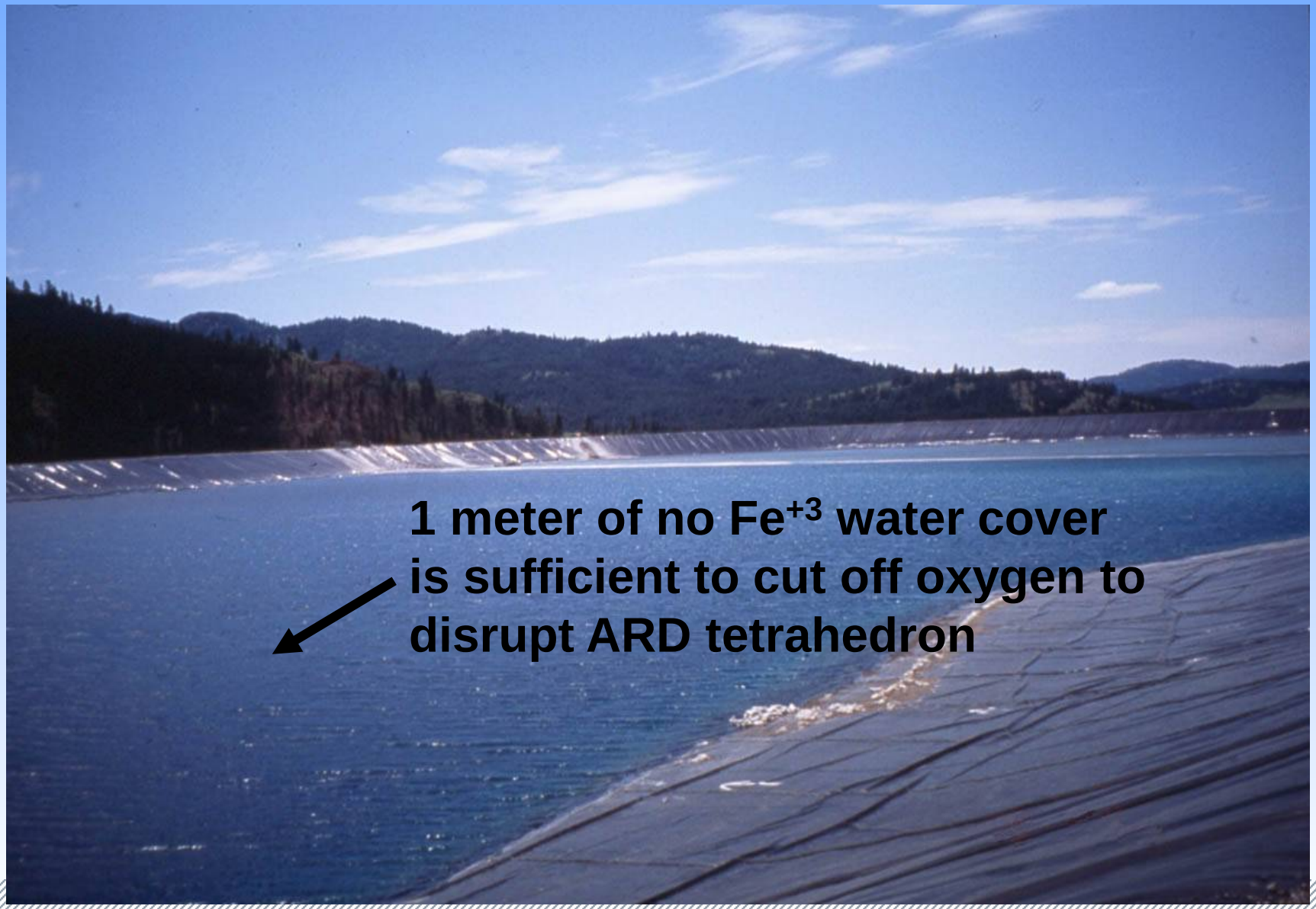
# Acid Rock Drainage Tetrahedron



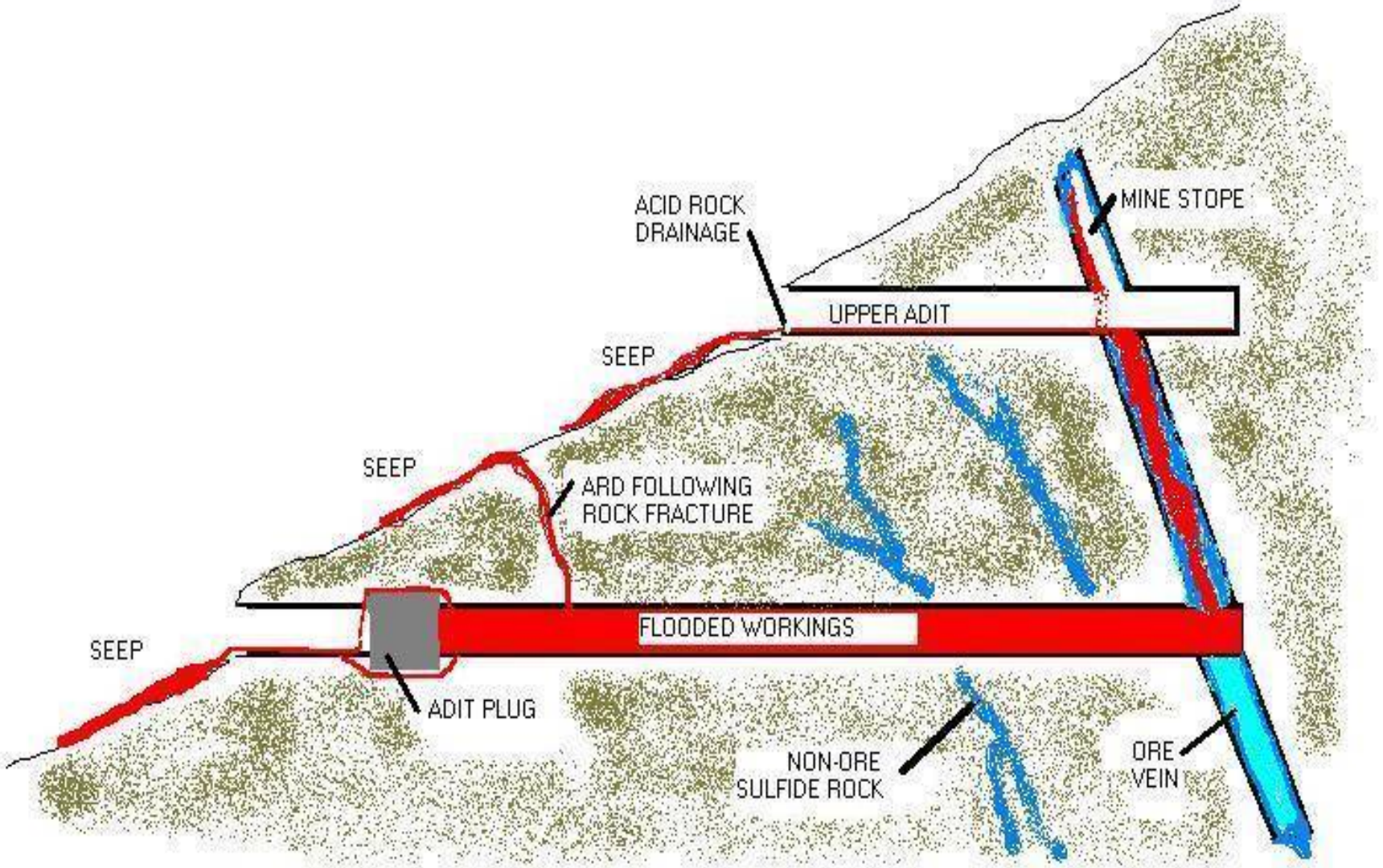
# Flooding Situations to Exclude Air

- Subaqueous tailings deposition
- Adit plugging - approach with caution
- Pit flooding (upper benches might be exposed – timing is everything)

