Produced Water Disposal

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Overview

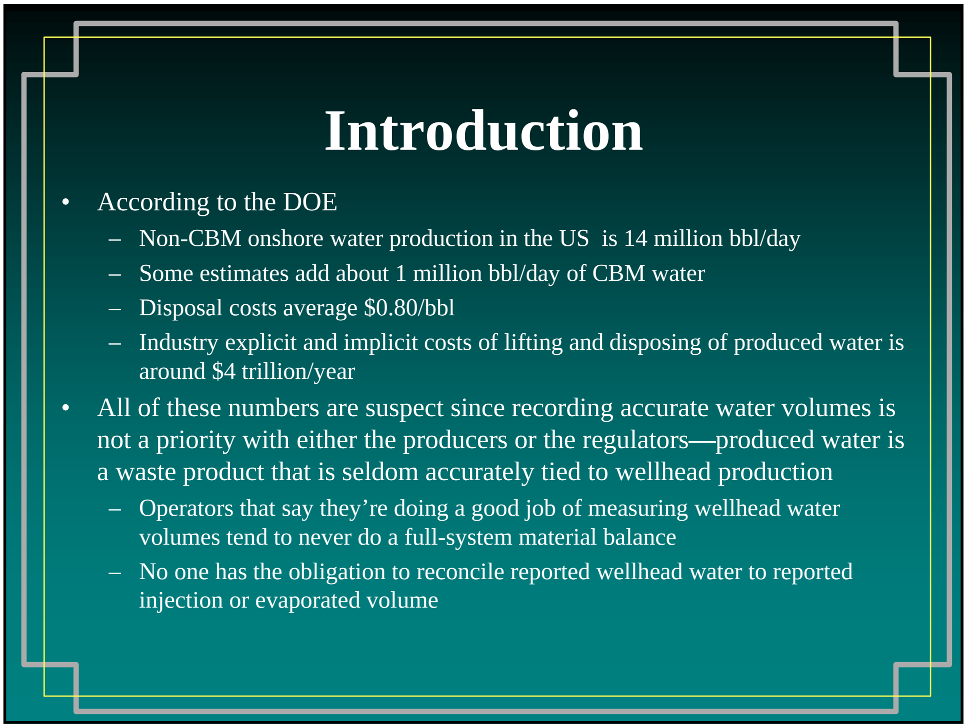
- Introduction
- Infrastructure for accumulation
- Disposal options
  - Underground injection
  - Evaporation
  - Beneficial Use
- Conclusions

Scope

- Managing produced water is the subject of thousands of pages of regulations and millions of pages of legal decisions
- Covering it in an hour means skimming over important and complex subjects
- The intent of this presentation is to give you the feel for the magnitude of the subject, not prepare you to deal with its complexities—get help from environmental, regulatory/legal, and engineering professionals early in the process
- This presentation is not intended to provide engineering or legal advice on your specific problems, any recommended practices in it are subject to be poor advice for certain conditions

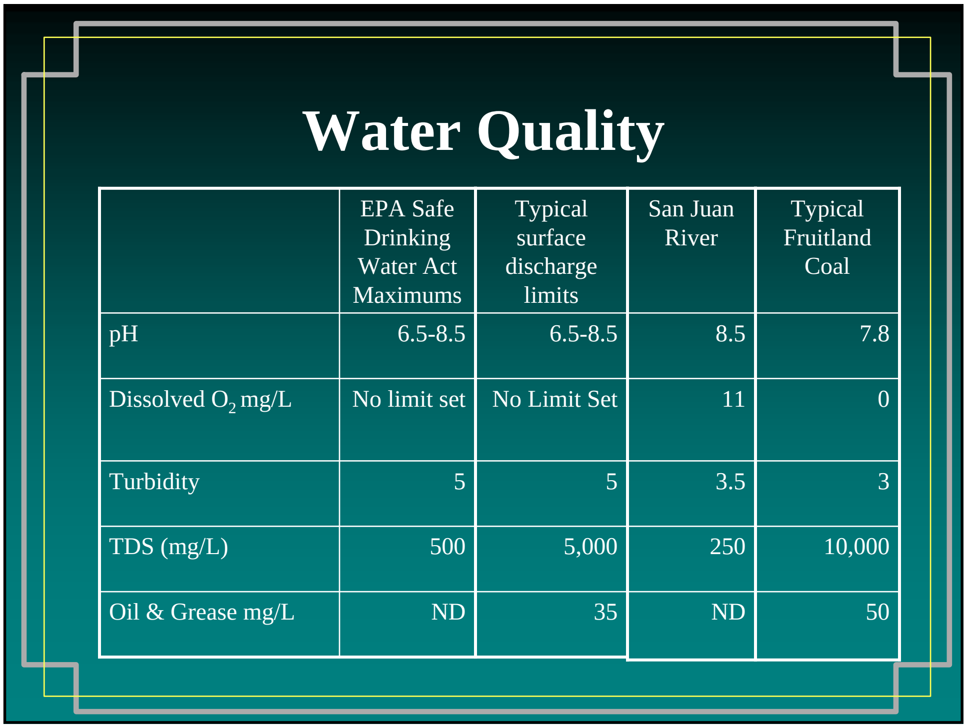
Introduction

- At today's product prices:
  - Wells remain economical with much higher LOE than in the past
  - A big part of the increased LOE is lifting and disposing of water
- More water is getting to the surface today than ever before
- The regulatory environment is getting more strict all of the time



