Olson, William

From: Bemis, John
Sent: Friday, April 09, 2004 8:42 AM
To: Olson, William
Subject: State Land Office Comments on Pit Guidelines

The State Land Office (SLO) has several concerns about the proposed Pit Guidelines. As an initial matter, the SLO is uncertain about the status of the guidelines and whether mandatory compliance is required by the "shall" language in the guidelines. The SLO understands the guidelines to be to be guidance for rule compliance but the nondiscretionary language in the guidelines may exceed the authority granted by the recent changes to the pit rules.

Second, the guidelines appear to add regulatory burdens that exceed the requirements of the new rules.The concern is that the guidelines go further than the pit rules and are de facto rule-making that may violate the New Mexico Rules Act..

Because of these outstanding issues, the new guidelines may create confusion as to whether the new pit rules or the new guidelines apply for operations on SLO leases. SLO anticipates conflicts could develop with operators over rule or guideline compliance and this will lead to uncertainty and confusion over pit requirements on SLO leases.

The SLO appreciates your consideration of these comments.

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RECEIVED

APR 9 2004

Oil Conservation Division
1220 S. St. Francis Drive
Santa Fe, NM 87505

COMMENTS
PIT GUIDELINES

The Surface Division of the New Mexico State Land Office offers the following comments for consideration to the New Mexico Oil Conservation Division. We applaud the efforts of the OCD to strengthen and enforce regulations that will protect natural resources for future generations of New Mexicans. All industries should operate under a consistent regulatory framework. Therefore, the burden of protection promulgated by this rule should not solely be placed on oil and gas operators, but all drilling activities.

Diligence should be used in the location of drilling pits and the level of protection given to our citizens and our resources will measure the success of these guidelines. Remediation of contaminated groundwater is costly and complex with uncertain and often times failed results.

Drilling or work over pits must not be left on site without absolute certainty of any migration of contents to surface or subsurface. Heavy equipment used in closure will in most cases rupture the liners. A pit left on site with any contaminates is an un-permitted waste disposal unit with no closure plan or post closure provisions. For fields with 40 acre spacing this could be to 16 waste disposal sites per square mile.

The transfer of liquids and solid waste from other sites (drilling wells, producing wells, well completions, etc.) should not be allowed in drilling or work over pits. The pit should only be used for the operation on the site. This is a current and common practice in the field, which is not noticed on the application to drill, or in any other manner.

Closed loop drilling systems provide the best and most certain protection to the states resources and its citizens. These systems are a method of prevention, and proactive to the problem. The rules and practices in place have been reactive to pollution of resources and a change is necessary. Closed loop systems will help prevent contamination and destruction of the surface and subsurface resources of the state. The increased cost of this practice will be prove cost effective by reducing the environmental hazards and long-term mitigation costs.

Liners for drilling and work over pits are not designed or constructed for long-term containment. Their purpose is solely to prevent fluid loss during drilling operations. The cuttings and weight of the mud will usually rupture the seams or cause rocks to puncture the liner. Drilling and work over pits should be constructed to afford the same protection to the environment as any other pit installation, if they are not temporary in nature and the contents to be removed immediately after drilling operation cease. Drilling and work over pits must have the same closure standards as other pits. Procedures to isolate or reclaim contaminants must be proven and accepted by industry and technically skilled members of the environmental community.

Protection of groundwater must be assured. "Reasonable probability" of no groundwater contamination is not acceptable in our arid state and to the citizens and neighbors of oil & gas drilling sites. The ranking criteria for water protection from hydrocarbon pollution is antiquated, not supported by science, has not been conclusively proven accurate by field results and should be updated and upgraded to insure protection of the resources of the state and citizens.

Chlorides and other non-hydrocarbon contaminates have not been considered in the past and must be accepted as major problems to the surface, subsurface, and water. Clean up and remediation of pit sites must be complete and permanent, as well as protect water and surface for many years into the future. Field sampling and testing that has not been certified or verified by independent analysis and oversight is not acceptable for final conclusions or results of contaminate levels and success of remediation actions.

Dried drilling mud and cuttings pose the same problems as any other waste left in place. Drilling or work over pits with salt-water mud, brine additives or drilling chemicals, cannot be left in place, this is another example of creating a waste disposal site. Soil removed in remediation actions must be excavated to the maximum extent possible, and sampled on all perimeters. There can be no provisions for changing the remediation levels without public hearings. Soils to be returned to the site must be remediated to the published levels. No other levels may be approved by OCD with out a public hearing proce

Land spreading of any waste material is not sound environmental policy and is unacceptable to the state and its citizens. Land spreading causes additional surface disturbance and damage, wastes will migrate by wind erosion, rainwater runoff, and flooding. Land spreading creates additional unauthorized waste disposal sites with no closure provisions.

Insitu treatment may be done only if all other methods are impossible, and must use proven methods that assure complete success. Insitu treatment zones must be at least 100' above groundwater.

Land farming operations must have surface owners permission and notice should be given to nearby owners, and neighbors. Land farms create future liability to the owner, operator, by the State (OCD) for permitting, the State (Land Office) for allowing the practice on State land, and US Government (BLM) for allowing the practice on BLM land. Land farming materials with contaminates other than crude oil or condensate should not be allowed – only light hydrocarbons that have been proven to bio-attenuate are responsive to land farming. Results of acceptable remediation of other contaminates Such as tank bottoms, drilling fluids, drill cuttings, produced water; completion fluids, well flow back fluids, gas plant waste, and refinery waste have not been demonstrated in theory or practice. Any soil that is proposed for land farming must be analyzed for all possible contaminates before treatment commences. Soils that have been land farmed must be certified to be above remediation levels by independent third party laboratory analysis, with OCD oversight. Land farms have no closure requirements that prevent the remaining contaminate from migrating by wind erosion, airborne particles, rainwater and storm water runoff, 100-year floods and deterioration of berms. Land farming destroys surface area that will never recover in the arid climate of New Mexico. Land farming of reserve pits requires 3 to 8 acres per well. Land farming is not an environmentally sound disposal method.

Increased awareness, enforcement, and compliance with any regulation set forth are the only way to prove the effectiveness of protection measures. We commend all involved in this rule making process and realize that there is a fine line that distinguishes good protection standards from burdensome rule making with costs passed on to operators. Your consideration and commitment are greatly appreciated.

PITS AND BELOW-GRADE TANK GUIDELINES
RECOMMENDED CHANGES

II. A. 1. **Location**

Add. "100-year flood plain " Add. " village, town, city, stream, river or lake"

Suggested Language

No pit shall be located in any wetland, watercourse, lakebed, sinkhole, 100-year flood plain, or playa lake. No pit shall be located within 2 miles of any village, town, city, stream, river, or lake. Pits adjacent to any such watercourse or depression shall be located safely above the high-water level of such watercourse or depression. The OCD may require additional protective measures for pits located in ground water sensitive areas or wellhead protection areas.

B. **Drilling and Work Over Pits**

Remove. "And the operator intends to encapsulate the pit contents in place upon completion of drilling or work over activities."

Add. "Brine water, mud oil, could possibly, and 30 mil."

Suggested Language

Drilling and work over pits shall be constructed with a synthetic liner at least 12 mils thick. If the pit will contain salt based drilling fluids, brine water, mud oil, hydrocarbon fluids or other contaminants that could possible contaminate fresh water the pit shall be constructed with a synthetic liner at least 30 mils thick. Liners shall be designed and constructed as follows:

IV. **Closure Procedures**

Add. "Drilling, Work over"

Change. "it can be shown" to "it has been demonstrated" and "surface water and soil quality"

Suggested Language

Prior to commencing closure of a storage, disposal, drilling, work over, or emergency pit, or below-grade tank, a closure plan must be submitted to and approved by OCD. If a number of pits or below-grade tanks are to be closed by a single company, the company may submit one general plan stating the areas and types of facilities to be closed, along with the procedures to be used during closure. Deviations from approved plans require OCD notification and approval.

Procedures may deviate from the following guidelines if it has been demonstrated that the proposed procedure will remove or isolate contaminants in such a manner that fresh waters, surface waters, soil quality, public health, and the environment will not be impacted by the remaining contaminates. Specific constituents and/or requirements for soil analysis and/or remediation may vary depending on site specific conditions.

V. A. 3. **Distance to nearest Surface Water Body**

Add. "Sink holes, depressions, and 100-year flood plains."

Suggested Language

The operator shall determine the horizontal distance to all wet lands, playas, irrigation canals, ditches, depressions, sinkholes. 100-year flood plains, and perennial and ephemeral watercourses.

V. C. **Ground Water Quality**

Change. "Reasonable probability to Possibility" in paragraph 2

Suggested Language

If there is a possibility of ground water contamination from any pit or below-grade tank based upon the level of contaminates in the soils directly beneath the pit or below-grade tank, or the extent of soil contamination defined during remedial activities, monitor wells may be required to assess potential impacts on ground water.

VI. A. 1. **Highly Contaminated/Saturated Soils**

Remove. "remediated insitu" Change. "practicable to possible"

Suggested Language

These soils shall be excavated to the maximum extent possible and remediated using techniques described in Section VIII.A.

VI. A. 2. (a) **Ranking Criteria**

Suggested Language

Dept To Ground Water	Ranking Score
<100 feet	20
100 – 200	10
>200	0

Wellhead Protection Area

<1000 feet from a private domestic fresh water well or spring, or:

<2500 feet from any other fresh water well or spring

Yes	20
No	0

Distance To Surface Water Body

<2500 horizontal feet	20
2500-5000 horizontal feet	10
> 5000 horizontal feet	0

(b) Hydrocarbon Remediation Levels

Remove. "remediated insitu"

Suggested Language

The total ranking score determines the level of remediation for hydrocarbon constituents that may be required at any given site. The total ranking score is the sum of all three individual ranking criteria listed in Section VI.A.2. (a). The table below lists the remediation level for hydrocarbon constituents that may be required for the appropriate total ranking score. Soils that contain hydrocarbon contaminants above the recommended remediation levels shall be excavated to the maximum extent practicable and remediated using techniques described in Section VIII.A

Total Ranking Score

Suggested Language

	≥19	10-19	0 – 9
Benzene (ppm)	5	5	5
BTEX (ppm)	30	30	30
TPH (ppm)	100	250	2000

Remove. "* ,**"

(c) **Remediation Levels For Non-Hydrocarbon Contaminants**

Remove. "remediated" Add. "excavated"

Change. "reasonable probability to possible"

Suggested Language

Soils contaminated by chloride contaminates in excess of 250 mg/kg shall be excavated to the maximum extent possible and the remaining chlorides be remediated or isolated so that remaining chlorides in the soil will not possibly contaminate ground water or surface water in excess of the standards in 19.15.1.19.B (2) NMAC and 19.15.1.B. (3) NMAC through leaching, percolation, or other transport mechanisms, or as the water table fluctuates; or pose a threat to human health or the environment.

Soils contaminated with any other non-hydrocarbon contaminants shall be excavated to the maximum extent possible and the remaining contaminates be remediated or isolated so that remaining contaminates in the soil will not possibly contaminate ground water or surface water in excess of the standards in 19.15.1.19 B (2) NMAC and 19.15.1.B (3) NMAC through leaching, percolation, or other transport mechanisms, or as the water table fluctuates; or pose a threat to human health or the environment.

VII. B. 1. **Unsaturated Contaminated Soils**

Remove. "(a),(b),(c),(d)"

VII. B. 2. **Field Soil Sampling/Screening**

Add. "Highly contaminated or saturated soils"

Suggested language

Field screening of contaminants during excavation of highly contaminated or saturated soils, and unsaturated contaminated soils may be conducted using industry accepted procedures. However, all final samples obtained to verify that the apporiate contaminant specific remediation level has been met, shall be analyzed at a laboratory using EPA approved methods and quality assurance/quality control procedures.

VIII. A.1. (b) **Residual Wastes**

Remove. "except for dried mud and cuttings in drilling or reserve pits which have been approved by the OCD for encapsulation under Section VIII.A.3.(a).

Suggested Language
Remaining solid wastes shall be removed from the pit or below grade tank.

VIII. A.2. (a) **Contaminated Soils**

Remove. "or a alternate OCD approval remediation level"
Change. "sample to samples"

Suggested Language
Excavated from the ground until representative samples from the walls and bottom of the excavation is below the contaminant specific remediation level listed in Section VI.A; or

VIII.A.2. (b) **Contaminated Soils**

Change. "practicable to possible"
Change. "sample to samples"

Suggested Language
Excavated to the maximum depth and horizontal extent possible. Upon reaching this limit samples shall be taken from the walls and bottom of the excavation to determine the remaining levels of soil contaminant; or

VIII. A.2. (c) **Contaminated Soils**

Remove. "or an alternate OCD approved remediation level"

Suggested Language
Treated in place as described in Section VIII.A.3. (b) (ii) until a representative sample is below the contaminant specific remediation level listed in Section VI.A.

VIII.A.3. (a) (ii) **Disposal**

Remove. "or an alternated OCD approved remediation level"

Suggested Language
Excavated soils may be returned to the excavated area if remediated to the recommended remediation levels in Section VI.A.2.

VIII.A.3. (a) (iii) **Soil and Waste Management Options**

Remove. (iii)

VIII.A.3. ~~(a)~~ (iv) **Disposal**
b (iii)

Soils shall not be mixed or diluted to reduce contaminate levels."

Suggested Language

Onetime applications of hydrocarbon-contaminated soils may be landfarmed on location by spreading the soil in a six-inch lift within a bermed area. All soils to be land farmed shall be analyzed for contaminate levels per Section VI.A.2. (b) & (c). Hydrocarbon contaminates to be landfarmed shall be biodegradable. Soils shall not be mixed or diluted to reduce contaminated levels. Soils with non-hydrocarbon contaminant levels above those listed in Section VI.A.2. (b) & (c) shall not be landfarmed. Soils containing plastic, wood, metal, concrete or trash shall not be landfarmed. The soils shall be disced regularly to enhance biodegradation of the contaminants. If necessary, upon approval by OCD, moisture and nutrients may be added to the soil to enhance aerobic biodegradation.

VIII.A.3. (b) (iii) **Treatment and Remediation Techniques**

Paragraph 2

Add. "100 year flood plain"
Add. "100 feet to groundwater"
Add. "surface owner written permission"
Add. "Landowner water right holders notice"

Suggested Language

Landfarming shall not occur within any wetland, watercourse, lakebed, sinkhole, playa lake, 100-year flood plain, groundwater sensitive area, wellhead protection area, or where depth to groundwater is less than 100 feet. Landfarming adjacent to any watercourse, lakebed, sinkhole, playa lake, or 100-year flood plain shall be located safely above the ordinary high water mark. Landfarming sites must have surface owners written consent. 30-day notice shall be given to surface owners and water right holders within 2 miles.

IX. A. **Termination or Remedial Action**

Paragraph 2

Change. "practicably to possibly"

Suggested Language

If soil action levels cannot possibly be attained an evaluation of risk maybe performed and provided to OCD for approval showing that the remaining contaminants will not pose a threat to present or foreseeable beneficial use of fresh water, public health and the environment.

LANDFARMING OF PETROLEUM AND RELATED CONSTITUENTS

- For the most part, discussions of landfarming (also known as land application or land treatment) are found in EPA Guidance documents associated with the remediation of refined petroleum products that have leaked or spilled from underground storage tanks (UST).
- Landfarming has been proven effective in reducing concentrations of constituents of petroleum products typically found at UST sites.
- Landfarming is particularly effective for remediation of soils contaminated with petroleum products with a significant volatile fraction.
- Although landfarming, in the context of best practices, is actually an active process by which concentrations of petroleum constituents are reduced through biodegradation, e.g. spreading excavated contaminated soils in a thin layer on the ground surface and stimulating aerobic microbial activity within the soils through aeration and/or the addition of minerals, nutrients, and moisture, much of the "remediation" is a function of releasing regulated volatile organic compounds (VOC) into the atmosphere.
- In the case of heavier (non-volatile) petroleum products or crude oil, evaporation of constituents in much less likely to occur and the only effective landfarming mechanism for remediation is biodegradation.
- Biodegradation is effective only if an intensive regime is established and properly maintained.

- Consequently, landfarming of crude oil spills at remote sites tends to be ineffective and frequently lapses into the un-permitted disposal of petroleum contamination in an unregulated setting.
- Landfarming of chloride contaminated soil, unlike landfarming of petroleum contamination, is based on the premise that the concentration of the contaminant will not be reduced, but simply relocated to a shallow depth below the ground surface.
- Landfarming of chloride contamination is controversial because of the counter-intuitive notion that decontamination of the ground surface is achieved by intentionally contaminating a shallow sub-surface zone.
- In the context of New Mexico Water Quality Control Commission Regulations, the practice probably violates groundwater protection standards.
- Landfarming of drilling/completion fluids and tank bottom treatment chemicals represents a fundamental misuse of the concept as it was originally developed. There is no reported evidence of treatment efficacy for that range of constituents in a landfarming regime.

OIL FIELD EXPLORATION AND PRODUCTION PITS

- The storage and disposal of hydrocarbons, related contaminants and produced water in open pits represent a potentially significant risk category for pollution of surface and groundwater resources in New Mexico

- Unlined pits represent the highest level of risk to water resources

- The Oil Conservation Division (OCD) of the Energy Minerals and Natural Resources Department has recently adopted a new rule (19.15.2.53 NMAC) to increase controls on the location and performance of pits

- Although the rule represents some improvement over the previous regulatory framework, it still allows applicants the latitude to request a permit to construct an unlined pit

- For lined pits, there are no specifications in the new rule for construction of liner systems

- There are no specific requirements for demonstrating that methods for closure of a pit will be protective of water resources

- There are no methods described for making the determination that a proposed closure plan will protect water resources

- There are no requirements for the disposition of liners when pits are closed

- The new rule does not prohibit the construction of pits in floodplains

- The new rule places no quantitative restrictions on the concentration of contaminants stored in pits

- Ultimately, even with the new rule in place, pits still remain a potentially significant source of contamination to the surrounding environment

DEFINITIONS

Add. "distance to groundwater"

Groundwater Sensitive Area shall mean an area specifically so designated by the division after evaluation of technical evidence when groundwater exists that would likely exceed Water Quality Control Commission standards if contaminants were introduced into the environment. Any area where depth to groundwater is less than 50 feet.

Soil the portion of the earth's surface consisting of disintegrated rock and humus.

Change. "distances"
Add. "municipal wells"

Wellhead Protection Area shall mean the area within 1000 horizontal feet of any private, domestic fresh water well or spring used by less than five household for domestic or stock watering purpose or within 2500 horizontal feet of any other fresh water well or spring or within 2 miles of any municipal water well.

Olson, William

From: Martin, Ed
Sent: Friday, April 23, 2004 11:03 AM
To: Olson, William
Subject: FW: Liners

-----Original Message-----
From: Rick Gasser [mailto:rick@wtplastics.com]
Sent: Tuesday, April 20, 2004 12:21 PM
To: Ed Martin
Cc: tgum@state; Ed Martin
Subject: Liners

Ed;

Thanks for you time today, as per our discussion I am sending you some additional information on Dura-Skrim. This material is what the majority of the Drilling and Workover pits are being lined with in Southeast New Mexico.

I would purpose the specifications for the Short-term storage less than 180 days be either a Mullen Burst ASTM D751 be a min of 250 psi **or** a Hydrostatic Resistance ASTM D751 be a min of 65 psi. and either a Tensile strength ASTM D751-95E be a min. of 125 lbs (warp) **or** Grab Tensile ASTM D751 be a min. of 75 lbs. These are two different test done on different types of material, the Mullen is normally performed on woven polyethylene material and the Hydrostatic is performed on mono film and polyester reinforced polyethylene's.

I would purpose the specifications for the Long-term storage more than 180 days be either a Mullen Burst ASTM D751 be a min of 500 psi **or** a Hydrostatic Resistance ASTM D751 be a min of 150 psi. and either a Tensile strength ASTM D751-95E be a min. of 300lbs (warp) **or** Grab Tensile ASTM D751 be a min. of 150 lbs.

This would enable the Oil and Gas producers the option of materials, not requiring them to only use a Woven Polyethylene. The Dura Skrims have worked well in the past and I think the producers would like the opportunity to use a familiar product if they so choose. At the same time it would still require them to use a quality liner, not simply a 6 mil non-reinforced material, which is a little stronger as your household trash bag liner.

Notice the elongation of the Dura Skrim products. This is very important when lining over irregular surfaces, i.e. rocks, stones and clumps. A majority of Drilling pits are not compacted smooth nor are they good quality pits with compacted walls, so the elongation helps the liner fit the pits surfaces better. The woven polyethylene's have great strength properties but they have very little elongation.

I read the closure section and I wonder if the pit contains an inside brine reserve pit, can the 40 mil liner at closing only cover the brine section of the pit and the outside fresh water pit be closed a stated for fresh water closure ? I think this would be sufficient, but I wanted some clarification.

Again, Thank you for the opportunity to share my thoughts with the OCD, and I will be available if you would have nay additional questions.

Rick Gasser
W T Plastics. Ltd

Work Copy

Olson, William

From: Prukop, Joanna
Sent: Friday, May 14, 2004 9:39 AM
To: Leach, Carol; MacQuesten, Gail; Olson, William; Anderson, Roger
Subject: FW: INTERIM GUIDELINES
Importance: High

Here's the input from NMOGA...please digest and let me know what you think...I'll read it over the weekend...thanks, Joanna

-----Original Message-----
From: Deborah Seligman [mailto:seligman@nmoga.org]
Sent: Friday, May 14, 2004 6:46 AM
To: Secretary Prukop
Subject: INTERIM GUIDELINES

Joanna,

Thank you for the opportunity to comment on the interim guidance document for pits and below-grade tanks, which I have attached.

Additionally, below are various comments NMOGA has received from companies who are having problems with the field offices and their interpretation of the guidance document.

Although we have been assured that the intent of the guidelines was not to interfere with drilling operations that has not been the case. Below is *cut and paste* from correspondence to NMOGA asking for assistance in working with the OCD Field offices with examples of what is currently taking place. It is apparent from the comments that each district office is establishing their own rules regardless of the guidelines and more importantly regardless of the rule.

Company comments on working with the Field Offices:

I have an APD that has been rejected by the Hobbs district office because I only filed a C-101 electronically. Prior to filing I checked with our office in Farmington on how they were instructed to file. The Aztec office is only accepting reserve pit permits on a C-101. We have to file a C-101 even on federal leases. I called Jane Proudy to inquire as how to e-file with the new information required on the C-101. She instructed us to write the additional information into the comment box. Jane indicated that the electronic C-101 was in the process of being revised.

Denny had asked for hard copies for 1-2 wks. Not issue now.

Ed is modifying form.

We received notice from the Hobbs office that we have to file a C-144 for the pit because the C-101 lacks the necessary information for the permit to be approved.

Company A was requested by the Hobbs office to file the C-144, plus a diagram of the well location, plus a diagram of the pit construction along with the electronic C-101. All of these additional forms must be hard copies because Jane Proudy has instructed the Industry not to attach additional forms unless they pertain to Non Standard Locations. Ed will check

Company B had their general plan for reserve pits approved by the Artesia district office and the same plan rejected by the Hobbs district office. The reason being general plans are not acceptable for reserve

didn't happen & need more info

pits.

Company C had their general plan for reserve pits approved by the Hobbs district office and the same plan rejected by the Artesia district office. This same company is having trouble getting any APD's approved from the Artesia district office.

The Hobbs district office staff has told Company D that they do not accept the results that their liner achieved based on the American Society for Testing and Materials (ASTM) standards. Yet, these standards are not only nationally accepted, but are internationally recognized. ? didn't happen

Other issues with the use of the C-144 is that it only allows for the pit location to be identified by latitude and longitude coordinates, where as the C-101 and C-103 only allow for footages. The C-144 requires the mil thickness be identified, while the guidelines do not specify a mil thickness for reserve pits only the ASTM values they must meet. Ed will look at

Some of the district offices are still using the original guidelines requirement of a 20-mil liner for fluids containing salt, and not the interim guidelines published ASTM values for short-term pits intended for use of less than 180 days. Wrong.

One district office staff member has stated that there is NOT a Pit Rule or a Guideline because the Governor hasn't approved it yet. Therefore, it is up to the district office to interrupt what they feel is necessary to protect ground water. We informed him that the Pit Rule was approved by the OCC, had been published and was effective April 15; yet he insisted until the Governor has acted on it, nothing was approved. ? Confusion

water. usgs.gov. USGS also has water data

The water data is not readily available on depth to ground water, and the OSE datasource on the internet is not complete. Company E was told there was only sand where their pit was to be located, but in gathering water data (6 hour round-trip drive to the OSE district office, where more data was located) he found the information that he needed but additionally found that there was clay/tight sands in the area as well.

Company F writes: All filings now require an additional 2 sheets of paper to be filed. In Aztec District office, a Notice of Intent is required for the construction of a pit and a for C-144 for the closure. In Hobbs & Artesia Districts, a C-144 is required for each the construction and the closure of a pit. On workovers that didn't require any type of filing, i.e. cleanouts, tbg change, etc., will now require 2 reports to be filed. On Federal wells that currently require a NOI sundry and a Subsequent sundry for workovers, will now require 2 additional reports for the pits (that's 4 pieces of paper to do a recomplete which is just too much!). Our concerns are not only industry resources but OCD resources as well. Aztec only has one person looking at all pit paperwork for 13+ operators in the SJ Basin.

Company F writes: a big concern in the SE is the 250 mg/kg chloride remediation level referenced in the guidelines. The public will see that as a standard regardless of ambient soil quality.

Again, thank you for the additional opportunity to comment.

Deborah Seligman
Director Governmental Affairs
New Mexico Oil & Gas Association
Santa Fe, NM
505.982.2568

PIT

AND

BELOW-GRADE TANK

GUIDELINES

(These are interim guidelines. NMOCD has not yet reviewed all of the written comments received, but all of the verbal comments received at the public meetings have been reviewed and incorporated into these guidelines if applicable. After review of the written comments, further changes may be forthcoming.)

(April 13, 2004)

NEW MEXICO OIL CONSERVATION DIVISION
1220 SOUTH ST. FRANCIS DR.
SANTA FE, NEW MEXICO 87505

TABLE OF CONTENTS

INTRODUCTION

The following guidelines apply to pits and below-grade tanks used for the containment of exploration, production, processing and storage wastes regulated by the New Mexico Oil Conservation Division (OCD), and classified as 1) exempt from Federal Resource Conservation and Recovery Act (RCRA) Subtitle C Regulations, or 2) non-hazardous by characteristic testing.

The intent of the guidelines is to outline the methods and specifications the OCD has approved for the design, construction, operation, maintenance and closure of pits and below-grade tanks in a manner that protects fresh waters, public health and the environment. **The guidelines are not mandatory**. However, to obtain a permit for a pit or below-grade tank or to close a pit or below-grade tank under 19.15.2.50 NMAC, an operator must either follow the guidelines or obtain the OCD's approval for an alternative approach. To obtain approval, the operator must demonstrate that the alternative approach will prevent contamination of fresh water and protect public health and the environment. It should be noticed that an alternative approach to the guidelines is NOT the same as asking for an exemption to the Rule, and is NOT subject to 19.15.2.50 part G.3 "(3) Exemptions may be granted administratively without hearing provided that the operator gives notice to the surface owner of record where the pit is to be located and to such other persons as the division may direct and (a) written waivers are obtained from all persons to whom notice is required, or (b) no objection is received by the division within 30 days of the time notice is given. If any objection is received and the director determines that the objection has technical merit or that there is significant public interest the director shall set the application for hearing. The director, however, may set any application for hearing."

Not all of single subject to this.

Compliance with the guidelines, or receipt of a permit under 19.15.2.50 NMAC, does not relieve an operator of liability for any releases or contamination which may pose a threat to fresh waters, human health and the environment, or relieve an operator of responsibility for compliance with any other federal, state or local laws and regulations.

DEFINITIONS:

A "pit" is defined as any surface or sub-surface impoundment, man-made or natural depression, or diked area on the surface. Excluded form this definition are berms constructed around tanks or other facilities solely for the purpose of safety and secondary containment. The term "pit" includes but is not limited to: produced water pits, dehydrator pits, blowdown pits, separator pits, tank drain pits, pipeline drip collector pits, compressor scrubber pits, flare pits, drilling pits reserve pits, workover pits and all other pits which receive exploration, production and processing wastes regulated by the OCD.

"Below-grade tanks" are defined as vessels, excluding sumps and pressurized pipeline drip tanks, where any portion of the sidewalls of the tank is below the surface of the ground and not visible. Sumps are defined as any impermeable single wall vessel with a capacity less than 500 gallons, where any portion of the sidewalls of the reservoir is below the surface of the ground and not visible which vessel remains predominantly empty, serves as a drain or receptacle for spilled or leaked liquids on an intermittent basis, and is not used to store, treat, dispose of, or evaporate products or wastes.

The New Mexico State Engineer has designated fresh waters as all surface waters and ground waters of the state containing 10,000 milligrams per liter or less of total dissolved solids (TDS) for which there is a present or reasonably foreseeable beneficial use. The term "reasonably foreseeable" generally has been taken to mean a time period of not less than 200 years into the future, but could be thousands of years.

I. **PERMITTING PROCEDURES**

A. Application for Permit

B. The applicant must submit a "PIT OR BELOW GRADE TANK APPLICATION" on Form C-144 Form C-101or Form C-103, as appropriate. The rule in Section B.1.b mandates that an operator use the ADP or sundry notices for Drilling or Production related Pits. This language was used to allow the acceptance of Federal APDs and Sundry Notices. "(b) Drilling or production. An operator shall apply to the appropriate district office for a permit for use of a pit or below-grade tank in drilling, production, or operations not otherwise identified in Subparagraph (a), Paragraph (1), Subsection B of 19.15.2.50 NMAC. The operator shall apply for the permit on the application for permit to drill or on the sundry notices and reports on wells, or electronically as otherwise provided in this chapter. Approval of such form constitutes a permit for all pits and below-grade tanks annotated on the form. A separate Corm C-144 is not required." For pits and below-grade tanks in existence prior to April 15, 2004, a permit application on Form C-101, C-103 or C-144 is required on, or prior to, September 30, 2004. This is contradictory to the rule B.3.b "(b) Existing pits or new below-grade tanks. For each pit or below-grade tank in existence on April 15, 2004 that has not received an exemption after hearing as allowed by OCC Order R-3221 through R-3221D inclusive, the operator shall submit a notice not later than April 15, 2004 indicating either that use of the pit or below-grade tank will continue or that such pit or below grade tank will be closed.". The rule only requires a notice, (not Sundry Notice) and NMOCD has provided on their web site a standard excel spreadsheet that they prefer for this notice. For pits and below-grade tanks constructed after April 15, 2004, the C-101 or C-103, as appropriate, will constitute an application for permit of the pit or below-grade tank. If an operator intends to use the same procedures for construction of pits and below-grade tanks at multiple sites, the operator may submit one general plan. A list of those sites, their locations, and other relevant site-specific information must be submitted with the general plans and specifications. For subsequent pits or below-grade tanks to be constructed under the general plan, the operator must only notify OCD of the location of the pit or below-grade tank on a C-101, C-103 or C-144. Deviation from an approved general permit requires OCD notification and approval.

OK Done

If any pit, berm or levee to be constructed is more than ten feet (10') in height from ground level, or if a pit volume is more than 10 acre-feet, the State Engineer Office must also review and issue a construction permit.

B. Definitions for Use in Completing the C-101, C-103, or C-144

1. Depth to Groundwater is defined as the vertical distance from the lowermost contaminants to the seasonal high water elevation of the ground water.
2. Distance to the Nearest Fresh Water Well is calculated as the horizontal

distance to the nearest private, domestic fresh water well or spring.

3. Distance to Nearest Surface Water Body is calculated as the horizontal distance to the nearest wetland, playa, irrigation canal, ditch, perennial watercourse or ephemeral watercourse.

C. Closure Report (Also see Section IV of these Guidelines)

Closure of pits and below-grade tanks must be reported on an OCD Form C-144 accompanied by the information necessary to evaluate the closure. It should be noted that Section IV does not include Drilling, workover, or production pits as pits requiring a closure plan prior to closing. The rule states in Section F that a closure report can submitted on a SUNDRY notice. This language is also used in Section B.1.b. The reference to the state C-103 was eliminated because of testimony at the rule hearing. For a Federal well a Federal APD or Sundry Notice 3160-5 is as acceptable as a State C-101 or C-103. This was to eliminate the need to having to file a state only form for federal wells "F. Closure and restoration.

(1) Closure. Except as otherwise specified in Section 50 of 19.15.2 NMAC, a pit or below-grade tank shall be properly closed within six months after cessation of use. As a condition of a permit, the division may require the operator to file a detailed closure plan before closure may commence. The division for good cause shown may grant a six-month extension of time to accomplish closure. Upon completion of closure a closure report (form C- 144), or sundry notices and reports on wells shall be submitted to the division. Where the pit's contents will likely migrate and cause ground water or surface water to exceed water quality control commission standards, the pit's contents and the liner shall be removed and disposed of in a manner approved by the division." It should also be noted that in the rule Section E for drilling fluids and drill cuttings the disposal method is to be identified at the time a permit is submitted. This is in effect the closure plan for these pits. The APD approval constitutes the approval of both the pit and its closure. "E. Drilling fluids and drill cuttings. Drilling fluids and drill cuttings shall either be recycled or be disposed of as approved by the division and in a manner to prevent the contamination of fresh water and protect public health and the environment. The operator shall describe the proposed disposal method in the application for permit to drill or the sundry notices and reports on wells." All plans and specifications must be submitted to and approved by the OCD prior to closure.

II. DESIGN AND CONSTRUCTION

A. GENERAL

1. Location

"No pit shall be located in any wetland, watercourse, lakebed, sinkhole, or playa lake. Pits adjacent to any such watercourse or depression shall be located safely above the high-water level of such watercourse or depression. The OCD may require additional protective measures for pits located in ground water sensitive areas or wellhead protection areas." OCD Rule 50.

2. Stockpiling of Topsoil

Prior to constructing any pit, except a pit constructed in an emergency, topsoil must be stripped and stockpiled for use as the final cover of fill at the time of closure.

3. Exclusion of Runoff Water

A pit must be constructed and maintained so that runoff water from outside the location is not allowed to enter the pit. Berms surrounding the pit must be maintained.

4. Freeboard

The designed freeboard allowance must take wave action into account to prevent overtopping due to wave action.

B. DRILLING AND WORKOVER PITS

1. Liners will be designed and constructed as follows (Unlined pits are allowed in certain areas. See OCD Rule 50):

SYNTHETIC LINER SPECIFICATIONS

Short-term storage of oil field wastes (less than 180 days)

Method	Coated Fabric
Cold crack (ASTM D2136-94, September 15, 1994)	-60 °F
Black carbon content (ASTM D1603-94, June 15, 1994)	2 % or greater
Carbon dispersion (ASTM D3015-95, September 10, 1995)	A-2 range
Tensile strength (ASTM D751-95E1, February 1997)	125 lbs (warp)
Mullen burst (ASTM D751-95E1, February 1997)	250 psi
One inch tensile strength (ASTM D882-97, June 10, 1997)	25 lbs. (warp)
Permeability	At least 1 X 10^{-7}
Oil resistance (ASTM D471-96, June 10, 1996)	No signs of deterioration and more than 80 % retention of tensile and seam strength after immersion for 30 days at 73 °F

Long-term storage of oil field wastes (more than 180 days)

Cold crack (ASTM D2136-94, September 15, 1994)	-60 °F
Black carbon content (ASTM D1603-94, June 15, 1994)	2 % or greater
Carbon dispersion (ASTM D3015-95, September 10, 1995)	A-2 range
Tensile strength (ASTM D751-95E1, February 1997)	300 lbs (warp)
Mullen burst (ASTM D751-95E1, February 1997)	500 psi
One inch tensile strength (ASTM D882-97, June 10, 1997)	45 lbs. (warp)
Permeability	At least 10^{-7} cm/sec
Oil resistance (ASTM D471-96, June 10, 1996)	No signs of deterioration and more than 80 % retention of tensile and seam strength after immersion for 30 days at 73 °F

The American Society for Testing and Materials (ASTM) methods may be obtained from the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pennsylvania 19103.

2. All materials used for lining pits must be resistant to hydrocarbons, salts, and acidic and alkaline solutions. The liners will be made of materials

suitable for outdoor use. Liner compatibility must comply with EPA Method 1990, *Compatibility Test for Wastes and Membrane Liners.*

3. The bed of the pit and inside grade of the berm will be smooth and compacted, free of holes, rocks, stumps, clods, or any other debris that may rupture the liner. In rocky areas, it may be necessary to cover the pit bed with a felt pad, compacted six-inch layer of sand, or other suitable cushioning materials.

4. The liner will rest smoothly on the pit bed and the inner face of the berms. In locations where temperature variations are significant, wrinkles or folds will be placed at each corner of the pit to allow for the contraction and expansion of the membrane due to temperature variations. The membrane manufacturer should be consulted on this matter.

5. At any point of discharge into the pit, the liner will be protected from the fluid force of discharges.

*

C. EMERGENCY PITS

Pits constructed in the event of a true emergency are not required to be fenced or lined. However, within 24 hours after the emergency has ceased to exist, such pits must be drained of all fluids and closed per the guidelines. If such a pit remains in operation, it ceases to qualify as an emergency pit and must be permitted, lined (single 20-mil liner) and fenced according to these guidelines and such a pit must be kept generally free of fluids or it will be classified as a storage pit.