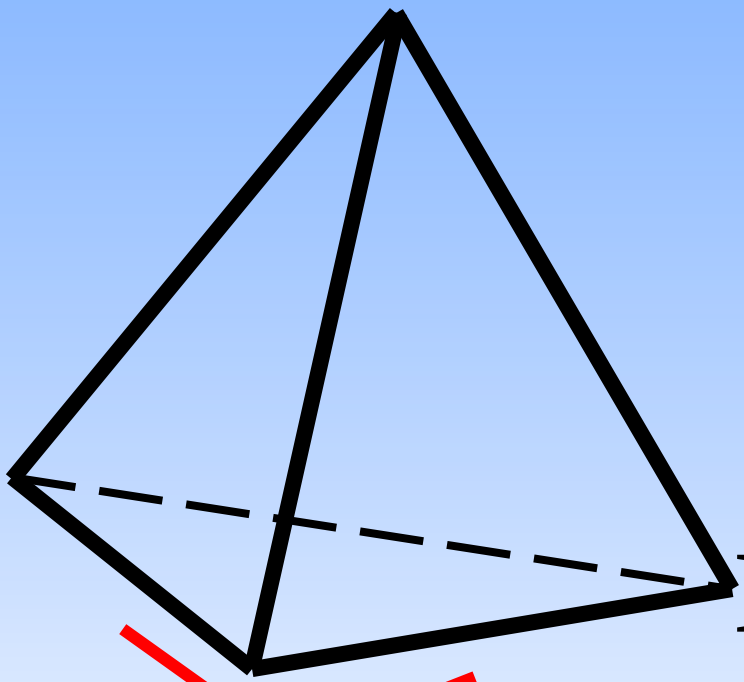
# Subaqueous Tailings Deposition



# Expect Problems with Flooding Underground Mines



# Acid Rock Drainage Tetrahedron



Water

Oxidizer

(Air, $Fe^{+3}$)

Bacteria

~~Pyrite~~

Surface

"Passivation"

# Passivation Additives (Liquid/Solid)

- Alkalinity (limestone, lime, cement kiln dust, steel smelter slag)
- Organic Material (alcohol, sugars, agricultural wastes, municipal biosolids, waste milk [patented])
- Other (Phosphate, micro-encap-sulation reagents (silicates), $KMnO_4$ )

# Passivation Additives - Cheap alkalinity

- Limestone (quarried) – ner fines?
- Dolomite
- Lim ent kiln dust
- dium bicarbonate

**WHAT'S THE GRAIN SIZE DISTRIBUTION????**

Note: We need to consider the *physics* of delivering and distributing a solid into a porous medium

# Passivation Additives - Cheap organics

- Sawdust (the finer, th
- Paper (ne
- [illegible]
-

**HOW DRY OR WET IS IT ?**
**MATERIAL HANDLING**
**AND/OR ODOR**
**CHALLENGES**

Note: We need to consider the *physics* of delivering and distributing a solid into a porous medium

# Surface Passivation - Physical –Bio Coatings

- Keeco Mix (micro-silica)
- Potassium permanga… UNR)
- **Milk** (patent pe… ch Institute)… *o-thiobacillus*
- R… al agricultural
- C…

GROUND MASS SATURATION ISSUES????

Note: We need to consider the *physics* of delivering and distributing a coating into a porous medium

# A Possible Solution:

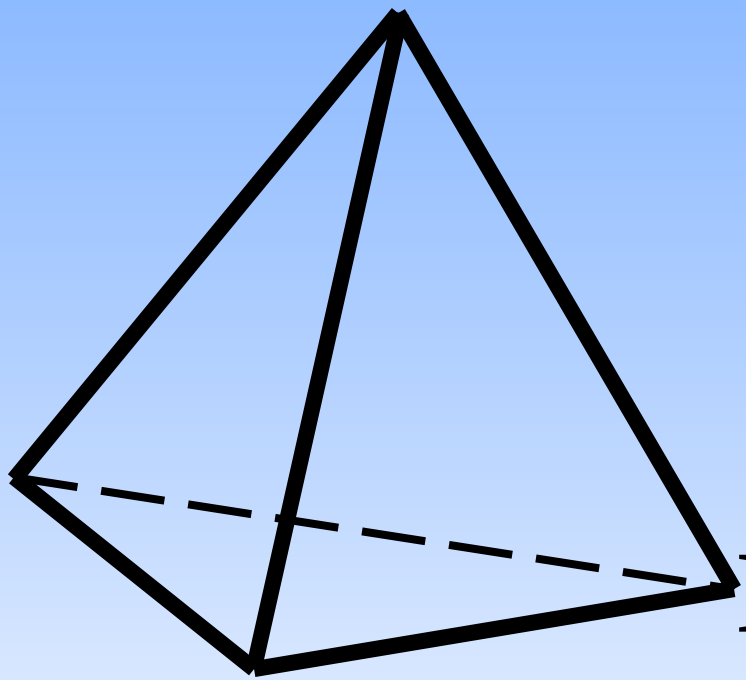
## Use FOAM as a delivery medium

- Use waste milk as  a portion of the liquid
- Use sodium lauryl sulfate or alkyl-benzene sulfonate (bactericides) as part of the surfactant mix
- Add powdered limestone for alkalinity
- Add paper, sawdust, or biosolids as the organic

*Ref:  Gusek, et al., ASMR 2012*

*This process is very similar to pressurized grouting, only the grout mass is mostly gaseous, engineered to be temporary, and designed to deposit a coating of active ingredients*

# Acid Rock Drainage Tetrahedron




Microbial
"Passivation"

# Known Bactericides

- Sodium lauryl sulfate (SLS)
- Slow release commercial products
  – ProMac *(no longer available)*
- Alkyl-benzene sulfonate (laundry detergent is cheaper than SLS)
- Sodium Thiocyanate (NaSCN)
- Bi-Polar Lipids (patented)