Introduction

- According to the DOE
  - Non-CBM onshore water production in the US is 14 million bbl/day
  - Some estimates add about 1 million bbl/day of CBM water
  - Disposal costs average $0.80/bbl
  - Industry explicit and implicit costs of lifting and disposing of produced water is around $4 trillion/year
- All of these numbers are suspect since recording accurate water volumes is not a priority with either the producers or the regulators—produced water is a waste product that is seldom accurately tied to wellhead production
  - Operators that say they're doing a good job of measuring wellhead water volumes tend to never do a full-system material balance
  - No one has the obligation to reconcile reported wellhead water to reported injection or evaporated volume



Water Quality

	EPA Safe Drinking Water Act Maximums	Typical surface discharge limits	San Juan River	Typical Fruitland Coal
pH	6.5-8.5	6.5-8.5	8.5	7.8
Dissolved O_2 mg/L	No limit set	No Limit Set	11	0
Turbidity	5	5	3.5	3
TDS (mg/L)	500	5,000	250	10,000
Oil & Grease mg/L	ND	35	ND	50

Infrastructure for Accumulation Transport

	Trucking	Pipeline
Capital Cost	Very Low	High
Operating Cost	Very High	Very Low
Main Risk	Road accidents	Line Failure

- The trade off is never clear or obvious
- A hybrid system is often the best economics
  - Strategically placed water-transfer stations with pumps
  - Water is trucked to transfer station
  - Pipeline runs from transfer station to central location

Transportation Example

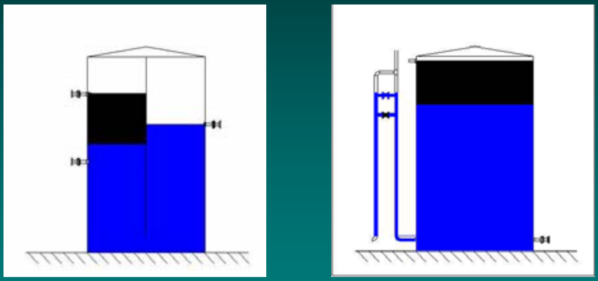
- A company drills a new well 5 miles from a transfer station:
  - Their trucking costs average $0.20/bbl/mile
  - Pipelines cost $35k/inch-mile
  - Similar wells in the area make water volumes consistent with 2-inch pipe
- They find that if the well makes less than 225 bbl/day they prefer trucking

Site-Entry Facilities

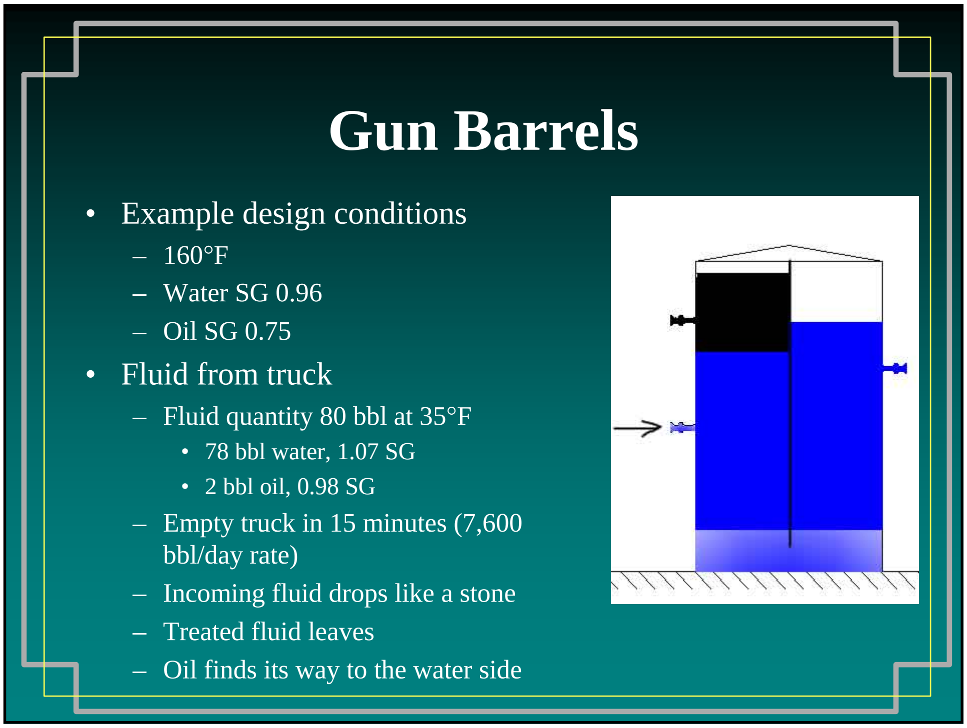
- Solids can be difficult for pumps and injection wells
  - Filters and strainers require monitoring
  - Filters designed for water tend to fail in oil
- Oil causes a problem with any sort of produced water facilities
  - Surface discharge limited by regulation to 35 mg/L
  - Oil in downhole injection wells will shorten the injection life of the well
  - Oil in an evaporation pond will reduce evaporation rate and is a hazard for birds