D.DISPOSAL AND STORAGE PITS

At minimum, disposal and storage pits must be constructed with a primary and secondary liner with a leak detection system. The liners may be synthetic liners, clay liners where the bottoms and sides have a hydraulic conductivity no greater than 1×10^{-7} centimeters per second, or an alternative liner or barrier approved by the OCD which is certified by a professional engineer registered to practice in the State of New Mexico. All disposal and storage pits must contain a leak detection system as described in Section II.E. Pit liner systems will be designed and constructed as follows:

1. Wall Slopes

The outside slope of pit walls will be no steeper than 3:1 horizontal to vertical (Figure 1). The inside slope of pit walls will be no steeper than 2:1 horizontal to vertical, except for natural liners which have slope specifications as set out in subsection 2 below.

2. Clay Liners

(a) Barriers constructed with natural clay materials will be at least two feet thick, placed in six-inch lifts, and compacted to 95 percent of the material's Standard Proctor Density (ASTM D-698).

(b) Clay materials used in a liner will undergo permeability testing before and after construction.

(c) Pre-construction permeability testing will consist of laboratory permeability tests on at least two specimens of representative clay liner materials compacted in the laboratory to 95 percent of the material's Standard Proctor Density (ASTM D-698).

(d) Post-construction permeability testing will consist of at least two laboratory permeability tests on the completed clay liner or one field permeability test on the completed soil liner. Particular emphasis will be placed on selecting the location(s) for permeability tests or test samples where non-uniformity in soil texture or color can be observed.

(e) Laboratory permeability test procedures must conform to one of the methods described for fine-grained soils in the Corps of Engineers Manual EM-1110-2-1906 Appendix VII. In no case will the pressure differential across the specimen exceed five feet of water per inch of specimen length. Field permeability tests will be conducted only by the double ring infiltrometer method as described in ASTM D-3385.

(f) If permeability testing shows that addition of bentonite or other approved material is needed to assist the clay in meeting the permeability standard, it will be applied at a minimum rate specified by the testing or engineering firm. Any bentonite used for liner material must not have been previously used as drilling mud.

(g) Any clay liner will be constructed by disturbing the soil to the depth of the bottom of the liner, applying fresh water as necessary to the clay materials to achieve a moisture content wet of optimum, then re-compacting it in six-inch lifts with heavy construction equipment, such as a footed roller, until the required density is achieved.

(h) Any clay liner must cover the bottom and interior of the pit entirely.

(i) Any clay liner must be installed on a slope no steeper than 3:1 horizontal to vertical.

3. Synthetic Liners

(a) Synthetic materials may be rigid, semi-rigid, or flexible, will be at least 40 mils thick, and must conform to the following specifications:

SYNTHETIC LINER SPECIFICATIONS

Short-term storage of oil field wastes (less than 180 days)

Method	
Cold crack (ASTM D2136-94, September 15, 1994)	-60 °F
Black carbon content (ASTM D1603-94, June 15, 1994)	2 % or greater
Carbon dispersion (ASTM D3015-95, September 10, 1995)	A-2 range
Tensile strength (ASTM D751-95E1, February 1997)	125 lbs (warp)
Mullen burst (ASTM D751-95E1, February 1997)	250 psi
One inch tensile strength (ASTM D882-97, June 10, 1997)	25 lbs. (warp)
Permeability	At least 1 X 10^{-7} cm/sec
Oil resistance (ASTM D471-96, June 10, 1996)	No signs of deterioration and more than 80 % retention of tensile and seam strength after immersion for 30 days at 73 °F

Long-term storage of oil field wastes (more than 180 days)

Cold crack (ASTM D2136-94, September 15, 1994)	-60 °F
Black carbon content (ASTM D1603-94, June 15, 1994)	2 % or greater
Carbon dispersion (ASTM D3015-95, September 10, 1995)	A-2 range
Tensile strength (ASTM D751-95E1, February 1997)	300 lbs (warp)
Mullen burst (ASTM D751-95E1, February 1997)	500 psi
One inch tensile strength (ASTM D882-97, June 10, 1997)	45 lbs. (warp)
Permeability	At least 10^{-7}
Oil resistance (ASTM D471-96, June 10, 1996)	No signs of deterioration and more than 80 % retention of tensile and seam strength after immersion for 30 days at 73 °F

The American Society for Testing and Materials (ASTM) methods may be obtained from the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pennsylvania 19103.

(b) All materials used for lining pits must be resistant to hydrocarbons, salts, and acidic and alkaline solutions. The liners will also be resistant to ultraviolet light or provision must be made to protect the material from the sun. Liner compatibility will comply with EPA Method 1990, *Compatibility Test for Wastes and Membrane Liners.*

(c) The bed of the pit and inside grade of the berm will be smooth and compacted, free of holes, rocks, stumps, clods, or any other debris that may rupture the liner. In rocky areas, it may be necessary to cover the pit bed with a compacted six-inch layer of sand or other suitable materials.

(d) A trench will be excavated on the top of the pit berm around the entire perimeter of the pit for the purpose of anchoring flexible liners. This trench will be located at least nine inches (9") from the slope break and will be at least twelve inches (12") deep. See Figure 3.

(e) The liner will rest smoothly on the pit bed and the inner face of the berms, and must be of sufficient size to extend down to the bottom of the anchor trench and come back out a minimum of two inches (2") from the trench on the side furthest from the pit. See Figure 3. In locations where temperature variations are significant, wrinkles or folds must be placed at each corner of the pit to allow for the contraction and expansion of the membrane due to temperature variations. The membrane manufacturer should be consulted on this matter.

(f) An anchor of used pipe or other similar material will be placed over the liner in the anchor trench and the trench back-filled.

(g) Certain conditions require the venting of gas that may accumulate beneath a liner. If organic matter exists in the soils under the liner, or if natural gas is present in the region, gas production is likely. When a fluctuating water table is present immediately below the pit bottom, pockets of air may also accumulate below the liner. The net result of gas or air accumulation below the liner may be the "floating" of the liner to the pit surface. Two possible vent designs are illustrated in Figure 4. A uniform layer of sand (which less than 5% will pass the 200 sieve) or a geotextile beneath the liners will allow the accumulated gas to vent. To achieve the best results from either of these media, the slope from the lowest point of the pit to the toe of the dike must be at least 2%. The venting medium is carried across the entire bottom and up the side slopes. Vents will be located approximately one foot (1') down from the crown of the dike. (See Figure 3)

(h) If the lining material used for the primary liner is not sun-resistant, at least one inch (1") of sand or other suitable material must be spread uniformly to cover the liner over the floor of the pit. Gravel or other wave-resistant material with sufficient angle of repose to remain in place will be used to cover the sloping inner wall of the berm. A geotextile liner must be placed beneath any gravel layer to provide protection for the membrane liner. Any gravel or sand layers used to protect the membrane liner from the sun will extend to the anchor trench.

(i) Placement of any sand or gravel layers on top of a membrane liner will be done in such a manner that the liner is not torn.

(j) At any point of discharge into the pit, the discharge will be directed away from the liner and the liner must be protected from the fluid force of discharges.

E. BELOW-GRADE TANKS

1. The tank will be of sufficient capacity to contain all intended fluids and wastes during periods of inclement weather when it is not possible to drain the tank on a regular schedule.

2. Tanks must be constructed of materials resistant to the particular contents of the tank. If fiber reinforced plastic tanks are used, the material must be resistant to sunlight and the tank's design must allow for expansion and contraction due to wide temperature shifts. If ferrous tanks are used, protective coatings or cathodic protection will be used to inhibit corrosion. The plans and specifications submitted for approval will include the type of material selected and its thickness.

3. The surface upon which the tank system rests must be level and free of rocks to prevent puncturing, cracking, or indentation of the liner or tank bottom.

4. All below grade tanks must have a leak detection system consisting of a double wall system with a mechanism for determining leaks, or a drainage and sump system. Drainage and sump systems will be constructed as follows:

   (a) First, place a synthetic impermeable liner at least 40 mils thick upon a smooth soil surface that will support the tank with the liner extending above the ground surface.

(b) Place a slotted or perforated drainage pipe (lateral) on the impermeable layer with the drainage pipe sloped at least one inch per 10 feet towards the sump. The drainage pipe will be at least one inch in diameter.

(c) Cover the drainage pipe with sand, gravel, or other material with sufficient permeability to convey fluids to the drainage pipe.

(d) Place the tank on this surface and connect a riser pipe (sump) to the drainage pipe. The riser pipe will be at least 2 inches in diameter.

(e) Strap the secondary liner to the tank above the ground surface in a manner to prevent rainwater from entering the space between the tank and liner.

5. Avoid placing tanks within ground water. If a tank is placed within ground water, the tank system will be placed in a one (1) foot thick concrete vault. The vault will be maintained in a dry condition at all times.

6. For tanks located below the ground surface in an open pit, no secondary containment is required. The tank will rest on a gravel pad at least one-inch thick, and the sides of the tank will be exposed to visually detect leaks. Such tanks may be placed upon I-Beams to facilitate inspection of the tank bottom.

F. LEAK DETECTION SYSTEM

1. Leak detection systems may consist of fail-safe electric detection systems or drainage and sump systems. Alternative systems may be proposed to the OCD.

2. If an electric grid detection system is used, provision must be made for adequately testing all components to ensure the system remains functional.

3. If a drainage and sump system is used, a network of slotted or perforated drainage pipes will be installed between the primary and secondary liners. The network must be of sufficient density so that no point in the pit bed is more than twenty feet (20') from such drainage pipe or lateral thereof. The material placed between the pipes and laterals must be sufficiently permeable to allow transport of the fluids to the drainage pipe. The slope for all drainage lines and laterals will be at least 12 inches (12") per hundred feet (100'). The slope of the pit bed must also conform to these values to assure fluid flow towards the leak detection system. The drainage pipe will convey liquids to a corrosion-proof sump located outside the perimeter of the pit (see Figure 2).

G. SKIMMER TANKS

"A skimmer tank may be used to separate oil from water prior to discharge of water into a pit. No measurable or visible layer of oil shall accumulate or remain anywhere on the surface of any pit." OCD Rule 50

H. FENCES, SIGNS AND NETTING

1. A fence will be constructed and maintained in good condition around the pit perimeter. Adequate space will be provided between the fence and berms for passage of maintenance vehicles. The fences will be constructed so as to prevent livestock from entering the pit area. Fences will not be constructed on berms. Active drilling or workover pits may have a portion of the pit unfenced to facilitate operations.

2. A sign not less than 12" x 24" with lettering of not less than two inches (2") will be posted in a conspicuous place on the fence surrounding the pit. The sign will be maintained in legible condition and must identify the operator of the pits, the location of the facility by quarter-quarter section <u>or unit letter</u>, township, and range, and provide emergency telephone numbers. If the pit is on a well location, the well sign required will suffice for this requirement.

OK Done

3. To protect migratory birds, all tanks exceeding 16 feet in diameter, and exposed pits and ponds must be screened, netted or covered. Upon written application by the operator, an exception to screening, netting or covering of a facility may be granted by the district supervisor upon a showing that an alternative method will protect migratory birds or that the facility is not hazardous to migratory birds. Drilling and workover pits are exempt from this netting requirement, if any visible or measurable layer of oil present is removed from the surface immediately after cessation of operations.

I. NOTIFICATION

At least twenty-four hours prior to installing liners or leak detection systems, the responsible party will notify the OCD District Office so that an inspection can be scheduled. The operator will take photographs of the installation and retain such records for OCD inspection if required. <u>Notification is not required by the rule. Notification of the installations of single liners with photographic documentation is not necessary. All previous references to notification dealt only with the installation of the secondary liner associated with leak detection systems.</u>

Already done

III. OPERATION AND MAINTENANCE OF BELOW-GRADE TANKS AND DISPOSAL AND STORAGE PITS

A. Leak detection sumps will be inspected at least once every thirty (30) days. The proposed frequency will be included with the plans and specifications submitted for approval.

B. The operator will report the detection of fluid within the leak detection sump to the appropriate OCD District Office within 24 hours of discovery. The operator will obtain a sample of the fluid, and have the sample analyzed for major cations/anions, benzene, toluene, ethylbenzene, total xylenes (BTEX), and any other potential water contaminant within the pit or below-grade tank. A copy of the analysis will be sent to the appropriate OCD District Office. An analysis of the fluids in the tank may be required for comparison with the above analysis. If the presence of fluid in the leak detection system is due to a tank leak, the contingency plan will be implemented.

C. The operator will prepare and maintain a contingency plan outlining the procedure for repairing the pit liner or tank in an expeditious manner in the event of a leak. It must describe how the operator proposes to guard against such accidents and detect them when they have occurred. The contingency plan also must describe the steps proposed to contain and remove the spilled substance or mitigate the damage caused by the discharge such that ground water is protected, or movement into surface waters is prevented.

IV. CLOSURE PROCEDURES

Prior to commencing closure of a storage, disposal or emergency pit, or below-grade tank, a closure plan must be submitted to and approved by OCD on OCD Form C-144. It should be noted here that this requirement does not include Drilling, workover, and production pits. All of the documents required as attachments to the form must be submitted at this time. If a number of pits or below-grade tanks are to be closed by a single company, the company may submit one general plan stating the areas and types of facilities to be closed, along with the procedures to be used during closure. Deviations from approved plans require OCD notification and approval.

Already changed
Does include drilling & workover & production

Procedures may deviate from the following guidelines if it can be shown that the proposed procedure will remove or isolate contaminants in such a manner that fresh waters, public health and the environment will not be impacted by remaining contaminants. Specific constituents and/or requirements for soil analysis and/or remediation may vary depending on site-specific conditions.

At a minimum, a closure plan will include the following elements:

1. Locations of all pits and below-grade tanks to be closed.

2. Procedures that will be used to assess the extent of contamination.

3. Procedures to be used to manage, remediate, or dispose of contaminated soil and wastes.

4. Schedules for submission of closure reports on each pit or below-grade tank.

V. CLOSURE SITE ASSESSMENT

Prior to final closure, the party responsible for a pit or below-grade tank will perform an assessment to evaluate the extent to which soils and/or ground water may have been impacted by its operation. Assessment results will form the basis of any required remediation. The sites will be assessed for the severity of contamination and potential environmental and public health threats using the risk based ranking system described in sections V and VI. If encapsulation and on-site burial is anticipated, the liner must be repaired, if necessary, prior to this activity.

The following characteristics must be determined in order to evaluate potential risks at a site, the need for remedial action and, if necessary, the level of cleanup required at the site:

A. GENERAL SITE CHARACTERISTICS

1. Depth To Ground Water

The operator must determine the depth to ground water to the extent of the ranking criteria in VI.A.2.a at each site. The depth to ground water is defined as the vertical distance from the lowermost contaminants to the seasonal high water elevation of the ground water. If the exact depth to ground water is unknown, the ground water depth can be estimated using either local water well information, published regional ground water information, data on file with the New Mexico State Engineer Office or the vertical distance from adjacent ground water or surface water. ?

2. Wellhead Protection Area

The operator must determine the horizontal distance to the extent of the ranking criteria in VI.A.2.a to all private, domestic fresh water wells or springs used by less than five households for domestic or stock watering purposes, and all other fresh water wells and springs.

already done radius

3. Distance To Nearest Surface Water Body

The operator must determine the horizontal distance to the extent of the ranking criteria in VI.A.2.a to all wetlands, playas, irrigation canals, ditches, and perennial and ephemeral watercourses.

already done radius

B. SOIL/WASTE CHARACTERISTICS

Soils/wastes within and beneath the pit or below-grade tank will be evaluated to determine the type and extent of contamination at the site. In order to assess the level of contamination at the pit or below-grade tank, observations will be made of the soils/wastes within the pit or below-grade tank and a sample of the potentially impacted soils will be taken from the interval at least 3 feet into the undisturbed native soils beneath the bottom of the pit or below-grade tank. Additional samples may be required to determine the vertical and horizontal extent of contamination. Samples will be obtained according to the sampling procedures in Section VII. This may be accomplished using a backhoe, drill rig, hand auger, shovel or other means. This requirement is not sensible and should not apply to drilling, workover, and completions pits. Penetrating the bottom of a drilling or workover pit, whether lined with natural soils or a synthetic liner, to capture a soil sample will lead to breaching the protection that the liner provides.

see 3(a) already exempt

The pit rule states under Section F. entitled "Closure and Restoration" that the pit or below grade tank shall be properly closed. Given that this pit and below grade tank rule addresses both disposal and storage pits (i.e. long term storage pits) and temporary drilling, workover, and completion pits (i.e., short term storage pits) it is incumbent upon OCD to properly define proper closure for these two categories on a scientifically defensible basis. Nowhere in the pit and below grade tank rule does it suggest, imply, specify, or require that testing of wastes is required or necessary to properly close a pit or a below grade tank. Hence, OCD has arbitrarily bypassed rulemaking by requiring the testing of wastes as part of a closure process and provided no scientific basis to justify this requirement.

If regulation of waste is deemed necessary and appropriate by the OCD, then a separate and formal rulemaking process should take place to:

i. set standards for allowing in place burial;
ii. set standards for land application;
iii. require testing in accordance with a formal protocol; and
iv. establish a formal process for waste tracking.

Such a rulemaking process was not undertaken. Instead, OCD has arbitrarily bypassed rulemaking by setting waste testing requirements under the Pit and Below Grade Tank Guidelines.

OCD representatives told NMOGA during several of the public meetings that the waste testing requirement was necessary to meet the terms of rule which states "Where the pit's contents will likely migrate and cause ground water or surface water to exceed water quality control commission standards, the pit's contents and the liner shall be removed and disposed of in a manner approved by the division. NMOGA takes extreme exception to that logic and statement. The "likelihood of migration" to surface and ground water is NOT based upon mineral or chemical content but is related to soil types and density, liner permeability, precipitation and rainfall, design of the pit, and other mechanical factors. NMOGA asks OCD how one would prove the "likelihood of migration" to groundwater or surface water if the drilling or workover pit contained element X based solely on a waste test. The fact is the obligation to test wastes, as specified in the guidelines, is an arbitrary requirement that provides no meaningful basis on how to "properly close the pit" as the rule requires.

Initial assessment of soil/waste contaminant levels in a pit or below grade tank is not required if an operator proposes to determine the final soil contaminant concentrations after a soil removal or remediation pursuant to section VIII.A.

Pits and below-grade tanks with secondary containment and leak detection that never had instances of fluid in the leak detection systems, and lined drilling and reserve pits do not need to have soil samples taken from undisturbed soils underlying the pit. However, waste samples will be taken and analyzed from any remaining waste materials if the contents are proposed to remain in place or be encapsulated in order to assess the potential for future migration of remaining contaminants. Waste sampling is not required by the rule. MSDS sheets are available for the components used in the drilling fluids. This process knowledge should be adequate to identify any waste. Any analytical sampling that does occurs should remain the private and confidential property of the company until it has been determined that migration has occurred.

Varying degrees of contamination may co-exist at an individual site. The following sections describe the degrees of contamination that must be documented during the assessment of the level of soil contamination:

1. **Highly Contaminated/Saturated Soils**

   Highly contaminated/saturated soils are defined as those soils containing a free liquid hydrocarbon phase or exhibiting gross staining.

2. **Unsaturated Contaminated Soils**

   Unsaturated contaminated soils are those soils which are not highly contaminated or saturated, as described above, but contain measurable concentrations of benzene, toluene, ethylbenzene and xylenes (BTEX) and total petroleum hydrocarbons (TPH), chloride or other waste specific constituents. Sampling and analytical methods for determining contaminant concentrations are described in detail in Section VII.

   (NOTE: The above definitions apply only to oilfield contaminated soils

which are exempt from federal RCRA Subtitle C hazardous waste provisions. Pits or below-grade tanks receiving non-exempt wastes are subject to evaluation for RCRA hazardous waste characteristics.)

C. GROUND WATER QUALITY

If ground water is encountered during the soil/waste characterization of underlying impacted soils, a monitor well will be installed directly adjacent and downgradient of the pit. After developing the well, a ground water sample will be obtained to assess potential impacts on ground water quality. Monitor well installation, development and sampling will be conducted using the procedures in Section VII.C. The installation of a monitor well is not required if the OCD approves of an alternate ground water investigation and sampling technique.

If there is a reasonable probability of ground water contamination from any pit or below-grade based upon the level of contaminants in the soils directly beneath the pit or below-grade tank, or the extent of soil contamination defined during remedial activities, monitor wells may be required to assess potential impacts on ground water.

If ground water contamination is discovered during investigation or remedial actions, the operator or responsible person must report the incident to the OCD pursuant to 19.15.3.116 NMAC.

VI. SOIL AND WATER REMEDIATION LEVELS

A. SOILS

Soils will be remediated to the criteria set out below. The OCD retains the right to require remediation to more stringent levels than those proposed below if warranted by site-specific conditions (i.e. native soil type, location relative to population centers and future use of the site or other appropriate site specific conditions.)

1. Highly Contaminated/Saturated Soils

These soils may be remediated insitu or excavated to the maximum extent practicable and remediated using techniques described in Section VIII.A.

2. Unsaturated Contaminated Soils

The general site characteristics obtained during the site assessment (Section V.A.) will be used to determine the appropriate soil remediation levels using a risk-based approach. Soils must be scored according to the ranking criteria below to determine their relative threat to public health, fresh waters and the environment.

(a) Ranking Criteria

Depth To Ground Water	Ranking Score
<50 feet	20
50 - 100	10
>100	0

Wellhead Protection Area	
<200 feet from a private domestic fresh water well or spring, or;	
<1000 feet from any other fresh water well or spring	
Yes	20
No	0

Distance To Surface Water Body	
<200 horizontal feet	20
200 - 1000 horizontal feet	10
>1000 horizontal feet	0

(b) Hydrocarbon Remediation Levels

The total ranking score determines the level of remediation for hydrocarbon constituents that may be required at any given site. The total ranking score is the sum of all three individual ranking criteria listed in Section VI.A.2.(a) The table below lists the remediation level for hydrocarbon constituents that may be required for the appropriate total ranking score. Soils that contain hydrocarbon contaminants above the recommended remediation levels may be remediated insitu or excavated to the maximum extent practicable and remediated using techniques described in Section VIII.A

	Total Ranking Score		
	>19	10 - 19	0 - 9
Benzene(ppm)*	10	10	10
BTEX(ppm)*	50	50	50
TPH(ppm)**	100	1000	5000

* A field soil vapor headspace measurement (Section VII.B.1) of 100 ppm may be substituted for a laboratory analysis of the Benzene and BTEX concentration limits.

** The contaminant concentration for TPH is the concentration above natural background levels.

(c) Remediation Levels For Non-Hydrocarbon Contaminants

Soils contaminated by chlorides will be remediated to 250 mg/kg, or remediated such that remaining chlorides in the soil will not with reasonable probability contaminate ground water or surface water in excess of the standards in 19.15.1.19.B.(2) NMAC and 19.15.1.B.(3) NMAC through leaching, percolation, or other transport mechanisms, or as the water table elevation fluctuates; or pose a threat to human health or the environment.

Soils contaminated with any other non-hydrocarbon contaminants will be remediated such that remaining contaminants in the soil will not with reasonable probability contaminate ground water or surface water in excess of the standards in 19.15.1.19.B.(2) NMAC and 19.15.1.B.(3) NMAC through leaching, percolation, or other transport mechanisms, or as the water table elevation fluctuates; or pose a threat to human health or the environment.

(d) Risk-Based Plans for Remediation

The stipulations of these standards do not preclude the presentation and possible acceptance of a risk-based remediation plan for a specific site.

B. GROUND WATER

Contaminated ground water is fresh ground water that contains free phase products, measurable concentrations of dissolved phase volatile organic constituents or other dissolved constituents in excess of the natural background water quality. Ground water contaminated in excess of the New Mexico Water Quality Control Commission (WQCC) ground water standards will be remediated according to an abatement plan pursuant to 19.15.1.19 NMAC

VII. SOIL AND WATER SAMPLING PROCEDURES

Below are the sampling procedures for soil and ground water contaminant investigations of pits and below-grade tanks that have received RCRA Subtitle C exempt oil field exploration and production wastes. Pits and below-grade tanks that have received non-exempt RCRA wastes are required to be tested to demonstrate that the wastes are not characteristically hazardous.

A. HIGHLY CONTAMINATED OR SATURATED SOILS

A soil is determined to be highly contaminated or saturated based upon physical observations. A representative sample of the soil should be studied for observable free phase hydrocarbons or immiscible phases and gross staining. The immiscible phase may range from free hydrocarbons to a sheen on any associated aqueous phase. A soil exhibiting any of these characteristics is considered highly contaminated or saturated.

B. UNSATURATED CONTAMINATED SOILS

The following methods will be used for determining the magnitude of contamination in unsaturated soils:

1. Soil Sampling Procedures for Hydrocarbon Headspace Analysis

A headspace analysis may be used to determine the total volatile organic vapor concentrations in soils (i.e. in lieu of a laboratory analysis for benzene and BTEX but not in lieu of a TPH analysis). Headspace analysis procedures will be conducted according to the procedures below. Samples taken for headspace analysis cannot be subsequently used for laboratory analysis.

(a) Fill a 0.5 liter or larger jar half full of sample and seal the top tightly with aluminum foil or fill a one quart zip-lock bag one-half full of sample and seal the top of the bag leaving the remainder of the bag filled with air.

(b) Ensure that the sample temperature is between 15 to 25 degrees Celsius (59-77 degrees Fahrenheit).

(c) Shake the sample jar vigorously for 1 minute or gently massage the contents of the bag to break up soil clods and allow aromatic hydrocarbon vapors to develop within the headspace of the sample jar or bag for 5 to 10 minutes.

(d) If using a jar, pierce the aluminum foil seal with the probe of either a PID or FID organic vapor meter (OVM), and then record the highest (peak) measurement. If using a bag, carefully open one end of the bag and insert the probe of the OVM into the bag and re-seal the bag around the probe as much as possible to prevent vapors from escaping. Record the peak measurement. The OVM must be calibrated to assume a benzene response factor.

2. Field Soil Sampling/Screening

Field screening of contaminants during excavation of unsaturated contaminated soils may be conducted using industry-accepted procedures. However, all final samples obtained to verify that the appropriate contaminant specific remediation level has been met will be analyzed at a laboratory using EPA approved methods and quality assurance/quality control procedures.

3. Soil Sampling Procedures For Laboratory Analysis

(a) Sampling Procedures

Soil sampling for laboratory analysis will be conducted according to EPA approved methods.

(b) Analytical Methods

All soil samples must be analyzed using EPA methods and must be analyzed within the holding time specified by the method. Below are some common laboratory analytical methods for analysis of soil samples. Analyses for constituents other than those listed below may be required if the impoundment has been used for anything other than hydrocarbon based fluids or produced water.

(i) Benzene, toluene, ethylbenzene and xylene

- EPA Method 8021

(ii) Total Petroleum Hydrocarbons

- EPA Method 418.1, or;
- EPA Method Modified 8015

(iii) Chloride

- EPA Method 300

C. MONITOR WELL INSTALLATION, DEVELOPMENT AND GROUND WATER SAMPLING

If an assessment of a potential impact to ground water quality is deemed necessary, it will be conducted according to EPA approved protocol. The following methods are standard OCD accepted methods used to sample and analyze ground water at RCRA exempt sites.

1. Monitor Well Installation/Location

One monitor well will be installed adjacent to and hydrologically down-gradient from the pit or below-grade tank to determine if fresh water has been impacted by the disposal activities. Additional monitor wells, located up-gradient and down-gradient of the pit or below-grade tank, may be required to determine potential impacts on ground water.

2. Monitor Well Construction

(a) Monitor well construction materials will be:

(i) selected according to industry standards;

(ii) chemically resistant to the contaminants to be monitored; and

(iii) installed without the use of glues or adhesives.

(b) Monitor wells will be constructed as follows:

(i) Place at least 15 feet of well screen across the water table interface with at least 5 feet of well screen above the water table and 10 feet of well screen below the water table.

(ii) Set an appropriately sized gravel pack in the annulus around the well screen from the bottom of the hole up to 2-3 feet above the top of the well screen.

(iii) Place a 2-3 foot bentonite plug above the gravel pack.

(iv) Grout the remainder of the hole to the surface with a cement grout containing 3-5% bentonite.

(v) Place a concrete pad and locking well cover around the well casing at the surface.

3. **Monitor Well Development**

When ground water is collected for analysis from monitoring wells, the wells will be developed prior to sampling. The objective of monitor well development is to repair damage done to the formation by the drilling operation so that the natural hydraulic properties of the formation are restored and to remove any fluids introduced into the formation that could compromise the integrity of the sample. Monitoring well development is accomplished by purging fluid from the well until the pH and specific conductivity have stabilized and turbidity has been reduced to the lowest level possible.

4. **Sampling Procedures**

Ground water will be sampled no less than 24 hours after the well has been developed. Samples will be obtained according to EPA accepted protocol. Samples will be collected in clean containers supplied by the laboratory that will conduct the analysis or from a reliable laboratory equipment supplier. Samples for different analyses require specific types of containers. The laboratory can provide information on the types of containers and preservatives required for sample collection. Below are standard OCD accepted sampling procedures:

(a) Monitor wells will be purged of a minimum of three well volumes (or as much as is practicable) of ground water using a clean bailer or pump prior to sampling to ensure that the sample represents the quality of the ground water in the formation and not stagnant water in the well bore.

(b) Samples will be collected in appropriate sample containers containing the appropriate preservative for the analysis required. No bubbles or headspace will remain in the sample containers obtained for benzene toluene, ethylbenzene and xylene analysis.

(c) Label the sample containers with a unique code for each sample.

(d) Cool and store samples with cold packs or on ice.

(e) Promptly ship sample for analysis using chain of custody procedures.

(f) All samples must be analyzed within the holding times for the laboratory analytical method specified by EPA.

5. **Ground Water Laboratory Analysis**

Samples will be analyzed for potential ground water contaminants contained in the waste stream, as defined by the New Mexico Water Quality Control Commission (WQCC). All ground water samples must be analyzed using EPA methods and must be analyzed within the holding time specified by the method. Below are common laboratory analytical methods for analysis of ground water samples analyzed for hydrocarbon and produced water related constituents. Additional analyses may be required if the impoundment has contained anything other than hydrocarbon fluids or produced water.

(a) <u>Analytical Methods</u>

(i.) Benzene, Toluene, Ethylbenzene and Xylene

- EPA Method 8021

(ii.) Total Dissolved Solids and Major Cations and Anions

- Various EPA or standard methods

(iii.) Heavy Metals

- ICAP EPA method 6010

(iv.) Polynuclear Aromatic Hydrocarbons

- EPA Method 8270

VIII. REMEDIATION

The following discussion summarizes alternatives for remediation of contaminated soil and ground water as defined in Section VI. All procedures used are to be approved by OCD prior to commencement of remediation activities. Separate OCD-approval for remediation is not required if the OCD has approved a general closure plan which includes the site remediation technique for any particular site. All procedures that deviate from the general closure plan, however, must be approved by OCD prior to commencement of remediation activities.

The OCD may consider a risk evaluation that demonstrates that remaining contaminants will not pose a threat to present or foreseeable beneficial use of fresh waters, public health and the environment.

A. RESIDUAL WASTE/SOIL MANAGEMENT AND REMEDIATION

RCRA exempt or RCRA nonhazardous oil and natural gas related residual waste and contaminated soil will be remediated and managed according to the criteria described below or by other OCD approved procedures which will remove, treat, or isolate contaminants in order to protect fresh waters, public health and the environment.

1. **Residual Wastes**

Residual wastes remaining in any pit or below-grade tank will be handled in the following manner:

(a) Remaining liquids will be removed from the pit or below-grade tank; and

(b) Remaining solid wastes will be removed from the pit or below-grade tank, except for dried mud and cuttings in drilling and reserve pits which have been approved by the OCD for encapsulation under Section VIII.A.3.(a).

2. **Contaminated Soils**

Highly contaminated/saturated soils and unsaturated contaminated soils exceeding the remediation levels in Section VI.A. will be either:

(a) excavated from the ground until a representative sample from the walls and bottom of the excavation is below the contaminant specific remediation level listed in Section VI.A. or an alternate OCD approved remediation level; or

(b) excavated to the maximum depth and horizontal extent practicable. Upon reaching this limit a sample will be taken from the walls and bottom of the excavation to determine the remaining levels of soil contaminants; or

(c) treated in place, as described in Section VIII.A.3(b)(ii), until a representative sample is below the contaminant specific remediation level listed in Section VI.A., or an alternate OCD approved remediation level.

3. **Soil and Waste Management Options**

Soil and waste management options must be submitted to and approved by OCD prior to commencement of remediation activities. Following is a list of options for on-site treatment, off-site treatment and disposal of contaminated soils and wastes:

(a) <u>Disposal</u>

(i) Excavated or removed soils and wastes may be disposed of at an off-site OCD-approved facility.

(ii) Excavated soils may be returned to the excavated area if remediated to the recommended remediation levels in Section VI.A.2, or an alternate OCD approved remediation level.

(iii) <u>(These are waste management options for the contents of drilling and work over pits and not forms of remediation. These guidelines need to be place in a different section)</u> Contents of drilling and workover pits drilled or worked over with fresh water may be landspread, if the pit has not contained hydrocarbons, and it can be shown that residual contaminants in the mud and cuttings do not pose a threat to surface water, ground water, human health or the environment.

(iv) <u>(These are waste management options for the contents of drilling and work over pits and not forms of remediation. These guidelines need to be place in a different section)</u> Contents of drilling and workover pits drilled or worked over with fresh water may be encapsulated onsite if it can be shown that residual contaminants in the mud and cuttings do not pose a threat to surface water, ground water, human health or the environment. Encapsulation will be accomplished by folding the edges of the liner over the remaining mud and cuttings and covering the encapsulated wastes with a minimum of 3 feet of clean soil.

(v) <u>(These are waste management options for the contents of drilling and work over pits and not forms of remediation. These guidelines need to be place in a different section)</u> Contents of drilling and workover pits drilled or worked over with salt water <u>(Salt water needs to be defined)</u> may be encapsulated onsite if it can be shown that residual contaminants in the mud and cuttings do not pose a future threat to surface water, ground water, human health or the environment, and the pit bottom is located at least 50 feet above a source of fresh water. Encapsulation will be accomplished by folding the edges of the liner over the remaining mud and cuttings; capping the pit with either a 1-foot thick clay cap compacted to ASTM standards, or a 40 mil <u>(The permeability factor of a 12 or 20 mil synthetic liner is equal to that of a 40 mil liner, and better than a 1-foot clay liner. The degradation of a buried 12, or 20 mil synthetic liner is equal to that of a 40 mil liner. The same protection can be obtained from using a 12 or 20 mil synthetic liner.)</u> minimum thickness synthetic liner meeting ASTM standards that is designed to be resistant to the material encapsulated; and

Done changed language

covering the cap with a minimum of 3 feet of clean soil.

(b) Treatment and Remediation Techniques

(i) Alternate Methods

The OCD encourages alternate methods of soil remediation including, but not limited to, active soil aeration, composting, bioremediation, solidification, and thermal treatment. Use of alternate methods must be approved by OCD prior to implementation.

(ii) Insitu Soil Treatment

Insitu treatment may be accomplished using vapor venting, bioremediation or other OCD approved treatment systems.

(iii) Landfarming

Onetime applications of hydrocarbon contaminated soils may be landfarmed on location by spreading the soil in a six-inch lift within a bermed area. Only soils that do not contain free hydrocarbon liquids can be landfarmed. The soils must be disked regularly to enhance biodegradation of the contaminants. If necessary, upon approval by OCD, moisture and nutrients may be added to the soil to enhance aerobic biodegradation.

Landfarming will not occur within any wetland, watercourse, lakebed, sinkhole, playa lake, ground water sensitive area, or wellhead protection area. Landfarming adjacent to any watercourse, lakebed, or playa lake will be located safely above the ordinary high water mark.

Landfarming sites that will receive soils from more than one location are considered centralized sites and must be permitted pursuant to 19.15.9.711 NMAC prior to operation.

B. GROUND WATER REMEDIATION

Ground water contaminated in excess of WQCC standards requires submission of an "Abatement Plan" pursuant to 19.15.1.19 NMAC. An exception to this requirement exists for sites where ground water is remediated to WQCC standards within 1 year of discovery. In these cases, ground water investigation and remediation plans will be submitted by the responsible person on a case-by-case basis, and reviewed and approved by OCD prior to commencement of activities.

IX. TERMINATION OF REMEDIAL ACTION

Remedial action may be terminated when the criteria described below have been met:

A. SOIL

Contaminated soils requiring remediation will be remediated so that residual contaminant concentrations meet the recommended soil remediation level for a particular site as specified in Section VI.A. Termination of remedial action will be approved by OCD upon a demonstration of completion of remediation as described above.

If soil action levels cannot practicably be attained, an evaluation of risk may be performed and provided to OCD for approval showing that the remaining contaminants will not pose a threat to present or foreseeable beneficial use of fresh water, public health and the environment.

B. GROUND WATER

For cases where ground water is remediated to WQCC standards within one year of discovery, ground water remedial actions may be terminated if 4 successive quarterly sampling events confirm that all recoverable free phase product has been removed, and the concentration of the remaining dissolved phase contaminants in the ground water does not exceed New Mexico WQCC water quality standards or natural background levels. Termination of remedial action will be approved by OCD upon a demonstration of completion of remediation as described in above.

X. FINAL CLOSURE

A. SURFACE RESTORATION

Upon termination of any required soil remedial actions, a pit or below-grade tank will be closed by backfilling and the operator will contour the surface where the pit was located to provide drainage away from the site and successfully re-vegetate the area. While it is understood that lack of re-vegetation is sometimes beyond the control of the operator, a good faith effort must be made. This must include re-seeding and, in the absence of sufficient rainfall, watering at the site to encourage growth. This guideline contradicts the rule in Section F.2. "(2) Surface restoration. Within one year of the completion of closure of a pit, the operator shall contour the surface where the pit was located to prevent erosion and ponding of rainwater." This guideline shall not be used to approve of closure.

already rewritten?