# Bactericides for Suppressing *Acidithiobacillus Ferro Oxidans*

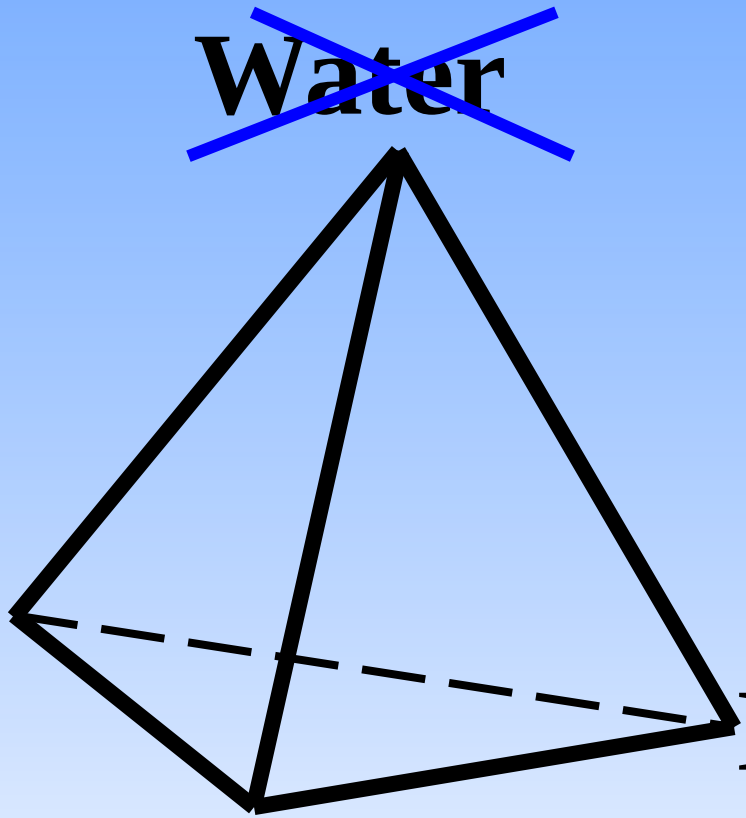
- Temporary effect only? *(maybe)*
- Vaccination vs. medication? *When do you apply it?*
- Case History - coal waste pile in PA (Plocus & Rastogi, ASSMR, 1997)
- What else does it take to prevent "re-infection"?

# Encapsulation/Waste Management

- Segregation of acid-producing wastes (waste rock or tailings) may be helpful in managing wastes to minimize ARD formation
  - protect waste from surface and ground water (liner and cap systems) as needed
  - if waste is “fresh”, consider underwater disposal by flooding or submergence; permanent flooding ***must*** be guaranteed
  - **What’s the pyrite “cut-off” grade that triggers encapsulation?**