Dealing with Oil

- Gun barrels are the typical solution to oil in gas fields

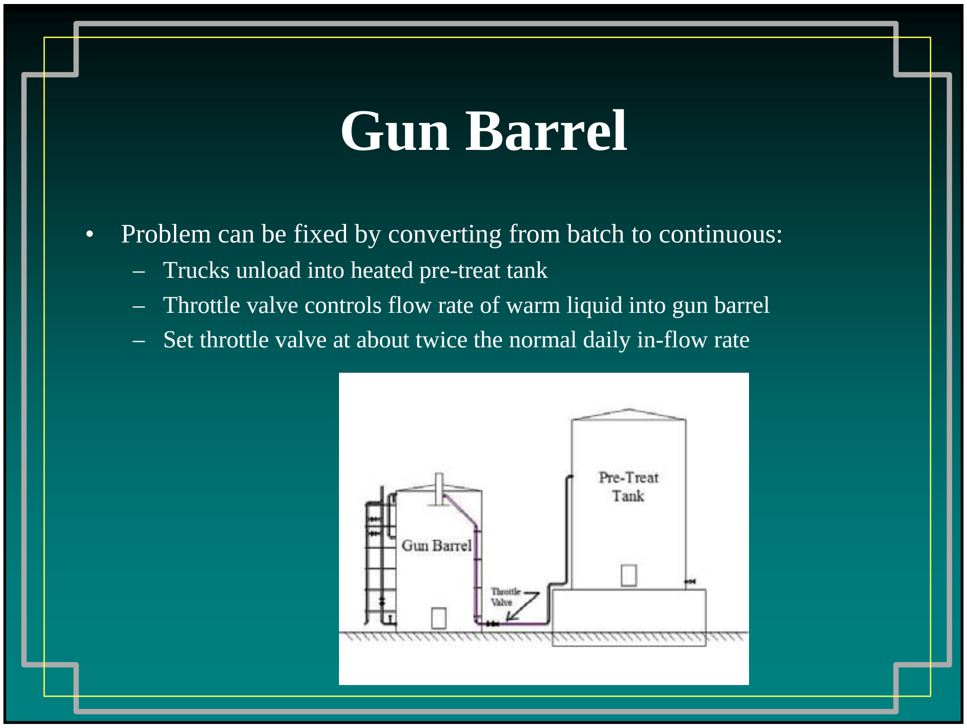


- When the fluids are exactly at design conditions:
  - Oil level is at the oil-outlet
  - Water level is at the water outlet
  - If a quart of liquid comes in, a quart must go out



Gun Barrels

- Example design conditions
  - 160°F
  - Water SG 0.96
  - Oil SG 0.75
- Fluid from truck
  - Fluid quantity 80 bbl at 35°F
    - 78 bbl water, 1.07 SG
    - 2 bbl oil, 0.98 SG
  - Empty truck in 15 minutes (7,600 bbl/day rate)
  - Incoming fluid drops like a stone
  - Treated fluid leaves
  - Oil finds its way to the water side



Gun Barrel

- Problem can be fixed by converting from batch to continuous:
  - Trucks unload into heated pre-treat tank
  - Throttle valve controls flow rate of warm liquid into gun barrel
  - Set throttle valve at about twice the normal daily in-flow rate

Underground Injection

- Deep-well injection must satisfy the requirements of the 1974 *Safe Drinking Water Act (SDWA)*
- Overall responsibility for the SDWA rests with EPA, but states can elect to manage parts or all of it
- The intent of the SDWA *Underground Injection Control (UIC)* protocols is to protect aquifers from contamination
- EPA estimates that 91% of all produced water is injected into a UIC well