B. MONITOR WELL PLUGGING

If a monitor well was installed to determine impacts upon ground water, the monitor well must be plugged and abandoned by cutting the casing off below ground surface and filling the casing annulus from bottom to top with a cement grout containing 3-5 % bentonite.

XI. CLOSURE REPORTS

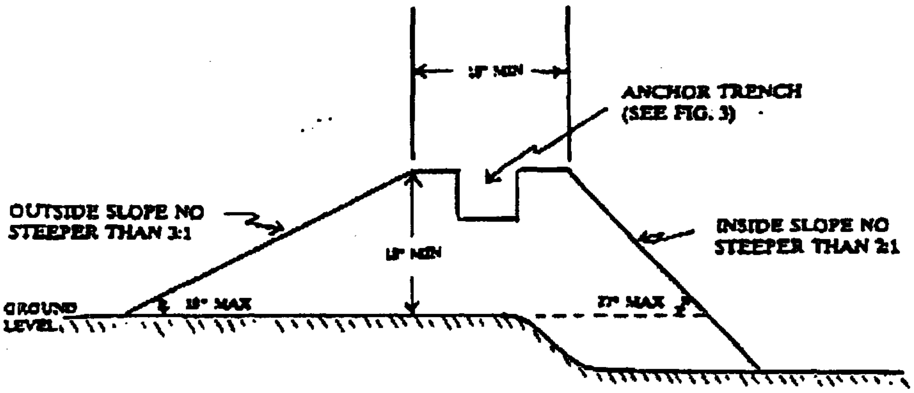
Moved

Closure plans will provide a schedule for reporting the results of all closure activities. The results of all closure activities will be documented by submission of a completed Pit or Below-Grade Tank Registration or Closure on Form C-144, This is contradictory to the rule in Section F.1 "(1) Closure. Except as otherwise specified in Section 50 of 19.15.2 NMAC, a pit or below-grade tank shall be properly closed within six months after cessation of use. As a condition of a permit, the division may require the operator to file a detailed closure plan before closure may commence. The division for good cause shown may grant a six-month extension of time to accomplish closure. Upon completion of closure a closure report (form C- 144), or sundry notices and reports on wells shall be submitted to the division. Where the pit's contents will likely migrate and cause ground water or surface water to exceed water quality control commission standards, the pit's contents and the liner shall be removed and disposed of in a manner approved by the division." A Sundry Notice is approved by the rule for use. It should also be further noted that the Closure Plan shall be a condition of the permit. and be accompanied by all supporting information necessary for the OCD to evaluate the closure actions.

already modified

Part IV Closure Procedures
under I Permitting Procedures

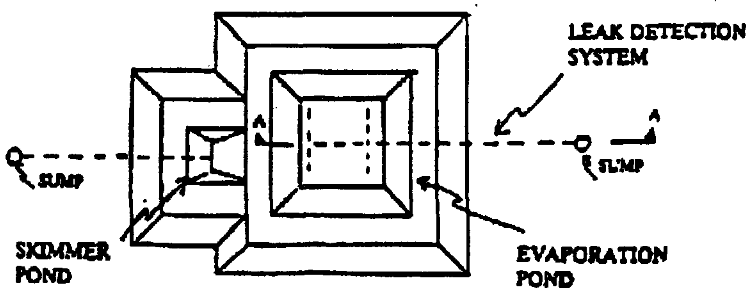
FIGURE 1: PIT CONSTRUCTION



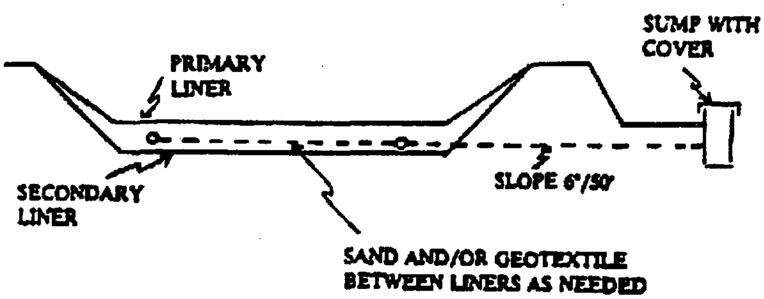
NOTE: LEVEE TO BE CONSTRUCTED IN A MANNER SUCH THAT DESIGN COMPACTION AND DIMENSIONS PROVIDE FOR A MINIMUM SAFETY FACTOR OF TWO FOR FORCES ACTING AGAINST THE LEVEE.

FIGURE 2 - LEAK DETECTION SYSTEM

PLAN



SECTION A-A



NOTE: SKIMMER POND TO HAVE SEPARATE LEAK DETECTION SYSTEM AND SUMP.

FIGURE 3 - ANCHOR TRENCH

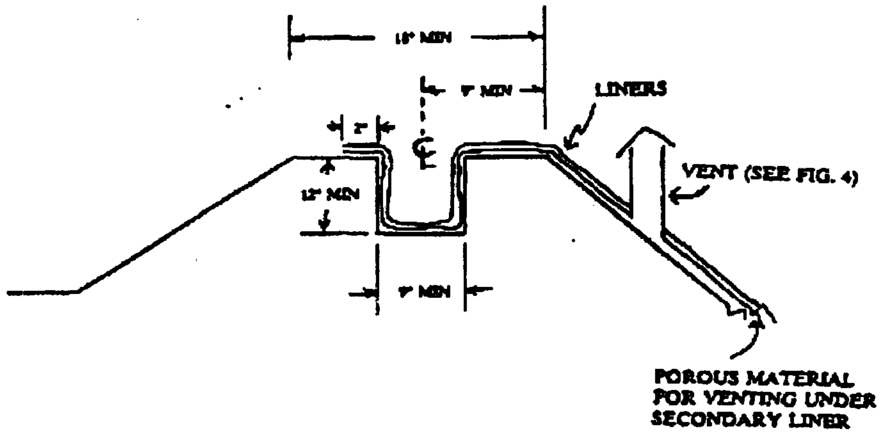
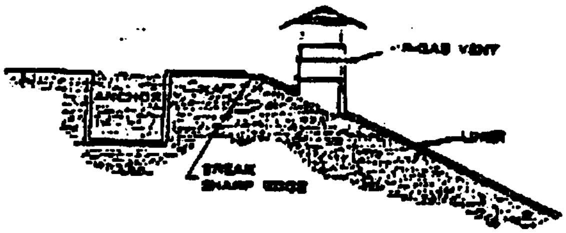
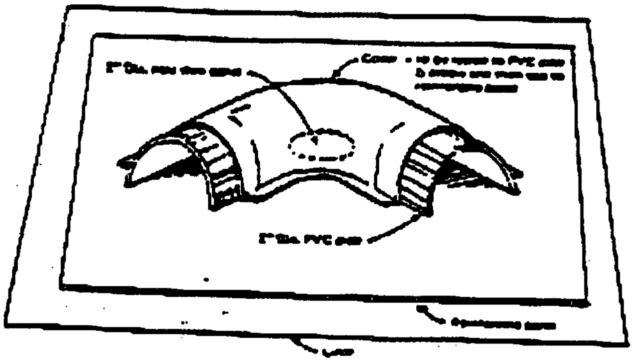


FIGURE 4 - VENT DESIGNS

SOURCE: EPA REPORT #SW-870, "LINING OF WASTE IMPOUNDMENT FACILITIES", PG. 260





Fax Recieved
3/31/04

Attn: Wayne Price
476-3462

Dear Wayne,

Could you fax me the Exact answers, per OCD rules and regulations, to these questions!

1. When does the 6 month closure period for pits start?
   A. When well is drilled to bottom hole depth.
   B. When well is completed and producing, or abandoned. (dry hole)

2. Is it legal or illegal for an oil company that is drilling a well and starts making more water than the pits can hold, to haul that extra water to another pit, at a ~~~~ well, that has been completed, (or abandoned) and put it in the pits at the completed, or abandoned well?

   If it is illegal to do so, what other alternatives, legally does the oil company have to dispose of this extra water?

A. Haul to injection well
B. Enlarge existing pits (
C. ?

This happened at Otero Mesa and has happend recently here where water sand starts at 18', of oil acti hand dug wells are within 1.5 mi.) water wells are pumping from 29' — 45', and there are fresh water seeps in salt lakes

If you need more detail and facts feel free to call or fax questions.

3986547 Home
369-5515 Mob
398-6549 Fax

Meeting was a bit more down to the real world than Santa Fe All, and I am absolutely convinced of this, facts lead to closed systems, cost is only thing holding it up and there is a large discrepancy between the high figures and low figures. High figures, 33% increase in cost of drilling well, low figures 2-3% increase in cost of drilling a well.

I think this cost deal needs to be pinned down as some people tend to exaggerate.

Paul [illegible] [illegible]

Haven't recieved anything from you on Penroc Either?

[illegible]

NEW MEXICO ENERGY, MINERALS and NATURAL RESOURCES DEPARTMENT

BILL RICHARDSON
Governor

Joanna Prukop
Cabinet Secretary
Acting Director
Oil Conservation Division

May 14, 2004

Mr. Carl Johnson
Box 917
Tatum, NM 88267

RE: INFORMATION REQUEST ON PIT RULES

Dear Mr. Johnson:

The New Mexico Oil Conservation Division (OCD) has reviewed your correspondence that was faxed to the OCD on March 31, 2004. This document requests a written response to several questions related to oilfield pits and the application of the new pit rule. Below you will find the OCD's response to your request.

1. When does the 6 month closure period for pits start?

19.15.2.50.F(1) NMAC states that "a pit or below-grade tank shall be properly closed within six months after cessation of use." This section of the rules also states "the division for good cause shown may grant a six-month extension of time to accomplish closure." The initial six-month time frame for achieving closure would start at the time that the pit is no longer used for drilling or completion activities related to the construction of an oil or gas well. If the well is plugged and abandoned (P&A), the six month time frame for achieving closure would start at the time that the pit is no longer used for activities related to the P&A of an oil or gas well. The above time frames would not apply if the operator has been issued a permit to convert the pit to a disposal or storage pit in accordance with the provisions of 19.15.2.50 NMAC.

2. Is it legal or illegal for an oil company that is drilling a well and starts making more water than the pits can hold, to haul that extra water to another pit at a well that has been completed or abandoned and put it in the pits at the completed or abandoned well?

The rules do not prohibit movement of water produced from one well to a pit at another site. However, according to 19.15.2.50.A. NMAC, discharge into or construction of, any pit or below-grade tank is prohibited absent possession of a permit issued by the OCD, unless an exemption is granted by the OCD. Therefore, any pit that receives waters must be permitted by the OCD. In addition, pits used for disposal or storage of wastes in pits at facilities that receive wastes from more than one well for disposal or storage purposes are not exempt from the permitting requirements of 19.15.9.711 NMAC and may need to be permitted as a centralized facility.

3. What other alternatives legally does the oil company have to dispose of the extra water.

Operators are responsible for the proper disposal of wastes that they generate. According to 19.15.1.13.B NMAC, "all operators, contractors, drillers, carriers, gas distributors, service companies, pipe pulling and salvaging contractors, treating plant operators or other persons shall at all times conduct their operations in or related to the drilling, equipping, operating, producing, plugging and abandonment of oil, gas, injection, disposal, and storage wells or other facilities in a manner that will prevent waste of oil and gas, the contamination of fresh waters and shall not wastefully utilize oil or gas, or allow either to leak or escape from a natural reservoir, or from wells, tanks, containers, pipe or other storage, conduit or operating equipment." Typically, waters produced during drilling are disposed of at a permitted injection well, permitted commercial or centralized disposal facility or are evaporated onsite in the drilling pit.

If you have any questions or require more specific information, please contact at (505) 476-3490.

Sincerely,

Will C. Olson

William C. Olson
Hydrologist
Environmental Bureau

Armstrong
ENERGY CORPORATION

500 NORTH MAIN STREET. SUITE 1000
P. O. BOX 1973
ROSWELL, NEW MEXICO 88202-1973
505/625-2222
FAX 505 622-2512

RECEIVED

APR 15 2004

OIL CONSERVATION
DIVISION

April 12, 2004

New Mexico Oil Conservation Division
1220 St. Francis Drive
Santa Fe, New Mexico 87505

Attention: Mr. Bill Olson, Hydrogeologist

Re: Draft Pit and Below Grade Tank Guidelines

Dear Mr. Olson:

I have had the opportunity to review the draft guidance document entitled "Pit and Below Grade Tank Guidelines". I have also reviewed the comments provided to the OCD by the New Mexico Oil and Gas Association (NMOGA).

I am in complete agreement with the comments of NMOGA and would ask that you consider those comments as my company's position as well.

I am also concerned that the comment period is very abbreviated and that further time for participative process would provide for a better policy.

I appreciate the opportunity to submit these comments.

Sincerely,

ARMSTRONG ENERGY CORPORATION

By: ______________________
Robert G. Armstrong, President

RGA/jb

FASKEN OIL AND RANCH, LTD.

303 WEST WALL AVENUE, SUITE 1800
MIDLAND, TEXAS 79701-5116

(432) 687-1777
jimmyc@forl.com

Jimmy D. Carlile
Regulatory Affairs Coordinator

April 8, 2004

Fax received 4/8/04

Mr. William C. Olson
New Mexico Oil Conservation Division
1220 South St. Francis
Santa Fe, NM 87505

Dear Bill,

Re: Comments on Proposed Pit Guidelines

Fasken Oil and Ranch, Ltd. is an active oil and gas operator in Southeast New Mexico with drilling and production operations in both Lea and Eddy Counties. We appreciate the opportunity to comment on the proposed Pit and Below-Grade Tank Guidelines. As both an oil and gas operator and a large ranch owner, Fasken fully understands the multi-use concept of land and fully supports good regulations, based on science, that support our environment. All regulations, irregardless of the industry, must be based on science, not emotion or innuendo or political motives. Our comments on these proposed guidelines follow.

II. B. Drilling and Workover Pits

The requirement for a liner to be at least 12 mils in thickness needs to be removed. There is no evidence that a liner in general use conditions needs to be more than 8 mils. The operator of the well knows the type liner required based on soil conditions and the length of use of a pit. He also knows he has the liability to protect groundwater. Operators should be able to make their own determination, without filing paperwork for an exception, when determining the thickness of a liner. As we discussed at the Hobbs meeting on March 30, 2004, there is no history (with only one or two exceptions) where closed drilling and workover pits have leaked causing a groundwater problem. There are thousands of these type pits throughout the oil fields. We cannot regulate to cover the exception.

And to require a 20 mil liner when the pit is to be buried and encapsulated is even more overkill. A closed drilling or workover pit is not where potential lies to cause groundwater contamination. Just look at the history of our industry.

To require a "cushioning material" should be the operator's decision, not a regulatory burden. Again, look at the history of our industry with drilling and workover pits. Do not regulate to the exception. Filing for an exception is not the way to handle this. The OCD is not staffed to handle all the exceptions this "guideline" will generate.

To require that liners must be protected from the "fluid force of discharges" is unnecessary. See comments above for the history of the integrity of liners in drilling and workover pits.

II. H. Notification

Taking photographs of pits being constructed has no value at all in this process. This needs to be removed.

V. A. General Site Characteristics

As was discussed in the Hobbs meeting, determining wellhead protection areas and distances to nearest surface water bodies needs to be limited to some reasonable distance such as within ¼ mile.

V. B. Soil/Wast Characteristics

How do you suppose we are to get soil samples under a lined pit after the pit is constructed and lined? Cut the liner? Again, look at the history of our industry when dealing with drilling and workover pits. There is no evidence of contamination, therefore, this is extreme overkill and adds nothing but cost to industry while providing no additional environmental protection.

VI. A. 2. (c) Remediation Levels for Non-Hydrocarbon Contaminants

Requiring chlorides to be remediated to 250 mg/kg must be removed from this "guideline". There is strong scientific evidence and study that concludes that 2300 to 2500 mg/kg is an appropriate number to use as a standard. Again, industry must have good regulation based on science. To simply grab a number out of the air is not only onerous, but unfair to all stakeholders.

VIII. B. Groundwater Remediation

Groundwater remediation should always be conducted to achieve the lesser of WQCC standards or background water. There is no reason to remediate to excess.

X. Final Closure

What is successful re-vegetation? If we water and get vegetation established only to see it die in the drought, was that successful? This needs to be better defined and clarified.

As a parting comment, these "guidelines" will greatly increase the workload of the OCD staff in the District Offices. These good people are already stretched too thin and cannot effectively get to all the projects that they should. How can we in good conscience add these unnecessary "guidelines" to their workloads?

Yours truly,

Jimmy D. Carlile

Jimmy D. Carlile
Regulatory Affairs Coordinator

Oil & Gas Accountability Project

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RECEIVED

APR 12 2004

Oil Conservation Division
1220 S. Saint Francis Drive
Santa Fe, NM 87505

April 9, 2004

William Olson
NMOCD
Environmental Bureau
1220 St. Francis Drive
Santa Fe, NM 87505

Re: Comments on March 16 Pit and Below-Grade Tank Guidelines

Dear Mr. Olson,

The Oil & Gas Accountability Project appreciates the opportunity to comment on the draft guidance document titled "PIT AND BELOW-GRADE TANK GUIDELINES", prepared by the OCD. Below, please find OGAP's comments on this draft guidance document.

General Comments

While OGAP appreciates the effort that has gone into developing this guidance document, the document suffers fundamentally from the gaps in the underlying rule, upon which it is based. That rule simply brought pits within the paper permit process of OCD without significantly restricting the use of unlined pits in those areas where the pits are most heavily used. Therefore, there is little evidence, at this point, that the rule or this guidance document will make any practical difference on the ground.

Moreover, the guideline is simply an advisory document with no legally binding authority. This shortcoming is illustrated by two of the open house hearings the Division held on this document. In Artesia, in response to a question asking if the guidelines were legally binding, and the answer being no, many of the industry representatives simply closed their notebooks and got up to leave. In Farmington, in response to industry questions, the Division representative began backtracking on the language of the guideline, weakening what was already a weak document to begin with.

Given the Division's admittedly limited staff and budget, we, therefore, remain quite skeptical that this guidance document represents much of an improvement over current bad industry practice. We hope the Division proves us wrong, but in light of past Division interactions with industry, the proof will be in the Division's actions and not its documents.

Specific Comments

BELOW GRADE TANKS

Item 6 is contrary to the language of the rule that was adopted. The rule stated that, after April 15, 2004, all below grade tanks shall be constructed with secondary containment and leak detection. The guidelines state that tanks in an open pit do not require secondary containment. This language should be changed to reflect the rule's requirement.

FENCES, SIGNS AND NETTING

Item 1 contains language not in the rule that was adopted. The guideline states, "unless permitted by the OCD", a fence shall be constructed and maintained around the facility perimeter. The rule language did not allow for exceptions, requiring for all pits fencing to prevent access and maintenance of that fencing. This exception language in the guideline should therefore be removed.

This part of the guideline also lacks a provision contained in the rule. The rule allowed the division to impose additional fencing requirements for wildlife in particular areas. This language should be added to the guideline.

CLOSURE PROCEDURES

The rule requires that a pit or below-grade tank "shall be properly closed within six months after cessation of use." Nowhere does the guideline mention this closure deadline. Therefore, the guideline should be revised to make clear the six month deadline for closure.

REMEDIATION – SOIL AND WASTE MANAGEMENT OPTIONS

The guideline section on disposal, items (iii), (iv) and (v) allows on site disposal via encapsulation if "residual contaminants in the mud and cuttings do not pose a threat to surface water, ground water, human health or the environment." This language is at odds with the language of the rule, which requires disposal of cuttings "in a manner to prevent the contamination of fresh water and protect public health and the environment". If the cuttings are admittedly contaminated, then how can the Division justify leaving them on-site as being consistent with the requirement to prevent contamination? Leaving a 'toxic burrito' permanently in place would seem to be the essence of contamination, not its prevention. Therefore, the guideline language should be modified in these sections to reflect the requirements of the rule.

Sincerely,

B. Baizel

Bruce Baizel
Staff Attorney
Oil & Gas Accountability Project
P.O. Box 1102
Durango, CO 81302
970/259-3353

cc: Jennifer Goldman

Doing It Right:
Best Oil & Gas Development Practices for New Mexico

NEW MEXICO: RICH IN OIL AND GAS RESOURCES

New Mexico is rich in oil and gas resources. Several counties in the state, including Colfax, Eddy, Lea, Rio Arriba and San Juan are in the midst of an oil and gas development boom. While this production provides economic benefit to these counties and the State of New Mexico, it also results in many negative impacts to the people and environment of our state.

DOING IT RIGHT IN THE FACE OF RAPID ENERGY DEVELOPMENT

The challenge facing New Mexicans now is not *whether* to increase fossil fuel production – energy companies are already on a record-setting pace as they accelerate development on public and private lands. Rather, the challenge facing us today is how best to protect our clean water and air, public health, and the environment in the face of rapid energy development. We support "doing it right:" responsible energy development that protects water, the environment, private property owners, sacred sites and public lands while enabling energy production. "Doing it right" is a reasonable approach to the long-term impacts of oil and gas development and can be achieved in New Mexico. In 2002, San Juan County alone produced over 4.5 billion dollars worth of oil and gas. We can afford to develop the resource <u>and</u> protect our lands and future prosperity. "Doing it right" means that some unique areas simply can't be drilled. Where oil and gas is developed, "doing it right" also means that the best oilfield practices must be pursued including:

1. **Preserving the private property rights of surface owners and surface users.**

- Oil and gas operators must negotiate a surface use agreement with landowners and surface users (i.e., permitees and lessees) detailing the placement of roads, well sites, pipelines, compressor stations and related facilities, and baseline testing of available water resources.
- Oil and gas operators must restore water and soil damaged by exploration and production, and provide temporary water supplies during remediation.
- Surface owners must be notified in writing at least 60 days in advance of lease sales and development.
- Restoration and adequate compensation for surface damages is critical.

2. **Existing laws must be enforced and strengthened.**

Surface, Soil and Water Protection

- Oil and gas operators must use available technologies such as directional drilling, horizontal drilling, multiple wells per drilling pad, and smaller well pads to reduce surface impacts and avoid fragmentation of wildlife habitat, ranchland and farmland.
- For formations and sites which do not require "frac-ing" or cavitation, post-drilling pads must be no more than 4/5 acre. For sites that need post-drilling activities, final pad sizes must be no more than one acre.
- Interim and final reclamation of well sites and related facilities, including restoring topsoil and native vegetation, is critical in our arid climate. Oil and gas operators

must begin reclamation no later than 6 months after completion or abandonment, which ever occurs first.

- To ensure safety and quality of life for oilfield residents, oil and gas wells must be "setback" at least one-half mile from a house or other domestic structure.
- Water quality in drilling areas must be protected by the use of closed-loop drilling systems (i.e. pitless drilling) and water-based drilling fluids.
- Substitutions for other toxic oil and gas field materials (e.g., solvents, paints) must be used when non-polluting options are available.
- Incidents of water, soil and vegetation contamination must be avoided by eliminating on-site disposal of waste.
- Proper management and disposal of produced water must require that any wastewater re-injected into the ground is reinjected into the same aquifer or formation, or into an aquifer or formation of equal or lesser quality, to prevent degrading higher quality ground water.
- Beneficial use of produced water must prioritize mitigation of oil and gas development impacts.

Air Quality Protection & Noise Standards

- In concern for regional air quality, all immobile oilfield equipment that emits nitrogen oxides (NOX), volatile organic compounds (VOCs) or other Hazardous Air Pollutants (HAPs), owned and/or operated by an individual operator, should be regulated as a single source and for its cumulative effect.
- Waste gas and flaring must be defined and managed as an " air emission" and meet a state emissions standard.
- Noise standards should apply to all exploration, development, work-over, transportation and refinement equipment.

Wildlife and Habitat Protection

- Remote monitoring and control devices must be installed to limit access by persons other than essential gas field personnel in and near wildlife habitat, wetlands, winter range, birthing and rutting areas, and other environmentally sensitive areas. Drilling activities must be avoided during periods of intensive wildlife use on public lands. Drilling activity must carefully comply with lease and permit stipulations and limit or exclude public access on oil and gas field roads.
- Whenever practical, bury utilities, particularly in and near areas of sensitive species critical habitat. Minimize the disturbance footprint by burying utilities along the road rather than cross-country.
- Any aerial power lines should be spaced to prevent or minimize raptor mortalities. Existing power poles should be modified to prevent raptor perching.
- Reclaim and revegetate all disturbed surfaces as soon as possible after completion of pipelines or well abandonment.
- All pits should be fenced and covered to prevent entry by birds and wildlife.

3. Protect the public interest

- At all stages of oil and gas development, the public should receive published notice and adequate opportunities to provide input. In New Mexico, a first step in enhancing our public input process would require posting spill, inspection and abatement reports on state websites, and fulfilling inspection report requests by mail.

- An equal emphasis in New Mexico should be placed on inspection, enforcement and bonding, as well as permitting wells. This emphasis will require that both state and federal permitting agencies have at least one inspector for every 500 active, inactive and known abandoned wells, with convenient public access to reports.
- New Mexico must require "full cost" bonding.
- Before new drilling is approved, the responsible agencies should fully analyze and disclose all potential impacts to allow for meaningful public input into decisions affecting the people and environment of our state. Such analysis should include cumulative impacts analysis, full consideration of other land uses such as ranching, farming, cultural and wildlife management.
- Agencies must fully coordinate with and consider the impact of development on tribal land and people. Such analysis will include cumulative impacts analysis, full consideration of other land uses (ranching and cultural) and full consultation with impacted communities.
- Environmental justice factors must be taken into consideration during planning processes, including consideration of existing pollution levels, race, cultural factors, income and demographics.

A NEW ENERGY TOMORROW

In the struggle to meet our energy demands, we need to work for fair standards that balance the interests of the oil and gas industry with the right of people to have clean air and water and for our children to inherit a legacy of unspoiled private and public lands. We need an energy policy that requires sustainable energy development and encourages conservation, fuel efficiency and renewable energy.

Independent Petroleum Association of New Mexico

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APR 1 3 2004

OIL CONSERVATION DIVISION

Fax Received 4/9/04

April 9, 2004

Mr. Bill Olson
New Mexico Oil Conservation Division
1220 St. Francis Dr.
Santa Fe, NM 87505

SENT VIA FAX: (505) 476-3462
ORIGINAL TO FOLLOW IN MAIL

Re: IPANM Comments on NMOCD "Pit and Below Grade Tank Guidelines"

Dear Mr. Olson:

Thank you for allowing IPANM to submit its comments on the proposed NMOCD Guidelines relating to the new pit rule.

Our comments are as follows:

GENERAL COMMENTS

1. While we realize the need to implement these guidelines given the looming April 15th effective date of the rule, IPANM hopes that the Division will consider further modifications to these guidelines going forward. The comment period was insufficient to allow for a thorough study and discussion of these guidelines by our members. Many of the technical provisions certainly appear to warrant further study before such precise direction should be given. Also, some of the reporting requirements will be very cumbersome for the high frequency, low impact activities carried out in the field such as minor workovers. This will result in a large paperwork and timing burden on industry and the OCD staff, while at the same time, yielding no improvement to the protection of groundwater and the environment.

2. The point was made repeatedly during the stakeholder meetings that the guidelines were just that, guidelines. Their purpose is to provide a framework that industry can follow, helping companies to comply with the rule and streamline approval of activities. They are not rules in themselves, and companies do not have to follow the guidelines to the letter if they can show that they are meeting the intent and letter of the rule. Therefore, all uses of absolute language in the guidelines should me removed, such as the words, "shall" and "must". Possible exceptions to this would be in the case where the guidelines relate to another rule such as the requirement to get State Engineer Office approval for construction of a pit that is more than ten feet in height, under part I.

PERMITTING PROCEDURES

3. I.: The guideline calls for formal approval of all drilling, workover, and completion pits. It was made clear by the OCD representatives in the workgroup that there was no intent to require a formal, detailed approval process for temporary drilling, workover, and completion pits. OCD representatives indicated that they merely wanted a general description on the existing APD (i.e., form C101 or Sundry Form C-103)) regarding whether a pit was going to be constructed, its location, a general description of the pit construction, and how closure was anticipated. Moreover, in cases where minimal workover operations are occurring, and no Sundry Form would otherwise be required, the OCD should implement an even more streamlined approval process that would allow pre-permitting, or very fast (within a matter of hours) approval to occur.

DESIGN AND CONSTRUCTION

4. II.A.4.: Freeboard markings are unnecessary for temporary pits. The guideline requires the markings be required on the liner to indicate freeboard. It seems unnecessary to require such markings on lined temporary drilling, workover, and completion pits. One can readily determine whether the 2-foot freeboard is met without such markings. IPANM would suggest that this guideline be applied to pits constructed for long-term (more than 180 days) continuous use.

5. II.B.: The requirement for 12 mil and then 20 mil liners seems to be arbitrary and excessive. Thinner liners and alternative media may be just as effective, more operationally useable and less costly. Moreover, unlined pits are permitted by the rule in certain areas.

6. II.C: Remove requirement for professional engineer. Any alternative to the guidelines will have to meet the approval of OCD staff. This should be handled on a case by case basis. This should not necessarily require the use of a professional engineer.

7. II.D.4. The specific construction steps are too restrictive and don't consider other, commonly used alternatives. Once again, the 40 mil liner seems excessive. What basis forms the requirement for such a think liner? Also, double walled tanks are commonly used and should be mentioned as an alternative.

8. II.D. 5 & 6: Remove both parts 5. and 6. These refer to an above ground tank and are not part of this rule.

9. II.G.2.: Exempt wellsites from this signage requirements. Signs that provide this information are already required to be on the wellsite.

10. II.H.: Change the wording to match the language in the rule that requires notification only for installing the primary liner on a system where secondary leak detection is required.

CLOSURE SITE ASSESSMENT

11. V.A.: Drilling and workover pits should be exempted from the assessment requirements. As long as there is not indication that the liner has been breached on the lined pit, then there should be no further site assessment or risk based ranking system necessary.

12. V.B.: Requiring waste samples to be taken on every closed drilling or workover pit is unnecessary. It is not required in the rule for a reason. It was clearly shown through testimony in the hearing for this rule that remaining wastes in these pits do not pose a threat where water unless groundwater is very shallow.

SOIL AND WATER REMEDIATION LEVELS

13. VI.A.: Background levels should also be considered in setting remediation standards.

REMEDIATION

14. VIII.3.(a)(iii): Change the wording in this section to allow for a workover or drilling pit that has had any surface oil removed.

15. VIII.3.(a)(v): Perhaps, the wording of this section should be more generic until further study of this issue can be completed. Current and ongoing scientific research has indicated that there are other methods that are as effective or better in preventing the migration of chlorides to groundwater. Also, define salt water, as highly concentrated brine. Water based drilling mud with some amount of KCL in it should not be subject to this provision.

FINAL CLOSURE

16. X.A.: Remove the re-vegetation requirement from the guidelines. This is not a requirement of the rule and should be left up to the specification listed in the applicable surface use permit obtained from the surface owner.

Once again, IPANM does appreciate the opportunity to comment on these guidelines, but would certainly like more time to do so in the future.

Sincerely,

John A. Byrom
IPANM rep. to NMOCD Pit Rule Stakeholders Group

Olson, William

From: Dan Girand [dgirand@mackenergycorp.com]
Sent: Friday, April 09, 2004 3:52 PM
To: WOLSON@state.nm.us
Subject: IPANM Comments_NMOCD Pit and Below Grade Tank Guidelines.doc

April 8, 2004

Mr. Bill Olson
Hydrogeologist
New Mexico Oil Conservation Division
1220 St. Francis Dr.
Santa Fe, NM 87505

RE: NMOCD Draft Guidance Document entitled "Pit and Below Grade Tank Guidelines"

Dear Bill:

The Independent Petroleum Association of New Mexico (IPANM) appreciates the opportunity to comment on the draft guidelines referenced above.

IPANM is pleased the NMOCD removed reference to the proposed guidelines from the final pit rule, Title 19, Chapter 15, Part 2, Section 50. Industry commented during the rulemaking that guidelines should be a guide for industry's selection of technology. Guidelines must be based on documented scientific research and peer reviewed data. Further, guidelines cannot replace the rulemaking process. Where NMOCD intends for minimum standards to be met to assure protection of ground water, public safety and the environment, then NMOCD has the responsibility and the obligation to enact such requirements through a formal rulemaking and not to use the guidelines as a mechanism to avoid the rulemaking process.

During the Stakeholder process, NMOCD indicated that adequate time would be given to the development of these guidelines. The pit rule, consumed considerably more time allowing for more time for comment and technical input. The expedited time frame for the guidance document too abbreviated and could lead to poor policy. There is a lack of complete scientific research and data used to develop this guideline document.

Following are specific issues of concern to IPANM:

1) **<u>INTRODUCTION:</u> The following specifications SHALL be used as a guide...**
"Shall" is used 105 times, and up to four times in one paragraph, throughout the draft . "Shall" is a word that mandates some action. Guidelines do not contain mandates so the word indicates that NMOCD is trying to circumvent the rulemaking process. NMOCD goes on to indicate an intent to mandate by requiring an Operator to use the C-144 to certify that they have adhered to the guidelines for construction and closure. Consequently, the guidelines the same force and effect as a regulation without being subject to a formal rulemaking process.

2) <u>PERMITTING PROCEDURES</u>: **The proposed guideline seems to require approval of all drilling, workover, and completion pits.**

There was tacit understanding and agreement between NMOCD and representatives in the workgroup that there was no need for a formal, detailed approval process for temporary drilling, workover, and completion pits. These temporary types of pits are authorized by the rule and do not require the redundancy of permitting. NMOCD representatives said that all they wanted was a general description on the APD (i.e., form C101 or Sundry Form C-103)) regarding where a pit was going to be constructed, a general description of the pit construction, and how closure was anticipated. This intent was achieved in the final rule by language that said in part "A separate form C-144 is not required." By incorporating the C-144 form into the form C101 and Form C-103, NMOCD has in fact required the C-144 form and required the more extensive detail that NMOCD representatives agreed was not necessary. There was no intent on any of the participants to approval for temporary drilling, workover, and completion pits.

3) <u>DESIGN AND CONSTRUCTION:</u> **The guideline calls for at least a 12 mil liner for drilling and workover pits except in the circumstances where salt based drilling fluids, hydrocarbon fluids, or other contaminants that have the potential to contaminate fresh water and where the operator intends to encapsulate the pit contents in place upon completion of drilling and workover activities.**

Unlined pits are allowed in areas specified in the rule (19.15.2.50 Section C, Paragraphs (g)(ii) and (g)(iii). So, the guidelines should make it clear that the liner guideline applies only as required by rule.

There is no evidence in practice or science that indicates a 12 mil or 20 mil synthetic liners should be the design standard. A suitable clay liner with equivalent permeability may be appropriate. It is common industry practice to use a synthetic liner but where local clays may be available; it should be acceptable to construct an equivalent clay liner. BLM Conditions of Approval for drilling reserve pits in the southeast area of the state containing all fluid types stipulate that 6 mil synthetic liners are adequate. Six mil synthetic liners are adequate for "fresh water based drilling fluids".

There is no evidence in practice or science to support a requirement for a 20 mil liner where salt based, oil based, or other contaminants have the potential to contaminate fresh water and where the operator intends to bury the pit contents in place. Technical documentation has been presented indicating that mil thickness is not a factor in maintaining the integrity of a buried synthetic liner. "Thicker is not better". Eight-mil liner is technically sufficient in most cases.

The general reference to "Salt Based Drilling Fluids" is inappropriate . In the Southeast area of the state naturally occurring salts are found in most of the fresh water. "Salt Based" needs to be defined. For the Northwest area of the state, salt based and oil based drilling fluids are not used but the catch all words, "other contaminants" is so broad as to be arbitrary. Practice of some forty years indicates a 8 mil liner for salt based, oil based, or other contaminants that have the potential to contaminate fresh water and where the operator intends to encapsulate the pit contents in place.

There is only one documented closed case, and one disputable case of ground water contamination from a temporary drilling, reserve, workover or completion pit in the State's files.

4) <u>DESIGN AND CONSTRUCTION:</u> **The guideline seems to require markings be on the liner to indicate freeboard.**

This and other requirements seem to indicate that operators will be required by non-binding guidelines to employ engineers to meet requirements in the proposed guidelines. We do not know any producer who has the technical expertise to calculate the dynamics of wave motion in pits. Unlined pits are allowed in certain areas; therefore, this marking would not be practical. It is unreasonable and unnecessary to require such markings on lined, temporary drilling, workover, and completion pits. Where do these waves come from?

5) **BELOW-GRADE TANKS: The guideline seems to require that below grade tanks be of strong, corrosion resistant construction, resistant to sunlight, installed on 1 inch of gravel, have visibility of the entire tank, and have a liner that is attached to the tank above grade.**

When guidelines are written they should provide several solutions to any issue, thus, it is not appropriate to suggest that any single solution such as, strapping a 40-mil synthetic liner to the tank, is the exclusive design standard. The guidelines seem not to allow for any manufactured double walled tanks. Corrosion resistant construction is inappropriate since this could be misinterpreted to mean stainless steel or more exotic materials. A better statement would be that the material must be compatible with the anticipated fluids. The resistant to sunlight requirement is inappropriate. Fiberglass, PVC, and other plastic materials manufactured today typically have UV inhibitors incorporated into the resins so there is no need for this specification. Of course there should be no specifications, only alternatives in guidelines. If NMOCD has a concern about tank materials, then a better statement would be that the materials must be suitable for outdoor exposure. There are other good alternatives to setting tanks located below ground surface on 1 inch of gravel. Some operators set tanks on I-beams to situate tanks off the ground, sand, or other suitable material is an acceptable design standard. For tanks installed below the ground surface in an open excavation, the guideline apparently requires that the entire tank shall be exposed to visually detect leaks. The definition of a below grade tank in the pit rule, is that they are defined as vessels where any portion of the sidewalls are not visible. The wording must be consistent in the pit rule and the pit guidelines.