# Acid Rock Drainage Tetrahedron

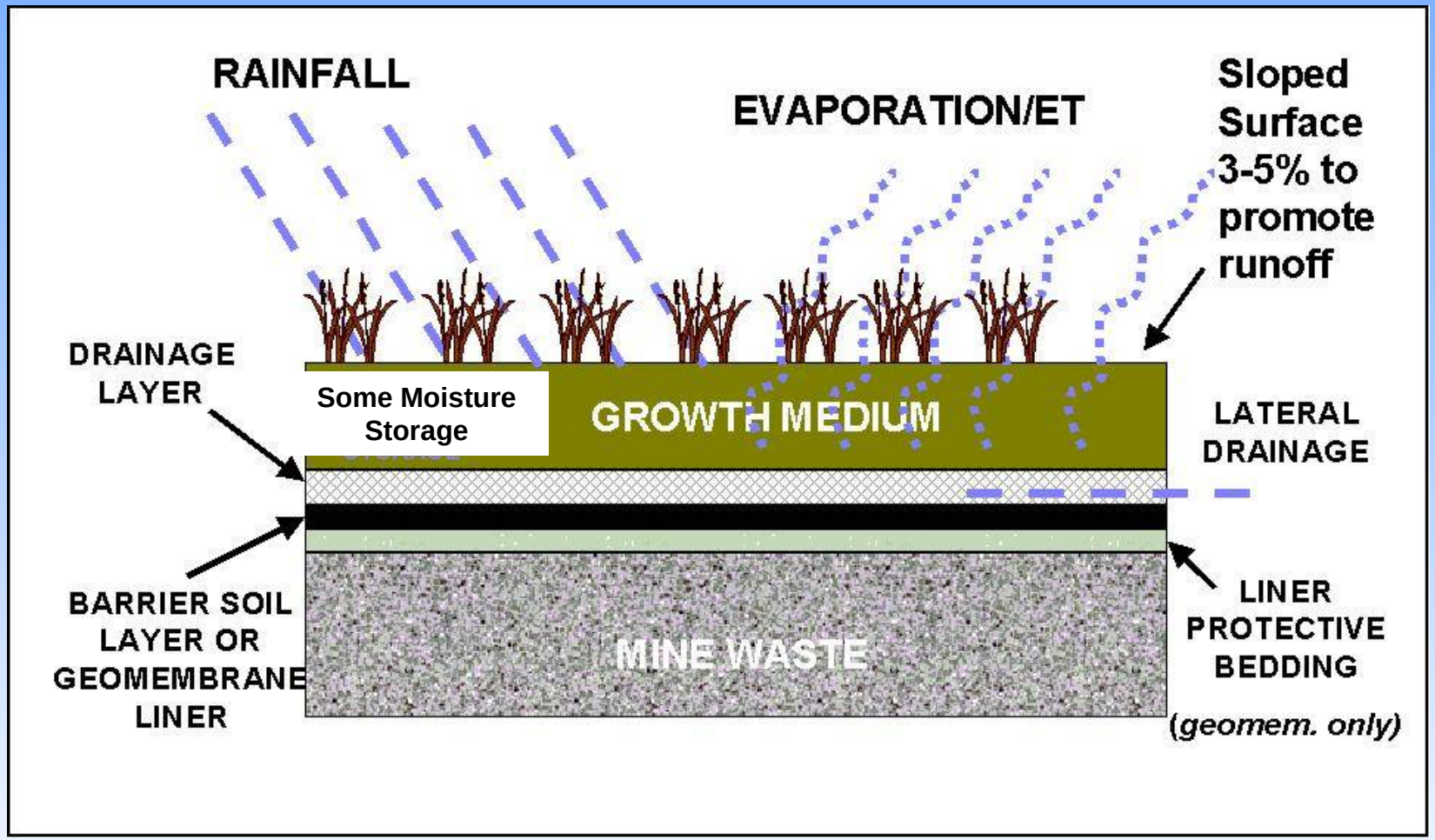
Caps and Covers



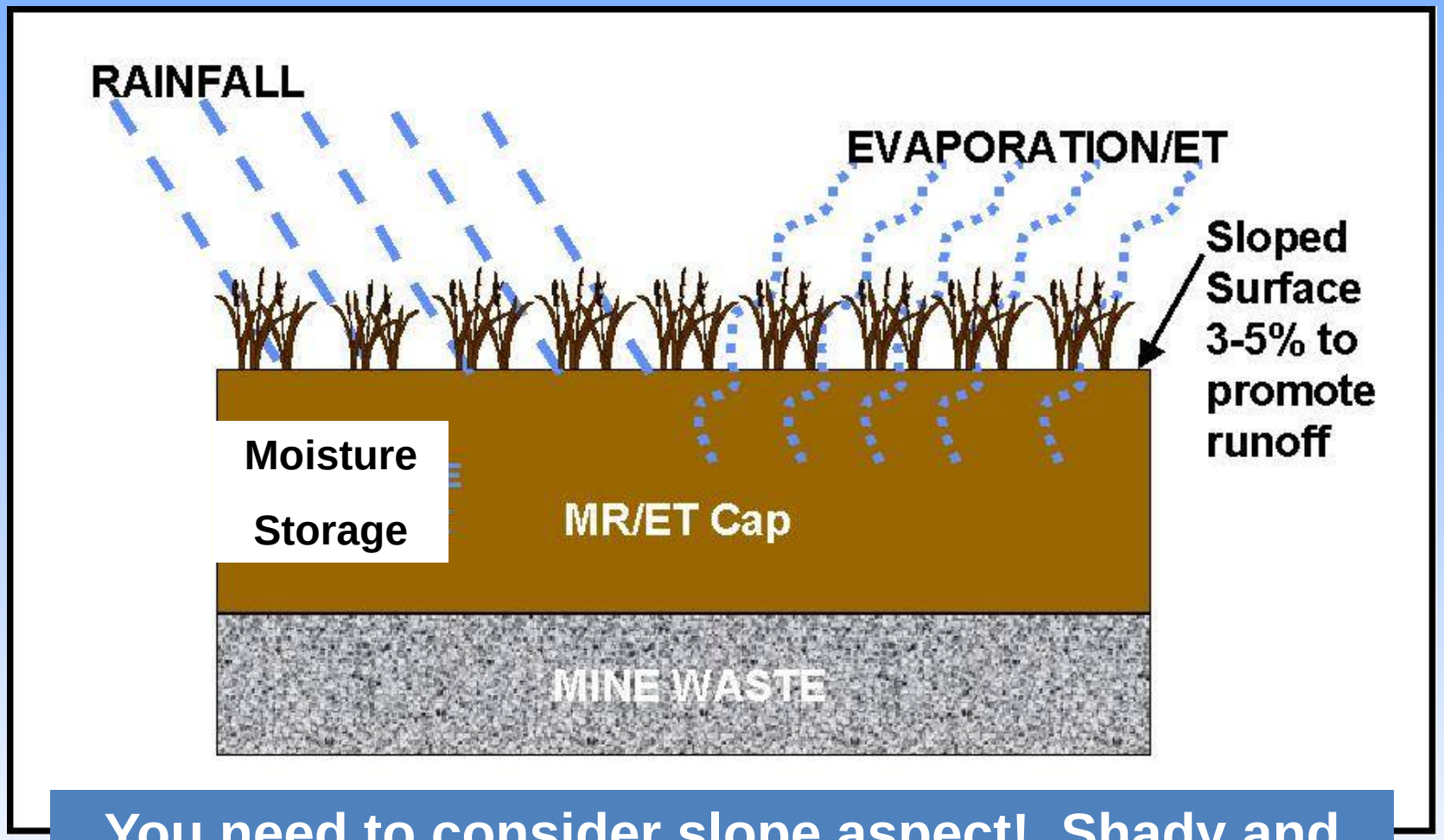
# Cap/Cover Types

- **Infiltration Barrier** - most applicable in wet climates – *Default design*
- **Moisture Retention/Evapotranspiration** (store &release covers) - most applicable in arid climates
- **Organic Barrier -** inexpensive source material available (forestry waste, agricultural waste, municipal biosolids, *BCR effluent?*)

# Infiltration Barrier Cap

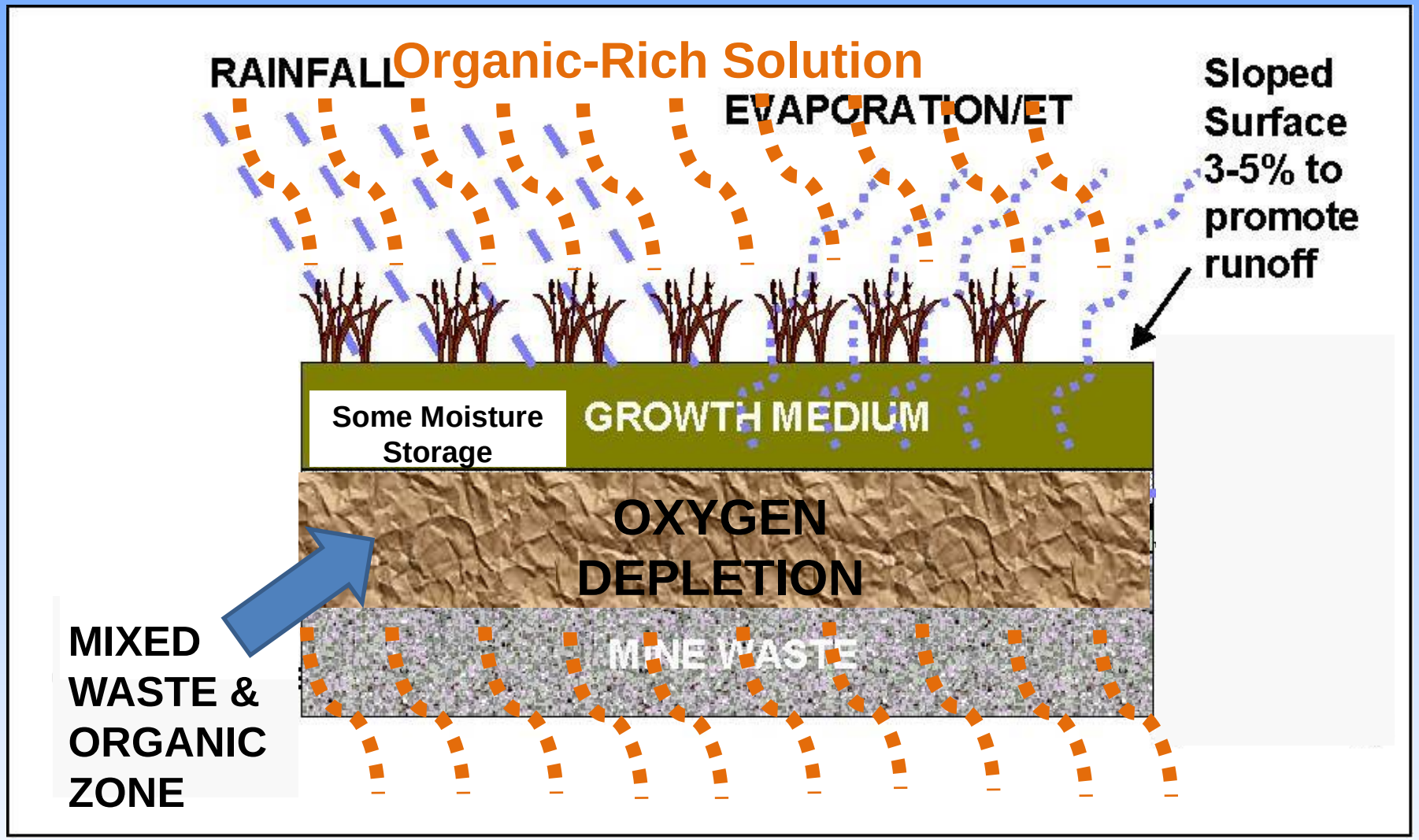


# Moisture Retention/ET Cap




**You need to consider slope aspect! Shady and sunny areas of the facility will have different ETs!**

# Organic Barrier Cap



# Design Assistance

Use EPA H.E.L.P. Model (or other models) to evaluate cap physical performance.