UIC Well Classes

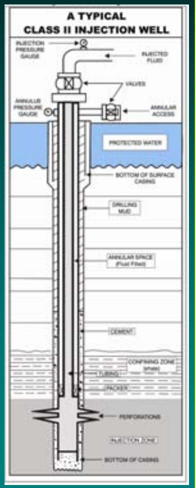
- Class I, Deep Wells – used for hazardous and non-hazardous industrial waste and non-hazardous municipal waste
- Class II, Oil & Gas Injection Wells – used for any well accepting Oil & Gas produced fluids (includes secondary and tertiary recovery projects in addition to produced water)
- Class III, Mining Wells – wells that are used for mining
- Class IV, Shallow hazardous and Radioactive Injection wells – these wells are mostly prohibited
- Class V, Shallow Injection Wells – wells that don’t fit into any of the other categories

UIC Classes

- Both New Mexico and Colorado have elected to be the primary regulator on state and private Class II UIC wells (EPA retains primacy on tribal surface)
- New Mexico has chosen to further subdivide the class into
  - Salt Water Disposal Wells
  - Enhanced Oil Recovery Wells
  - Hydrocarbon Storage Wells

Required Permit Information

- A map showing all nearby wells that penetrate the injection formation with detailed information on each well
- Average and maximum daily injection rate
- Total volume of fluids to be injected
- Detailed geologic data on the injection zone
- Detailed wellbore and facilities design
- Proposed well-stimulation program
- Actions required on nearby wells that penetrate the injection formation
- P&A Plan



Stipulations

- Permit stipulations can include almost anything, but typically they have at least:
  - Requirements for a Mechanical Integrity test, including requirements for periodic re-tests (typically every 5 years)
  - Approval of operating procedures including
    - Calculated fracture gradient
    - Injectivity tests to establish fracture pressure
    - Steps required in a failure of either mech integrity or injectivity
    - Filling and verifying that tubing/casing annulus is liquid-full
  - Instrumentation to continuously record injection pressure and volume along with calibration frequency
  - Annual bradenhead test

New Mexico Common Reasons for UIC Permit Rejection

- Using the wrong address for the OCD
- Not including enough data on the adjacent wells, they want a spreadsheet with
  - API Numbers
  - Cement Tops and method of verifying tops
- Not notifying adjacent well operators or mineral owners
- Application protested

Equipment Needed for UIC Well

- Tanks – it is a good idea to have about 1-2 days of storage
- Filtration – most successful UIC operations filter the water to about 25 microns
- Pumps
  - Charge pump – required for long-term operation of plunger injection-pumps (not needed for progressing cavity or multi-stage centrifugal injection pumps).
  - Injection pump – needs to be able to pump the daily volume into the permitted injection pressure
- Automation
  - Need to be able to stop the process if injection pressure approaches UIC limit or tank level gets too low

Evaporation

- 6% of all produced water is disposed of through evaporation
- Evaporation ponds are regulated:
  - In New Mexico by the NMOCD under Rule 711 (proposed to be replaced by Rule 53 in the near future)
  - In Colorado by the COGCC under Rule 903
  - New Mexico regulations are the most specific, following them in the design would satisfy the rules of Colorado

Permitting Requirements (proposed under Rule 53)

- Engineering design plan (certified by a registered PE):
  - Operating and maintenance procedures with monitoring and inspection plans
  - Pit closure plan
  - Hydrologic report which includes sufficient information on the site's topography, soils, geology, surface hydrology, and groundwater hydrology
  - Dike protection and structural integrity
  - Leak detection
  - Liner inspection procedures and compatibility report
  - Freeboard and overtopping prevention
  - Nuisance and hazardous odor prevention
  - Emergency response plan
  - Type of waste stream (including chemical analysis)
  - Climatological factors including freeze/thaw cycles
  - Other information the OCD may request

Proposed Construction Standards

- Each Pond must be designed, constructed, and operated so as to contain liquids and solids in a manner that will prevent contamination of fresh water and protect public health and the environment
- Foundation or firm, unyielding base free of rocks, debris, sharp edges, or irregularities
- Dike
  - 2H:1V maximum slope inside pond
  - 3H:1V maximum slope outside pond
  - Wide enough to include anchor trench, room for inspection and maintenance
- May not be larger than 10 acre-ft
- Must be netted or have other approved means of protecting migratory birds

Liners

- Primary (upper) liner made of synthetic material
- Secondary (lower) liner can be synthetic or other material approved by OCD
- Upper and lower liners must be separated by at least 2 ft of compacted soil with leak detection equipment between the liners and under lower liner
- Shall meet:
  - At least 30 mils (0.030 inches) thick
  - Impervious to hydrocarbons, salts, acidic and alkaline solutions
  - Resistant to UV light
- At any point where fluid enters pit, liner must be protected from fluid force and mechanical damage

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$F = 1.0 - 1.7\times10^{-5} * z$