6) **FENCES, SIGNS, AND NETTING: The guideline seems to require that fencing be around the perimeter of the facility, that a sign not less than 12" x 24" with lettering not less than 2"shall be posted on the fence, that the fencing not be constructed on berms, and the location on of the facility be identified by quarter-quarter section, township, and range.**

Fencing around the perimeter of a facility is not a guideline, it is a rule. In addition there is no definition of a facility so an operator does not know what must be fenced. Fencing is covered in the pit rule. If a fence around a pit or below grade tank is effective in preventing livestock access, then that is sufficient evidence of good design. Signs are already required by OCD and BLM rules, with great specificity. There is no need for any other signs.

7) **NOTIFICATION: The guideline seems to require that notification be given to NMOCD for installing all liners or leak detection systems.**

According to the pit rule, notification only should be given to NMOCD for installing a leak detection primary liner. This is another instance where it appears the guidelines are trying to broaden the rule. The guidelines and the rule must track each other.

8) **CLOSURE SITE ASSESSMENT: The guideline seems to require a general site assessment for all pits.**

Nothing in the pit rule requires an assessment for drilling, workover, and completion pits. It is unreasonable and unnecessary to expand the rule through the guidelines by seeming to require such an assessment. Hence, this section seems only applicable to existing or new storage or disposal pits at the point of reaching closure.

If there is a requirement, and we do not accept a guideline can expand a rule, the guideline in Section V.A.2. Wellhead Protection Area, requires the operator to determine the horizontal distance to all private, domestic fresh water wells or springs used by less than five households for domestic stock watering purposes and all other fresh water wells and springs. The word "known" should be inserted before "private, domestic fresh water wells or springs... It is not uncommon to have difficulty identifying these, particularly if the wells have not been registered or the landowners are unwilling to disclose the information. The guidelines do not make it clear how far from the pit this information should be obtained. Is it assumed that the ranking criteria are the radius? For example, the wellhead protection area is <200 feet from a private domestic fresh water well or spring or <1000 feet from any other fresh water well or spring. In the absence of any specifics in the guideline regarding a required radius, we would proceed with our data collection based upon the ranking criteria. Consequently, it may be of value to clarify the intent and include the radii of the information requested. The operator should only determine distance to the extent of the ranking criteria.

The guideline in Section V.A.3, Distance To Nearest Surface Water Body, seems to require the operator to determine the horizontal distance of all wetlands, playas, irrigation canals, ditches and perennial and ephemeral watercourses. There are many definitions of wetlands, playas perennial and ephemeral watercourses. This should be removed or a set of definitions included. The operator should only determine distance to the extent of the ranking criteria.

9) **<u>SOIL/WASTE CHARACTERISTICS:</u> The guideline says that soil testing is not required for lined drilling and reserve pits and that waste sampling is necessary for all drilling and reserve pits.**

Lined workover and completion pits are of the same nature as drilling and reserve pits and that they should be excluded from the requirement of soil sampling. During the pit rule hearing extensive testimony ywas provided that testing of any drilling, reserve, or workover pit was unnecessary. Not all drilling, workover, and completion pits require liners, so the guidelines should say that unlined pits do not require soil testing as well. The location of the pit will be documented and process knowledge of the drilling fluids will exist, so sampling should not be required.

10) **<u>SOIL AND WATER REMEDIATION LEVELS:</u> The guideline seem to require chlorides in the soil be remediated to 250 mg/kg, and ground water contaminated in excess of WQCC standards be remediated.**

250 mg/kg is the WQCC standard for water, not soil. Remediation of chlorides must consider background levels. No operator can be expected to clean up soil or water to better than background. There are many instances in the southeast area of the state where back ground levels are much higher than 250 mg/kg. Remediation could be prescribed when no contamination has occurred.

In the "UNLINED SURFACE IMPOUNDMENT CLOSURE GIDELINES" dated February 1993 ground water contamination in excess of NM WQCC ground water standards or natural background water quality will require remediation. In the southeast area of the state, where water in excess of NM WQCC ground water standards is naturally occurring, the 1993 original wording must be retained to avoid situations requiring remediation when no contamination has actually occurred.

Data developed from the NMOGA TPH and Chlorides workgroup must be considered when establishing remediation levels. The API Chloride Study must be considered as a valid method of determining the reasonable probability to contaminate ground water or surface water in excess of the standards in 19.15.1.19.B. (2) NMAC and 19.15.1.B. (3) NMAC through leaching, percolation, or other transport mechanisms.

10. SOIL And WATER SAMPLING PROCEDURES: The guideline seems to require in Section C. 4.(a), that the monitoring wells shall be purged a minimum of three well volumes of ground water..... in order to ensure the sample represents the quality of ground water in the formation and not stagnant in the wellbore.
It is not always possible to acquire three well volumes of ground water from a monitoring well. There are cases where the nature of a given aquifer will not yield three well volumes during a sampling episode. A suggestion would be to insert the words "To the extent hydraulically possible, monitor wells shall be purged…".

11) SOIL AND WASTE MANAGEMENT OPTIONS: The guideline calls for the contents of drilling and workover pits drilled or worked over with salt water that are to be encapsulated onsite be capped with either a 1-foot thick clay cap compacted to ASTM standards, or a 40 mil minimum thickness synthetic liner meeting ASTM standards that is designed to be resistant to the material encapsulated and when the bottom of the pit is located at least 50 feet above a source of fresh water.
There are many ways to capture the contents of drilling pits, none of them scientifically studies yet. Capping with clay or a 40 mil synthetic liner is not the exclusive design standard to prevent migration of contaminants. Technical documentation has been presented indicating that mil thickness is not a factor in maintaining the integrity of a synthetic liner when buried. "Thicker is not better". In this recent work, at a site in Arizona, the USGS (Andraski et. al, 2002) (http://toxics.usgs.gov/pubs/agu_poster/) reports "chloride-concentration profiles indicate that percolation past the 10-m depth (approximately 33 feet) has been negligible for the past 16,000 years". NMOCD should use 10 meters or 33 feet instead of 50 feet. Other current and ongoing scientific research has indicated that there are other methods that are as effective or better in preventing the migration of chlorides. One study indicated that a current practice, similar to the prescribed guideline, could enhance the migration of chlorides to the surface. The API Chloride Study, and the recent USGS work, must be used to allow other designs that would be technically supportable.

12) SURFACE RESTORATION: The guideline seems to require successful re-vegetation of the area.
According to the pit rule, within one year of the completion of closure of a pit, the operator shall contour the surface where the pit was located to prevent erosion and ponding of rainwater. The guideline must be changed to correspond to the rule language.

13) CLOSURE REPORTS: The guidelines seem to require a separate closure form be filed.
The pit rule allows for filing a general permit for a class of like facilities and requires the proposed disposal method of drilling fluids and cuttings to be described on the application. When the general plan is approved and the closure is within the allowed 180 days, the application and closure report are one in the same.

We appreciate the opportunity to work with NMOCD and provide input and comments. The

appearance of "shall" and "must" so many times in the guidelines draft, concerns us very much and those words need to come out of the draft. This latest draft was substantially different from the last one we worked on and therefore, more time should be given to study and comment on this guideline using a collaborative approach. The studies that have been cited should become the basis for rules and guidelines.

Sincerely,

Dan Girand
IPANM, Regulatory Committee
Box 1836
Roswell, New Mexico 88201

POB 1089 Eunice, New Mexico 88231

RESOURCE DEVELOPMENT TECHNOLOGY LLC

April 12,2004

State of New Mexico: Oil Conservation Division

Members of the Commission

Ladies & Gentlemen:

I am requesting that Mr. Frank Chavez, the District Supervisor of your NW New Mexico District Office, forward this letter to your attention.

I attended the meeting on April 1, 2004 at the San Juan College to explain the State of New Mexico's Proposed Pit and Below Grade Tank Guidelines. There was quite a bit of give-and-take between your staff and the operating community as regards the evolution of these guidelines and their concerns regarding implementation. The general public expressed a lack-of-confidence in the staff and the operators. I have just a few comments in these regards.

The operators are faced with a decision in regards to their continued use of production pits. I believe that requiring a complete inventory of pits on 4/15/2004 is appropriate.

Until the guidelines are finalized, however, in order that the operators can assess their proper response to those guidelines, it seems inappropriate to me to start any deadline counter running as regards pit closures. When these guidelines are finalized and adopted then the imposition of deadlines would make sense. I believe that the guidelines are near to being finalized --- this should not unreasonably delay their implementation.

The public was concerned about what goes into reserve pits. It was obvious to me that the industry has not effectively communicated the past 25 years of progress in meeting environmental safety requirements for drilling/completion fluids.

Simply requiring operators to submit a mud recap (amount and type of drilling fluid additives used) and a list of stimulation fluid components/amounts with their generic names would provide a simple record of non-drilled & non-water pit contents. Maybe others might object. For me it is simple insurance in communicating that fluid components are non-hazardous. An alternative might be a simple chemical analysis of the pit water immediately after the cessation of drilling and completion operations including pH, chlorides and hardness in the water-phase.

Lastly, based on the amount of water and bentonite gel used in conventional fresh-water drilling operations I feel certain that reserve pits filled with fresh-water drilling fluids and cuttings after being allowed to evaporate and dessicate in-place, are stable and relatively impermeable to leaching or movement. I believe it would be altogether reasonable for unlined fresh-water ONLY drilling reserve pits to be allowed.

PO BOX 1020 • MORRISON, CO • 80465 USA
PHONE: 303-674-6571 • FAX: 303-957-9957
EMAIL: TSCHWERING@COMCAST.NET

I would propose that the fresh-water drilling unlined reserve pits would only be made available to operators that DID NOT USE an unlined reserve pit for completion fluid discharge after completing fresh-water drilling operations OR encounter any massive salts. Your geology staff can determine areas where this exception would be appropriate (no massive salts or brine flows). Perhaps you could consider this in the alternative to lined pits with the disclosure of drilling fluids additives as outlined above. Unlined reserve pits dry much faster and can be closed more efficiently and economically.

My Background:
I was raised in the State of New Mexico and have worked on leases and facilities there since 1972. I have supervised drilling and production operations in your State since 1981 and am a Graduate in Petroleum Engineering from the New Mexico Institute of Mining and Technology (1981). I designed and constructed facilities near Avalon Lake outside of Carlsbad, NM, that won your 1999 Environmental Merit Award for Bonneville Fuels Corporation where I was the Operations Manager. I come to you desirous to protect New Mexico's environment and water quality.

Thank You,
Resource Development Technology, LLC.

RA Schwering, PE & CES
Operations Manager

Cc: Environmental File

LAW OFFICES

HEIDEL, SAMBERSON, NEWELL, COX & McMAHON

C. GENE SAMBERSON
MICHAEL T. NEWELL
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311 NORTH FIRST STREET
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F.L. HEIDEL
(1913-1985)

April 9, 2004

Bill Olson
NMOCD
Environmental Bureau
1220 St. Francis Dr.
Santa Fe, NM 87505

Re: Pit and Below Ground Tank Guidelines

Dear Mr. Olson,

As per your March 16, 2004 letter regarding the above-referenced matter, please accept the following as my comments on the draft Pit and Below Ground Tank Guidelines (hereinafter "draft Guidelines"):

> Let me first say that I am glad to see the NMOCD take a closer look at pits and their associated problems. I think that the Guidelines are a much needed step in the right direction. The protection of groundwater should be of the utmost concern for the NMOCD, oil and gas operators and New Mexicans' alike. However, instead of "guidelines" these rules and regulations should be just that, rules and regulations. History has shown us that the NMOCD's policy of voluntary compliance does not work. If the NMOCD is going to take the time and effort to address this issue, these new rules and regulations need to be mandatory and they need to be enforced.
>
> Second, regarding drilling and workover pits, a mandatory closed loop mud system should be required. A closed loop system offers substantially more protection of groundwater and the environment in general. The cost of a closed system is not prohibitive when one considers the escalating costs of dirt work and the added risk and expense of undertaking remediation of a leaking pit. In fact, closed loop systems are generally required by the Lea County-Lovington ETZ Authority for drilling

operations inside the extra-territorial zone. This requirement has not had the effect of chilling oil and gas development inside the ETZ. In addition, closed systems would dramatically reduce the need for site inspections by NMOCD field representatives who are already overburdened. Lastly, a closed system would eliminate the burden placed on the surface estate by the burying in place of harmful and/or toxic wastes.

Third, the ranking criteria identified in the draft Guidelines should be reconsidered. Specifically, "Depth to Groundwater" and "Wellhead Protection Area". I am requesting that you review NMOCD environmental files to determine whether or not the ranking criteria that is used to determine cleanup standards adequately protects groundwater. Does a situation exist where TPH levels at the surface were found to be at or near 1,000 ppm yet groundwater found at a depth of at least 100 feet was impacted? Likewise, given the size of the groundwater contamination plumes that NMOCD encounters, should the Wellhead Protection Area be revised. Have any groundwater plumes traveled more than 1,000 feet? Given the sheer number of groundwater contamination cases caused by oil and gas activities,[1] I am requesting that the Depth to Groundwater Ranking of 20 include groundwater found at a depth of 100 feet and that the Wellhead Protection Area Ranking of 20 include domestic and other freshwater wells and springs to a distance of 2,640 feet.

Fourth, the draft Guidelines fail to address chloride contamination levels in soils.

Fifth, the draft Guidelines should include a mandatory requirement for an operator of a pit or below ground storage tank to timely provide a copy of any and all applications, permits, reports, correspondence and like documents, generated as a result of their compliance with the final version of the draft Guidelines, to the surface owner where such pit or above ground storage tank is located.

Sixth, the NMOCD needs to properly equipt the field offices with the necessary resources and qualified personnel to enforce the final version of the draft Guidelines. Currently, the District 1 Office, which covers 5,289,722 acres in Lea, Roosevelt and Curry Counties, has only two environmental specialists and six field representatives.

---

[1] Despite misplaced beliefs to the contrary, in the past eighty years the oil and gas industry *has* caused groundwater contamination in Lea County as a result of their oil and gas operations.

Each environmental specialist is responsible for 2,633,861 acres or an area roughly three times the size of the state of Rhode Island. Granted, not every acre of these counties contains oil and gas activity, but the sheer size of the District 1 coverage area makes an already tough job almost impossible.

Seventh, the draft Guidelines are deficient for the following reasons:

A. The draft Guidelines are vague, arbitrary and capricious.

B. The draft Guidelines do not adequately protect groundwater.

C. The draft Guidelines do not adequately protect surface and subsurface soils.

D. The draft Guidelines do not adequately protect the public health, safety and well-being.

E. The draft Guidelines place an undue burden on the public.

F. The draft Guidelines place an undue burden on real property owners.

G. The draft Guidelines place an undue burden on the surface estate.

H. The draft Guidelines adversely affect real property rights.

I. The draft Guidelines conflict with public policy.

Lastly, I want to thank you for providing a public forum for review of the draft Guidelines in Hobbs on March 30, 2004.

If you have any questions, please do not hesitate to call.

Sincerely,

HEIDEL, SAMBERSON, NEWELL, COX & MCMAHON

By:

Patrick B. McMahon

PBM:cd

April 2004

To: Bill Olson
New Mexico Oil Conservation Division – Environmental Bureau

From: Caren Cowan, Executive Director
New Mexico Cattle Growers' Association
P.O. Box 7517
Albuquerque, New Mexico 87194
nmcga@nmagriculture.org

Subject: **Comment For The Proposed "Pit and Below-Grade Tank Guidelines"**

Thank you for the opportunity to comment on the proposed guidelines for Pits and Below-Grande Tanks. The New Mexico Cattle Growers' Association (NMCGA) represents some 2000 members, most of whom are producers. Impacts of oil and gas exploration, development and production have an obvious and sometimes intense impact on ranchers. NMCGA is not opposed to oil and gas production but, in fact, supports the need for domestic production. However, present situations coupled with some unsatisfactory history have created the need to make improvements. The purpose of these comments is to define the problem area and request practical solutions. NMCGA believes that domestic production, exploration, and operations can be improved and must be conducted in a manner that minimizes damages to the surface, aquifers and air, regardless of ownership. Total reclamation of the land after a site has closed is impossible, especially under current practices. The New Mexico Oil Conservation Division (NMOCD) should require comprehensive specifications to insure that the methods used have the least impact to the environment and are implemented.

The following comments represent NMCGA's points for consideration.

1. ***Introduction – last paragraph, pg. 4 –*** operator liability should be clearly defined. Aggressive guidelines for project clean up and repair of historical and existing damages as well as new projects should be included.
2. ***Design and Construction – general – location, pg. 5 –*** with the understanding that permits issued by the New Mexico Environment Department seek to prevent contamination of surface and ground water, the addition of clear definitions of "additional protective measures" should be included in the guidelines.
3. ***Disposal and Storage Pits – clay liners, pg. 7 –*** Industries that have to have pits and or lagoons have used clay liners and that practice has been used prevalently in the southwest, however, historical data has shown that these liners do allow for seepage and have caused extreme contamination of ground water. The level and type of contaminants present should mandate that clay liners be eliminated as an acceptable practice in favor of synthetic liners. At the very least, a monitoring well should be required as a leak detection system as a clay liner is not adequate protection against contamination.
    a. Regular reporting should be required by the NMOCD and twice yearly, should take independent water samples to insure compliance.
4. ***Closure Site Assessment – first paragraph, pg. 14 –*** The responsible party shall have an assessment performed by an independent company, to evaluate the extent of the impact. The operator should not provide the assessment, which should include cumulative affects and a damage resolution and reclamation plan.
5. ***Soil / Waste Characteristics – second paragraph, pg. 15 –*** An initial assessment of soil/waste contaminant levels in addition to a final determination of contaminant concentrations after soil removal or remediation should be required. The initial assessment will determine if existing concentrations are too high to install a pit or tank as well as provide a baseline to evaluate the final figures.
6. ***Soil / Waste Characteristics – third paragraph, pg. 15 –*** Waste materials and contents need to be removed in order to achieve even partial reclamation, remaining contents encapsulated or otherwise, should not be allowed. Some pit sites are over forty years old and only noxious weeds or brush species grow over them. Note: The condition of the surface should not be subordinate to the subsurface.

7. ***Unsaturated Contaminated Soils – first paragraph, pg. 19*** – A full laboratory analysis for Benzene and BTEX as well as TPH should be required. This eliminates the possibility of the operator's results being less than accurate, resulting in a contaminated site with less than adequate remediation.
8. ***Remediation – second paragraph, pg. 23*** – All sites should be required to have a risk evaluation, even if a general closure plan is submitted.
9. ***Soil and Waste Management Options – Disposal – iv. & v, pg 25*** – Encapsulation of contents on site should not be allowed. Leak detection while a site is active is required, why would the risk suddenly change if a liner is simply folded over and buried? Eventually, the materials will break down and there is a strong probability that the soil above and below will become contaminated.
10. ***Final Closure – Surface Restoration, pg. 27*** – Often re-vegetation of the area is not successful because of contamination that was not discovered until after the completion of the final closure requirements. The NMOCD needs to establish regulations or requirements that insure a closed site remediation is successful. This would include several inspections of the closed sites by the NMOCD for a specified period of time. The operator would be responsible for any site that was not successfully closed without optimum remediation, i.e., vegetation has died and only noxious weeds and brush inhabit the site.

Consistent enforcement and compliance is critical for the protection of the public and the environment when dealing with toxic contaminants.

Again, thank you for the opportunity to comment.

Olson, William

From: nmwgi@nmagriculture.org
Sent: Friday, April 09, 2004 7:01 PM
To: wolson@state.nm.us
Subject: Comments for "Pit and Below-Grade Tank Guidelines"

ATT109018.doc

Mr. Olson,

Attached are comments provided by Don L. Lee, President of New Mexico Cattle Growers' Association.

Asking for comments on these guidelines is appreciated.

Sincerely,

B.J. Brock

April 9, 2004

To: Bill Olson
NMOCD – Environmental Bureau

From: Don L. Lee, President
New Mexico Cattle Growers' Association

Subject: Comment For The Proposed "Pit and Below-Grade Tank Guidelines"

Thank you for the opportunity to comment on the proposed guidelines for Pits and Below-Grande Tanks. Domestic production, exploration, and operations can be improved and must be conducted in a manner that minimizes damages to the surface, aquifers and air, regardless of ownership. Total reclamation of the land after a site has closed is impossible, especially under current practices. The New Mexico Oil Conservation Division (NMOCD) should require comprehensive specifications to insure that the methods used have the least impact to the environment and are implemented.

The following comments represent points for consideration.

1. ***Permitting Procedures, pg. 4*** – Ideally, pits should be eliminated. Waste and bi-products should be put into tanks using a closed loop system. All pits, if that is method used, should be approved by the office of the State Engineer before permits are issued, to determine if the flood plain may breach them or if there is the possibility of water contamination.
2. ***Design and Construction – general – location, last sentence, pg. 5*** – Should read: "The OCD **shall** require additional....
3. ***Drilling and Workover Pits / Disposal and Storage Pits – pgs. 6,7*** – All pits should have synthetic liners using the specifications for drilling and work over pits. If clay liners are used, bentonite should be required in all clay-lined pits.
4. ***Fences, Signs and Netting, pg.*** 12 – The landowner or lessee should always be involved in these decisions on a site-specific basis.
5. ***Soil / Waste Characteristics – second paragraph, pg. 15*** – All locations considered for pits and tanks should have soil samples taken prior to construction.
6. ***Ground Water Quality, pg. 16*** – Before a permit is approved by the OCD, the nearest water user should be identified and allowed to be involved in the permitting process.
7. ***Ground Water Quality, second paragraph, pg. 16*** – Only above ground tanks should be used at all of these locations
8. ***Ground Water, pg. 18*** – If ground water is contaminated, all activities should be halted immediately, until remediation is completed.
9. ***Soil and Water Sampling Procedures, pgs. 18,19*** – No exemptions should be allowed under this category.
10. ***Monitor Well installation, Development and Ground Water Sampling, pg. 21*** – There should be no exemptions in this category. All sites should be assessed for

potential impacts to ground water quality. The landowner and lessee should be promptly notified, involved in the process and receive all monitoring information.

11. ***Soil and Waste/Soil Management and Remediation, Contaminated Soils, pg. 24*** – "C" should be stricken.
12. ***Soil and Waste Management Options – Disposal – iv. & v, pg 25 –*** Encapsulation of contents on site should not be allowed. All contents should be removed to an off-site OCD approved facility. Nothing should remain on the site. Leak detection while a site is active is required, why would the risk suddenly change if a liner is simply folded over and buried? Eventually, the materials will break down and there is a strong probability that the soil above and below will become contaminated.
13. ***Soil and Waste Management Options, Treatment and Remediation Techniques, Landfarming, iii, pg. 26*** – Landfarming should not be an alternative unless it is scientifically proven that vegetation similar to the adjacent land can be permanently reintroduced.
14. ***Termination of Remedial Action, Soil, pg. 27*** – No contaminated soils should be left on drilling sites. All materials should be shipped to an off-site OCD approved facility for disposal.

Consistent enforcement and compliance is critical for the protection of the public and the environment when dealing with toxic contaminants.

Again, thank you for the opportunity to comment.

Olson, William

From: Walter_Dueease@xtoenergy.com
Sent: Monday, April 12, 2004 1:51 PM
To: wolson@state.nm.us
Cc: Lindsey_Dingmore@xtoenergy.com
Subject: Guidelines

nmpitguidelines304.doc

Bill:

Attached please find XTO's comments for the proposed pit guidelines. XTO also supports those comments submitted by the New Mexico Oil and Gas Association.

Should you have any questions regarding these comments, please contact me at any of the numbers below.

Regards,

Walt

(See attached file: nmpitguidelines304.doc)

Walter Dueease
XTO Energy Inc.
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Fort Worth, Texas 76102
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March 24, 2004

Energy Minerals and Natural Resources Department
New Mexico Oil Conservation Division
1220 South St. Francis Drive
Santa Fe, New Mexico 87505
Mr. Bill Olsen

RE: Pit and Below Grade Tank Guidelines

Dear Mr. Olsen:

XTO Energy has reviewed the substantive changes made to the existing guidelines and we support the NMOCD's interest in strengthening the requirements for the prevention of pollution of surface and subsurface waters of the state. We believe that significant improvements have been made to the guidelines, yet it is necessary to review current successful industry practice and proposals to maintain soil and water protection. We wish to offer the following comments.

Section I Permitting Procedures – The proposed requirement to prepare Forms C-144, C-101A or C-103A prior to construction poses no significant increase workload on oil and gas operators. New Mexico operators have enjoyed a prompt permit approval time with existing applications and hope that no additional time shall be required to review and approve additional permit requirements with existing staff levels.

This section also provides operators the liberty to apply for construction permits of pits and below grade tanks at multiple sites. We appreciate the opportunity to use general construction plans to save time and money associated with the application process.

Section B Drilling and Workover Pits – The proposed guideline – to apply a statewide minimum standard that is the equivalent of a 12 mil non-reinforced liner for fresh water pits and 20 mil liner for those pits containing salt based drilling fluids, hydrocarbon fluids or other contaminants – seems to suggest that the best regulatory approach is to impose a standard that will be protective under the most severe conditions found anywhere in the state, while allowing operators to ask for variances from the District for those where less stringent standards are appropriate. XTO strongly disagrees with the concept that statewide standards should be based on worst-case scenarios. In this instance, operators will be routinely forced to choose between spending money to meet stringent liner standards that do not produce incremental environmental benefits or tying up NMOCD and industry resources on requests for variances. The liner material most commonly used in New Mexico for reserve pit lining is the six-mil non-reinforced liner. We know of very few areas of the state where site-specific circumstances warrant the use of 12-mil or equivalent liners to protect surface or subsurface water.

We believe that the Districts are knowledgeable about the areas that they regulate and about which liners are being used successfully in the different parts of their Districts. From a practical standpoint, the Districts will find it much easier to define areas where a more stringent standard is needed than to grant variances to operators to apply something less than what the NMOCD has defined as "minimum" statewide. Setting a reasonable standard- and empowering the District Directors to establish alternative standards where warranted- will also level the playing field for smaller operators who may find it more difficult than larger operators with larger and more specialized staffs to develop such technical information as Districts may require to justify obtaining local variances from statewide standards for their operations.

Section H Notification – XTO is concerned with the requirement to notify District personnel to schedule inspections for pit liner installations. We would support an inspection of a leak detection system prior to service, however, with this requirement it also seems possible to unnecessarily delay workover and drilling operations for an inspection of properly constructed pit lining material. With current rig utilization it is unlikely that an inspection by District staff may be made of all lined pits without significant delay of costly wellsite operations. This section does not address the purpose of the scheduled inspection whatsoever. Is the inspection to reveal the mere installation itself or to specifically test the performance standards of the material in place?

This section would also require operators to supply the District with as built photographs of the liner installation. No detail is supplied here to advise industry as to the type and quality of photographs required and there is no ability of the operator or District to verify if the photographs are actually those taken of the proposed site construction.

We would request that this section be revised to require operators to only notify District offices of proposed lining and leak detection systems. If District staff chooses to schedule an inspection it may done in such manner to not interrupt continuous operations.

Section VII. A. 3. (a) – Paragraph (iii) proposes to permit operators to landspread or landfarm pit contents that have not contained hydrocarbons and can be demonstrated that the mud contaminants pose no threat to water, health or the environment. We welcome the thought of the Division to allow this procedure as successfully practiced in other states yet we would advise that all operators should seek permission from the surface owner to landfarm mud and cuttings.

Paragraph (iv) proposes to allow operators the option to encapsulate fresh water pit contents onsite by backfilling the pit walls and covering the pit with 3 feet of clean soil. Our objection to this proposal rests with the requirement to cover a pit with that amount of soil. In most areas of southeast New Mexico soil is a rare commodity and it is unlikely that even when following the stockpiling requirement of the pit rule that an accumulation of soil in that quantity could be found. We would request that word "soil" be stricken and be replaced with <u>material.</u> Once the clean material is distributed over the disturbed area, any stockpiled soil from the reserve pit construction may be added to the restoration.

Paragraph (v) proposes to require operators to encapsulate salt water reserve pits with a compacted clay cap or a 40 mil liner; and covering the cap with a minimum of 3 feet of clean soil. We are concerned with the requirement to apply a liner of this thickness on top of the pit prior to closure. The existing proposal would only require a 20 mil liner for the floor of the reserve pits and we would question the necessity to apply a much thicker liner on the surface of the pit prior to closure. It is uncertain whether this procedure of applying a synthetic liner as a cap over a drying reserve pit has ever been practiced successfully.

Even with the current Rule 50 allowance of 180 days for pit evaporation it is unlikely that tracked equipment could spread clean material over a reserve pit covered with additional synthetic material and not damage the protective cover intended to shed surface water and prevent vertical migration of contaminants. This proposal appears to suggest that the best regulatory approach is to impose a standard that will be protective under the most severe conditions anywhere in the state. This onerous provision allows no latitude for operators to test new techniques for isolating contaminants and specifies what must be done by an untested method in the field. We would request that this provision be removed from the guidelines until it is proven to be successful and supported by field tested methods for prevention of vertical migration and successful plant growth at the surface.

Section X. A. Surface Restoration - This section would require operators to successfully "re-vegetate" a disturbed area after being backfilled and re-contoured. The expectation of successful "re-vegetation" is an extreme requirement that imposes significant burden on an operator's reasonable use of the surface estate. Current industry practice to backfill and re-contour is easily achieved in virtually all parts of the state and industry welcomes the opportunity to improve those disturbances caused by our exploration and production activities. The requirement to ensure successful re-vegetation exceeds those requirements of the New Mexico State Land Office and the Bureau of Land Management. Those surface management agencies share a common goal in working with industry to promote the enhancement of disturbed areas by soil stabilization and germination of desired plant community species through seeding efforts. These seeding requirements allow operators to seed an area once it has been re-contoured to promote stabilization, a second seeding is then required if the area has not responded to the initial seeding of the disturbed area. We would request that the word "re-vegetate" be stricken from the guidelines. The process for the recovery of vegetative growth in these guidelines should be consistent with other surface management agencies in the state of New Mexico. We would propose that operators be allowed to seed a disturbed area once and then only be required to perform an additional seeding after two years if no vegetative growth has occurred, but in no case would an operator be required to seed more than two times. To re-vegetate implies a requirement to plant living species and ensure their survival in an otherwise hostile environment of the desert southwest.

XTO Energy applauds the efforts of the NMOCD to revise the guidelines for pits and below grade tanks. We understand the desire of the Division to implement the proposed changes to the guidelines before the compliance date of the existing pit rule, 19.15.2.50 NMAC. We wish to express our concern over the extensive changes proposed and the short period of time to review the proposals and solicit comments from all of the affected parties. XTO respectfully requests for a formal comment period on the proposed guidelines not to exceed 30 days and the opportunity for all interested parties to express their concerns to the NMOCD.

Thank you for your attention and consideration of XTO Energy's comments and recommendations. We look forward to working with the NMOCD to integrate these recommendations into the proposals prior to its approval by the Division. Should you have any questions regarding this matter, please contact me at (800) 299-2800.

Yours truly,

Walter Dueease

Marathon Oil Company

Southern Business Unit

P. O. Box 3487
Houston, TX 77253-3487

5555 San Felipe Road
Houston, TX 77056-2723

Telephone: (713) 629-6600
FAX: (713) 296-3598

For review 4/12/04

April 8, 2004

Mr. Bill Olson
Hydrogeologist
New Mexico Oil Conservation Division
1220 St. Francis Drive
Santa Fe, NM 87505

Re: Comments on NMOCD Draft Guidance Document entitled "Pit and Below Grade Tank Guidelines"

Dear Bill:

Marathon Oil Company (Marathon) appreciates the opportunity to provide comments on the draft guidance document referenced above.

Marathon is pleased to see the NMOCD has removed reference of theses guidelines from the final pit and below grade tank rule, Title 19, Chapter 15, Part 2, Section 50. Marathon, through our participation with the New Mexico Oil & Gas Association (NMOGA), stated that during the rulemaking that the subject guidelines should be a guide for industry's use in expediting approval of permits. To better assure the proper design and closure of pits and below grade tanks, these minimum guidelines need to be based on documented scientific research and peer reviewed data. Further, these guidelines should not replace the rulemaking process. Where the NMOCD intends for minimum standards to be met to assure protection of ground water, public safety, and the environment, then NMOCD has the responsibility and the obligation to enact such requirements through a formal rulemaking and not to use the guidelines as a mechanism to avoid the rulemaking process.

For the pit and below grade tank rule, NMOCD allowed considerably more time and a more participative process for all parties to provide comment and technical input into the rule. Marathon is concerned that the expedited comment period for the guidance document is far too abbreviated and could lead to poor policy. Further, a concern exists about the lack of some complete scientific research and data that is critical to developing this guideline document.

Provided below are specific issues of concern to Marathon with respect to the above referenced guideline:

1) INTRODUCTION: The following specifications SHALL be used as a guide...

   Marathon has concerns that the guidelines shall be used. This implies that the guidelines are required and not suggested, indicating that the NMOCD is trying to circumvent the rulemaking process. This effort is further enforced by the rule requiring the Operator to use the C-144 form and certify that they have adhered to the guidelines for construction and closure. Consequently, it appears the guidelines now have the same status as a regulation without being subject to a formal rulemaking process.

2) PERMITTING PROCEDURES: The guideline calls for formal approval of all drilling, workover, and completion pits.

   Marathon and NMOGA provided extensive testimony regarding this issue, and there was tacit understanding and agreement by the NMOCD representatives in the workgroup that there was no need for a formal, detailed approval process for temporary drilling, workover, and completion pits. We believe that these temporary types of pits were in fact authorized by the rule and did not require the redundancy of permitting. NMOCD representatives indicated that they merely wanted a general description on the existing APD (i.e., Form C101 or Sundry Form C-103) regarding whether a pit was going to be constructed, a general description of the pit construction, and how closure was anticipated. Although the NMOGA suggested language was not accepted by NMOCD in the final rule, the intent was achieved by the final rule language that stated in part "A separate Form C-144 is not required." By incorporating the C-144 form into the Form C101 and Form C-103, NMOCD has in fact required the C-144 form and required the more extensive detail that NMOCD representatives agreed was not necessary. Marathon vigorously objects to this approach to require approval for temporary drilling, workover, and completion pits.

3) DESIGN AND CONSTRUCTION: The guideline calls for at least a 12 mil liner as acceptable for drilling and workover pits, except in the circumstances where salt based drilling fluids, hydrocarbon fluids, or other contaminants that have the potential to contaminate fresh water and where the operator intends to encapsulate the pit contents in place upon completion of drilling and workover activities.

First, Marathon wishes to clarify that a lined pit is not always required and unlined pits are allowed in areas so specified in the Rule 19.15.2.50 Section C, Paragraphs (g)(ii) and (g)(iii). Hence, we believe that the guidance document should reference that the liner guideline applies as required by rule.

Second, Marathon disagrees that either the 12 mil or 20 mil synthetic liner is the exclusive design standard. A suitable clay liner with equivalent permeability may be appropriate. Marathon understands that it is common industry practice to use a synthetic liner; but, where local clays may be available, it should be acceptable to construct an equivalent clay liner, where appropriate. Additionally, BLM Conditions of Approval for drilling reserve pits in the southeast area of the state containing all fluid types stipulate that 6 mil synthetic liners are adequate. Marathon believes, as a minimum, that 6 mil synthetic liners are adequate for "fresh water based drilling fluids."

Third, Marathon disagrees with the requirement that a 20 mil liner is required where salt based, oil based, or other contaminants have the potential to contaminate fresh water and where the operator intends to bury the pit contents in place. Technical documentation is attached indicating that mil thickness is not a factor in maintaining the integrity of a synthetic liner when buried. "Thicker is not better". Marathon believes that as a minimum, the commonly used 8-mil liner is technically sufficient in most of these cases. Unless NMOCD has specific and justified concerns for a given location, it can be specified in the approval that a 20-mil liner be required.

Fourth, Marathon is concerned about the general reference to "Salt Based Drilling Fluids". In the Southeast area of the state, naturally occurring salts are found in most of the fresh water. Marathon believes that "Salt Based" needs to be defined. For the Northwest area of the state, salt based and oil based drilling fluids are not used, but the term "other contaminants" is not specific enough for proper interpretation. NMOGA recommends that the wording be changed to require a 10 mil liner for salt based, oil based, or other contaminants specified by the NMOCD that have the potential to contaminate fresh water and where the operator intends to encapsulate the pit contents in place.

Fifth, Marathon would like to reiterate that there is only one documented closed case and one disputable case of ground water contamination by a temporary drilling, reserve, workover or completion pit in the State's files.

4) DESIGN AND CONSTRUCTION: The guideline requires the markings be required on the liner to indicate freeboard.

Again, Marathon would reiterate the comments above that unlined pits are allowed in certain areas; therefore, this marking would not be practical in that circumstance. Furthermore, it seems unreasonable and unnecessary to require such markings on lined temporary drilling, workover, and completion pits. From our experience, one can readily determine whether the 2-foot freeboard is met without such markings. NMOGA would suggest that this guideline be applied to pits constructed for long-term (more than 180 days) continuous use.

5) BELOW-GRADE TANKS: The guideline requires that below grade tanks be of strong corrosion resistant construction, resistant to sunlight, installed on 1 inch of gravel, have visibility of the entire tank, and have a liner that is attached to the tank above grade.