**H**ydrologic **E**valuation of **L**andfill **P**erformance

*http://el.erdc.usace.army.mil/index.cfm*

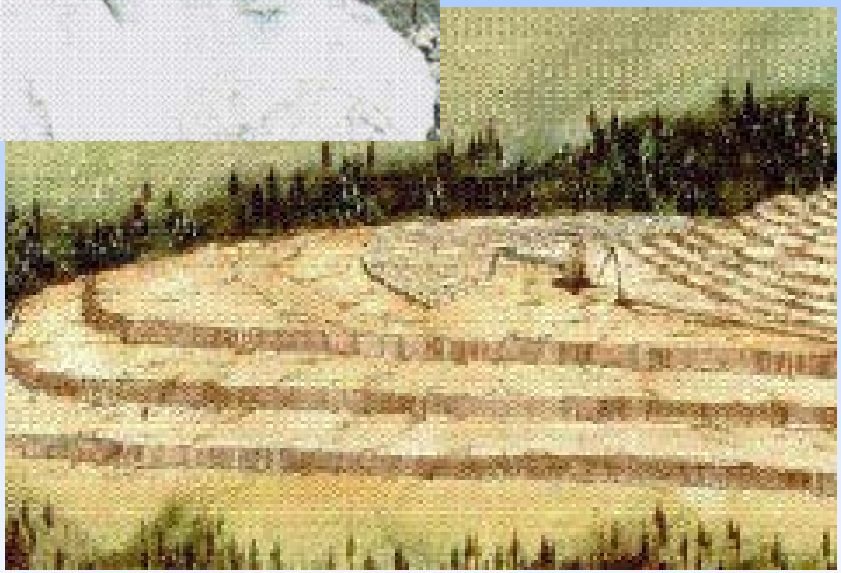
*Under "models & tools"*

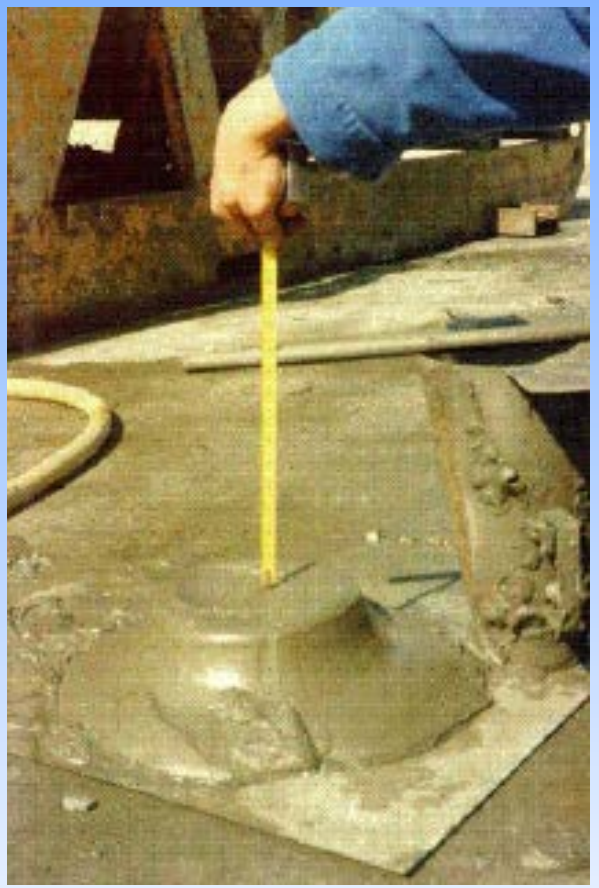
*Go to "landfill"*

# Other Water–Related ARD Mitigation Controls

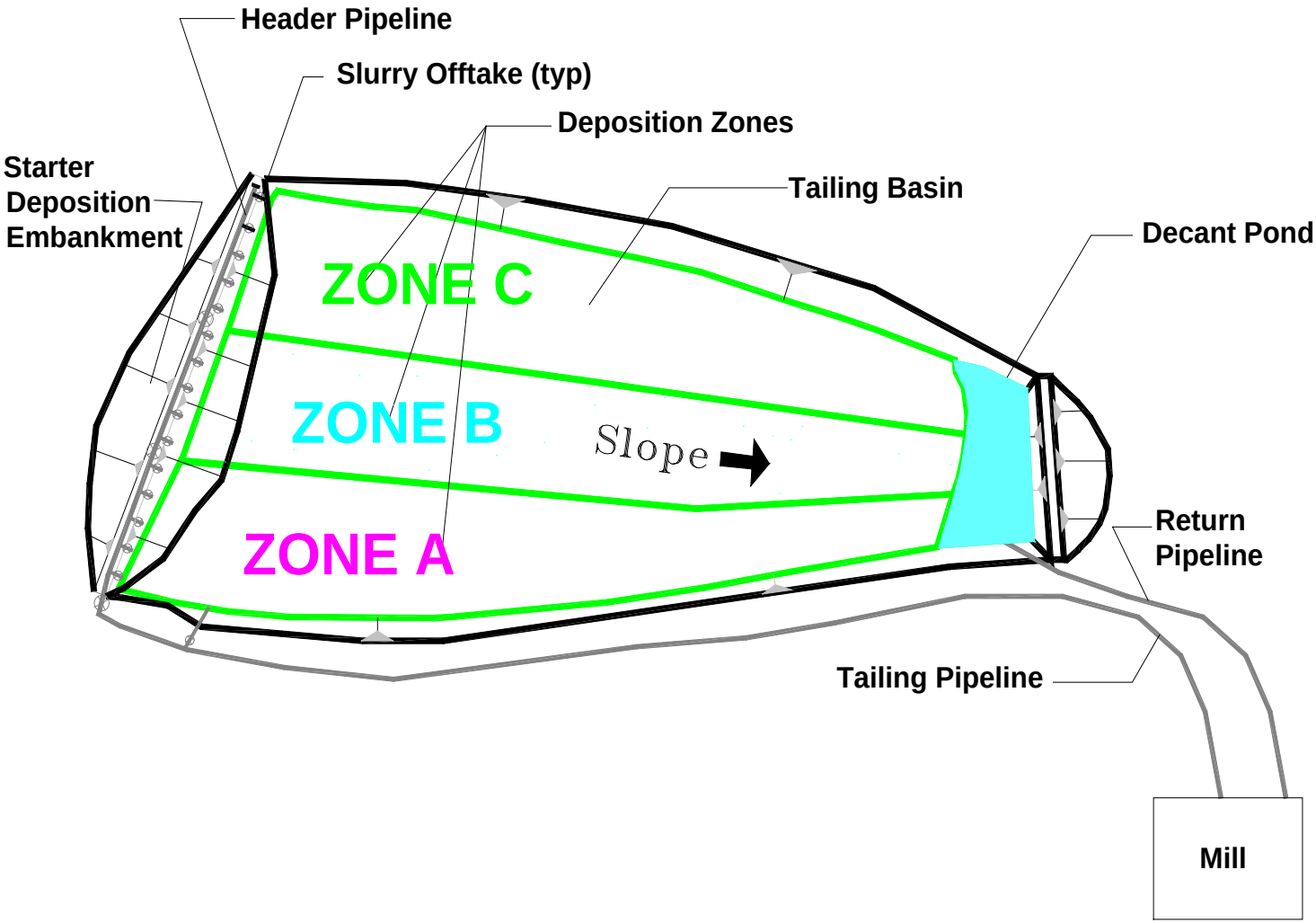
- Pa$te Tailing$ Di$po$al
- Managed  (Sub-Aerial) Tailings Deposition
- Wick Drains
- Co-Disposal of Tailings and Waste Rock