Pond Size

- Start with the PenPan equation to get evaporation rate

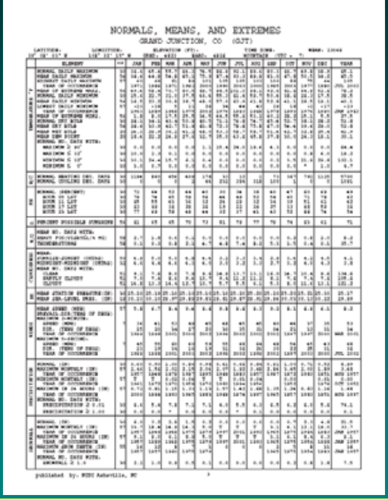
$$E_0 = \left(0.015 - 0.00042T_m + z * 10^{-6}\right)\left(0.8 * R_s - 40\right) + 2.5 * F * u\left(T_m - T_D\right)$$

- The terms of this equation are:
  - E_0 = Evaporation rate (mm/day)
  - F = A factor that accounts for the change in air density with changes in elevation $F = 1.0 - 1.7\times10^{-5} * z$
  - R_s = Solar irradiance (W/m^2) $R_s = 10.8 * T_m + 153$
  - T_D = Mean dew point temperature (°C)
  - T_m = Mean daily temperature (°C)
  - u = Wind velocity at 2 meters above surface (m/s)
  - z = Elevation above sea level (m)

Pond Size

- Go to NOAA and get climatological data
  - It includes average temp, rainfall, dew points, etc. for every month
  - It also includes minimums and maximums for each term
- With NOAA data and the PenPan equation you can estimate
  - average net evaporation (i.e., evaporation minus precipitation),
  - evaporation in the worst year (min temps and max precipitation)
  - evaporation in the best year (max temp, min precipitation)
- Determine the pond size needed for the expected inflow during the worst months of the worst year
- Add a safety factor for a worst of the worst year

Page 1 of NOAA Data



NORMALS, MEANS, AND EXTREMES

GRAND JUNCTION, CO (GJT)

Extra Considerations

- For 10,000 TDS water
  - Every barrel evaporated will leave 3.5 lb (0.03 ft^3) in the pond
  - When the pond fills up with solids it will have to be drained to muck out
- Bird netting will reduce evaporation rate
- Properly designed spray heads will improve evaporation rate
- My preference is to design two ponds, each sized for full expected inflow and average conditions
  - Flow into one pond
  - Suck out of inflow pond and spray over other pond
  - When pond fills with solids, turn sprayer over inflow pond and muck out other pond
- Aeration equipment may be needed to control odors

Spray Heads

- The best information on evaporation from sprayers comes from people doing irrigation
  - They avoid sprayers that break water drops up very small
  - They use sprayers that put out large drops
  - With large drops, evaporation is a surface function
  - With small drops, evaporation is a volume function
- For evaporation ponds it is good to use spray heads that cut the drops to less than 50 microns
  - Increases buoyancy so drops stay in the air longer
  - Allows bulk temperature to participate in evaporation
  - Overspray becomes a larger issue

Spray Options

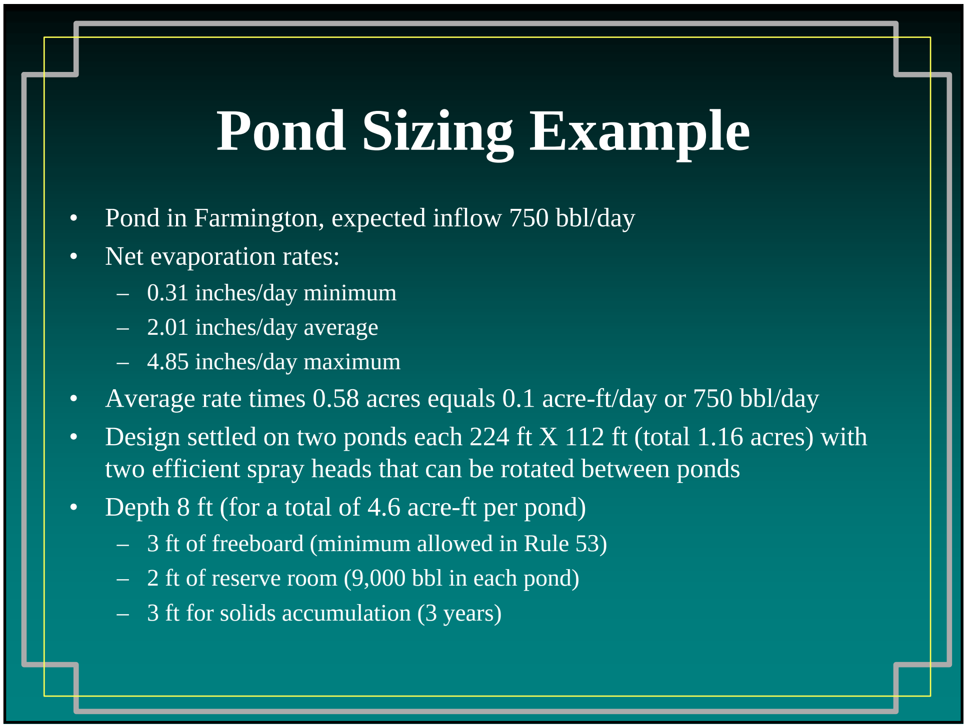

Notice how stirred up the surface is and how little spray remains in the air

Notice the smooth surface of the pond (with two 3,500 bbl/day evaporators)
Fencing is to control overspray