Marathon has numerous concerns about this section of the guideline. Marathon disagrees that strapping a 40-mil synthetic liner to the tank is the exclusive design standard. The guidelines do not allow for any manufactured double walled tanks. The corrosion resistant construction requirement seems inappropriate since this could be misinterpreted to mean stainless steel or more exotic materials. Marathon believes that a simple statement that the material must be compatible with the anticipated fluids seems more appropriate. The resistant to sunlight requirement seems inappropriate as well. Marathon assumes that NMOCD's concern is with fiberglass or other plastic materials; and, that this guideline is a holdover from the 1993 guidelines. Fiberglass, PVC, and other plastic materials manufactured today typically have UV inhibitors incorporated into the resins so Marathon questions the need for this specification. Would an operator need to have proof of UV inhibitors and keep this on record to meet this guideline? If NMOCD still has a concern about tank materials, then a better statement would be that the materials must be suitable for outdoor exposure. Another concern is the requirement to set tanks located below ground surface on 1 inch of gravel. Marathon believes that utilizing I-beams to situate tanks off the ground, sand, or other suitable material is as an acceptable design standard without requiring the exclusive use of gravel. Finally, for tanks installed below the ground surface in an open excavation, the guideline states that the entire tank shall be exposed to visually detect leaks. According to the definition of a below grade tank as developed for the pit rule, they are defined as vessels where any portion of the sidewalls are not visible. Hence, April 12, 2004

Marathon recommends that this wording be changed to correspond with the matching regulatory definition.

6) <u>FENCES, SIGNS, AND NETTING:</u> The guideline requires that fencing be around the perimeter of the facility, that a sign not less than 12" x 24" with lettering not less than 2"shall be posted on the fence, that the fencing not be constructed on berms, and the location of the facility be identified by quarter-quarter section, township, and range.

   Marathon believes that the intent of preventing livestock from access is the key point so the prescriptive nature of this requirement is not necessary. If a fence around a pit or below grade tank is effective in preventing livestock access, then that is sufficient evidence of good design. With regard to the signs, Marathon objects to the need for an additional sign on the location since all locations are already required to have a sign designating the same information as listed in the guideline. Marathon believes that location identification allowing the use of a Unit Letter in lieu of providing ¼ ¼ section, as specified in Rule 19.15.3.103 Section F.4., is sufficient. If another company adds a pit to a location as part of a co-located well or gathering system pit, then they must too post a sign designating their operation. Consequently, this requirement seems redundant and unnecessary.

7) <u>NOTIFICATION:</u> The guideline requires that notification be given to NMOCD for installing all liners or leak detection systems.

   According to the pit rule, notification only should be given to NMOCD for installing a leak detection primary liner. Hence, Marathon respectfully requests that the guideline be changed to correspond to the rule language and the as built documentation be limited to the installation of leak detection.

8) <u>CLOSURE SITE ASSESSMENT:</u> The guideline requires a general site assessment for all pits.

   First, nothing in the pit rule required such an assessment for drilling, workover, and completion pits, and it is unreasonable and unnecessary to require such an assessment. When an APD or Sundry is prepared for a given well, a general site assessment has already been prepared, fully acknowledging any established groundwater sensitive area, wellhead protection area, or surface water body. Hence, this section seems only applicable to existing or new storage or disposal pits at the point of reaching closure.

Second, the guideline in Section V.A.2. Wellhead Protection Area, requires the operator to determine the horizontal distance to all private, domestic fresh water wells or springs used by less than five households for domestic stock watering purposes and all other fresh water wells and springs. A question exists as to the radius from the pit from which this information should be obtained. Is it assumed that the ranking criteria are the radius? For example, the wellhead protection area is <200 feet from a private domestic fresh water well or spring or <1000 feet from any other fresh water well or spring. In the absence of any specifics in the guideline regarding a required radius, we would proceed with our data collection based upon the ranking criteria. Consequently, it may be of value to clarify the intent and include the radii of the information requested. Further, the word "known" should be inserted before "private, domestic fresh water wells or springs... It is not uncommon to have difficulty identifying these, particularly if the wells have not been registered or the landowners are unwilling to disclose the information. Marathon recommends that the operator only determine distance to the extent of the ranking criteria.

Third, the guideline in Section V.A.3, Distance To Nearest Surface Water Body, requires the operator to determine the horizontal distance of all wetlands, playas, irrigation canals, ditches, and perennial and ephemeral watercourses. As with the comment above, we are assuming, using the risk ranking criteria, between 200' and 1,000' is the radius of concern for accumulating this data. Again, including the radius suggested from the ranking criteria would help clarify the expectation of the assessment. Marathon recommends that the operator only determine distance to the extent of the ranking criteria.

9) SOIL/WASTE CHARACTERISTICS: The guideline states that soil testing is not required for lined drilling and reserve pits, and that waste sampling is necessary for all drilling and reserve pits.

Marathon believes that lined workover and completion pits are of the same nature as drilling and reserve pits, and that they should be excluded from the requirement of soil sampling. NMOGA provided extensive testimony that testing of any drilling, reserve, or workover pit was unnecessary unless a breach of that pit occurred. Given the fact that not all drilling, workover, and completion pits require liners, it should be further stated that unlined pits do not require soil testing as well. With regard to wastes that will remain within the pit for closure, there is no reason to test such pits where oil based and salt-based muds have not been used. Marathon also believes that since the location of the pit will be documented and process knowledge of the drilling *fluids will exist, sampling should be limited to cases when its value can be demonstrated.*

10) SOIL AND WATER REMEDIATION LEVELS: The guideline requires chlorides in the soil be remediated to 250 mg/kg, and ground water contaminated in excess of WQCC standards be remediated.

First 250 mg/kg is the WQCC standard for water, not soil. Marathon believes that remediation of chlorides should consider background levels. There are many instances in the southeast area of the state where back ground levels are much higher than 250 mg/kg. Remediation could be prescribed when no contamination has occurred.

Second, in the "UNLINED SURFACE IMPOUNDMENT CLOSURE GUIDELINES," dated February 1993, ground water contamination in excess of NM WQCC ground water standards or natural background water quality will require remediation. Marathon believes that in the southeast area of the state, where water in excess of NM WQCC ground water standards is naturally occurring, that the 1993 original wording be retained to avoid situations requiring remediation when no contamination has actually occurred.

Third, Marathon would like the data developed from the NMOGA TPH and Chlorides workgroup be considered when establishing remediation levels. Marathon would also like the API Chloride Study be considered as a valid method of determining the reasonable probability to contaminate ground water or surface water in excess of the standards in 19.15.1.19.B. (2) NMAC and 19.15.1.B. (3) NMAC through leaching, percolation, or other transport mechanisms.

11) SOIL And WATER SAMPLING PROCEDURES: The guideline requires in Section C. 4.(a), that the monitoring wells shall be purged a minimum of three well volumes of ground water..... in order to ensure the sample represents the quality of ground water in the formation and not stagnant in the wellbore.

It is important to note that it is not always possible to acquire three well volumes of ground water from a monitoring well. There are cases where the nature of a given aquifer will not yield three well volumes during a sampling episode. A suggestion would be to insert the words "To the extent hydraulically possible, monitor wells shall be purged...".

12) <u>SOIL AND WASTE MANAGEMENT OPTIONS:</u> The guideline calls for the contents of drilling and workover pits drilled or worked over with salt water that are to be encapsulated onsite be capped with either a 1-foot thick clay cap compacted to ASTM standards, or a 40 mil minimum thickness synthetic liner meeting ASTM standards that is designed to be resistant to the material encapsulated and when the bottom of the pit is located at least 50 feet above a source of fresh water.

Marathon disagrees that capping with clay or a 40 mil synthetic liner is the exclusive design standard to prevent migration of contaminants. Technical documentation has been provided to the NMOCD by NMOGA indicating that mil thickness is not a factor in maintaining the integrity of a synthetic liner when buried. "Thicker is not better". Marathon would recommend that NMOCD consider using 10 meters or 33 feet instead of 50 feet. Other current and ongoing scientific research has indicated that there are other methods that are as effective or better in preventing the migration of chlorides. One study indicated that a current practice, similar to the prescribed guideline, could enhance the migration of chlorides to the surface. Marathon would again emphasize that the API Chloride Study, and the recent USGS work, be used to allow other designs that would be technically acceptable.

13) <u>SURFACE RESTORATION:</u> The guideline requires successful re-vegetation of the area.

According to the pit rule, within one year of the completion of closure of a pit, the operator shall contour the surface where the pit was located to prevent erosion and ponding of rainwater. Hence, Marathon respectfully requests that the guideline be changed to correspond to the rule language. Re-vegetation could be considered to include non-native species and noxious weeds which is obviously not the intent.

14) <u>CLOSURE REPORTS:</u> The guidelines require a separate closure form be filed.

The rule allows for the filing of a general permit for a class of like facilities and requires the proposed disposal method of drilling fluids and cuttings to be described on the application. Marathon believes that when the general plan is approved and the closure is within the allowed 180 days, the application and closure report are one in the same. When an APD or Sundry is prepared for a given well, a general site assessment has already been prepared, fully *acknowledging any established groundwater sensitive area, wellhead protection area, or surface water body.*

In closing, Marathon appreciates the opportunity of providing the following comments on this guideline. However, we want to reiterate our recommendation that more time should be given to study and comment on this guideline using a collaborative approach. By doing so, a better final product will result that achieves the intended goal of the document.

Respectfully,

Marathon Oil Company

K.W. Tatarzyn
Permian Basin Asset Team Leader

cc: J.W. Sologub
J.D. Malody

Williams

Environmental Department
188 County Road 4900
Bloomfield, NM 87413
505/632-4625
505/632-4781 Fax

April 9, 2004

Mr. Bill Olson
State of New Mexico - Oil Conservation Division
Environmental Bureau
1220 South St. Francis Dr.
Santa Fe, NM 87505

RE: Comments on Proposed Pit & Below-Grade Tank Guidelines

Thank you for the opportunity to comment on the draft guidance document. Please accept the following comments:

Prescriptive Language:

The guidance document provides numerous references to prescriptive measures and requirements. This language discourages the use of new technology and methodologies. Additionally, it does not provide for professional judgment and experience to determine the measures that are equivalent or more protective of the public health and environment. An example includes:

> C: Disposal and Storage Pits
> 2. Clay Liners
> (e) … Field permeability tests shall be conducted only by the double ring infiltrometer method as described in ASTM D-3385.

The author has personal knowledge and 10-years experience with the design, construction and evaluation of clay liners and caps. The ASTM D-3385 field method has many problems with reliability and there are several other field methods that provide quicker, more dependable and in many cases more accurate measurements of a clay liners integrity. Similar examples can be found in the guidance document related to construction, sampling, remediation and closure procedures. This issue is prevalent in many of NMOGAs comments submitted on April 8, 2004.

We would suggest that NMOCD include language that would allow for professional judgment and experience to determine if a equivalent or better method of compliance is available. For example:

> C: Disposal and Storage Pits
> 2. Clay Liners
> (e) … Field permeability tests shall be conducted ~~only~~ by the double ring infiltrometer method as described in ASTM D-3385, or equivalent methods acceptable to NMOCD. Written NMCOD acceptance must received prior to approval of an alternative test method.

Soil Sampling and Testing for Total Petroleum Hydrocarbons (TPH):

Due to advancements in technology, amino-assay testing methods (e.g. PetroFLAG®) have become very reliable for the measurement of TPH in soils. It has been documented that this testing method is equivalent to the Laboratory EPA Method 418.1 and may even be more reliable as the testing is done in the field with minimal sample handling and shipping. We ask that NMOCD include field testing for TPH as an equivalent method to laboratory testing for the following reasons:

1) Field testing for BTEX and Benzene by use of a heated-headspace method is allowed in lieu of laboratory testing. There is little QA/QC required for this testing, yet the results are considered acceptable for closure. Amino-assay test methods include similar if not more stringent QA/QC.
2) Amino-assay testing has been shown to be equivalent to Laboratory Method 418.1. Method 418.1 tends to be a more conservative measure of TPH as compared to Method 8015 (modified). Samples to be tested for TPH using the amino-assay method would have minimal handling and in turn minimize the loss of volatile organics prior to testing. As such, testing by amino-assay should provide a conservative measure of TPH.
3) One of the most readily available units is the Drexel PetroFLAG® which is being accepted by several states, EPA, the Department of Energy and the Corp of Engineers. PetroFLAG® has received SW-846 draft method approval number 9074 from EPA's Office of Solid Waste.
4) Field testing for TPH will expedite the closure of pits by providing "real-time" results.

Again thank you for your consideration and the opportunity to comment. Please contact me at (505) 632-4625 if you have any questions or need additional information.

Respectfully submitted,

Michael K. Lane, PE
Williams Energy Services
Four Corners Area Environmental Specialist

CC: NMOGA

Olson, William

From: John Rees [jrees@acrnet.com]
Sent: Thursday, April 08, 2004 7:55 AM
To: wolson@state.nm.us
Subject: Pit & tank guidelines

NMOCD
William C. Olson, Hydrologist
Environmental Bureau
1220 St. Francis Dr.
Santa Fe, NM 87505

Dear Mr. Olson,

We are writing you to comment on the Pit and Below-Grade Tank Guidelines since we were not be able to attend the recent public meeting in Farmington. We appreciate this opportunity to comment.

Because of our interests in birds and other wildlife, we care deeply about the protection of wildlife and habitat. We remain concerned about the potential for water contamination affecting people and wildlife through the continued use of unlined pits. We also remain concerned about the future potential spread of contaminants from buried pits due to exposure to the elements where the solid contaminants could be carried via the wind or erosion.

Our next area of concern is II. DESIGN AND CONSTRUCTION, G. FENCES, SIGNS & NETTING, number 1. Fencing is required to keep livestock, **but not wildlife**, out of pits. We understand that the Oil Conservation Commission accepted Mr. Anderson's testimony fall, 2003, that fencing designed to exclude wildlife is not required except where a particular wildlife concern is identified. We contend that, if cattle are attracted to the fluids in these pits, wildlife will be attracted as well. Therefore it should be the obligation of the industry to fence to prevent wildlife entry. We don't believe that industry will fence even if employees find evidence of wildlife entry. Furthermore, animal deaths and illness can have already occurred by the time evidence of entry is noted. It is our belief that animal deaths have not been noted in the same way cattle deaths have because deer and elk are more prone to travel a distance from "watering" sites than are cattle.

Under number 3 in this section protection for migratory birds by screening, netting, or covering is only required for tanks exceeding 16 feet in diameter. While this might be adequate for waterfowl, it does nothing to prevent smaller birds from accessing the fluids in such tanks. There should be no exception to this requirement, nor should exemptions be granted for alternative methods. A U.S. Fish & Wildlife website http://mountain-prairie.fws.gov/contaminants/contaminants1c.html. cites the most effective deterrent is netting in contrast to deterrents that do not work-flagging, reflectors, strobe lights and Zon guns. The agency in this site also advocated closed containment systems; **we believe that closed containment systems are the best way to handle fluids and that industry should be required to use such systems in New Mexico as the best solution to the problem.**

We also question the exemption from this requirement of drilling and workover pits if visible of measurable layers of oil are removed. The U.S. Fish & Wildlife Service http://mountain-prairie.fws.gov/contaminants/contaminants1a.html reports that even a small amount of oil on a bird's egg can result in the death of the embryo. This site also reports other problems with oil-birds bathe and drown because of the weight of the oil. Carcasses may not be evident because they sink to the bottom of the pits. The site further states that oil destroys the ability of feathers to insulate. Even a "light sheen on the water surface can be deadly." It is our understanding that the majority of New Mexico's birds fall under the protection of the International Migratory Bird Treaty Act.

Sincerely,
Janet & John Rees
1400 Saiz Rd.
Bloomfield, NM 87413

Olson, William

From: Dneeper@aol.com
Sent: Thursday, April 08, 2004 10:32 PM
To: WOLSON@state.nm.us
Subject: Pit Guidelines Comment

NEW MEXICO CITIZENS FOR CLEAN AIR & WATER, INC.
Comments on draft Pit Guidelines dated March 16, 2004.

Donald A. Neeper dneeper@aol.com
2708 B. Walnut St.
Los Alamos, NM 87544-2050
505-662-4592

The sections of these comments are numbered so as to separate the topics upon which comments are made. Following the general comments, items appear in the order of the topics in the draft guidelines. However, the numbers of the comments do not correspond to the numbering of the sections of the draft guidelines themselves.

1. GENERAL COMMENTS
Liners.
Although the adopted rule exempts most of the San Juan basin and some of the southeastern producing area from the requirement for pit liners, the guideline for general practice should be to use a liner except when a pit will contain only fresh water and/or non hazardous minerals.

Pits within pads.
The rules and the draft guidelines necessarily treat pits as objects separate from other structures. However, pits (particularly drilling and workover pits) become part of the pad remaining after drilling is completed and the well is producing. The pad often becomes a broad, bladed area repeatedly traversed in any direction by vehicles and heavy equipment. The exact location of the pit will not be recorded if a general closure plan is used for numerous wells by one operator. Frequently, the pit remains buried at an unmarked location under a barren pad, unvegetated, subject to continuing surface disturbance and erosion. When large debris, such as trees, are buried in a pit, the surface will eventually subside, enhancing the infiltration of water. When the pit cannot be closed and restored separately from continuing site activities, we recommend that the guidelines specifically require marking of the pit boundaries, and subsequent surface restoration coincident with site closure. Prior to site closure, the filled pit should be protected from undue erosion.

2. DESIGN AND CONSTRUCTION
The guideline requiring stockpiling of topsoil is welcome. We suggest this requirement should also apply to the entire pad area. We have found pads of one to three acres in size, repeatedly disturbed by traffic, eroding by rainfall, with steep bare sides washing into adjacent arroyos. We suggest that best management practices be applied to limit dust, erosion by water, and to exclude

vehicles and encourage revegetation on all areas not absolutely required for traffic.

3. DRILLING AND WORKOVER PITS

Membrane materials should be specified by performance, not thickness. Performance includes specific strength and punctures as tested by particular ASTM methods. The ASTM methods specify tests, but not necessarily the performance standards required by a specific application.

4. DISPOSAL AND STORAGE PITS

The proposed guideline specifies that a clay liner have a thickness of at least two feet and a hydraulic conductivity no greater than 10^-7 cm/s. This is acceptable for a pit with a double liner and an intervening leak detection system. However, as shown below, the guideline may lead to frequent alarms of apparent leaks that are, in fact, seepage from the liner.

The pond above such a liner might be four feet deep, thereby generating a head of six feet from water surface to the bottom of the two-foot liner. The seepage allowed by the draft specification would allow annual seepage of a layer of salt water approximately 3.7 inches thick. This would saturate a soil with porosity 30% to an increasing depth of approximately one foot each year. Such a situation would be unacceptable without the second liner and leak detection system. However, in time, half the head would develop across the second liner, resulting in discharge to the ground. In long term use in deep ponds, liner systems that meet but do not exceed the guideline conductivity would prove unacceptable--leading to disregard of the guideline.

Furthermore, the draft guideline specifies that permeability tests be done in the laboratory or at a localized spot of the site. Experience shows that permeability is scale dependent--the larger the area over which permeability is measured, the larger will be the measured value of the permeability. This is attributed to the fact that flow occurs preferentially in larger channels, and a larger area tends to incur more large channels than a selected small area or sample of clay material. The effective permeability might be an order of magnitude larger than the value measured in a laboratory sample or measured at one spot in the field. Thus, at a large pit, the specified liner might permit seepage of salt water sufficient to saturate approximately ten feet of soil per year. We suggest that the measured hydraulic conductivity of any liner, whether clay or synthetic, be less than 10^-9 cm/s. Again, the resistance to tears and punctures must be specified as numerical property values. Citing an ASTM test specifies the test procedure, but does not specify the property of the tested material.

In an arid climate, infiltration into the soil beneath a liner could be inhibited by installation of a ventilated capillary barrier beneath the liner. If such an installation were used, the thin layer of contaminated soil and barrier material should be removed when the pit is closed. We suggest that OCD stimulate industry's consideration and evaluation of such a system, in case it proves more reliable or less costly than the specified double liner.

5. FENCES AND NETTING

The draft guideline specifies that a fence be maintained around the facility perimeter. Presumably, "facility" includes wellhead, tanks, separators, fixed equipment, and the pad. We have observed few facilities with such fences, but we welcome such practice. We have seen fences around particular equipment, such as an inhibitor tank or blowdown pit. We suggest that the bottom two feet of fence be covered with chicken wire or equivalent, to exclude small mammals. The entries to all fenced areas should have gates or other closures that exclude animals as effectively as the fence itself. We have seen otherwise excellent fences constructed with a permanent opening for personnel that also admits animals--thereby negating the effectiveness of the fence!

The draft guideline permits exception to the requirement for netting if the facility is proved to be "not hazardous to migratory birds." It is unclear how one might prove that a facility is not hazardous, unless it contains only non hazardous materials. Furthermore, it is insufficient to grant an exception based on migratory birds only. In an arid area, other birds will drink from an uncovered pond. It is acceptable to exempt drilling and workover pits--but only so long as personnel are on the site 24 hours per day.

6. OPERATION AND MAINTENANCE
The draft guideline specifies that the operator have a contingency plan in case of a leak. The guideline specifies that the plan must describe steps to mitigate damage to ground or surface waters. The guideline should also specify mitigation of damage to the vadose zone.

7. SOIL AND WATER REMEDIATION LEVELS
The ranking criteria are not indicative of the risk to either the vadose zone or water. If contamination were more than 1000 horizontal feet from a well or surface water, or more than 100 feet above ground water, the contamination would be rated as zero risk. However, contamination often is transported by so-called "fast paths" much farther than 100 vertical feet, and various forms of transport will move the contamination horizontally. Thus, the guideline in effect allows pollution to continue unabated.

The draft guideline requires remediation for salts only if contamination of useful water is expected. This permits--even encourages--pollution of the vadose zone on which almost all plant life depends. Ignoring the vadose zone is not protective of the environment. The guideline should protect the vadose zone.

8. REMEDIATION
This draft guideline encourages burial of wastes, including salt, so long as the pit bottom is more than 50 feet above ground water. Such a guideline ignores subsurface transport, encourages deliberate pollution of the vadose zone, and disposal of wastes in areas that may, in the future, be needed for other purposes. Other industries are not permitted to bury toxic wastes. The petroleum industry should not be allowed to do so. Nothing other than non hazardous mineral wastes should be buried on site. Other burial leaves a legacy of pollution, and ultimately, generates liability.

9. GROUND WATER CONTAMINATION

The draft guideline is in error in its statement that an abatement plan is not required "for sites where ground water is remediated to WQCC standards within 1 year ..." Rule 19(B) says "The vadose zone shall be abated so that water contaminants in the vadose zone will not with reasonable probability contaminate ground water or surface water ..." It is not sufficient to remediate only the ground water, and the guideline must not suggest that such limited action is sufficient. The vadose zone must be remediated and sampled to assure that the expected remediation has occurred.

10. CONCLUDING REMARK

Both in this guideline, and elsewhere as noted in these comments, the draft guidelines ignore or even encourage contamination of the vadose zone. This is at best inadequate regulation; some people may regard it as a dereliction of duty. We encourage the OCD to recognize that, under the RCRA exemption, OCD has a challenge to protect the environment as well as might be done under RCRA, but with the opportunity for much less formality and paperwork. NMCCA&W recognizes that a dollar spent on paperwork cannot also be spent on prevention or abatement. We are therefore inclined to encourage informal working relationships and voluntary cleanup beyond the numerical standards. The water, the soil, and the biota all merit protection. Petroleum development need not generate permanently sacrificed real estate.

Yolanda Perez
Sr. Regulatory Analyst
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Houston, Texas 77252-2197
Tel: 832-486-2329
Fax: 832-486-2764

ConocoPhillips

April 8, 2004

New Mexico Oil Conservation Department
1220 South Francis Dr.
Santa Fe, New Mexico 87505

Attn: Mr. Bill Olson
Hydrogeologist

Re: Comments regarding NMOCD Draft "Pit and Below-Grade Tank Guidelines" (issued March 16, 2004)

Dear Mr. Olson:

ConocoPhillips Company (COPC) appreciates the opportunity to submit these comments on the draft Pit and Below-Grade Tank Guidelines issued March 16, 2004. COPC operates approximately 5000 wells in the Northwestern and Southeastern part of New Mexico and maintains an active drilling and workover program. COPC recognizes the amount of work required by NMOCD to develop the Draft Guidelines. However, we do have concerns about the Draft Guidelines, and are hereby submitting comments to reflect our concerns. COPC further supports comments on the draft submitted by the New Mexico Oil and Gas Association (NMOGA).

Our primary concern relating to the Draft Guidelines is their enforceability on a statewide basis for all sites. New Mexico statutes define a "rule" as:

> the whole or any part of every regulation, standard, statement or other requirement of general or particular application adopted by an agency to implement, interpret or prescribe law or policy enforced or administered by an agency, if the adoption or issuance of such rules is specifically authorized by the law giving the agency jurisdiction over such matters. It also includes any

> statement of procedure or practice requirements specifically authorized by the Administrative Procedures Act or other law. . ..

New Mexico Administrative Procedures Act, NM Stat. Ann. § 12-8-2(G)

Language in the Draft Guidelines (e.g. "shall...") suggests that stipulations contained in the document are required and enforceable in all cases. Clearly, if these Draft Guidelines are applied to all situations without the flexibility to propose or consider other methods or practices which would meet the Commission's published rules relating to pits at NMAC 19.15.2.50, the Guidelines must be published as a rule. The rulemaking requirements of the New Mexico Administrative Procedures Act have not been met by the issuance procedures for the Draft Guidelines.

This issue is further highlighted by several very specific conditions required by the Draft Guidelines that are derived from the regulation, but are much more specifically prescribed in the Draft Guidelines (e.g. waste sampling and liner specifications). If these specific limitations are applicable at all sites without limitation, the Draft Guidelines must be published as a rule.

In addition to the Draft Guidelines, the NMOCD has issued form C-144. At the conclusion of the form, applicants are required to "certify" the application is in compliance with the Draft Guidelines. This certification is not supported by the rule, and requiring such a certification raises concerns of strict statewide enforcement of the Draft Guidelines as discussed above. This certification must be removed, or the form should be the subject of a rulemaking by the agency.

Further, we would like to see a statement added excluding historical pits or below-grade tanks from the Rule and Draft Guidelines.

We are deeply concerned with the Draft Guidelines treatment of chloride remediation targets. The Draft Guidelines set a technically unsupportable and unrealistically low target concentration for chlorides in soil based on the secondary drinking water standards. The application of water standards to soil concentrations of a contaminant is scientifically questionable. We would propose that the language currently contained in Section VI.A.2(c) be modified to read as follows:

<u>(c) Remediation Levels For Non-Hydrocarbon Contaminants</u>

Soils contaminated by chlorides or other associated contaminants shall be assessed to determine the reasonable probability that said contaminants could be detrimental to groundwater or surface water in excess of the standards in 19.15.19B. (2) NMAC and 19.15.1.B (3) NMAC contaminate leaching, percolation, or other transport mechanisms, or as the water table elevation fluctuates; or pose a threat to human health or the environment. If assessment determines standards cannot be met, soils will be managed to meet the standards in 19.15.19B. (2) NMAC and 19.15.1.B (3) NMAC.

In their treatment of sampling The Draft Guidelines should allow for representative waste sampling/analysis rather than requiring analysis of each site.

In conclusion, COPC would like to bring attention to the extensive administrative burden for industry and the NMOCD due to requiring drilling and workover pits to be permitted.

ConocoPhillips Company appreciates the opportunity to comment on the Draft Guidelines, and we are available to clarify these comments or to discuss possible changes to the Draft Guidelines. If you have specific questions about these comments, please contact Yolanda Perez at (832) 486-2329 or Michael Nelson at (832) 486-2316.

Sincerely,

Yolanda Perez

Yolanda Perez
Sr. Regulatory Analyst
Mid America Business Unit

Olson, William

From: Jack Duffey [jduffey@leaco.net]

Sent: Wednesday, April 07, 2004 8:52 AM

To: wolson@state.nm.us

Subject: odc drilling and workover pit requirements

Dear Sir,

I operate a oilfield service company dealing mostly with pit lining. After reviewing ODC requirements for drilling and workover pits I have some concerns about these specifications. The 12 mil requirement is too general in my opinion. Many liner materials may be 12 mil but that doesn't mean that they are good for lining pits. We commonly use an 8 mil reinforced liner that is superior to a 12mil poly. Not only is it stronger but lighter which allows us to use larger sheets requiring fewer field seams. The 8 mil also expands and contracts less making it easier to lay a pit liner that has ample slack to allow for expansion and contraction, as well as any shift of the pit walls. As you can tell thicker does not always mean better.

I would like to see your specifications to focus on liner standards that insure a good pond liner membrane is used at all times. Having a mil thickness requirement does not accomplish this goal. Thanks for your time.

Sincerely,
Jack Duffey
Akome Inc.
Hobbs NM

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elpaso | Field Services

April 1. 2004

New Mexico Oil Conservation Division
Environmental Bureau
1220 S. St. Francis Dr.
Santa Fe, NM 98505

RE: Comments on NMOCD Pit and Below Grade tank Guidelines

Dear Sirs:

El Paso Field Services Co. ("EPFS") operates a number of compressor station, several plants, and an extensive natural gas gathering system in the state of New Mexico. EPFS appreciates the opportunity to comment on the NMOCD Pit and Below Grade Tank Guidelines.

Section II – paragraph A. 2. EPFS believes it is impracticable to stockpile top soils from pit construction at large, long life facilities. The Chaco Gas Plant, located south of Farmington, NM has been in operation for well over 40 years. Had there been an attempt to stockpile the top soils from pits in use at Chaco, those stockpiles would have long since been lost to erosion.

Section II – paragraph A. 4. EPFS operates several industrial waste water ponds ranging in size from 120' by 120' up to 350' by 1,000'. We have seen no evidence that wave action has caused any overtopping in those small ponds. There seems to be little benefit in trying to determine the effects of wave action over such small areas. In addition, in the absence of wave action determinations, two feet of freeboard in a pond in our extremely arid environment seems to be excessively strict.

Section II, paragraph E. 1. EPFS has operated a number of double walled below grade tanks for the past 10 years. These buried tanks are made up of two complete steel tank shells, one nested within the another. The outer tank is protected by an external corrosion coating. There are spacers installed in the bottom of the outer tank so the floor of the inner and outer tank are approximately two inches apart. The inner and outer tank are welded to a common top, with sample ports installed to monitor the leak detection space. The leak detection method used has been to physically check the interstitial space once each calendar quarter. We have never found a leak in any of the inner tanks during the ten years of operation. EPFS believes that such physical "dip stick" inspections provide more than adequate protection, and should be included in the guidelines. A ten year operational history should also be adequate to support quarterly rather than monthly monitoring (Section III, paragraph A.).

Section VI. EPFS believes very strongly that <u>all</u> closure standards should be based on a Risk Based Closure Assessment("RBCA") system. The closure and clean up criteria in the Guidelines were developed approximately ten years ago. EPFS recommends that in lieu of the current proposed guideline, the OCD Guidelines should adopt the research conducted by Dr. William Rixey of the University of Houston as a basis for closure assessments. Dr. Rixey's work was specific to New Mexico oil and gas production areas, and provides a valid scientific basis for determining the closure standards and clean up levels applicable to each individual site. Other oil and gas producing states have adopted clean up standards based on or similar to Dr. Rixey's work, even though his research was focused on the Permian and San Juan Basins.

Sincerely yours,

David Bays

David Bays, REM
Principal Environmental Scientist

BURLINGTON
RESOURCES

RECEIVED

APR 12 2004

Oil Conservation Division
1220 S. Saint Francis Drive
Santa Fe, NM 87505

April 8, 2004

Fax received
4/8/04

Mr. Bill Olson
Hydrogeologist
New Mexico Oil Conservation Division
1220 St. Francis Dr.
Santa Fe, NM 87505

RE: Burlington Resources Updated Comments on NMOCD Draft Guidance Document entitled "Pit and Below Grade Tank Guidelines"

Dear Mr. Olson:

Burlington Resources (BR) appreciates the opportunity to provide updated comments on the draft guidance document referenced above.

BR is pleased to see the NMOCD has removed reference of theses guidelines from the final pit and below grade tank rule, Title 19, Chapter 15, Part 2, Section 50. Both BR and NMOGA stated that during the rulemaking that the subject guidelines should be a guide for industry's use in expediting approval of permits. To better assure the proper design and closure of pits and below grade tanks, these minimum guidelines need to be based on documented scientific research and peer reviewed data. Further, these guidelines should not replace the rulemaking process. Where the NMOCD intends for minimum standards to be met to assure protection of ground water, public safety and the environment, then NMOCD has the responsibility and the obligation to enact such requirements through a formal rulemaking and not to use the guidelines as a mechanism to avoid the rulemaking process.

During the time Mr. Ed Hasely represented BR on the Stakeholders committee, the NMOCD indicated that adequate time would be given to the development of these guidelines. For the pit and below grade tank rule, NMOCD allowed considerably more time and a more participative process for all parties to provide comment and technical input into the rule. BR is concerned that the expedited comment period for the guidance document is far too abbreviated and could lead to poor policy. Further, a concern exists about the lack of some complete scientific research and data, which is critical to developing this guideline document.

Provided below are specific issues of concern to BR with respect to the above referenced guideline:

1) **<u>INTRODUCTION:</u> The following specifications SHALL be used as a guide...**

BR has concerns that the guidelines shall be used. This implies that the guidelines are required and not suggested indicating that the NMOCD is trying to circumvent

the rulemaking process. This effort is further enforced by the rule requiring the Operator to use the C-144 form and certify that they have adhered to the guidelines for construction and closure. Consequently, it appears the guidelines now have the same status as a regulation without being subject to a formal rulemaking process.

2) **PERMITTING PROCEDURES: The guideline calls for formal approval of all drilling, workover, and completion pits.**

Both NMOGA and BR provided extensive testimony regarding this issue and there was tacit understanding and agreement by the NMOCD representatives in the workgroup that there was no need for a formal, detailed approval process for temporary drilling, workover, and completion pits. BR felt that these temporary types of pits were in fact authorized by the rule and did not require the redundancy of permitting. NMOCD representatives indicated that they merely wanted a general description on the existing APD (i.e., form C101 or Sundry Form C-103)) regarding whether a pit was going to be constructed, a general description of the pit construction, and how closure was anticipated. Although BR suggested language was not accepted by NMOCD in the final rule, the intent was achieved by the final rule language that stated in part "A separate form C-144 is not required." By incorporating the C-144 form into the form C101 and Form C-103, NMOCD has in fact required the C-144 form and required the more extensive detail that NMOCD representatives agreed was not necessary. BR vigorously objects to this approach to require approval for temporary drilling, workover, and completion pits.

3) **DESIGN AND CONSTRUCTION: The guideline calls for at least a 12 mil liner as acceptable for drilling and workover pits except in the circumstances where salt based drilling fluids, hydrocarbon fluids, or other contaminants that have the potential to contaminate fresh water and where the operator intends to encapsulate the pit contents in place upon completion of drilling and workover activities.**

First, BR wishes to clarify that a lined pit is not always required and unlined pits are allowed in areas so specified in the rule (19.15.2.50 Section C, Paragraphs (g)(ii) and (g)(iii). Hence, BR believes that the guidance document should reference that the liner guideline applies as required by rule.

Second, BR disagrees that either the 12 mil or 20 mil synthetic liner is the exclusive design standard. A suitable clay liner with equivalent permeability may be appropriate. BR understands that it is common industry practice to use a synthetic liner but where local clays may be available; it should be acceptable to construct an equivalent clay liner, where appropriate. Additionally BLM Conditions of Approval for drilling reserve pits in the southeast area of the state containing all fluid types stipulate that 6 mil synthetic liners are adequate. BR believes as a minimum, that 6 mil synthetic liners are adequate for "fresh water based drilling fluids".

Third, BR disagrees with the requirement that a 20 mil liner is required where salt based, oil based, or other contaminants have the potential to contaminate fresh water and where the operator intends to bury the pit contents in place. Technical *documentation is attached indicating that mil thickness is not a factor in maintaining the integrity of a synthetic liner when buried. "Thicker is not better". BR believes that as a minimum the commonly used 8-mil liner is technically sufficient in most of these cases. Unless NMOCD has specific and justified concerns for a given location, it can be specified in the approval that a 20-mil liner be required.*

Fourth, BR is concerned about the general reference to "Salt Based Drilling Fluids". In the Southeast area of the state naturally occurring salts are found in most of the fresh water. BR believes that "Salt Based" needs to be defined. For the Northwest area of the state, salt based and oil based drilling fluids are not used but the term "other contaminants" is not specific enough for proper interpretation. BR recommends that the wording be changed to require a 10 mil liner for salt based, oil based, or other contaminants specified by the NMOCD that have the potential to contaminate fresh water and where the operator intends to encapsulate the pit contents in place.

Fifth, BR would like to reiterate that there is only one documented closed case, and one disputable case of ground water contamination by a temporary drilling, reserve, workover or completion pit in the State's files.

4) **DESIGN AND CONSTRUCTION: The guideline requires the markings be required on the liner to indicate freeboard.**

Again, BR would reiterate the comments above that unlined pits are allowed in certain areas; therefore, this marking would not be practical in that circumstance. Furthermore, it seems unreasonable and unnecessary to require such markings on lined temporary drilling, workover, and completion pits. From our experience, one can readily determine whether the 2-foot freeboard is met without such markings. BR would suggest that this guideline be applied to pits constructed for long-term (more than 180 days) continuous use.