# Paste Tailings Disposal - Store ***Solids***, NOT Water





# Plan View, Typical Sub-Aerial Tailings Basin




Managed Tailings Deposition Stores ***Solids***, NOT Water

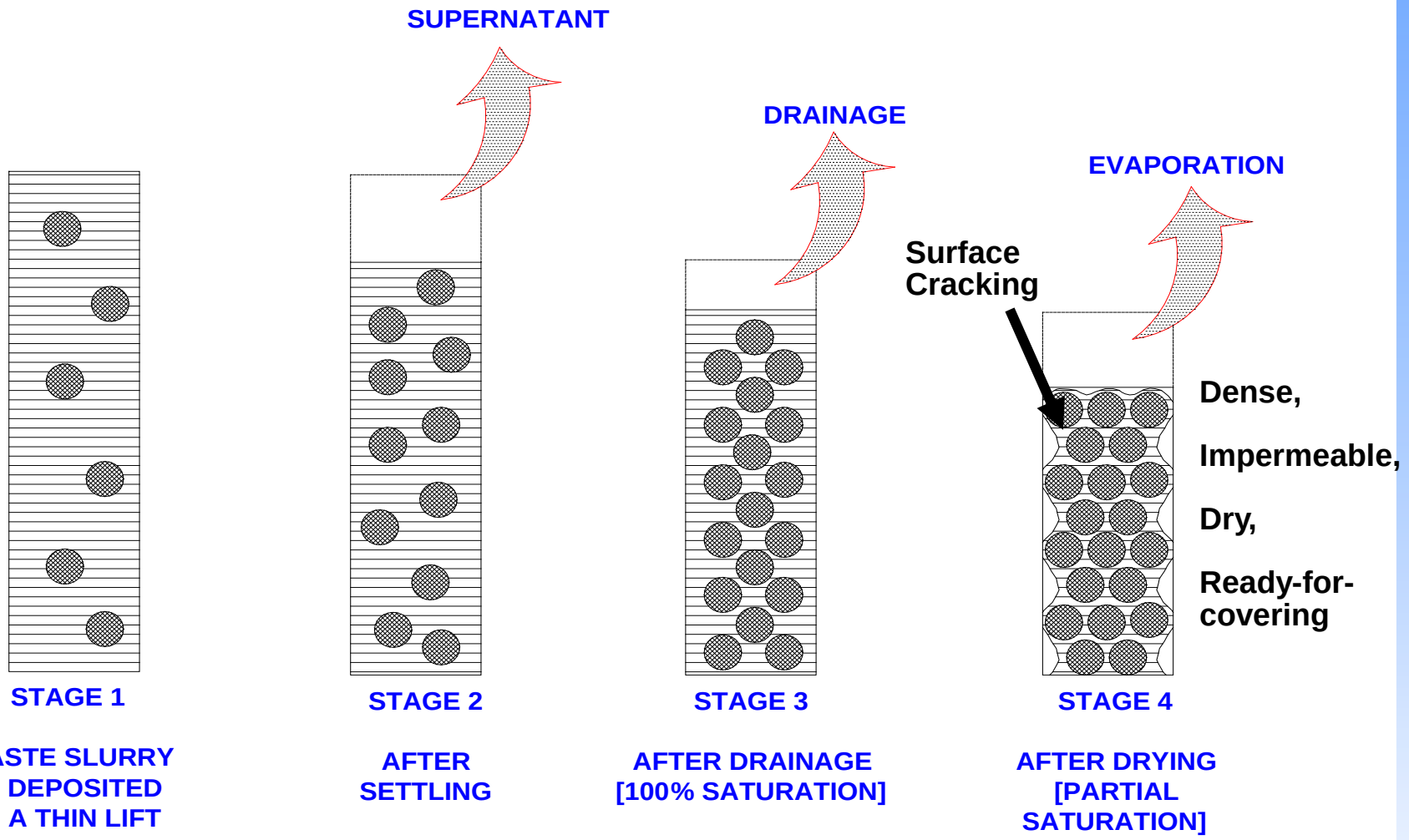
# Managed (Sub-Aerial) Tailings Deposition


Week 0 - depositing

Week 2 – ready for another lift of tails

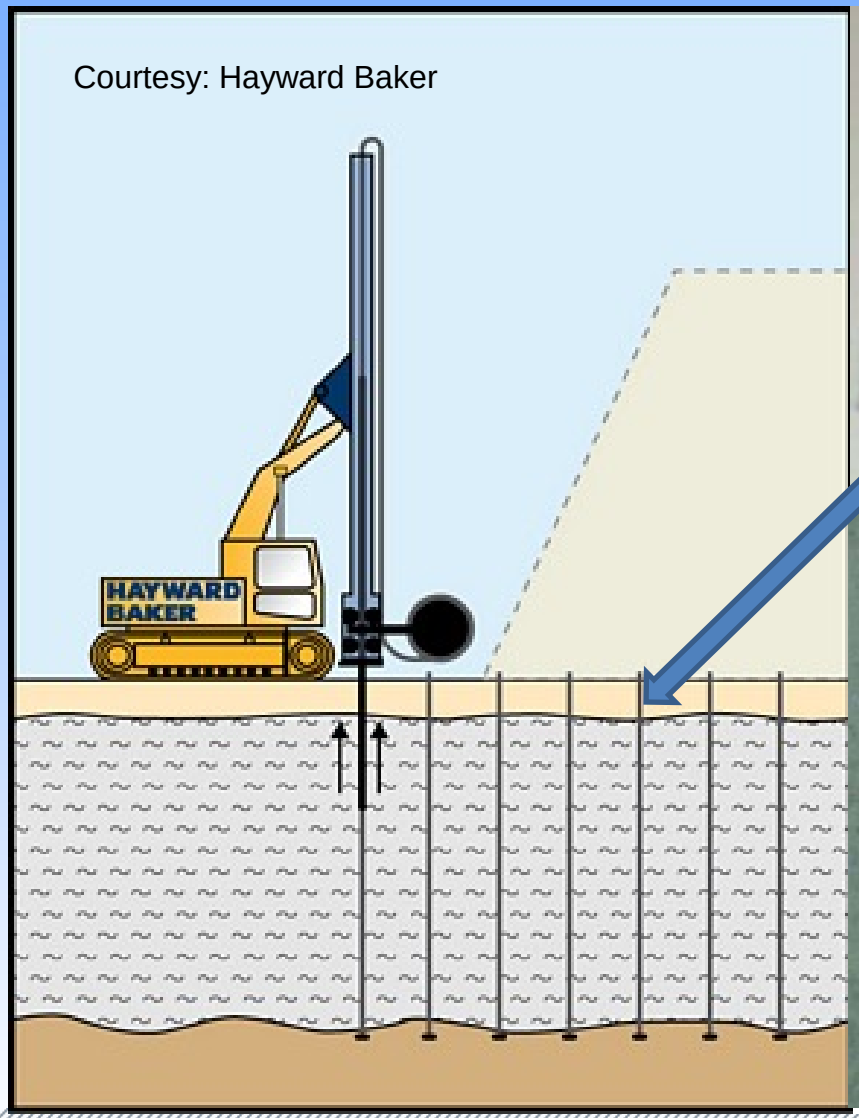
**Rubber-tired equipment can drive on sub-aerial deposited tailings within a week or two of cessation of placement**