- Drop diameter about 200 microns
- Drop diameter about 25 microns

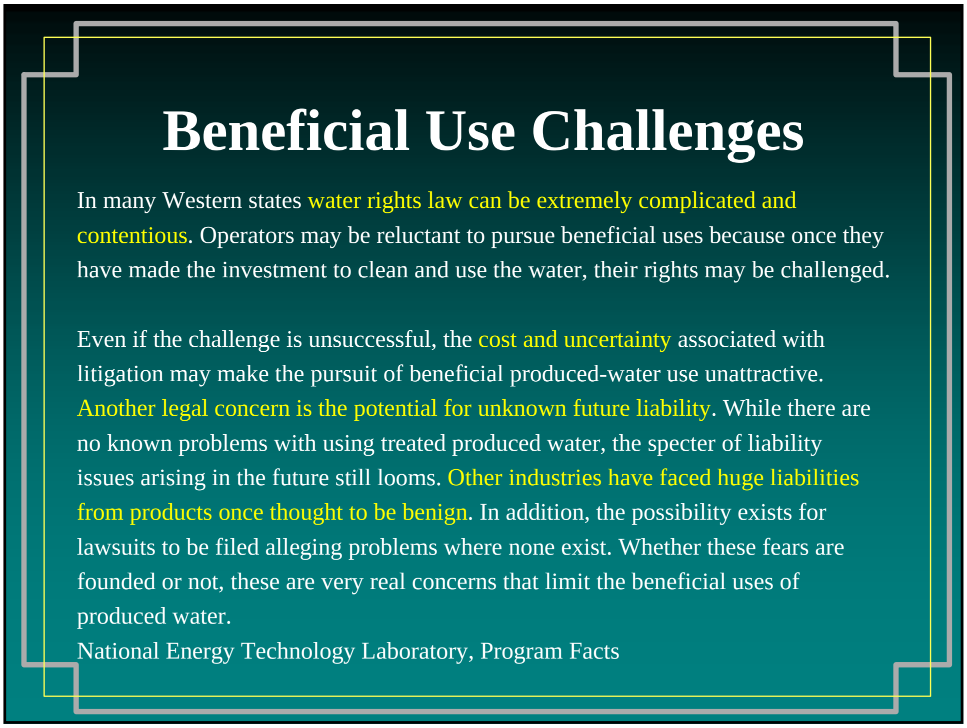
Bottom Line on Pond Size

- Bird Netting cuts evaporation
- Wind fencing cuts evaporation
- Aerators increase evaporation at moderate and high ambient temperatures
- Well-designed spray heads significantly increase evaporation in all temperatures
- The net result is probably close to natural evaporation from an uncovered pond in an "average" year



Pond Sizing Example

- Pond in Farmington, expected inflow 750 bbl/day
- Net evaporation rates:
  - 0.31 inches/day minimum
  - 2.01 inches/day average
  - 4.85 inches/day maximum
- Average rate times 0.58 acres equals 0.1 acre-ft/day or 750 bbl/day
- Design settled on two ponds each 224 ft X 112 ft (total 1.16 acres) with two efficient spray heads that can be rotated between ponds
- Depth 8 ft (for a total of 4.6 acre-ft per pond)
  - 3 ft of freeboard (minimum allowed in Rule 53)
  - 2 ft of reserve room (9,000 bbl in each pond)
  - 3 ft for solids accumulation (3 years)



Beneficial Use Challenges

In many Western states water rights law can be extremely complicated and contentious. Operators may be reluctant to pursue beneficial uses because once they have made the investment to clean and use the water, their rights may be challenged.