5) **BELOW-GRADE TANKS: The guideline requires that below grade tanks be of strong corrosion resistant construction, resistant to sunlight, installed on 1 inch of gravel, have visibility of the entire tank, and have a liner that is attached to the tank above grade.**

BR has numerous concerns about this section of the guideline. BR disagrees that strapping a 40-mil synthetic liner to the tank is the exclusive design standard. The guidelines do not allow for any manufactured double walled tanks. The corrosion resistant construction requirement seems inappropriate since this could be misinterpreted to mean stainless steel or more exotic materials. BR believes that a simple statement that the material must be compatible with the anticipated fluids seems more appropriate. The resistant to sunlight requirement seems inappropriate as well. BR assumes that NMOCD's concern is with fiberglass or other plastic materials, and that this guideline is a holdover from the 1993 guidelines. Fiberglass, PVC, and other plastic materials manufactured today typically have UV inhibitors incorporated into the resins so BR questions the need for this specification. Would an operator need to have proof of UV inhibitors and *keep this on record to meet this guideline? If NMOCD still has a concern about tank materials, then a better statement would be that the materials must be suitable for outdoor exposure. Another concern is the requirement to set tanks located below ground surface on 1 inch of gravel. BR believes that utilizing I-beams to situate tanks off the ground, sand, or other suitable material is as an acceptable design standard without requiring the exclusive use of gravel. Finally, for tanks installed below the ground surface in an open excavation, the guideline states that the entire tank shall be exposed to visually detect leaks. According to the definition of a below grade tank as developed for the pit rule, they are defined as vessels where any portion of the sidewalls are not visible. Hence, BR recommends that this wording be changed to correspond with the matching regulatory definition.*

6) **FENCES, SIGNS, AND NETTING: The guideline requires that fencing be around the perimeter of the facility, that a sign not less than 12" x 24" with lettering not less than 2" shall be posted on the fence, that the fencing not be constructed on berms, and the location on of the facility be identified by quarter-quarter section, township, and range.**

BR believes that the intent of preventing livestock from access is the key point so the prescriptive nature of this requirement is not necessary. If a fence around a pit or below grade tank is effective in preventing livestock access, then that is sufficient evidence of good design. With regard to the signs, BR objects to the need for an additional sign on the location since all locations are already required to have a sign designating the same information as listed in the guideline. BR believes that location identification allowing the use of a Unit Letter in lieu of providing ¼ ¼ section, as specified in rule 19.15.3.103 section F.4. is sufficient. If another company adds a pit to a location as part of a co-located well or gathering system pit, then they must too post a sign designating their operation. Consequently, this requirement seems redundant and unnecessary.

7) **NOTIFICATION: The guideline requires that notification be given to NMOCD for installing all liners or leak detection systems.**

According to the pit rule, notification only should be given to NMOCD for installing a leak detection primary liner. Hence, BR respectfully requests that the guideline be changed to correspond to the rule language and the as built documentation be limited to the installation of leak detection.

8) **CLOSURE SITE ASSESSMENT: The guideline requires a general site assessment for all pits.**

First, nothing in the pit rule required such an assessment for drilling, workover, and completion pits and it is unreasonable and unnecessary to require such an assessment. When an APD or Sundry is prepared for a given well, a general site assessment has already been prepared, fully acknowledging any established groundwater sensitive area, wellhead protection area, or surface water body. Hence, this section seems only applicable to existing or new storage or disposal pits at the point of reaching closure.

Second, the guideline in Section V.A.2. Wellhead Protection Area, requires the operator to determine the horizontal distance to all private, domestic fresh water wells or springs used by less than five households for domestic stock watering purposes and all other fresh water wells and springs. A question exists about which radius from the pit this information should be obtained. Is it assumed that the ranking criteria are the radius? For example, the wellhead protection area is <200 feet from a private domestic fresh water well or spring or <1000 feet from any other fresh water well or spring. In the absence of any specifics in the guideline regarding a required radius, we would proceed with our data collection based upon the ranking criteria. Consequently, it may be of value to clarify the intent and include the radii of the information requested. Further, the word "known" should be inserted before "private, domestic fresh water wells or springs... It is not uncommon to have difficulty identifying these, particularly if the wells have not been registered or the landowners are unwilling to disclose the information. BR recommends that the operator only determine distance to the extent of the ranking criteria.

Third, the guideline in Section V.A.3, Distance To Nearest Surface Water Body, requires the operator to determine the horizontal distance of all wetlands, playas, irrigation canals, ditches and perennial and ephemeral watercourses. As with the comment above, we are assuming, using the risk ranking criteria, which between 200' and 1,000' is the radius of concern for accumulating this data. Again, including the radius, suggested from the ranking criteria, would help clarify the expectation of the assessment. BR recommends that the operator only determine distance to the extent of the ranking criteria.

9) **<u>SOIL/WASTE CHARACTERISTICS:</u> The guideline states that soil testing is not required for lined drilling and reserve pits and that waste sampling is necessary for all drilling and reserve pits.**

BR believes that lined workover and completion pits are of the same nature as drilling and reserve pits and that they should be excluded from the requirement of soil sampling. Both NMOGA and BR provided extensive testimony that testing of any drilling, reserve, or workover pit was unnecessary unless a breach of that pit occurred. Given the fact that not all drilling, workover, and completion pits require liners, it should be further stated that unlined pits do not require soil testing as well. With regard to wastes that will remain within the pit for closure, there is no reason to test such pits where oil based and salt based muds have not been used. BR also believes that since the location of the pit will be documented and process knowledge of the drilling fluids will exist, sampling should be limited to cases when its value can be demonstrated.

10) **<u>SOIL AND WATER REMEDIATION LEVELS:</u> The guideline requires chlorides in the soil be remediated to 250 mg/kg, and ground water contaminated in excess of WQCC standards be remediated.**

First 250 mg/kg is the WQCC standard for water, not soil. BR believes that remediation of chlorides should consider background levels. There are many

instances in the southeast area of the state where back ground levels are much higher than 250 mg/kg. Remediation could be prescribed when no contamination has occurred.
Second, in the "UNLINED SURFACE IMPOUNDMENT CLOSURE GIDELINES" dated February 1993 ground water contamination in excess of NM WQCC ground water standards or natural background water quality will require remediation. BR believes that in the southeast area of the state, where water in excess of NM WQCC ground water standards is naturally occurring, that the 1993 original wording be retained to avoid situations requiring remediation when no contamination has actually occurred.
Third, BR would like the data developed from the BR TPH and Chlorides workgroup be considered when establishing remediation levels. BR would also like the API Chloride Study be considered as a valid method of determining the reasonable probability to contaminate ground water or surface water in excess of the standards in 19.15.1.19.B. (2) NMAC and 19.15.1.B. (3) NMAC through leaching, percolation, or other transport mechanisms.

10. SOIL And WATER SAMPLING PROCEDURES: The guideline requires in Section C. 4.(a), that the monitoring wells shall be purged a minimum of three well volumes of ground water..... in order to ensure the sample represents the quality of ground water in the formation and not stagnant in the wellbore.
It is important to note that it is not always possible to acquire three well volumes of ground water from a monitoring well. There are cases where the nature of a given aquifer will not yield three well volumes during a sampling episode. A suggestion would be to insert the words "To the extent hydraulically possible, monitor wells shall be purged...".

<u>11) SOIL AND WASTE MANAGEMENT OPTIONS:</u> The guideline calls for the contents of drilling and workover pits drilled or worked over with salt water that are to be encapsulated onsite be capped with either a 1-foot thick clay cap compacted to ASTM standards, or a 40 mil minimum thickness synthetic liner meeting ASTM standards that is designed to be resistant to the material encapsulated and when the bottom of the pit is located at least 50 feet above a source of fresh water.
BR disagrees that capping with clay or a 40 mil synthetic liner is the exclusive design standard to prevent migration of contaminants. Technical documentation is attached indicating that mil thickness is not a factor in maintaining the integrity of a synthetic liner when buried. "Thicker is not better". A technical document "Hydrologic issues in arid, unsaturated systems and implications for contaminant transport" is attached. In this recent work, at a site in Arizona, the USGS (Andraski et. al, 2002) (<u>http://toxics.usgs.gov/pubs/agu_poster/</u>) reports "chloride-concentration profiles indicate that percolation past the 10-m depth (approximately 33 feet) has been negligible for the past 16,000 years". BR would recommend that NMOCD consider using 10 meters or 33 feet instead of 50 feet. Other current and

ongoing scientific research has indicated that there are other methods that are as effective or better in preventing the migration of chlorides. One study indicated that a current practice, similar to the prescribed guideline, could enhance the migration of chlorides to the surface. BR would again emphasize that the API Chloride Study, and the recent USGS work, be used to allow other designs that would be technically acceptable.

12) <u>SURFACE RESTORATION:</u> The guideline requires successful re-vegetation of the area.

According to the pit rule, within one year of the completion of closure of a pit, the operator shall contour the surface where the pit was located to prevent erosion and ponding of rainwater. Hence, BR respectfully requests that the guideline be changed to correspond to the rule language. Re-vegetation could be considered to include non-native species and noxious weeds which is obviously not the intent..

13) <u>CLOSURE REPORTS:</u> The guidelines require a separate closure form be filed.

The rule allows for the filing of a general permit for a class of like facilities and requires the proposed disposal method of drilling fluids and cuttings to be described on the application. BR believes that when the general plan is approved and the closure is within the allowed 180 days, the application and closure report are one in the same. When an APD or Sundry is prepared for a given well, a general site assessment has already been prepared, fully acknowledging any established groundwater sensitive area, wellhead protection area, or surface water body.

In closing, BR appreciates the opportunity of providing the following comments on this guideline. However, we want to reiterate our recommendation that more time should be given to study and comment on this guideline using a collaborative approach. By doing so, a better final product will result that achieves the intended goal of the document. BR would gladly participate in such an approach if given the opportunity.

Respectfully,

Bruce A Gantner

Bruce A. Gantner, PE
Manager, EHS

Cc: John Zent, Rick Muncrief, Donnie Sperry, Larry Dillon, Ed Hasely

Olson, William

From: Dan Girand [dgirand@mackenergycorp.com]
Sent: Friday, April 09, 2004 4:45 PM
To: WOLSON@state.nm.us
Subject: Pit guidelines

Mr. Bill Olson

Hydrogeologist

New Mexico Oil Conservation Division

1220 St. Francis Dr.

Santa Fe, NM 87505

RE: NMOCD Draft Guidance Document entitled "Pit and Below Grade Tank Guidelines"

Dear Bill:

Mack Energy is pleased to comment on the proposed draft guidelines for pits and below grade tanks. We participated in the pit rule meeting and the OCC hearing on that rule. We appreciate working with OCD personnel on issues of mutual interest.
We incorporate by reference the comments by NMOGA and IPANM on these draft guidelines.
We are very concerned about the direction taken by the pit rule and now the draft guidelines.
This is not a guideline, but a rule masquerading as a guideline, without going through the hearing process.
There are 105 "shalls" and 12 "musts". "shall" appears in one paragraph four times. Guidelines are not enforceable like a rule is and over 100 "shalls" do not make a guideline. This draft must be rewritten.
In many of the 'shalls", it sounds as if we will have to have a professional engineer to meet the requirements. It must be made clear that nothing in the guidelines can be construed to require an engineer.
The draft refers to many outside standards we must use. This makes the guidedlines a rule. Also if there is a reference to outside standards, they must be attached to the guideline.
There is no science to support most of the requirements listed in this draft.
The draft sems to require industry to remediate water to WQCC standards, but

much of our water, naturally, does not meet WQCC standards. We cannot improve on nature.

Deletions, additions, and comments are in red.

PIT

AND

BELOW-GRADE TANK

GUIDELINES

(March 16, 2004)

NEW MEXICO OIL CONSERVATION DIVISION
1220 SOUTH ST. FRANCIS DR.
SANTA FE, NEW MEXICO 87505

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INTRODUCTION

The following specifications shall be used as a guide for pits or below-grade tanks used for the containment of exploration, production, processing and storage wastes regulated by the New Mexico Oil Conservation Division (OCD), and classified as 1) exempt from Federal Resource Conservation and Recovery Act (RCRA) Subtitle C Regulations, or 2) non-hazardous by characteristic testing. This document provides guidance for permit application, design, construction, operation, maintenance and closure of ~~unlined~~ pits and below-grade tanks in a manner that protects fresh waters, public health and the environment. Pits and below-grade tank permits and closures are reviewed and approved pursuant to 19.15.2.50 NMAC.

The New Mexico State Engineer has designated fresh waters as all surface waters and ground waters of the state containing 10,000 milligrams per liter or less of total dissolved solids (TDS) for which there is a present or reasonably foreseeable beneficial use. The term "reasonably foreseeable" generally has been taken to mean a time period of not less than 200 years into the future, but could be thousands of years. **As I read the Environmental Law Handbook for New Mexico by Bohannon, the WQCC says they protect water of less than 10,000 mg/l tds for present and future use as domestic and agricultural water supply. P. 64 Groundwater is interstitial water which is capable of entering a well in sufficient amounts to be utilized as a water supply. In the original EID hearing on water in 1976 EID testified that an aquifer is a subsurface water bearing unit that transmits water rapidly enough to supply useful quantities to springs and wells. A domestic water supply would be a source that is able to produce water in sufficient quantities not to run dry under normal use. Any source to be acceptable as a water supply must be present on a year-round basis. This is the only water we need to protect.**
We should not have to protect all water less than 10,000 TDS for ever.

A pit is defined as any surface or sub-surface impoundment, man-made or natural depression, or diked area on the surface. Excluded from this definition are berms constructed around tanks or other facilities solely for the purpose of safety and secondary containment. The term pit includes but is not limited to: -produced water pits, dehydrator pits, blowdown pits, separator pits, tank drain pits, pipeline drip collector pits, compressor scrubber pits, flare pits, drilling pits, reserve pits, workover pits and all other pits which receive exploration, production and processing wastes regulated by the OCD. Below-grade tanks are defined as vessels, excluding sumps and pressurized pipeline drip tanks, where any portion of the sidewalls of the tank is below the surface of the ground and not visible. Sumps are defined as any impermeable single wall vessel with a capacity less than 500 gallons, where any portion of the sidewalls of the reservoir is below the surface of the ground and not visible which vessel remains predominantly empty, serves as a drain or receptacle for spilled or leaked liquids on an intermittent basis, and is not used to store, treat, dispose of, or evaporate products or wastes.

Compliance with these guidelines does not relieve an operator of liability for any releases or contamination which may pose a threat to fresh waters, human health and the environment, or relieve an operator for responsibility for compliance with any other federal, state or local laws and regulations.

I. PERMITTING PROCEDURES

The applicant shall submit a "PIT OR BELOW GRADE TANK APPLICATION, REGISTRATION OR CLOSURE FORM" on either Form C-144, Form C-101A or Form C-103A, as appropriate, accompanied by the information necessary to evaluate the application. *All* Pplans and specifications shall be submitted to and approved by the OCD prior to construction. Designs for Cconstruction and operations may deviate from the following specifications if the operator shows that the proposed design and operation of the facility will prevent contamination of fresh water and protect public health and the environment. **I do not remember we are required by the rules to have a plan for all pits. "Plans and specifications" and "designs" sounds like an engineering design. It will certainly be construed that way. It appears we will have to submit every pit design, including drilling pits, with the seal of a registered professional engineer. The last sentence requires industry to prove a negative and that is impossible. Ed Hasley thought** it was to be as simple as stating - "A lined reserve pit and an unlined blow pit will be constructed on location. The pits will be closed within 180 days of completion by backfilling once the free liquids have evaporated."

If an operator intends to use the same procedures for construction of pits and below-grade tanks at multiple sites, the operator may submit one general plan. A list of those sites, their locations, and other relevant site-specific information shall be submitted with the general plans and specifications. Deviation from an approved general permit requires OCD notification and approval.

If any pit, berm or levee to be constructed is more than ten feet (10') in height from ground level, or if a pit volume is more than 10 acre-feet, the State Engineer Office must also review and issue a construction permit.

A permit under 19.15.2.50 NMAC does not relieve the applicant of responsibility should the operation result in pollution of surface or ground waters or the environment. In addition, a permit under 19.15.2.50 NMAC does not relieve the applicant of responsibility to comply with any other federal, state or local laws or regulations.

II. DESIGN AND CONSTRUCTION

A. GENERAL

1. Location

No pit shall be located in any wetland, watercourse, lakebed, sink-hole, or playa lake. We need a definition of these. There are many different definitions and everything could be included. Without definitions, these words must come out. Pits adjacent to any such watercourse or depression shall be located safely above the high-water level of such watercourse or depression. In most of our SE areas, there is no way to determine the high water level. This is all so vague as to be arbitrary. The OCD may require additional protective measures for pits located in ground water sensitive areas or wellhead protection areas. What is a ground water sensitive area? Without definitions these words must come out. See comments from Environmental Law Handbook above. These guidelines greatly expand the parameters to be protected.

2. Stockpiling of Topsoil

Prior to constructing any pit, except a pit constructed in an emergency, top soil shall be stripped and stockpiled for use as the final cover of fill at the time of closure.

3. Exclusion of Runoff Water

A pit shall be constructed and maintained so that runoff water from outside the location is not allowed to enter the pit.

4. Freeboard

The design freeboard **They need to define freeboard.** allowance shall take wave action into account to prevent overtopping due to wave action. A determination of the wave type (breaking or non-breaking) shall be made to determine the forces acting upon the berm. Such calculations shall be submitted with the details for pit construction. In the absence of such calculations, the minimum freeboard shall be two feet. Liner markings or some other device shall be installed to accurately measure freeboard. **This will require an engineer. I have never heard of the wave action damaging a pit. Looks as if all these apply to drilling and workover pits also. That was not the deal from our meetings.**

B. DRILLING AND WORKOVER PITS

Drilling and workover pits shall be constructed with a synthetic liner at least 12 mils thick. If the pit will contain salt based drilling fluids, hydrocarbon fluids or other contaminants that have the potential to contaminate fresh water and the operator intends to encapsulate the pit contents in place upon completion of drilling or workover activities, the pit shall be constructed with a synthetic liner at least 20 mils thick. Liners shall be designed and constructed as follows: **No the science industry provided at the pit hearing, which was not disputed, indicated the stuff in pits will not migrate for 600 years or so. That was from the API study. There will always be some salt based stuff in the pits along with hydrocarbon fluids, but the critical issue is "other contaminants" which is anyting. This is too broad and vague so as to be arbitrary in implementation of the guidelines.**

1. Membrane materials shall have good resistance to tears or punctures and shall meet minimum ASTM standards*. **I do not know what these are. A guideline is not a rule.**

so how can it contain reference to a standard with is not flexible? All these standards change over the years and there is no provision to update the OCD guidelines. Each opertor cannot be expected to join an association and purchase these standards. The pertinent parts must be extracted and made a part of the guidelines.

2. All materials used for lining pits shall be resistant to hydrocarbons, salts, and acidic and alkaline solutions. The liners shall be made of materials resistant to ultraviolet light or protected from the sun. Liner compatibility shall comply with EPA Method 1990, *Compatibility Test for Wastes and Membrane Liners.* ***NO there is nothing wrong with the liner material we have now. These are guidelines, but we must comply with some EPA rule we know nothing about. Liners for drilling and workover pits are not in place long enough to deteriorate. IPANM and NMOGA attached studies to their comments about pit lining.***

3. The bed of the pit and inside grade of the berm shall be smooth and compacted, free of holes, rocks, stumps, clods, or any other debris that may rupture the liner. In rocky areas, it may be necessary to cover the pit bed with a felt pad, compacted six-inch layer of sand, or other suitable cushioning materials. **There is about 1000% overkill here. We have had very few liners that were breached and none that reached ground water that we know of.**

4. The liner shall rest smoothly on the pit bed and the inner face of the berms. In locations where temperature variations are significant, wrinkles or folds shall be placed at each corner of the pit to allow for the contraction and expansion of the membrane due to temperature variations. The membrane manufacturer should be consulted on this matter. **The draft is full of broad undefined statements which leave the industry with no idea or certainty about what is required.**

5. At any point of discharge into the pit, the liner shall be protected from the fluid force of discharges. **How is this done?**

* **The American Society for Testing and Materials (ASTM) standards may be obtained from the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pennsylvania 19103. No they must be attached to the guidelines. But since these are guidelines, there can be no standards used.**

C. DISPOSAL AND STORAGE PITS

At minimum, disposal and storage pits must be constructed with a primary and secondary liner with a leak detection system. The liners may be synthetic liners, clay liners where the bottoms and sides have a hydraulic conductivity no greater than 1×10^{-7} centimeters per second, or an alternative liner or barrier approved by the OCD which is certified by a professional engineer registered to practice in the State of New Mexico. All disposal and storage pits shall contain a leak detection system as described in Section II.E. Pit liner systems shall be designed and constructed as follows: **This is too much detail for a guideline. It is written like a rule. We cannot be expected to hire Professional Engineers to meet planning and design criteria. There are not enough of them in the SE or NW for the workload this will create. The message from industry is that there is no, or at worst, a de minimus problem.**

2. Wall Slopes

The outside slope of pit walls shall be no steeper than 3:1 horizontal to vertical (Figure 1). The inside slope of pit walls shall be no steeper than 2:1 horizontal to vertical, except for natural liners which have slope specifications as set out in subsection 2 below.

2. Clay Liners

(a) Barriers constructed with natural clay materials shall be at least two feet thick, placed in six-inch lifts, and compacted to 95 percent of the material's Standard Proctor Density (ASTM D-698).

(b) Clay materials used in a liner shall undergo permeability testing before and after construction.

(c) Pre-construction permeability testing shall consist of laboratory permeability tests on at least two specimens of representative clay liner materials compacted in the laboratory to 95 percent of the material's Standard Proctor Density (ASTM D-698).

(d) Post-construction permeability testing shall consist of at least two laboratory permeability tests on the completed clay liner or one field permeability test on the completed soil liner. Particular emphasis shall be placed on selecting the location(s) for permeability tests or test samples where non-uniformity in soil texture or color can be observed.

(e) Laboratory permeability test procedures must conform to one of the methods described for fine-grained soils in the Corps of Engineers Manual EM-1110-2-1906 Appendix VII. In no case shall the pressure differential across the specimen exceed five feet of water per inch of specimen length. Field permeability tests shall be conducted only by the double ring infiltrometer method as described in ASTM D-3385.

(f) If permeability testing shows that addition of bentonite or other approved material is needed to assist the clay in meeting the permeability standard, it shall be applied at a minimum rate specified by the testing or engineering firm. Any bentonite used for liner material shall not have been previously used as drilling mud. **Testing by an engineering firm? These are guidelines, not rules and most of this is in the form of a rule.**

(g) Any clay liner shall be constructed by disturbing the soil to the depth of the bottom of the liner, applying fresh water as necessary to the clay materials to achieve a moisture content wet of optimum, then re-compacting it in six-inch lifts with heavy construction equipment, such as a footed roller, until the required density is achieved.

(h) Any clay liner shall cover the bottom and interior of the pit entirely.

(i) Any clay liner shall be installed on a slope no steeper than 3:1 horizontal to vertical.

3. Synthetic Liners

(a) Synthetic materials may be rigid, semi-rigid, or flexible and shall be at least 40 mils thick. **Where did 40 mils come from and is there any science tosupport this requirement? 40 mil is not available in New Mexico and the t cost will be very high.**

(b) If rigid or semi-rigid materials are used, leak proof expansion joints shall be provided, or the material shall be of sufficient thickness and strength to withstand (without cracking) expansion, contraction, and settling movements in the underlying earth.

(c) If flexible membrane materials are used, they shall have good resistance to tears or punctures and shall meet minimum ASTM specifications.

(d) All materials used for lining pits shall be resistant to hydrocarbons, salts, and acidic and alkaline solutions. The liners shall also be resistant to ultraviolet light or provision shall be made to protect the material from the sun. Liner compatibility shall comply with EPA Method 1990, *Compatibility Test for Wastes and Membrane Liners.*

(e) The bed of the pit and inside grade of the berm shall be smooth and compacted, free of holes, rocks, stumps, clods, or any other debris that may rupture the liner. In rocky areas, it may be necessary to cover the pit bed with a compacted six-inch layer of sand or other suitable materials.

(f) A trench shall be excavated on the top of the pit berm around the entire perimeter of the pit for the purpose of anchoring flexible liners. This trench shall be located at least nine inches (9") from the slope break and shall be at least twelve inches (12") deep. See Figure 3.

(g) The liner shall rest smoothly on the pit bed and the inner face of the berms, and shall be of sufficient size to extend down to the bottom of the anchor trench and come back out a minimum of two inches (2") from the trench on the side furthest from the pit. See Figure 3. In locations where temperature variations are significant, wrinkles or folds shall be placed at each corner of the pit to allow for the contraction and expansion of the membrane due to temperature variations. The membrane manufacturer should be consulted on this matter.

(h) An anchor of used pipe or other similar material shall be placed over the liner in the anchor trench and the trench back-filled.

(i) Certain conditions require the venting of gas that may accumulate beneath a liner. If organic matter exists in the soils under the liner, or if natural gas is present in the region, gas production is likely. When a fluctuating water table is present immediately below the pit bottom, pockets of air may also accumulate below the liner. The net result of gas or air accumulation below the liner may be the "floating" of the liner to the pit surface. Two possible vent designs are illustrated in Figure 4. A uniform layer of sand (which less than 5% will pass the 200 sieve) or a geotextile beneath the liners will allow the accumulated gas to vent. To achieve the best results from either of these media, the slope from the lowest point of the pit to the toe of the dike must be at least 2%. The venting medium is carried across the entire bottom and up the side slopes. Vents shall be located approximately one foot (1') down from the crown of the dike. (See Figure 3)

(j) If the lining material used for the primary liner is not sun-resistant, at least one inch (1") of sand or other suitable material shall be spread uniformly to cover the liner over the floor of the pit. Gravel or other wave-resistant material with sufficient angle of repose to remain in place shall be used to cover the sloping inner wall of the berm. A geotextile liner shall be placed beneath any gravel layer to provide protection for the membrane liner. Any gravel or sand layers used to protect the membrane liner from the sun shall extend to the anchor trench.

(k) Placement of any sand or gravel layers on top of a membrane liner shall be done in such a manner that the liner is not torn.

(l) At any point of discharge into the pit, the discharge shall be directed away from the liner and the liner shall be protected from the fluid force of discharges.

D. BELOW-GRADE TANKS

1. The tank shall be of sufficient capacity to contain all intended fluids and wastes during periods of inclement weather when it is not possible to drain the tank on a regular schedule.

2. Tank construction materials shall exhibit strong corrosion resistance to those fluids the tank will store. If fiber reinforced plastic tanks are used, the material shall be resistant to sunlight and the tank's design shall allow for expansion and contraction due to wide temperature shifts. If ferrous tanks are used, protective coatings or cathodic protection shall be used to inhibit corrosion. The plans and specifications submitted for approval shall include the type of material selected and its thickness.

3. The surface upon which the tank system rests shall be level and free of rocks to prevent puncturing, cracking, or indentation of the liner or tank bottom.

4. All below grade tanks shall have a leak detection system consisting of a double wall system

with a mechanism for determining leaks, or a drainage and sump system. Drainage and sump systems shall be constructed as follows:

(a) First, place a synthetic impermeable liner at least 40 mils thick upon a smooth soil surface that will support the tank with the liner extending above the ground surface.

(b) Place a slotted or perforated drainage pipe (lateral) on the impermeable layer with the drainage pipe sloped at least one inch per 10 feet towards the sump. The drainage pipe shall be at least one inch in diameter.

(c) Cover the drainage pipe with sand, gravel, or other material with sufficient permeability to convey fluids to the drainage pipe.

(d) Place the tank on this surface and connect a riser pipe (sump) to the drainage pipe. The riser pipe shall be at least 2 inches in diameter.

(e) Strap the secondary liner to the tank above the ground surface in a manner to prevent rainwater from entering the space between the tank and liner.

5. Avoid placing tanks within ground water. If a tank is placed within ground water the tank system shall be placed in a one (1) foot thick concrete vault. The vault shall be maintained in a dry condition at all times.

6. For tanks located below the ground surface in an open pit, no secondary containment is required. The tank shall rest on a gravel pad at least one-inch thick, and the entire tank shall be exposed to visually detect leaks.

E. LEAK DETECTION SYSTEM

1. Leak detection systems may consist of fail-safe electric detection systems or drainage and sump systems.

2. If an electric grid detection system is used, provision must be made for adequately testing all components to ensure the system remains functional.

3. If a drainage and sump system is used, a network of slotted or perforated drainage pipes shall be installed between the primary and secondary liners. The network shall be of sufficient density so that no point in the pit bed is more than twenty feet (20') from such drainage pipe or lateral thereof. The material placed between the pipes and laterals shall be sufficiently permeable to allow transport of the fluids to the drainage pipe. The slope for all drainage lines and laterals shall be at least 12 inches (12") per hundred feet (100'). The slope of the pit bed shall also conform to these values to assure fluid flow towards the leak detection system. The drainage pipe shall convey liquids to a corrosion-proof sump located outside the perimeter of the pit (see Figure 2).

F. SKIMMER TANKS

A skimmer tank may be used to separate oil from water prior to discharge of water into a pit. No measurable or visible layer of oil shall accumulate or remain anywhere on the surface of any pit.

G. FENCES, SIGNS AND NETTING

1. Unless otherwise permitted by the OCD, a fence shall be constructed and maintained in good condition around the facility perimeter. Adequate space shall be provided between the fence and berms for passage of maintenance vehicles. The fences shall be constructed

so as to prevent livestock from entering the facility area. Fences shall not be constructed on berms. Active drilling or workover pits may have a portion of the pit unfenced to facilitate operations. **What is a facility? There is no definition to allow an operator to know what is supposed to be fenced.**

2. A sign not less than 12" x 24" with lettering of not less than two inches (2") shall be posted in a conspicuous place on the fence surrounding the facility. The sign shall be maintained in legible condition and shall identify the operator of the pits, the location of the facility by quarter-quarter section, township, and range, and provide emergency telephone numbers. **There are already signs on these locations.**

3. To protect migratory birds, all tanks exceeding 16 feet in diameter, and exposed pits and ponds must be screened, netted or covered. Upon written application by the operator, an exception to screening, netting or covering of a facility may be granted by the district supervisor upon a showing that an alternative method will protect migratory birds or that the facility is not hazardous to migratory birds. Drilling and workover pits are exempt from this netting requirement, if any visible or measurable layer of oil present is removed from the surface immediately after cessation of operations.

H. NOTIFICATION

At least twenty-four hours prior to installing liners or leak detection systems, the responsible party shall notify the OCD District Office so that an inspection can be scheduled. The operator shall take photographs of the installation and submit copies of the photographs with as built construction information, as required. **There is a difference between liners with leak detection and drilling and workover pits. The later should be excluded from these requirements. Photos are ridiculous.**

III. OPERATION AND MAINTENANCE OF BELOW-GRADE TANKS AND DISPOSAL AND STORAGE PITS

A. Leak detection sumps shall be inspected at least once every thirty (30) days. The proposed frequency shall be included with the plans and specifications submitted for approval.

B. The operator shall report the detection of fluid within the sump to the appropriate OCD District Office within 24 hours of discovery. The operator shall obtain a sample of the fluid, and have the sample analyzed for major cations/anions, benzene, toluene, ethylbenzene, total xylenes (BTEX), and any other potential water contaminant within the pit or below-grade tank. A copy of the analysis shall be sent to the appropriate OCD District Office. An analysis of the fluids in the tank may be required for comparison with the above analysis. If the presence of fluid in the leak detection system is due to a tank leak, the contingency plan shall be implemented.

C. The operator shall submit a contingency plan for approval along with the application outlining the procedure for repairing the pit liner or tank in an expeditious manner in the event of a leak. It must describe how the discharger proposes to guard against such accidents and detect them when they have occurred. The contingency plan also must describe the steps proposed to contain and remove the spilled substance or mitigate the damage caused by the discharge such that ground water is protected, or movement into surface waters is prevented.

IV. CLOSURE PROCEDURES

Prior to commencing closure of a storage, disposal or emergency pit, or below-grade tank, a closure plan must be submitted to and approved by OCD. If a number of ~~unlined~~ pits or below-grade tanks are to be closed by a single company, the company may submit one general plan stating the areas and types of facilities to be closed, along with the procedures to be used during closure. Deviations from approved plans require OCD notification and approval.

Procedures may deviate from the following guidelines if it can be shown that the proposed procedure will remove or isolate contaminants in such a manner that fresh waters, public health and the environment will not be impacted by remaining contaminants. Specific constituents and/or requirements for soil analysis and/or remediation may vary depending on site-specific conditions.

At a minimum, a closure plan shall include the following elements:

1. Locations of all pits and below-grade tanks to be closed.
2. Procedures which will be used to assess the extent of contamination.
3. Procedures to be used to manage, remediate, or dispose of contaminated soil and wastes.
4. Schedules for submission of closure reports on each pit or below-grade tank.

V. CLOSURE SITE ASSESSMENT

Prior to final closure, the party responsible for a pit or below-grade tank shall perform an assessment to evaluate the extent to which soils and/or ground water may be impacted by its operation. Assessment results will form the basis of any required remediation. The sites shall be assessed for the severity of contamination and potential environmental and public health threats using the risk based ranking system described in sections V and VI. **Need specific language that drilling and workover pits are not included. In the paragraphs above there is a specific list of pits included, but in this paragraph it just says pits so that could be construed to mean all pits.**

The following characteristics must be determined in order to evaluate potential risks at a site, the need for remedial action and, if necessary, the level of cleanup required at the site:

A. GENERAL SITE CHARACTERISTICS

1. Depth To Ground Water

The operator shall determine the depth to ground water at each site. The depth to ground water is defined as the vertical distance from the lowermost contaminants to the seasonal high water elevation of the ground water. **How do we determine high water? It cannot be the top of the column in a well, as has been used by OCD already.** If the exact depth to ground water is unknown, the ground water depth can be estimated using either local water well information, published regional ground water information, data on file with the New Mexico State Engineer Office or the vertical distance from adjacent ground water or surface water.

2. Wellhead Protection Area

The operator shall determine the horizontal distance to all private, domestic fresh water wells or springs used by less than five households for domestic or stock watering purposes, and all other fresh water wells and springs.

3. Distance To Nearest Surface Water Body

The operator shall determine the horizontal distance to all wetlands, playas, irrigation canals, ditches, and perennial and ephemeral watercourses.

B. SOIL/WASTE CHARACTERISTICS

Soils/wastes within and beneath the pit **but not drilling or workover pit**, or below-grade tank shall be evaluated to determine the type and extent of contamination at the site. In order to assess the level of contamination at the pit or below-grade tank, observations shall be made of the soils/wastes within the pit or below-grade tank and a sample of the potentially impacted soils shall be taken from the interval at least 3 feet into the undisturbed native soils beneath the bottom of the pit or below-grade tank. Additional samples may be required to determine the vertical and horizontal extent of contamination. Samples shall be obtained according to the sampling procedures in Section VII. This may be accomplished using a backhoe, drill rig, hand auger, shovel or other means.

Initial assessment of soil/waste contaminant levels in a pit or below grade tank is not required if an operator proposes to determine the final soil contaminant concentrations after a soil removal or remediation pursuant to section VIII.A.

Pits and below-grade tanks with secondary containment and leak detection that never had instances of fluid in the leak detection systems, and lined drilling and reserve pits do not need to have soil samples taken from undisturbed soils underlying the pit. However, waste samples shall be taken and analyzed from any remaining waste materials if the contents are proposed to remain in place or be encapsulated in order to assess the potential for future migration of remaining contaminants.

Varying degrees of contamination may co-exist at an individual site. The following sections describe the degrees of contamination that shall be documented during the assessment of the level of soil contamination:

1. **Highly Contaminated/Saturated Soils**

Highly contaminated/saturated soils are defined as those soils containing a free liquid hydrocarbon phase or exhibiting gross staining. **All the bad stuff is gone when staining is left. What is gross staining? The term is too broad to understand and open to interpretation. NMOGA committee and the API study found no problem from hydrocarbons on the ground.**

2. Unsaturated Contaminated Soils

Unsaturated contaminated soils are those soils which are not highly contaminated or saturated, as described above, but contain measurable concentrations of benzene, toluene, ethylbenzene and xylenes (BTEX) and total petroleum hydrocarbons (TPH), chloride or other waste specific constituents. Sampling and analytical methods for determining contaminant concentrations are described in detail in Section VII.

(NOTE: The above definitions apply only to oilfield contaminated soils which are exempt from federal RCRA Subtitle C hazardous waste provisions. Pits or below-grade tanks receiving non-exempt wastes are subject to evaluation for RCRA hazardous waste characteristics.)

C. GROUND WATER QUALITY

If ground water is encountered during the soil/waste characterization of underlying impacted soils, a monitor well shall be installed directly adjacent and downgradient of the pit. After developing the well, a ground water sample shall be obtained to assess potential impacts on ground water quality. Monitor well installation, development and sampling shall be conducted using the procedures in Section VII.C. The installation of a monitor well is not required if the OCD approves of an alternate ground water investigation and sampling technique.

If there is a reasonable probability of ground water contamination from any pit or below-grade based upon the level of contaminants in the soils directly beneath the pit or below-grade tank, or the extent of soil contamination defined during remedial activities, monitor wells may be required to assess potential impacts on ground water. **Reasonable probability is too broad. Gives unbridal authority to OCD.**

If ground water contamination is discovered during investigation or remedial actions, the operator or responsible person shall report the incident to the OCD pursuant to 19.15.3.116 NMAC.

VI. SOIL AND WATER REMEDIATION LEVELS

A. SOILS

Soils shall be remediated to the criteria set out below. The OCD retains the right to require remediation to more stringent levels than those proposed below if warranted by site-specific conditions (ie. native soil type, location relative to population centers and future use of the site or other appropriate site specific conditions.)

1. Highly Contaminated/Saturated Soils

These soils shall be remediated insitu or excavated to the maximum extent practicable and remediated using techniques described in Section VIII.A.