# Sub-Aerial Tailings Deposition




East, et al., circa 1989

# Wick Drains


Courtesy: Hayward Baker
HAYWARD BAKER


Courtesy: Hayward Baker
~ 4 inches/ 10 cm


Courtesy: Aerix Industries
Permeable concrete “wick”

# Co-Disposal of De-Watered Tailings and Waste Rock

Table 1. Hydraulic conductivity values for selected Co-Mix blends.

| Blend | Tailings | $K_{sat}$ (m/sec) | Comments |
|---|---|---|---|
| 1:1:2 | R3 | $2 \times 10^{-7}$ | 100 mm Slump |
| 1:1:2 | R3 | $2 \times 10^{-7}$ | 200 mm Slump |
| 1:1:2 | R3 | $4 \times 10^{-8}$ | Standard Proctor |
| 1:1:2 | R3 | $3 \times 10^{-8}$ | 200 mm Slump with 1.5% Bentonite |
| 1:1:2 | R3 | $5 \times 10^{-9}$ | Compacted with 1.5% Bentonite |
| 0:1:1 | Fresh | $1 \times 10^{-7}$ | > 250mm Slump |
| 1:1:1 | Fresh | $1 \times 10^{-7}$ | 50 mm Slump |
| 1:1:1 | Fresh | $5 \times 10^{-8}$ | Standard Proctor |

**Glacial till – natural analogue**

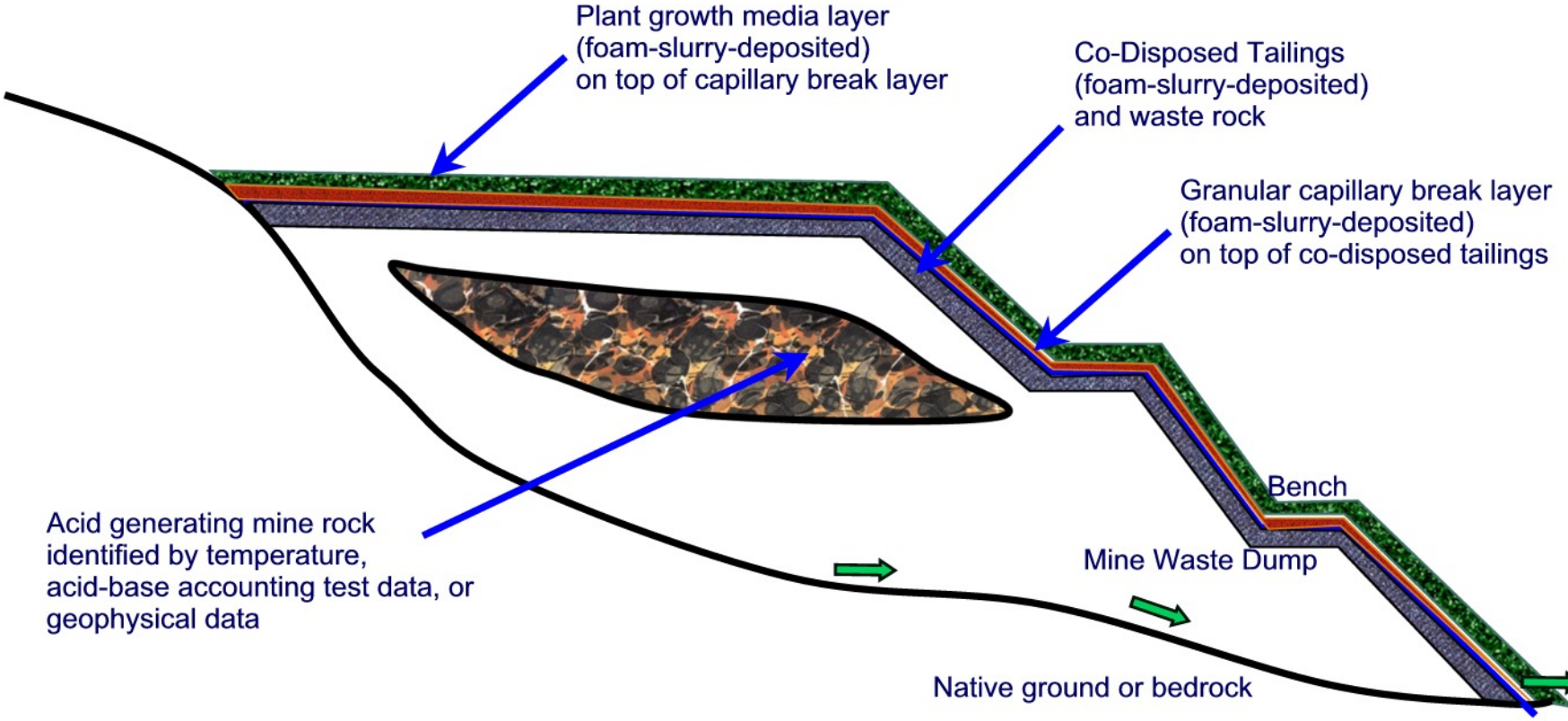
Refs: Wilson et al. ASMR/7th ICARD 2006 (St. Louis) &
Wilson et al. 6th ICARD 2003 (Cairns)

# Co-Disposal of De-Watered Tailings and Waste Rock

# Co-Disposal Alternative

- "Fluidize" paste or dry tailings with *foam* (not patented)
- Land-apply foam-fluidized tailings on top of lift of ***coarse*** mine waste, (rip waste if needed), compact if needed.