Even if the challenge is unsuccessful, the cost and uncertainty associated with litigation may make the pursuit of beneficial produced-water use unattractive. Another legal concern is the potential for unknown future liability. While there are no known problems with using treated produced water, the specter of liability issues arising in the future still looms. Other industries have faced huge liabilities from products once thought to be benign. In addition, the possibility exists for lawsuits to be filed alleging problems where none exist. Whether these fears are founded or not, these are very real concerns that limit the beneficial uses of produced water.
National Energy Technology Laboratory, Program Facts

Beneficial Use

- Treatment
- Surface Discharge to rivers
- Irrigation
- Stock/wildlife watering
- New uses

Treatment

- In the San Juan Basin virtually all water must be treated before it is useable for most beneficial use options
- Reverse Osmosis (RO) is the most common treatment method used in Oil & Gas
  - Can concentrate solids into 30-40% of volume (i.e., 100 bbl of 10,000 TDS water can become 70 bbl of 200 TDS water and 30 bbl of 32,800 TDS concentrate
  - The concentrate is typically disposed of in a Class II well, but an evap pond can be used
  - Has failed repeatedly in San Juan due to complex filtering requirements

Treatment

- Distilling
  - Water is boiled and the steam is condensed
  - Can concentrate further than RO
  - It takes a lot of energy, manpower, and capital
  - It only makes economic sense if the steam can be used to do useful work
- Manmade Wetlands
  - Can be an effective way to purify a large volume of water
  - Be sure you understand all of the ramifications prior to starting
  - Can create an obligation to maintain the wetlands in perpetuity

Treatment
Freeze/Thaw Evaporation

- “Purer” water will freeze before less pure water
- Over time the ice on a pond will be nearly pure
- The rub is how to remove the ice to someplace where it won’t recontaminate
- Amoco did a study on this in 1996-97 and it works well in the San Juan Basin in winter (8,000 bbl of 12,800 TDS yielded 6,400 bbl of 1,010 TDS and 1,600 bbl of 44,900 TDS in 60 days of operation)

Surface Discharge

- The Clean Water Act requires any discharge that can reach surface waters to have an NPDES permit
  - Permits are either issued by EPA or by the state (both Colorado and New Mexico issues permits)
  - EPA promulgated Effluent Limitation Guidelines for certain categories of discharge, but not for CBM.
- Treated water may still kill fish/vegetation because it has no oxygen or aerobic bacteria and is at a different temperature than the river
- Additional tests such as "fish kill" may be required on water that otherwise meets guidelines
- This is an expensive option in San Juan, but in other locations it is very reasonable due to water quality
- RO and surface discharge can cost $3-5/bbl

Irrigation

TDS	Irrigation Comments
<400	No restrictions to crop growth
400-1,900	Slight restrictions to crop growth
>1,900	Severe restrictions to crop growth

- San Juan water tends to be:
  - Fruitland – 10,000 mg/l
  - Mesaverde – 40,000 mg/l
  - Dakota - > 40,000 mg/l

Irrigation

- Sodium Absorption Ratio (SAR) is defined as:

$$SAR = \frac{\left[Na^{+}\right]}{\sqrt{\frac{1}{2}\left(\left[Ca^{2+}\right]+\left[Mg^{2+}\right]\right)}}$$

SAR	Irrigation Comments
<3	No restrictions to crop growth
3-12	Some crops can tolerate the sodium well, some will be stressed and reduce output, some will die
>12	Serious effects on soils and vegitation

- San Juan Fruitland water tends to be around 28

Livestock/Wildlife Watering

TDS (mg/L)	Stock Watering Comments
<1,000	Excellent for all stock
1,000-2,999	Very Satisfactory, may cause mild diarrhea in animals until acclimated
3,000-4,999	Satisfactory, may be refused by animals not used to it
5,000-6,999	Avoid use for pregnant or lactating animals
7,000-10,000	Avoid use with very young or very old stock
>10,000	Unsatisfactory for all classes of animal

New Uses

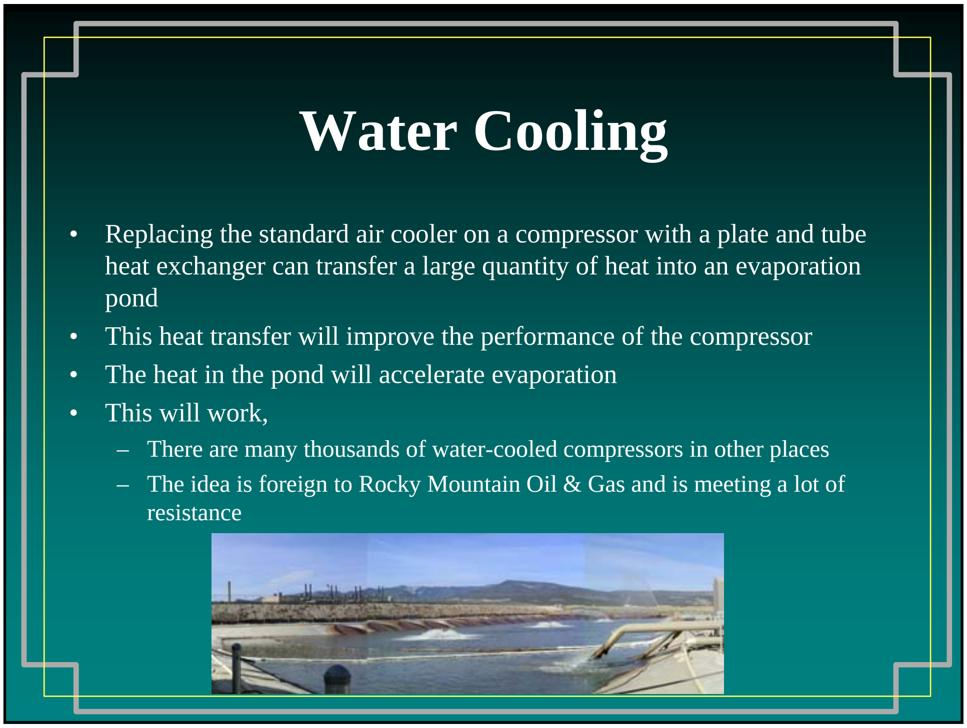
- Large-scale industrial cooling
- Small-scale industrial cooling
  - Swamp cooler
  - Water cooled equipment