2. Unsaturated Contaminated Soils

The general site characteristics obtained during the site assessment (Section V.A.) will be used to determine the appropriate soil remediation levels using a risk-based approach. Soils shall be scored according to the ranking criteria below to determine their relative threat to public health, fresh waters and the environment.

(a) Ranking Criteria

Depth To Ground Water Ranking Score

<50 feet 20

50 - 100 10

>100 0

Wellhead Protection Area

<200 feet from a private domestic fresh water well
or spring, or;

<1000 feet from any other fresh water well or spring

Yes 20

No 0

Distance To Surface Water Body

<200 horizontal feet 20

200 - 1000 horizontal feet 10

>1000 horizontal feet 0

(b) Hydrocarbon Remediation Levels

The total ranking score determines the level of remediation for hydrocarbon constituents that may be required at any given site. The total ranking score is the sum of all three individual ranking criteria listed in Section VI.A.2.(a) The table below lists the remediation level for hydrocarbon constituents that may be required for the appropriate total ranking score. Soils that contain hydrocarbon contaminants above the recommended remediation levels shall be remediated insitu or excavated to the maximum extent practicable and remediated using techniques described in Section VIII.A

	Total Ranking Score		
	≥19	10 - 19	0 - 9
Benzene(ppm)*	10	10	10
BTEX(ppm)*	50	50	50
TPH(ppm)**	100	1000	5000

* A field soil vapor headspace measurement (Section VII.B.1) of 100 ppm may be substituted for a laboratory analysis of the Benzene and BTEX concentration limits.

** The contaminant concentration for TPH is the concentration above background levels.

(c) Remediation Levels For Non-Hydrocarbon Contaminants

Soils contaminated by chlorides shall be remediated to 250 mg/kg, or remediated such that remaining chlorides in the soil will not with reasonable probability contaminate ground water or surface water in excess of the standards in 19.15.1.19.B.(2) NMAC and 19.15.1.B.(3) NMAC through leaching, percolation, or other transport mechanisms, or as the water table elevation fluctuates; or pose a threat to human health or the environment. **NO, evidence is that there is little if any percolation. The only real question with chlorides is movement to the surface.**

Soils contaminated with any other non-hydrocarbon contaminants shall be remediated such that remaining contaminants in the soil will not with reasonable probability contaminate ground water or surface water in excess of the standards in 19.15.1.19.B.(2) NMAC and 19.15.1.B.(3) NMAC through leaching, percolation, or other transport mechanisms, or as the water table elevation fluctuates; or pose a threat to human health or the environment.

B. GROUND WATER

Contaminated ground water is fresh ground water that contains free phase products, measurable concentrations of dissolved phase volatile organic constituents or other dissolved constituents in excess of the natural background water quality. Ground water contaminated in excess of the New Mexico Water Quality Control Commission (WQCC) ground water standards shall be remediated according to an abatement plan pursuant to 19.15.1.19 NMAC **Must add language that we will only remediate to existing background levels. We cannot make water cleaner than it is naturally.**

VII. SOIL AND WATER SAMPLING PROCEDURES

Below are the sampling procedures for soil and ground water contaminant investigations of pits and below-grade tanks that have received RCRA Subtitle C exempt oil field exploration and production wastes. Pits and below-grade tanks that have received non-exempt RCRA wastes are required to be tested to demonstrate that the wastes are not characteristically hazardous.

A. HIGHLY CONTAMINATED OR SATURATED SOILS

A soil is determined to be highly contaminated or saturated based upon physical observations. A representative sample of the soil should be studied for observable free phase hydrocarbons or immiscible phases and gross staining. The immiscible phase may range from free hydrocarbons to a sheen on any associated aqueous phase. A soil exhibiting any of these characteristics is considered highly contaminated or saturated. **I do not know what free phase hydrocarbsons are. Must have a definition. What are immiscible phases. This language must be put in oil field terms, not environmental terms. No one can understand what is required.**

B. UNSATURATED CONTAMINATED SOILS

The following methods shall be used for determining the magnitude of contamination in unsaturated soils:

1. Soil Sampling Procedures for Hydrocarbon Headspace Analysis

A headspace analysis may be used to determine the total volatile organic vapor concentrations in soils (i.e. in lieu of a laboratory analysis for benzene and BTEX but not in lieu of a TPH analysis). Headspace analysis procedures shall be conducted according to the procedures below. Samples taken for headspace analysis cannot be subsequently used for laboratory analysis.

(a) Fill a 0.5 liter or larger jar half full of sample and seal the top tightly with aluminum foil or fill a one quart zip-lock bag one-half full of sample and seal the top of the bag leaving the remainder of the bag filled with air.

(b) Ensure that the sample temperature is between 15 to 25 degrees Celsius (59-77 degrees Fahrenheit).

(c) Shake the sample jar vigorously for 1 minute or gently massage the contents of the bag to break up soil clods and allow aromatic hydrocarbon vapors to develop within the headspace of the sample jar or bag for 5 to 10 minutes.

(d) If using a jar, pierce the aluminum foil seal with the probe of either a PID or FID organic vapor meter (OVM), and then record the highest (peak) measurement. If using a bag, carefully open one end of the bag and insert the probe of the OVM into the bag and re-seal the bag around the probe as much as possible to prevent vapors from escaping. Record the peak measurement. The OVM must be calibrated to assume a benzene response factor. **There is entirely too much testing required here. We have not damaged water with no testing, now we must do what appears to be new, extensive tests.**

2. Field Soil Sampling/Screening

Field screening of contaminants during excavation of unsaturated contaminated soils may be conducted using industry-accepted procedures. However, all final samples obtained to verify that the appropriate contaminant specific remediation level has been met shall be analyzed at a laboratory using EPA approved methods and quality assurance/quality control procedures.

3. Soil Sampling Procedures For Laboratory Analysis

(a) Sampling Procedures

Soil sampling for laboratory analysis shall be conducted according to EPA approved methods.

(b) Analytical Methods

All soil samples must be analyzed using EPA methods and must be analyzed within the holding time specified by the method. Below are some common laboratory analytical methods for analysis of soil samples. Analyses for constituents other than those listed below may be required if the impoundment has been used for anything other than hydrocarbon based fluids or produced water.

(i) Benzene, toluene, ethylbenzene and xylene

- EPA Method 8021

(ii) Total Petroleum Hydrocarbons

- EPA Method 418.1, or;
- EPA Method Modified 8015

(iii) Chloride

- EPA Method 300

C. MONITOR WELL INSTALLATION, DEVELOPMENT AND GROUND WATER SAMPLING

If an assessment of a potential impact to ground water quality is deemed necessary, it shall be conducted according to EPA approved protocol. **What is this, where do we find it.** The following methods are standard OCD accepted methods used to sample and analyze ground water at RCRA exempt sites. **These sites are exempt, that means EPA decided there is little or no risk. Why are we doing all this testing? There is no science to support this.**

1. Monitor Well Installation/Location

One monitor well shall be installed adjacent to and hydrologically down-gradient from the pit or below-grade tank to determine if fresh water has been impacted by the disposal activities. Additional monitor wells, located up-gradient and down-gradient of the pit or below-grade tank, may be required to determine potential impacts on ground water.

2. Monitor Well Construction

(a) Monitor well construction materials shall be:

(i) selected according to industry standards;

(ii) chemically resistant to the contaminants to be monitored; and

(iii) installed without the use of glues or adhesives.

(b) Monitor wells shall be constructed as follows:

(i) Place at least 15 feet of well screen across the water table interface with at least 5 feet of well screen above the water table and 10 feet of well screen below the water table.

(ii) Set an appropriately sized gravel pack in the annulus around the well screen from the bottom of the hole up to 2-3 feet above the top of the well screen.

(iii) Place a 2-3 foot bentonite plug above the gravel pack.

(iv) Grout the remainder of the hole to the surface with a cement grout containing 3-5% bentonite.

(v) Place a concrete pad and locking well cover around the well casing at the surface.

3. Monitor Well Development

When ground water is collected for analysis from monitoring wells, the wells shall be developed prior to sampling. The objective of monitor well development is to repair damage done to the formation by the drilling operation so that the natural hydraulic properties of the formation are restored and to remove any fluids introduced into the formation that could compromise the integrity of the sample. Monitoring well development is accomplished by purging fluid from the well until the pH and specific conductivity have stabilized and turbidity has been reduced to the lowest level possible.

4. Sampling Procedures

Ground water shall be sampled no less than 24 hours after the well has been developed. Samples shall be obtained according to EPA accepted protocol. Samples shall be collected in clean containers supplied by the laboratory that will conduct the analysis or from a reliable laboratory equipment supplier. Samples for different analyses require specific types of containers. The laboratory can provide information on the types of containers and preservatives required for sample collection. Below are standard OCD accepted sampling procedures: **This term is used several times. OCD accepted procedures is not a guideline, it is a rule.**

(a) Monitor wells shall be purged of a minimum of three well volumes of ground water using a clean bailer or pump prior to sampling to ensure that the sample represents the quality of the ground water in the formation and not stagnant water in the well bore.

(b) Samples shall be collected in appropriate sample containers containing the appropriate preservative for the analysis required. No bubbles or headspace shall remain in the sample containers obtained for benzene toluene, ethylbenzene and xylene analysis.

(c) Label the sample containers with a unique code for each sample.

(d) Cool and store samples with cold packs or on ice.

(e) Promptly ship sample for analysis using chain of custody procedures.

(f) All samples must be analyzed within the holding times for the laboratory analytical method specified by EPA.

5. Ground Water Laboratory Analysis

Samples shall be analyzed for potential ground water contaminants contained in the waste stream, as defined by the New Mexico Water Quality Control Commission (WQCC). All ground water samples must be analyzed using EPA methods and must be analyzed within the holding time specified by the method. Below are common laboratory analytical methods for analysis of ground water samples analyzed for hydrocarbon and produced water related constituents. Additional analyses may be required if the impoundment has contained anything other than hydrocarbon fluids or produced water.

(a) Analytical Methods

(i.) Benzene, Toluene, Ethylbenzene and Xylene

- EPA Method 8021

(ii.) Total Dissolved Solids and Major Cations and Anions

- Various EPA or standard methods

(iii.) Heavy Metals

- ICAP EPA method 6010

(iv.) Polynuclear Aromatic Hydrocarbons

- EPA Method 8270

VIII. REMEDIATION

The following discussion summarizes alternatives for remediation of contaminated soil and ground water as defined in Section VI. All procedures used are to be approved by OCD prior to commencement of remediation activities. Separate OCD-approval for remediation is not required if the OCD has approved a general closure plan which includes the site remediation technique for any particular site. All procedures that deviate from the general closure plan, however, must be approved by OCD prior to commencement of remediation activities.

The OCD may consider a risk evaluation that demonstrates that remaining contaminants will not pose a threat to present or foreseeable beneficial use of fresh waters, public health and the environment.

A. RESIDUAL WASTE/SOIL MANAGEMENT AND REMEDIATION

RCRA exempt or RCRA nonhazardous oil and natural gas related residual waste and contaminated soil shall be remediated and managed according to the criteria described below or by other OCD approved procedures which will remove, treat, or isolate contaminants in order to protect fresh waters, public health and the environment. **These are exempt wastes, but OCD treats them like they have seriously contaminated soil or ground water. That has not happened.**

1. Residual Wastes

Residual wastes remaining in any pit or below-grade tank shall be handled in the following manner:

(a) Remaining liquids shall be removed from the pit or below-grade tank; and

(b) Remaining solid wastes shall be removed from the pit or below-grade tank, except for dried mud and cuttings in drilling and reserve pits which have been approved by the OCD for encapsulation under Section VIII.A.3.(a).

2. Contaminated Soils

Highly contaminated/saturated soils and unsaturated contaminated soils exceeding the remediation levels in Section VI.A. shall be either:

(a) excavated from the ground until a representative sample from the walls and bottom of the excavation is below the contaminant specific remediation level listed in Section VI.A. or an alternate OCD approved remediation level; or

(b) excavated to the maximum depth and horizontal extent practicable. Upon reaching this limit a sample shall be taken from the walls and bottom of the excavation to determine the remaining levels of soil contaminants; or

(c) treated in place, as described in Section VIII.A.3(b)(ii), until a representative sample is below the contaminant specific remediation level listed in Section VI.A., or an alternate OCD approved remediation level.

3. Soil and Waste Management Options

Soil and waste management options must be submitted to and approved by OCD prior to commencement of remediation activities. Following is a list of options for on-site treatment, off-site treatment and disposal of contaminated soils and wastes:

(a) <u>Disposal</u>

(i) Excavated or removed soils and wastes may be disposed of at an off-site OCD-approved facility.

(ii) Excavated soils may be returned to the excavated area if remediated to the recommended remediation levels in Section VI.A.2, or an alternate OCD approved remediation level. **None of the following are acceptable. Our expert who testified at the OCC hearing on pits had a good, and cheaper idea on how to do this.**

(iii) Contents of drilling and workover pits drilled or worked over with fresh water may be landspread, if the pit has not contained hydrocarbons, and it can be shown that residual contaminants in the mud and cuttings do not pose a threat to surface water, ground water, human health or the environment.

(iv) Contents of drilling and workover pits drilled or worked over with fresh water may be encapsulated onsite if it can be shown that residual contaminants in the mud and cuttings do not pose a threat to surface water, ground water, human health or the environment. Encapsulation shall be accomplished by folding the edges of the liner over the remaining mud and cuttings and covering the encapsulated wastes with a minimum of 3 feet of clean soil .

(v) Contents of drilling and workover pits drilled or worked over with salt water may be encapsulated onsite if it can be shown that residual contaminants in the mud and cuttings do not pose a future threat to surface water, ground water, human health or the environment, and the pit bottom is located at least 50 feet above a source of fresh water. Encapsulation shall be accomplished by folding the edges of the liner over the remaining mud and cuttings; capping the pit with either a 1-foot thick clay cap compacted to ASTM standards, or a 40 mil minimum thickness synthetic liner meeting ASTM standards that is designed to be resistant to the material encapsulated; and covering the cap with a minimum of 3 feet of clean soil.

(b) <u>Treatment and Remediation Techniques</u>

(i) Alternate Methods

The OCD encourages alternate methods of soil remediation including, but not limited to, active soil aeration, composting, bioremediation, solidification, and thermal treatment. Use of alternate methods must be approved by OCD prior to implementation.

(ii) Insitu Soil Treatment

Insitu treatment may be accomplished using vapor venting, bioremediation or other OCD approved treatment systems.

(iii) Landfarming

Onetime applications of hydrocarbon contaminated soils may be landfarmed on location by spreading the soil in a six-inch lift within a bermed area. Only soils that do not contain free hydrocarbon liquids can be landfarmed. The soils shall be disced regularly to enhance biodegradation of the contaminants. If necessary, upon approval by OCD, moisture and nutrients may be added to the soil to enhance aerobic biodegradation.

Landfarming shall not occur within any wetland, watercourse, lakebed, sinkhole, playa lake, ground water sensitive area, or wellhead protection area. Landfarming adjacent to any watercourse, lakebed, or playa lake shall be located safely above the ordinary high water mark.

Landfarming sites that will receive soils from more than one location are considered centralized sites and must be permitted pursuant to 19.15.9.711 NMAC prior to operation.

B. GROUND WATER REMEDIATION

Ground water contaminated in excess of WQCC standards **Must be remediated only to natural background.** requires submission of an "Abatement Plan" pursuant to 19.15.1.19 NMAC. An exception to this requirement exists for sites where ground water is remediated to WQCC standards within 1 year of discovery. In these cases, ground water investigation and remediation plans shall be submitted by the responsible person on a case-by-case basis, and reviewed and approved by OCD prior to commencement of activities.

IX. TERMINATION OF REMEDIAL ACTION

Remedial action may be terminated when the criteria described below have been met:

A. SOIL

Contaminated soils requiring remediation shall be remediated so that residual contaminant concentrations meet the recommended soil remediation level for a particular site as specified in Section VI.A. Termination of remedial action will be approved by OCD upon a demonstration of completion of remediation as described above.

If soil action levels cannot practicably be attained, an evaluation of risk may be performed and provided to OCD for approval showing that the remaining contaminants will not pose a threat to present or foreseeable beneficial use of fresh water, public health and the environment.

B. GROUND WATER

For cases where ground water is remediated to WQCC standards within one year of discovery, ground water remedial actions may be terminated if 4 successive quarterly sampling events confirm that all recoverable free phase product has been removed, and the concentration of the remaining dissolved phase contaminants in the ground water does not exceed New Mexico WQCC water quality standards or background levels. Termination of remedial action will be approved by OCD upon a demonstration of completion of remediation as described in above.

X. FINAL CLOSURE

A. SURFACE RESTORATION

Upon termination of any required soil remedial actions, a pit or below-grade tank shall be closed by backfilling and the operator shall contour the surface where the pit was located to provide drainage away from the site and successfully re-vegetate the area.

B. MONITOR WELL PLUGGING

If a monitor well was installed to determine impacts upon ground water, the monitor well must be plugged and abandoned by cutting the casing off below ground surface and filling the casing annulus from bottom to top with a cement grout containing 3-5 % bentonite.

XI. CLOSURE REPORTS

Closure plans shall provide a schedule for reporting the results of all closure activities. The results of all closure activities shall be documented by submission of a completed "Pit or Below-Grade Tank Application, Registration or Closure Form" on either Form C-144, C-101A or C-103A, and be accompanied by all supporting information necessary for the OCD to evaluate the closure actions.

Dan Girand
Mack Energy Corp.
Regulatory Affairs
Box 386
Roswell, NM 88201
505 623-8119

From: Manthei, Robert/Bob L [MANTHER1@bp.com]
Sent: Friday, April 09, 2004 3:53 PM
To: Olson, William
Cc: Toner, Matt A; McKenna, David P; Lowe, Jon D (Permian); Lowe, Margaret J; Brown, David R; Benko, Brittany D; Browning, Dyke A
Subject: Comment to guidelines

Importance: High

6BB-8BB Cert.pdf Comments_NMOCD Pit and Below G... High Density Polyethylene.pdf HYDROLOGIC ISSUES.pdf Liners and Installations.pdf Transport Of Brine And Hydroca... Bill

I have attached my comments and several documents related to the Guidelines for Pits and Below Grade Tanks.
Thanks

Bob Manthei
Regulatory/Measurement Team Lead
POB 1089 Eunice, NM 88231
Office: 505.394.1602
Cellular: 505.390.9250
manther1@bp.com

<<6BB-8BB Cert.pdf>> <<Comments_NMOCD Pit and Below Grade Tank Guidelines BP.pdf>> <<High Density Polyethylene.pdf>> <<HYDROLOGIC ISSUES.pdf>> <<Liners and Installations.pdf>> <<Transport Of Brine And Hydrocarbon Releases In Soils & Water.pdf>>

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INDUSTRIES

RAVEN INDUSTRIES INC.
CERTIFICATE OF COMPLIANCE

SUBJECT: Dura-Skrim 6BB & 8BBR

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DATE: 3/30/2004

It is here by certified that Dura-Skrim 6BB and 8BBR have been successfully used as an Oilfield Temporary Reserve Pit Liners for over 8 years. When Dura-Skrim products are used in a buried application, there are no natural degradation processes that will shorten the life of the product.

Gary W Kolbasuk

Gary Kolbasuk
New Product Development Manager
Engineered Films Division

Phone – 800-635-3456

Fax – 605-331-0333

bp

BP America Production Company

March 29, 2004

Mr. Bill Olson
Hydrogeologist
New Mexico Oil Conservation Division
1220 St. Francis Dr.
Santa Fe, NM 87505

RE: Comments on NMOCD Draft Guidance Document entitled "Pit and Below Grade Tank Guidelines"

Dear Mr. Olsen:

BP America Production Company (BP) appreciates the opportunity to provide comments on the draft guidance document referenced above.

BP endorsed comments from our Trade Association, the New Mexico Oil and Gas Association (NMOGA), stating that during the rulemaking that the subject guidelines should be a guide for industry's use in expediting approval of permits. BP also endorses NMOGA's comments on the "Pit and Below Grade Tank Guidelines". To better assure the proper design and closure of pits and below grade tanks, these minimum guidelines need to be based on documented scientific research and peer reviewed data. Further, these guidelines should not replace the rulemaking process. Where the NMOCD intends for minimum standards to be met to assure protection of ground water, public safety and the environment, then NMOCD has the responsibility and the obligation to enact such requirements through a formal rulemaking and not to use the guidelines as a mechanism to avoid the rulemaking process.

During the time I represented NMOGA on the Stakeholders committee, the NMOCD indicated that adequate time would be given to the development of these guidelines. For the pit and below grade tank rule, NMOCD allowed considerably more time and a more participative process for all parties to provide comment and technical input into the rule. BP is concerned that the expedited comment period for the guidance document is far too abbreviated and could lead to poor policy. Further, a concern exists about the lack of some complete scientific research and data, which is critical to developing this guideline document.

I am attaching technical documentation on liners and their Internet links.
http://www.fieldliningsystems.com/HDPE.html
http://www.greatwesternliner.com/reservoir.html

I am also attaching technical documentation with links to chloride studies for arid climates. The main thrust of the paper is as follows. Many of the studies that provide the input to parameter selection for models of contaminant transport through the vadose zone were done in the East, where groundwater is shallow and humidity is high. However, Potential evaporation in much of the Southwest is much greater than average annual precipitation and groundwater is typically deeper than in the East. Given that vadose zone transport of constituents of concern (chloride, for example) is highly dependant on the amount of recharge in the area where chlorides have occurred, Scanlon, et. al. (1997) believe that we should consider the possibility that in many parts of the Arid Southwest, recharge does not occur at all, due to rapid evapotranspiration rates of the desert southwest coupled with depths to groundwater that exceed 40 feet below ground surface.

Here in New Mexico, evaporation from a Class A pan is more than 110 inches in our southeastern valleys, while average annual precipitation ranges from 12 inches in Carlsbad to 16 inches in Hobbs (Western Regional Climate Center, Desert Research Center, http://www.wrcc.dri.edu/). This condition results in evaporation of a large majority of the precipitation, leaving very little to infiltrate. In recent work, at a site in Arizona, the USGS (Andraski et. al, 2002) (http://toxics.usgs.gov/pubs/agu_poster/) reports "chloride-concentration profiles indicate that percolation past the 10-m depth (approximately 33 feet) has been negligible for the past 16,000 years".

This is not to say that infiltration never occurs in the Arid Southwest, just that it requires uncommon circumstances that may not be present at many site of concern to the Oil and Gas Industry.

In closing, BP America Production Company appreciates the opportunity of providing the following comments on this guideline. However, we want to reiterate our recommendation that more time should be given to study and comment on this guideline using a collaborative approach. By doing so, a better final product will result that achieves the intended goal of the document. BP would gladly participate in such an approach if given the opportunity.

Respectfully,

Bob Manthei

Bob Manthei
Regulatory/ Measurement Team Lead

Cc: David Brown, Margaret Lowe, Jon Lowe, David McKenna, and Matt Toner

POB 1089 Eunice, New Mexico 88231

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Field Lining Systems, Inc., has installed millions of square feet of HDPE in all types of applications.Field Lining Systems specializes in the installation of a variety of flexible membrane linings. This HDPE liner was installed into a reservoir system.

Because HDPE is resistant to a broad range of chemicals in varying degrees of concentration as well as sunlight and UV attack, it is an excellent application for leach pads, wastewater ponds, landfills, aquaculture systems, landfill covers, secondary containment and tanks.

Field Lining Systems has installed HDPE sheet in sumps, ponds, canals, landfills, tanks, pit and trenches made of concrete, steel, dirt and wood for transfer and containment of chemical waste products. The fusion process is used for seaming panels together. This is achieved by using a split wedge type welding equipment. The liner seams are then pressure tested to ensure a leak free lining system.

HDPE is available in thickness of 20 mil to 100 mil to meet your lining needs. Whether it is studded in place in concrete, steel, wood or the edges are buried for attachment in earthen ponds, HDPE is the toughest lining available for these industrial applications.

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For environmental protection, HDPE Geomembranes are the perfect solution for lining landfill facilities. Field Lining Systems, Inc., has extensive experience installing many types of geomembranes in a variety of landfill applications. Landfill lining today takes a great deal of expertise and planning to ensure coordination with other contractors involved in the installation itself.

Field Lining Systems, Inc. has proven itself, by the millions of square feet installed, that they have the knowledge, professionalism and capabilities to ensure a top quality lining system.

Landfill covers pose some difficulty due to the constant settling and shifting of the decomposing refuse heaps, but there are HDPE membranes that have been produced just for this reason.

Field Lining Systems has the solutions to your landfill cover lining project.

LEACHATE PONDS

HDPE linings in leachate ponds keep the leachate contained that is collected from landfill cells. HDPE lining systems are extremely durable and can withstand the fluctuating extreme heat and bitter cold weather elements they are constantly exposed to.

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HDPE geomembranes can be used for primary containment of hydrocarbons, fuels, chemicals, potable water, and most hazardous liquids. HDPE can be attached to steel tanks, concrete foundations or used as a floating or fixed roof cover on the tank. Preserve and protect your tank walls from corrosion. You can also keep your potable water free from deteriorating contaminants entering your water system.

SECONDARY CONTAINMENT

Reliable secondary containment is crucial to keeping hazardous chemicals and waste from seeping from the primary containment vessel to the surrounding area. HDPE liner protection is a proven secure method for secondary containment in many types of applications.

MINING APPLICATIONS

Long lasting and durable geomembrane lining systems are used in some of the most demanding mining facilities. HDPE provides an outstanding chemical resistant and puncture resistant lining system. Variable thickness', textures and widths of the materials ensure faster installation time and less opportunity for leakage.

CANAL LINING

HDPE is the industry choice for lining all types of clean water canals and waterways for secure water containment. Concrete and earthen canals can lose great amounts of precious water due to cracking, leaking and erosion problems.

UV-stabilized HDPE can be exposed for long periods of time without decline in their performance level, or the lining system can be covered with a soil or concrete. Some canal linings require a concrete covering on top of the geomembrane. Canal lining systems do need protection form debris, equipment, vandals.

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With low permeability rates, erosion protection, long lasting, secure containment, cleaning and disinfecting capabilities and long life, an HDPE lining system for your shrimp and fish farming facility will greatly benefit the quality and quantity of your harvest. Risk of disease is greatly diminished. Water quality is superior as HDPE liners contain no additives or chemicals which can leach out into your system.

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This is a lightweight film monolayer membrane material consisting of a blended medium density polyethylene. Minimum carbon black content of 2.5% provides excellent protection from UV rays and harsh weather conditions. Puncture and tear strengths far exceed common polyethylene or vinyl films. This product is used mostly for larger ponds, including lagoons, canal liners, fire ponds, remediation liners, cargo covers, oil field pit liners, silage covers, outdoor covers, brine ponds, mine trailing ponds, interim landfill caps, leachate collection ponds. All panels are accordion folded every 5 feet and tightly rolled on a heavy-duty core for ease of handling and time saving installation. Material comes in 10, 30 & 40 mil. vailable in one piece applications up to 50,000 square foot panels in the 20 mil, 33,000 square foot panels in 30 mil and 25,000 square foot panels in 40 mil. 20 years is the average life.
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HYDROLOGIC ISSUES IN ARID, UNSATURATED SYSTEMS AND IMPLICATIONS FOR CONTAMINANT TRANSPORT

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University of Texas at Austin

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Abstract. Analysis of unsaturated flow and transport in arid regions is important, not only in water resource evaluation but in contaminant transport as well, particularly in siting waste disposal facilities and in remediating contaminated sites. The water fluxes under consideration have a magnitude close to the errors inherent in measuring or in calculating these water fluxes, which makes it difficult to resolve basic issues such as direction and rate of water movement and controls on unsaturated flow. The purpose of this paper is to review these issues on the basis of unsaturated zone studies in arid settings. Because individual techniques for estimating water fluxes in the unsaturated zone have limitations, a variety of physical measurements and environmental tracers should be used to provide multiple, independent lines of evidence to quantify flow and transport in arid regions. The direction and rate of water flow are affected not only by hydraulic head gradients but also by temperature and air pressure gradients. The similarity of water fluxes in a variety of settings in the southwestern United States indicates that vegetative cover may be one of the primary controls on the magnitude of water flow in the unsaturated zone; however, our understanding of the role of plants is limited. Most unsaturated flow in arid systems is focused beneath topographic depressions, and diffuse flow is limited. Thick unsaturated sections and low water fluxes typical of many arid regions result in preservation of paleoclimatic variations in water flux and suggest that deep vadose zones may be out of equilibrium with current climate. Whereas water movement along preferred pathways is common in humid sites, field studies that demonstrate preferential flow are restricted mostly to fractured rocks and root zones in arid regions. Results of field studies of preferential flow in humid sites, generally restricted to the upper 1–2 m because of shallow water tables, cannot be applied readily to thick vadose zones in arid regions.

1. INTRODUCTION

In the past, unsaturated-zone studies in arid settings were conducted primarily for water resource evaluation. During the past 2 decades, however, emphasis has shifted from water resources to waste disposal and contaminant transport. In addition to remediation of contaminated sites in arid regions, arid areas are also being proposed for low-level and high-level radioactive waste disposal [*Montazer and Wilson*, 1984; *Scanlon*, 1992a; *Prudic*, 1994]. Water resource evaluation studies generally assume uniform rates of water movement throughout a study area because that assumption may not greatly affect resource estimates. In contrast, application of uniform rates of water movement to contaminant transport analyses in areas of spatially variable water movement could invalidate estimated rates of contaminant transport. Knowledge of spatial variability in unsaturated flow is therefore critical for realistic assessment of transport rates because such spatially variable rates could allow contaminants in some areas to migrate rapidly, essentially bypassing the buffering capacity of much of the unsaturated zone.

Low precipitation rates and high evapotranspiration rates should result in low rates of water movement in arid settings. The book *Deserts as Dumps* by *Reith and Thomson* [1992] evaluates many issues related to waste disposal in arid regions. Groundwater contamination in many arid settings such as Hanford, Washington [*Dresel et al.*, 1996], Sandia, New Mexico [*Crowson et al.*, 1993], and the Negev Desert, Israel [*Nativ et al.*, 1995], has resulted in considerable debate about the suitability of arid settings for waste disposal. In the past, National Academy of Science (NAS) panels suggested that arid sites are unsuitable for radioactive waste disposal because of limited information on flow processes in arid regions [*National Research Council (NRC)*, 1957, 1966]. The findings of a recent NAS panel suggest, however, that interstream settings in arid regions should be suit-

[1]Also at Department of Environmental and Resource Sciences, University of Nevada, Reno.

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able for waste disposal [*NRC*, 1995]. Does this shift in opinion reflect an increased understanding of unsaturated flow and transport processes in arid settings?

Much research on unsaturated-zone hydrology has been conducted in humid sites; however, fundamental differences between humid and arid regions limit the applicability of techniques developed at humid sites to arid sites. Such fundamental differences include thickness of the unsaturated zone, which can be as much as several hundred meters in arid regions but commonly is only meters thick in humid sites. Water fluxes and water content of unsaturated media also have a much greater range in arid sites than in humid sites. Greater thickness of the unsaturated zone and lower water fluxes in many arid settings result in much longer timescales being represented by unsaturated sections in arid regions (up to thousands of years) than in humid regions (up to tens of years). Because of these differences the results of studies conducted in humid regions should not be applied directly to arid regions.

Questions about the suitability of arid settings for waste disposal may result from limited understanding of unsaturated-flow processes, in turn reflecting the limitations of various techniques for quantifying the extremely low water fluxes typical of interfluvial settings in many arid regions. As a result of low water fluxes and the limitations of various techniques to quantify flow, basic issues such as (1) direction and rate of water movement and (2) mechanisms and controls of water flow are difficult to resolve. The purpose of this paper is to examine some of the basic issues related to unsaturated flow by reviewing unsaturated-zone studies in arid settings. Some of the issues that will be considered are as follows:

1. What are the difficulties inherent in various techniques used to evaluate flow and transport?
2. What are the direction and rate of water movement?
3. How important is preferential flow in arid regions?
4. What are the most important controls on water flow and transport?
5. What is the role of vegetation in controlling water flow?
6. What effect do potential climate changes have on unsaturated flow?
7. How can we numerically simulate flow in arid settings?

An understanding of these issues is important for evaluation of water resources in arid regions and also for analysis of contaminant transport related to municipal, hazardous, and radioactive waste disposal.

Although arid regions occur throughout the world, unsaturated-zone studies have been conducted primarily in the western United States and in Australia; limited studies have been conducted in Africa, Israel, and Saudi Arabia. Results of studies of these arid settings are evaluated in this paper to provide insights into some of the basic issues described above.

Most of the studies referenced in this paper were conducted in the western United States. These studies include remediation of contaminated areas such as at Hanford, Washington [*Dresel et al.*, 1996] and Sandia (near Albuquerque), New Mexico [*Crowson et al.*, 1993], and at several uranium mill tailings sites [*Reith and Thomson*, 1992]. In addition, arid sites have been proposed for low-level radioactive waste disposal (from medical and research activities, and power plants) in Ward Valley, California, and Eagle Flat, Texas. Commercial facilities for disposing of low-level radioactive waste include Richland, Washington, and Beatty, Nevada (1962–1992). Deep (~300 m) geological disposal in the unsaturated zone at Yucca Mountain, Nevada, is proposed for high-level radioactive waste, which includes spent fuel from nuclear power plants and material from the nuclear weapons industry. Because much of the waste remains radioactive for a long time, we are concerned not only with flow and transport in the natural system, which can serve as a long-term (hundreds to thousands of years) barrier, but also with how we can engineer systems so as to minimize water fluxes.

To evaluate flow processes in the unsaturated zone, we need detailed information at small scales (~0.3 m); however, results from small-scale studies may have implications for much larger areas. Timescales of interest range from days to thousands of years, depending on the problem being evaluated. Arid systems are generally characterized by episodic flow that can occur in days in response to a sequence of precipitation events. In contrast, the period of time required for high-level nuclear waste to remain isolated from the accessible environment is ~10,000 years [*NRC*, 1995].

First we evaluate various techniques for quantifying unsaturated flow that use both hydraulic and hydrochemical approaches. Then we discuss the various driving forces for water movement that control the direction of water flow. Next we review preferential flow and how important it is in desert systems. The controls on unsaturated flow, including vegetation, climate, texture, and topography, are evaluated with reference to published studies. Recent improvements in numerical modeling that apply to simulations of flow and transport in arid regions are discussed, and results of case studies are presented. We close the discussion with some implications for waste disposal in arid settings and a brief overview of important areas for future research.

2. TERMINOLOGY

The glossary at the end of this paper should help the reader understand many of the terms used in unsaturated-zone hydrology. Some of these terms are discussed in more detail below.

"Unsaturated zone" refers to the zone in which the pore space contains at least two phases, water and air. "Vadose zone" refers to the zone between land surface and the underlying aquifer. Although the terms "unsaturated zone" and "vadose zone" are generally used interchangeably, "unsaturated zone" may not be strictly accurate in some cases where perched water (which includes saturated zones) accumulates above impeding layers in an otherwise unsaturated zone. The more general term "vadose zone" may be preferred in these cases, or "variably saturated" can be used to overcome this problem.

Some classifications of arid/semiarid/humid regions have been based on mean annual precipitation (hyperarid, 0–50 mm; arid, 50–200 mm; semiarid, 200–500 mm; and humid, >500 mm [*Lloyd*, 1986]), whereas others classify regions on the basis of precipitation/evaporation ratios [*Potter*, 1992] (arid, <0.5; semiarid, 0.5–1.0; and humid, >1.0). These classifications give some idea of what is meant by "arid" and "semiarid." The term "recharge" has been generally used to describe downward water movement in the unsaturated zone; however, in thick unsaturated sections where water is moving slowly, it may be impossible to determine whether downward moving water in the upper 10–20 m will recharge the aquifer at depths ≥100 m. To avoid this problem, we use "infiltration" to refer to water movement from the surface into the subsurface and "percolation" or "drainage" to refer to penetration of water below the shallow subsurface, where most evapotranspiration occurs. "Recharge" is restricted to situations where it is likely that the water reaches the water table (shallow water table or high water flux). Although the terms "percolation" and "recharge" imply downward water movement, determining the direction of water movement is often difficult. In these situations, "water flux" is better because it implies no particular direction.

3. TECHNIQUES FOR EVALUATING WATER FLOW

Because many reviews of techniques for evaluating water flow in arid regions exist [*Edmunds et al.*, 1988; *Allison et al.*, 1994; *Phillips*, 1994], this section is not a comprehensive review of techniques. Many issues related to unsaturated flow in arid systems result from limitations of techniques used to evaluate flow; therefore a review of the limitations and assumptions associated with these techniques is important.

Techniques that are used to quantify water fluxes can be generally subdivided into physical and chemical tracer techniques. Most studies are restricted to application of one of these techniques, and although few studies apply both, use of physical and tracer methods together can provide a more comprehensive understanding of water flow. The physical approach provides an understanding of current processes, whereas chemical tracers provide information on current and long-term net water flux. Because of inherent difficulties in quantifying low water fluxes that are characteristic of many arid sites, it is important to use multiple, independent lines of data to examine unsaturated-flow processes.