# Co-Disposal Alternative Design Opportunity



# Summary of ARD Prevention Measures

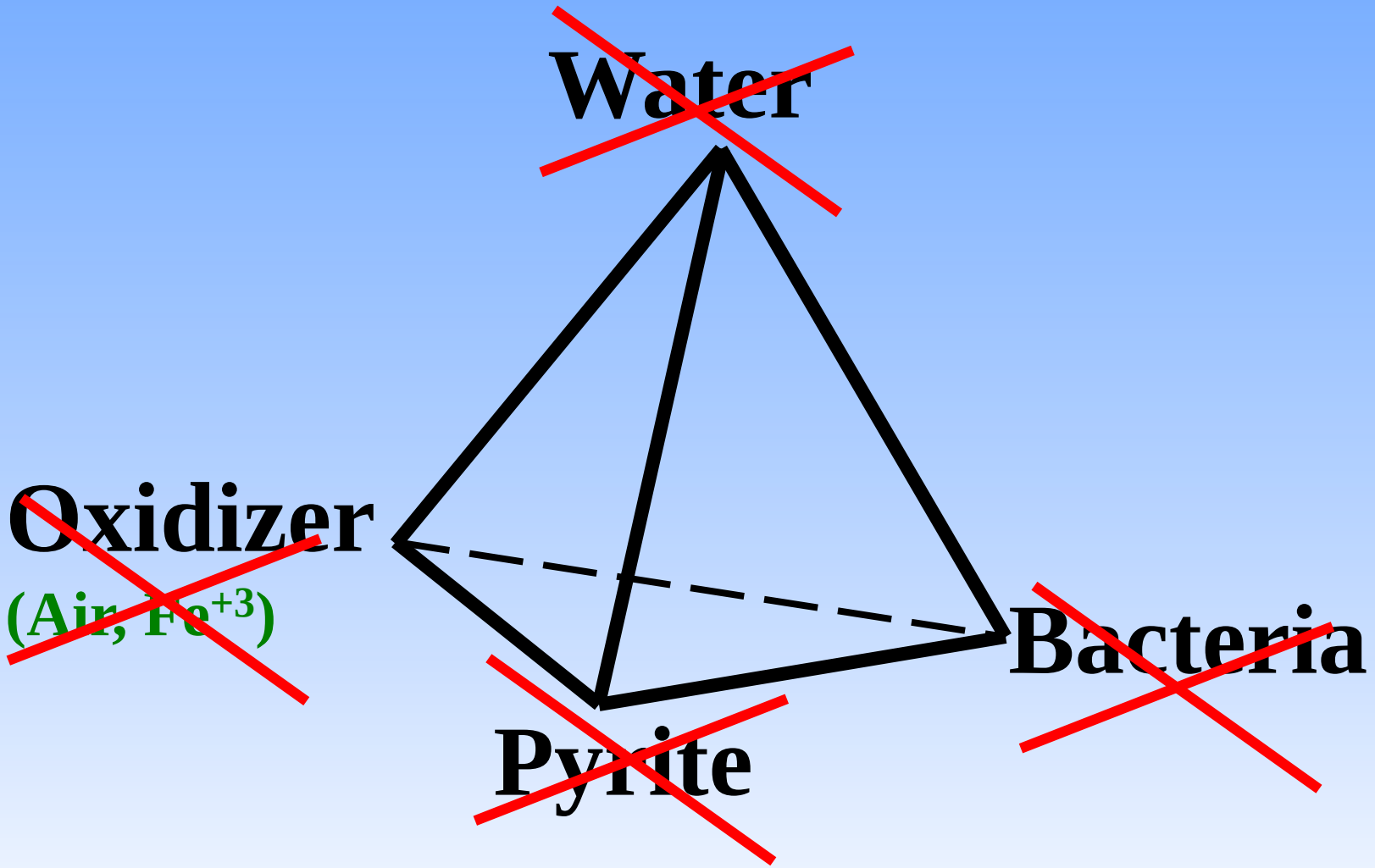
**Disrupt the ARD TETRAHEDRON** by using:

- Pyrite surface passivation amendments
- Bactericides (more passivation)
- Encapsulation (dry or wet)

**Alone or in combination**

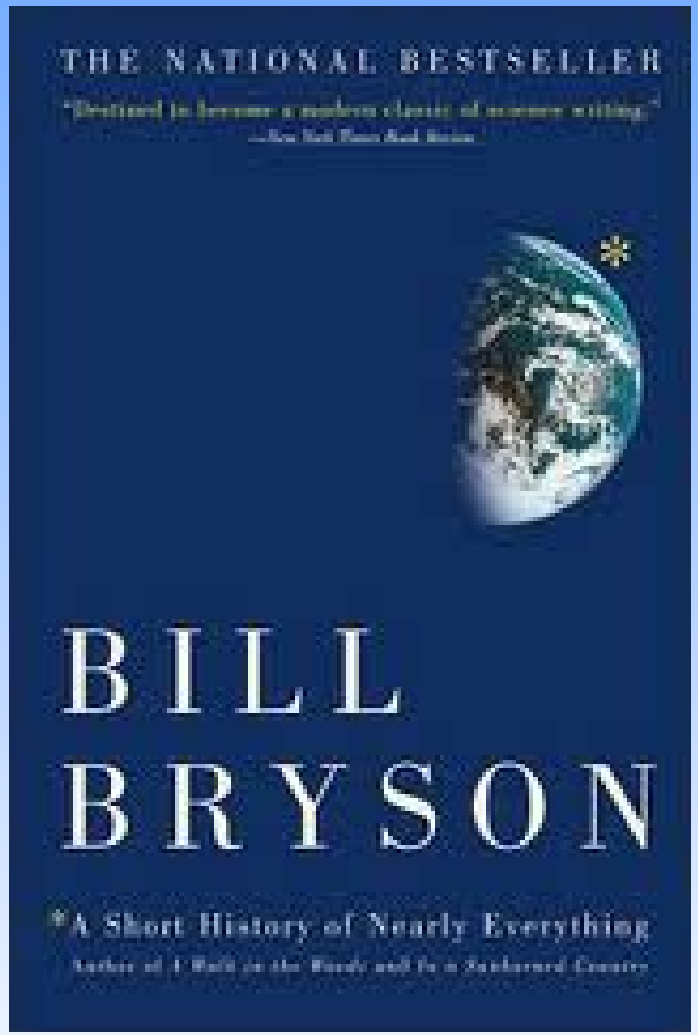
***Incorporate these concepts into the ENGINEERING of the ARD management situation;***
***Testing should yield information to support an engineered design basis.***

# Acid Rock Drainage Tetrahedron




**DO SOMETHING (<u>anything</u>) = PATHWAY TO WALK-AWAY**

# Thank You




"In France, a chemist named Pilatre de Rozier tested the flammability of hydrogen by gulping a mouthful and blowing across an open flame, proving at a stroke that hydrogen is indeed explosively combustible and that eyebrows are not necessarily a permanent feature of one's face."

"There are three stages in scientific discovery. First, people deny that it is true, then they deny that it is important; finally, they credit the wrong person."

— Bill Bryson, *A Short History of Nearly Everything*

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