Power Plant Cooling

- A local San Juan County power plant evaporates 500,000 bbl/day (64 acre-ft/day or 15,000 gpm) of river water in cooling towers
- They have conducted feasibility studies of replacing 50,000 bbl/day with produced water.
- The project is still under consideration, but some enthusiasm was dampened by last year’s record-high rainfall

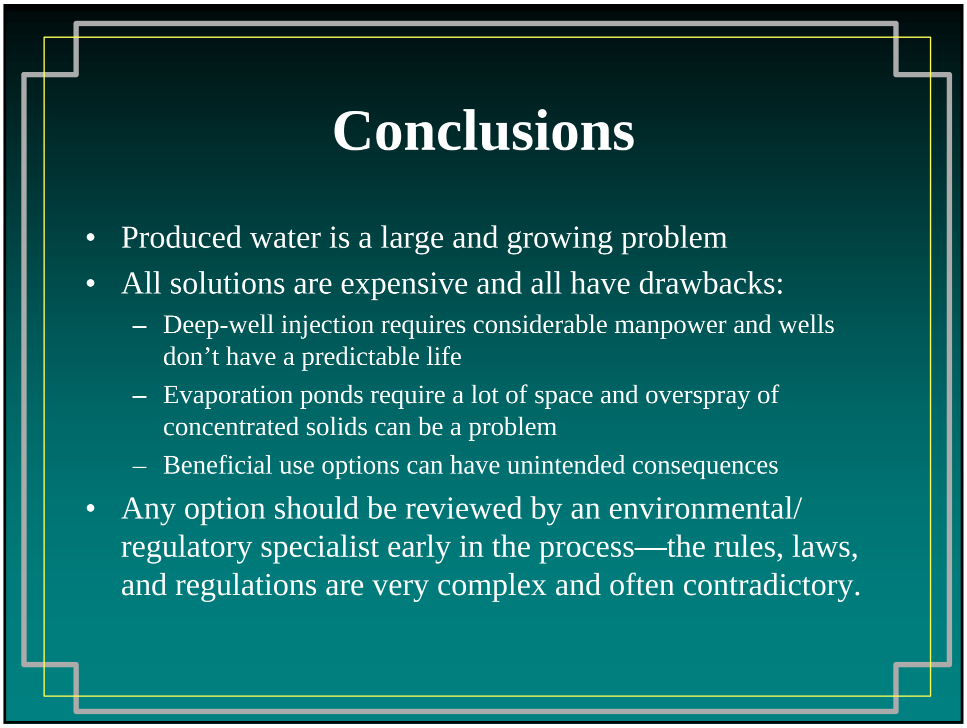
Small Scale Cooling

- Swamp coolers have proven very effective in arid regions
- A swamp cooler for a compressor has real potential
  - Air is cooled to about 20°F below ambient
  - Air is saturated with water vapor (further increasing heat transfer)
  - Can add significant hp for compression
- Biggest concern is that solids might get onto cooling surfaces and foul them
- Mist pads do clog quickly, but choice of pads may help that



Water Cooling

- Replacing the standard air cooler on a compressor with a plate and tube heat exchanger can transfer a large quantity of heat into an evaporation pond
- This heat transfer will improve the performance of the compressor
- The heat in the pond will accelerate evaporation
- This will work,
  - There are many thousands of water-cooled compressors in other places
  - The idea is foreign to Rocky Mountain Oil & Gas and is meeting a lot of resistance



Conclusions

- Produced water is a large and growing problem
- All solutions are expensive and all have drawbacks:
  - Deep-well injection requires considerable manpower and wells don’t have a predictable life
  - Evaporation ponds require a lot of space and overspray of concentrated solids can be a problem
  - Beneficial use options can have unintended consequences
- Any option should be reviewed by an environmental/ regulatory specialist early in the process—the rules, laws, and regulations are very complex and often contradictory.