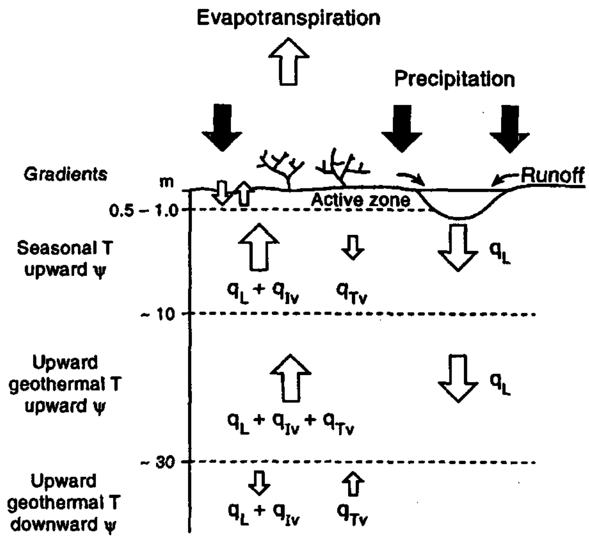

Figure 1. Schematic of unsaturated water fluxes in relation to different driving forces with depth. T is temperature, ψ is water potential, q_L is liquid water flux, q_{Iv} is isothermal vapor flux, and q_{Tv} is thermal vapor flux.

3.1. Physical Techniques

Physical techniques include water budgets to estimate water fluxes. The water balance equation can be represented by

$$D = P - R_0 - \mathrm{ET_a} - \Delta S \tag{1}$$

where D is drainage or percolation, P is precipitation (includes rain and snow), R_0 is surface runoff, $\mathrm{ET_a}$ is actual evapotranspiration, and ΔS is change in water storage (Figure 1). ET is used to describe the combined processes of evaporation (conversion of water to vapor) from the soil and transpiration from the plants. Significant improvements have been made in measuring evapotranspiration [*Malek et al.*, 1990; *Nichols*, 1994; *Albertson et al.*, 1995]; however, measurements of the different components of the water budget are generally too imprecise (±5% for P; ± 10% for $\mathrm{ET_a}$) to allow confidence in calculating the difference between numbers of nearly equal value (such as precipitation and evapotranspiration) to estimate drainage as shown by *Gee and Hillel* [1988].

Lysimeters, used to measure components of the water budget, have an artificially enclosed volume of unsaturated material [*Brutsaert*, 1982; *Allen et al.*, 1991; *Young et al.*, 1996]. Traditional lysimeters generally consist of round or square tanks that range from 1 to 5 m^2 in area and from 1 to 4 m in depth that are filled with disturbed or undisturbed soil that may be vegetated. Nonweighable lysimeters simply measure the drainage rate or amount of water percolating from the base of the lysimeter. Water storage changes can be estimated in these lysimeters by monitoring water content with a neutron probe or other device. Precipitation can be measured with a rain gauge. Most lysimeters have a rim around the surface to prevent runoff. Weighable lysimeters measure precipitation, storage changes, and drainage directly, and in this way evapotranspiration may be calculated over time spans as short as 15 min. Lysimeter measurements are considered to provide the best determination of actual evapotranspiration and are used to compare other techniques.

Lysimeter data provide valuable insights into the effects of vegetation and sediment on water movement at different sites [*Gee et al.*, 1994; *Wing and Gee*, 1994]. Deep (18 m), nonweighable lysimeters at the Hanford, Washington, site measured drainage below the root zone [*Gee et al.*, 1994]. To overcome the problem of limited areal extent associated with the individual lysimeters just described, large-pan lysimeters (92–322 m^2) were installed beneath engineered cover systems at the Hanford site to monitor drainage with a precision of ±2 mm [*Tyler et al.*, 1997]. Disadvantages of lysimeter studies include expense of construction, time required for maintenance, limited areal extent, boundary effects, and disturbance of the natural system. The large-pan lysimeters overcome the areal limitation, however, and when they are installed to evaluate engineered cover systems, disturbance of the natural system is not an issue.

3.1.1. Water content. Water content of sediment or rock samples can be measured readily in the laboratory by weighing samples before and after oven drying (the gravimetric method) [*Gardner*, 1986]. Because samples are destroyed during processing, this technique is generally used for collecting baseline data, for one-time routine measurements, and for calibration of other methods. It is used generally for evaluating spatial variability in water content, but not as readily for examining temporal variability. Traditionally, water content has been monitored with a neutron probe (Figure 2a) [*Gardner*, 1986], which is placed in an access tube that is installed horizontally or vertically. The neutron probe emits high-energy neutrons that collide with hydrogen nuclei and are slowed and reflected back to the probe, where they are counted. Neutron probes are calibrated against laboratory-measured water content of sediment or rock samples taken around neutron probes in the field. Calibrations are stable, and neutron probes are robust (both important for long-term monitoring). Disadvantages of neutron probes include health hazards associated with a radioactive source, time required for monitoring (generally done manually), and difficulty of monitoring the near-surface zone (top 0.15 m). Long-term (9 years) monitoring of water content was conducted in the Chihuahuan Desert, New Mexico, to evaluate spatial and temporal variability in water content [*Wierenga et al.*, 1987]. Results of the monitoring show that in 8 of the 9 years, all precipitation was taken up by plant roots in the upper 1.3 m and lost by evapotranspiration back into the atmosphere.

More recently, developments in time domain reflectometry (TDR) have led to its increased use in monitoring water content (Figure 2b) [*Dalton*, 1992]. A time domain reflectometry system consists generally of a two- or three-rod probe that is connected through a transmission line to a reflectometer, such as the Tektronix 1502B (Tektronix Inc., Redmond, Oregon), at the surface. A high-frequency pulse is applied by the reflectometer to the probe or waveguide, and reflections at the beginning and end of the probe caused by impedance changes are analyzed and displayed by the reflectometer. The time required for the electromagnetic pulse to travel along the waveguide is determined by the dielectric properties of the unsaturated medium. The TDR system measures the transit time t of the pulse along the TDR probe, and the dielectric constant ε is calculated as

$$\varepsilon = (ct/2l)^2 \qquad (2)$$

where c is the velocity of light in a vacuum (3×10^8 m s^{-1}) and l is the probe length. Because of large differences in the dielectric constant of water (~80), sediment or rock (~4–8), and air (~1), the dielectric constant of the unsaturated medium is controlled largely by the water content. Although *Topp et al.* [1980] developed an empirical third-order polynomial relationship between water content and dielectric constant that applies to many different sediment textures, individual calibrations can also be developed for different sediments. The average water content along the length of the TDR probe is measured. TDR probes can be installed vertically to measure average water content to a particular depth or horizontally to monitor movement of wetting fronts. A typical probe uses 0.3-m-long rods, ~5 mm in diameter, and ~20-mm spacing between rods (Campbell Scientific Inc., Logan, Utah). The advantages of TDR systems are the absence of a radioactive source, automated water content monitoring that can be operated remotely, and the ability to monitor the near-surface zone. Although TDR has not been widely implemented in arid settings, the automated measurement of water content by TDR should lead to large databases that document water content changes in arid regions.

Remote sensing has also been used to estimate water content in the unsaturated zone [*Jackson*, 1993]. This technique is based on variations in the dielectric constant with water content in unsaturated material, which is similar to that described for TDR measurements. Passive microwave remote sensing detects water content in the upper 50 mm of the unsaturated zone at a spatial resolution of ~200 m [*Jackson et al.*, 1993]. The shallowness of the zone being evaluated and the low spatial resolution make this technique unsuitable for evaluation of unsaturated-zone water fluxes at small scales; it is generally more applicable in basin-scale studies and climate modeling.

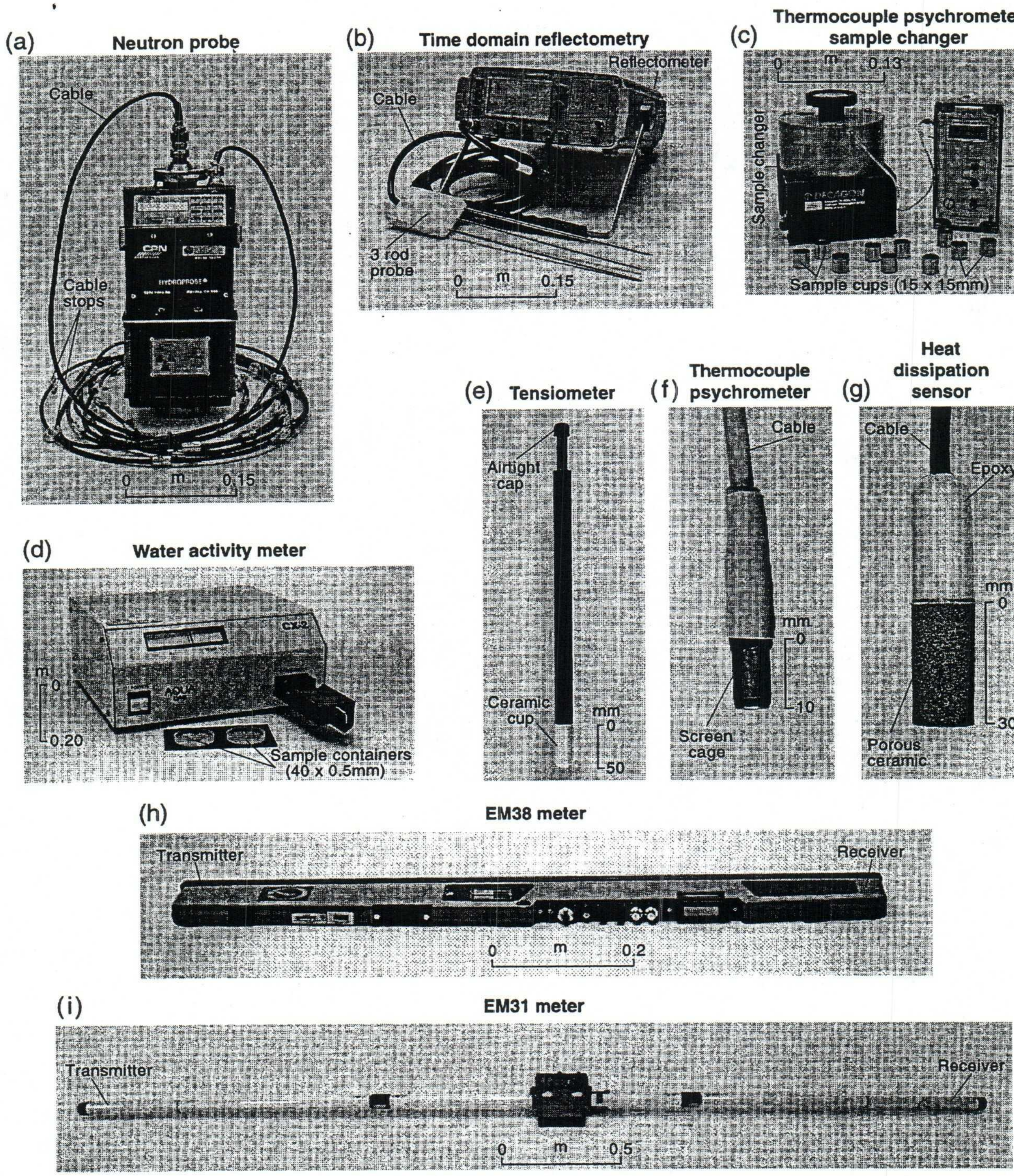

Figure 2. Instrumentation used for monitoring various parameters in the unsaturated zone: (a) neutron probe (model CPN 503DR), (b) time domain reflectometry system (reflectometer and three-rod probe), (c) thermocouple psychrometer sample changer, (d) water activity meter, (e) tensiometer, (f) thermocouple psychrometer, (g) heat dissipation sensor, (h) EM38 meter, and (i) EM31 meter.

Spatial variability in water content cannot be used to evaluate water flux in heterogeneous systems because water content varies with sediment type: clays, for example, retain more water than do sands. In contrast, temporal variations in water content can be used to evaluate the movement of water pulses through the unsaturated zone, particularly in areas of moderate to high water flux; however, in areas of low water flux, typical standard

TABLE 1. Summary of Instruments Used to Measure Various Hydraulic Parameters in Arid Systems

Parameter	*Instrument*	*Range*	*Accuracy*	*Notes*
Water content	neutron probe	0 to 100% saturation	±1%	robust, radioactive source
	TDR	0 to 100% saturation	±1%	robust, nonradioactive, automated
Matric potential	HDS	−0.01 to −1.4 MPa		not robust, automated
	tensiometer	0 to −0.08 MPa		automated
Water potential	TCP	−0.2 to −8.0 MPa	±0.2 MPa	not robust, automated
	Filter paper	−0.2 to −90 MPa		laboratory measurement
	SC10A sample changer	−0.2 to −8.0 MPa (Peltier)	±0.2 MPa	laboratory measurement affected by temperature gradients; time consuming
		−0.2 to −300 MPa (Spanner)	±0.2 MPa	
	water activity meter	0 to −312 MPa	±0.003 activity units	rapid laboratory measurement
Hydraulic conductivity	centrifuge method	$\geq 10^{-11}$ m s^{-1}	~±10%	expensive

Abbreviations are TDR, time domain reflectometry; HDS, heat dissipation sensor; and TCP, thermocouple psychrometer.

errors (~±1% for calibration curves for instruments (Table 1)) associated with water content measurements at one location over time may be too high to detect low water fluxes. Water content cannot be used to estimate water flux under steady flow conditions because water content does not vary.

3.1.2. Potential energy. In contrast to water content, which cannot be used to evaluate the direction of water movement because water content is discontinuous across the interface between different sediment textures, potential energy can be used to assess the direction of the driving force for water movement. Water flows from regions of high potential to regions of low potential. Potential energy in the unsaturated zone includes capillary, adsorptive, gravitational, solute or osmotic, and pneumatic components (Table 2). Capillary and adsorptive components combine to form the matric potential, which is the component of potential energy associated with the matrix of the unsaturated zone. The term "matrix" describes the particles and pore space that make up the unsaturated medium; "matric" is its adjectival form (Webster's Third International Dictionary). "Gravitational potential" represents the elevation of the measurement point above a reference level, such as the water table. Solute or osmotic potential results from the reduction in energy associated with addition of solutes to pore water. Matric and osmotic components are combined to form water potential. Because osmotic potential is generally neglected except in cases where high solute concentrations exist, "water potential" and "matric potential" are often used interchangeably. Pneumatic potential results from changes in air pressure in the unsaturated zone. Potential energy is generally expressed as energy per unit volume (pressure equivalent in megapascals) or energy per unit weight (head equivalent in meters).

The pore space in unsaturated media is partially filled with water, and pressures are negative. Matric potentials and water potentials are negative, whereas suction or tension, the negative of the matric potential, is positive (Table 2). The general term "pressure potential" is used in this paper, along with more appropriate, specific terms for clarity. Pressures close to 0 correspond to near-saturated conditions, and low negative pressures correspond to dry conditions. Water flows from regions of high potential, where pressures are less negative, to

TABLE 2. Various Types of Potential Energy Important for Understanding Unsaturated Flow

Potential Energy Type	*Description*
Gravitational potential	elevation above reference level (e.g., water table)
Matric potential	capillary and adsorptive forces associated with the soil matrix
Suction or tension	negative matric potential
Osmotic (solute) potential	variations in potential energy associated with solute concentration
Water potential	matric + osmotic potential
Pneumatic potential	associated with variations in air pressure
Hydraulic head	matric + gravitational potential head

Water potential approximates matric potential when osmotic potential is negligible. Tensiometers generally measure matric potential because air pressure is usually atmospheric. Heat dissipation sensors measure matric potential. Thermocouple psychrometers measure water potential. Potential energy is generally expressed as energy per unit weight of water, which is equivalent to head (meters) or energy per unit volume of water, which is equivalent to pressure (megapascals).

regions of low potential, where pressures are more negative.

Tensiometers (Soil Measurement Systems, Tucson, Arizona; Soil Moisture Equipment Corporation, Santa Barbara, California) can be used to monitor high (≥ -0.08 MPa) pressure potentials (matric and pneumatic) generally found in humid sites; however, pressure potentials in arid sites have a wide range (0 to < -200 MPa), and thus tensiometers can only be used where the vadose zone is relatively moist (Figure 2e; Table 1). Tensiometers consist of a ceramic cup connected to an airtight PVC tube that is filled with water (Figure 2e) [*Cassel and Klute*, 1986]. Water in the tensiometer equilibrates with the surrounding unsaturated medium, and a vacuum is developed that is measured by a pressure transducer.

Heat dissipation sensors (Campbell Scientific Inc., Logan, Utah) (Figure 2g), also called matric potential sensors, measure matric potential over a range (-0.01 to -1.4 MPa) greater than that of tensiometers [*Campbell and Gee*, 1986; *Phene et al.*, 1992]. Heat dissipation sensors consist of a ceramic block, a heater, and a temperature transducer. Heat dissipation sensors (1) measure the matric potential of the unsaturated medium by equilibrating a standard matrix, such as porous ceramic, with the surrounding sediments and (2) determine the water content of the sensor by measuring the rate of heat dissipation, which is a function of water content of the ceramic block. The higher the water content of the soil and the less negative the matric potential, the more rapidly the heat dissipates, and the lower the recorded voltage. The temperature change is measured with a data logger before and after application of a 30 s heat pulse. Temperature measurements are related to matric potentials through calibration curves between temperature or voltage and matric potential measured in the laboratory. Because matric potential is continuous across material types, the matric potential of the heat dissipation sensor is the same as that of the surrounding unsaturated medium [*Thamir and McBride*, 1985].

Thermocouple psychrometers (J.R.D. Merrill Specialty Co., Logan, Utah; Wescor, Logan, Utah) are required to measure much more negative water (matric + osmotic) potentials associated with typically dry sediments in arid systems. Thermocouple psychrometers measure the relative humidity of the vapor phase in the unsaturated zone, which is related to the water (pressure) potential in the liquid phase, according to the Kelvin equation

$$\psi = \frac{RT}{V_w} \ln \frac{P}{P_0} \tag{3}$$

where R is the ideal gas constant (8.314 J mol^{-1} °K), T is the Kelvin temperature, V_w is the molar volume of water (1.8×10^{-5} m^3 mol^{-1}), and P/P_0 is the relative humidity expressed as a fraction (P is the vapor pressure of the air in equilibrium with the sample, and P_0 is the saturation vapor pressure) [*Rawlins and Campbell*, 1986]. There are two basic types of thermocouple psychrometers: (1) Peltier or Spanner psychrometers (Figure 2f) and (2) Richards psychrometers (Figure 2c). Peltier psychrometers consist of a small thermocouple junction in a sample chamber such as the screen cage in Figure 2f that is cooled by the Peltier effect to condense water on it. The Richards psychrometer mechanically adds a drop of water to the thermocouple junction that is within the sample chamber (Figure 2c) and is restricted to laboratory measurements. Both systems measure temperature depression of the wet, or measuring, junction relative to a dry, or reference, thermocouple junction in the chamber. Temperature depression varies with the rate of evaporation, which is greater at lower relative humidity. A primary source of error results from temperature gradients between the reference junction and pore water in the unsaturated zone. A temperature gradient of 1°C at 20°C results in an error in measured water potentials of 13 MPa [*Rawlins and Campbell*, 1986]. Thermocouple psychrometers are calibrated with salt solutions of known osmotic potential.

In situ thermocouple psychrometers (Figure 2f) are used to monitor water potential between -0.2 and -8.0 MPa. Water potentials have been monitored in various arid settings to a maximum depth of 387 m to evaluate the direction of water movement and to estimate water fluxes [*Montazer et al.*, 1985; *Fischer*, 1992; *Scanlon*, 1994]. Significant improvements have been made in thermocouple psychrometry for monitoring water potentials in the field in recent years as a result of advances in data acquisition systems and newly developed thermocouple psychrometers for installation in deep boreholes [*Kume and Rousseau*, 1994].

One problem inherent in monitoring pressure potentials in arid systems is that the installation process may significantly affect the natural system, causing the monitoring data to be an artifact of the installation process rather than a reflection of the natural system. Although thermocouple psychrometers are generally installed in dry materials, because equilibration of the backfill sediments may take a long time, determining the true potential of the sediments may be difficult. Numerical simulations conducted to examine the effect of borehole backfill on monitored water potentials in a fractured tuff site show that backfill material could greatly disturb the natural system [*Montazer*, 1987]. Heat dissipation sensors are generally installed in wet silica flour because they require good contact with the surrounding sediment [*Montazer et al.*, 1985]; however, measured discrepancies between closely spaced thermocouple psychrometers and heat dissipation sensors suggest that the wetted sediments may not equilibrate for a long time. Because the calibration is unstable and because the instruments are not robust and have a high failure rate, thermocouple psychrometers may be unsuitable for long-term (≥ 10 years) monitoring unless they are retrievable. Installation of retrievable thermocouple psychrometers in caissons and in boreholes [*Fischer*, 1992; *Prudic*, 1994] has allowed recalibration of these instruments.

Because of the expense and difficulties of installing thermocouple psychrometers in the field, we generally obtain information on spatial variability of water (pressure) potential on the basis of laboratory measurements on disturbed samples by using a thermocouple psychrometer with a sample changer (Figure 2c) or a water activity meter (Decagon Devices, Pullman, Washington) (Figure 2d). The sample changer uses a Richards thermocouple psychrometer to measure a wide range in water (pressure) potentials (−0.2 to −300 MPa [*Rawlins and Campbell*, 1986]). Laboratory measurements of water potential made by thermocouple psychrometers are time-consuming and sensitive to the effects of temperature gradients [*Rawlins and Campbell*, 1986].

A water activity meter (Figure 2d) can also be used to measure water (pressure) potential in the laboratory. Water activity is synonymous with relative humidity. Water potential measurements made by a water activity meter are neither as time-consuming nor as sensitive to the effect of temperature gradients as are measurements made by thermocouple psychrometers [*Gee et al.*, 1992]. The measurement of water activity of a sediment or rock sample takes only a few minutes, ranging from 0.100 to 1.000 (−312 to 0 MPa water potential) with uniform resolution of ±0.003 water activity units throughout the range [*Gee et al.*, 1992]. The water activity meter uses a chilled mirror to measure the dew point of water vapor above a small sample of sediment or rock (40 mm in diameter by 5 mm thick). A Peltier cooling device controlled by a data logger is used to cool the mirror until dew forms and then to heat the mirror to eliminate the dew. Temperature of the sediment or rock sample is measured with an infrared thermometer. Vapor pressure of air is equal to the saturation vapor pressure at the dew point temperature, by definition of the dew point. Saturation vapor pressure is approximated by

$$P_0(T) = a \exp\left(\frac{bT_s}{T_s + c}\right) \tag{4}$$

where a, b, and c are constants and T_s is the surface temperature [*Buck*, 1981].

$$\begin{aligned} A_w = \frac{P}{P_0(T_s)} &= a \exp\left(\frac{bT_d}{T_d + c}\right)\left[a \exp\left(\frac{bT_s}{T_s + c}\right)\right]^{-1} \\ &= \exp\left(\frac{bT_d}{T_d + c} - \frac{bT_s}{T_s + c}\right) \\ &= \exp\left(\frac{bc(T_d - T_s)}{(T_d + c)(T_s + c)}\right) \end{aligned} \tag{5}$$

where T_d is the dew point temperature in degrees celsius. A microprocessor-controlled algorithm is used to convert the air dew point temperature and the sample temperature to water activity or relative humidity readings. The Kelvin equation (equation (3)) is then used to estimate the water potential. Temperature control is unimportant because change in water activity with temperature is generally <0.003°C^{-1}. Because the chilled mirror dew point technique is a primary measurement method of relative humidity, no calibration is required.

The filter paper method, also used to measure matric or water potentials on sediment or rock samples in the laboratory ranging from −0.2 to −90 MPa, does not require expensive instrumentation [*Greacen et al.*, 1987; *American Society for Testing and Materials*, 1994]. This method assumes that porous media in liquid or vapor contact with the filter paper will exchange water until the matric or water potentials of both are the same. The filter paper can be placed in direct contact with the sample to measure the matric potential, or it can be separated from the sample by a vapor gap to measure water potential (matric and osmotic potential). Although the time required for equilibration varies with the potential of the medium, equilibrium is generally reached within 7 days. Whatman no. 42 filter papers are generally used, and the increase in mass of the filter paper is measured and related to matric or water potential through a previously determined calibration curve. *Greacen et al.* [1987] listed calibration equations for different ranges in water potential. The greatest source of error in all laboratory measurements of pressure (water or matric) potentials is the possibility of samples drying during collection, particularly in coarse-textured material.

3.1.3. Hydraulic conductivity. Information on hydraulic conductivity is required for estimating water flux using Darcy's law under steady flow conditions or using Richards' equation under transient flow conditions. Darcy's law is empirical and was originally developed for the saturated zone. Darcy's law shows that water flux under steady flow is proportional to the hydraulic head gradient, the proportionality constant being the hydraulic conductivity. Hydraulic head is the sum of the matric (pressure) potential head and the gravitational potential head. In the saturated zone, hydraulic conductivity is constant at a point in space. Darcy's law was modified by *Buckingham* [1907] for the unsaturated zone by allowing the hydraulic conductivity K to vary with water content θ:

$$q_l = -K(\theta)\frac{\partial H}{\partial z} = -K(\theta)\left(\frac{\partial h(\theta)}{\partial z} + 1\right) \tag{6}$$

where q_l is the liquid water flux, H is the hydraulic head, and h is the matric potential head, which is a function of the water content. Richards' equation is required to predict water content or matric potential in the unsaturated zone during transient flow and combines the conservation of mass with Darcy's equation (conservation of momentum):

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_l}{\partial z} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h(\theta)}{\partial z} + 1\right)\right] \tag{7}$$

Although unsaturated hydraulic conductivity is the least well known flow parameter, it has a great effect on estimated water fluxes because hydraulic conductivity may vary over several orders of magnitude in the range of water contents found in arid regions. Unsaturated hydraulic conductivity can be estimated from water retention and saturated hydraulic conductivity data by assuming that the unsaturated medium behaves like a bundle of capillary tubes [*Mualem*, 1976; *van Genuchten*, 1980]; however, in many arid regions, water may be adsorbed as films, and estimates of hydraulic conductivity based on capillary flow may not apply.

There are numerous field and laboratory methods for determining the unsaturated hydraulic conductivity as a function of water content. These methods are either steady state or transient and are described in detail by *Klute* [1986]. Recent developments in ultracentrifuge technology allow measurement of unsaturated hydraulic conductivity at fairly low water contents. *Nimmo et al.* [1987, 1992] and *Conca and Wright* [1992] developed steady state centrifuge methods to measure unsaturated hydraulic conductivity. Large forces ($\leq$2000 g per unit mass) applied to the unsaturated sample result in removal of water from the sample. The magnitude of the force is controlled by the radius and speed of rotation of the centrifuge [*Kutilek and Nielsen*, 1994]. The various centrifuge methods apply water at a constant rate to the inner side of a small sediment sample or rock core either through precision pumps or through a water reservoir and porous ceramic plate. The sample generally reaches a steady state water content in a fairly short time. The steady state water flux can be described by a modified Darcy equation:

$$q_l = -\frac{K(\theta)}{g}\left(\frac{dh(\theta)}{dr} - \omega^2 r\right) \tag{8}$$

where K is the unsaturated hydraulic conductivity, g is the gravitational acceleration, r is the radius of the sample, and $\omega^2 r$ is the centripetal force per unit mass. Assuming a negligible or unit gradient ($dh/dr = 1$), the unsaturated hydraulic conductivity is calculated by dividing the measured flux q_l by $\omega^2 r g^{-1}$. The sample is removed from the centrifuge, and the water content and/or matric potential is measured. The experiment is rerun at different flow rates to calculate the unsaturated hydraulic conductivity at different water contents or matric potentials.

3.1.4. Noninvasive techniques for estimating water content and movement. Because of the difficulties and expense of installing dedicated equipment, particularly in contaminated sites, noninvasive techniques for evaluating unsaturated water movement are highly desirable. In disposal sites, equipment installation should be minimized to maintain site integrity and to avoid creating preferred pathways for contaminants.

Electromagnetic induction (EMI) has been used to evaluate spatial variability in unsaturated flow over large regions [*Cook et al.*, 1992; *Cook and Kilty*, 1992]. EMI is a noninvasive technique that measures apparent electrical conductivity, which can be used to evaluate unsaturated flow. The theoretical basis for electromagnetic induction measurements is described by *McNeill* [1992]. The instruments (e.g., EM38 meter (Figure 2h) or EM31 meter (Figure 2i), Geonics Inc., Mississauga, Ontario) generally consist of a transmitter coil placed on the ground that is energized by an alternating current at an audio frequency. This current generates a primary magnetic field, which in turn induces small currents that generate their own secondary magnetic field. The receiver coil responds to both the primary and secondary magnetic field components. Under low values of induction number, the secondary magnetic field is a linear function of apparent electrical conductivity. The instrument can be operated with both transmitter and receiver coils lying horizontally (vertical dipole mode) or vertically (horizontal dipole mode) on the ground.

Ground-based EMI surveys can be conducted with a variety of instruments that range in exploration depth from 0.75 to 40 m (Figure 2) [*McNeill*, 1992]. Apparent electrical conductivity (EC_a) in the subsurface is related to water content, salt content, texture, structure, and mineralogy:

$$EC_a = EC_w \theta \tau + EC_s \tag{9}$$

where EC_w is pore-water conductivity, θ is volumetric water content, τ is tortuosity, and EC_s is surface conductance of the sediment [*Rhoades et al.*, 1976]. Higher recharge generally occurs in more coarsely textured soils (lower EC_a) and results in higher relative water content (higher EC_a) and lower chloride content (lower EC_a) [*Cook et al.*, 1992]. Because of competing effects of texture, chloride, and water content on EC_a, EMI will work well only in recharge estimation where any one of these factors dominates or where two factors operate synergistically on EC_a. In an Australian study, because the correlation between recharge and EC_a was controlled by soil texture, the EMI survey mapped primarily soil texture at the site [*Cook et al.*, 1992]. Comparison of ground measurements of EC_a with recharge estimated according to unsaturated-zone chloride data at 20 sites resulted in a coefficient of determination (R^2) of 0.5. These data suggest that although EMI cannot estimate recharge directly, it may be useful in reconnaissance and interpolation between borehole measurements.

An electromagnetic meter (Geonics model EM31 (Figure 2i)) has also been used to monitor temporal variations in water content along an ~2-km transect [*Sheets and Hendrickx*, 1995]. The researchers found a linear relationship between apparent conductivity measured using the EM31 meter and water content in the upper 1.5 m of soil logged in 65 neutron probe access tubes along the transect. This technique shows promise for monitoring water content in disposal facilities, once a calibration equation has been developed.

TABLE 3. Summary of Environmental Tracers Commonly Used in Arid Regions and Their Attributes

Tracer	*Type*	*Liquid/Vapor Phase*	*Dating Period, years*	*Notes*
Chloride		liquid	≤1000s	qualitative
^{36}Cl	bomb pulse	liquid	0–40	used in evaluating water fluxes and preferential flow
	cosmogenic variation	liquid	≤70,000	small signal ≤2 × background; advection-dominated systems
	radioactive decay	liquid	50,000–1,000,000	used at Yucca Mountain, Nevada
^{3}H	bomb pulse	liquid + vapor	0–40	used in evaluating water fluxes and preferential flow

3.2. Tracer Techniques for Estimating Water Movement

It is difficult to estimate rates of water movement in unsaturated media because the rates are generally low. Physical methods that depend on Darcy's or Richards' equations are restricted by uncertainties in estimated unsaturated hydraulic conductivities. Chemical tracers can provide information on current water fluxes and long-term net water fluxes for up to thousands of years. In humid sites, applied tracers (such as bromide) are used for evaluating solute transport. Organic dyes (such as FD&C (food, drug, and cosmetics) blue dye and Rhodamine dye) have also been used in delineating preferred pathways in humid regions [*Steenhuis et al.*, 1990]. Use of applied tracers has generally been limited in arid regions to irrigated areas [*Wierenga et al.*, 1991] or localized zones of high water fluxes [*Scanlon*, 1992b]. The low water fluxes typical of many arid settings limit the penetration depth of applied tracers. In some arid settings, contaminants in the unsaturated zone can be considered long-term applied tracers. Bromide that originated in a factory that had been operating for 18 years was used to evaluate water flow and solute transport at a site in the Negev Desert, Israel [*Nativ et al.*, 1995].

A wide variety of environmental tracers exists that span different time scales (Table 3). These tracers, including ^{36}Cl and ^{3}H, are produced naturally in the Earth's atmosphere and have existed in the natural environment for millions of years. The concentration of these tracers was greatly increased by nuclear testing in the mid-1950s to early 1960s, however (Figure 3). Some tracers exist in both liquid and vapor phases (tritiated water), whereas others exist only in the liquid phase in the subsurface (Cl and ^{36}Cl). We will review some of the most widely used environmental tracers and examine the assumptions associated with these tracers and how accurately they represent the flow system.

3.2.1. Meteoric chloride. The chloride mass balance approach uses chloride concentrations in pore water to estimate liquid water fluxes for up to thousands of years at many arid sites [*Allison and Hughes*, 1983]. Chloride from precipitation, dry fallout, or irrigation may concentrate in the root zone as a result of evapotranspiration [*Gardner*, 1967]. Chloride transport through the unsaturated zone is described by

$$q_{Cl} = q_l c_{Cl} - D_h \frac{\partial c_{Cl}}{\partial z} \tag{10}$$

where q_l is the volumetric liquid water flux below the root zone ($L\,T^{-1}$), q_{Cl} is the chloride deposition flux at the surface ($M\,L^{-2}\,T^{-1}$), c_{Cl} is the pore water chloride concentration ($M\,L^{-3}$), and D_h is the hydrodynamic dispersion coefficient ($L^2\,T^{-1}$), a function of θ (volumetric water content) and v (average pore water velocity). The first term on the right represents the chloride flux that results from advection, and the second term represents the flux from hydrodynamic dispersion. The mechanical dispersion coefficient D_m and the effective molecular diffusion coefficient D_e compose the hydrodynamic dispersion coefficient. Mechanical dispersion is the mixing that occurs as a result of variations in pore water velocity due to (1) the parabolic velocity distribution within a pore, (2) different pore sizes, and (3) the effects of tortuosity or branching of pore channels. Molecular diffusion results from the thermal or kinetic energy of particles. Mechanical dispersion is assumed to be negligible because flow velocities are generally <7 m yr^{-1}, which *Olsen and Kemper* [1968] specified as the water velocity below which mechanical dispersion can be ignored. The effective molecular diffusion coefficient differs from the diffusion coefficient in pure water because of the reduced cross-sectional area in unsaturated media (represented by the water content)

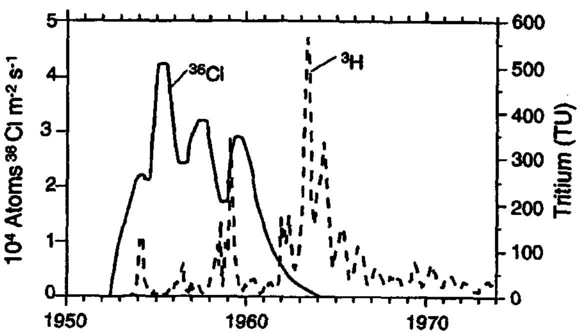

Figure 3. Temporal variations in predicted bomb ^{36}Cl fallout between 30°N and 50°N latitude [*Bentley et al.*, 1986] and in ^{3}H fallout of precipitation in the northern hemisphere [*IAEA*, 1983], decay corrected to 1989.

and the increased path length for the water (tortuosity). At low water fluxes the diffusive flux may be dominant. In many arid systems the hydrodynamic dispersion coefficient can be assumed to be negligible [*Allison and Hughes*, 1978], and equation (10) is simplified to

$$q_l = q_{Cl}/c_{Cl} \tag{11}$$

The age of the chloride and, by implication, that of the water can be calculated by dividing the integrated Cl content from the surface to the depth of interest by the annual chloride deposition flux. Chloride concentration in pore water is inversely proportional to water flux: low chloride concentrations indicate high water flux, and high chloride concentrations indicate low water flux (Figure 4).

Chloride deposition flux at a site can be estimated by (1) measuring chloride concentrations in precipitation and dry fallout or (2) dividing the natural ^{36}Cl fallout at a site, which varies according to latitude (as predicted by *Andrews and Fontes* [1991]), by the prebomb $^{36}Cl/Cl$ ratio (i.e., ratios before the first atmospheric nuclear explosion). An independent estimate of chloride deposition was also calculated for chloride profiles at the Hanford site, Washington [*Murphy et al.*, 1996]. Late Pleistocene floods, resulting from breaching of glacial dams, reset the chloride mass balance clock at the beginning of the Holocene. Estimates of chloride deposition that were calculated by dividing the chloride mass by the time since flooding when all chloride was flushed out of the sediments (15,000 years) agreed with estimates based on prebomb $^{36}Cl/Cl$ ratios. Because chloride mass balance equations are linear, uncertainties in the chloride deposition flux result in corresponding uncertainties in estimated water fluxes. If chloride concentration in precipitation is controlled (to first order) by distance from the ocean, its concentration should not vary significantly with time. Higher precipitation during Pleistocene times would result in correspondingly higher chloride deposition. Chloride deposition from dry fallout of dust and salts is of the same magnitude as that from precipitation in Nevada [*Dettenger*, 1989]. The contribution of dry fallout from saline lakes can be examined by measuring prebomb $^{36}Cl/Cl$ ratios because saline lakes have signatures markedly different from those of modern precipitation [*Phillips et al.*, 1995]. The prebomb $^{36}Cl/Cl$ ratios refer to $^{36}Cl/Cl$ ratios at depth that reflect fallout that occurred before the bomb pulse. At many sites, prebomb $^{36}Cl/Cl$ ratios are similar (500×10^{-15} [*Scanlon*, 1992a; *Fabryka-Martin et al.*, 1993]), which suggests that the contribution of ^{36}Cl from saline lakes is negligible at these sites. In addition to rain and dry fallout, other sources of chloride include rocks at Yucca Mountain [*Fabryka-Martin et al.*, 1993] and runon or runoff that should be quantified.

The chloride mass balance approach assumes piston-like flow, or uniform downward movement of water that displaces the initial water in the profile. The assumption

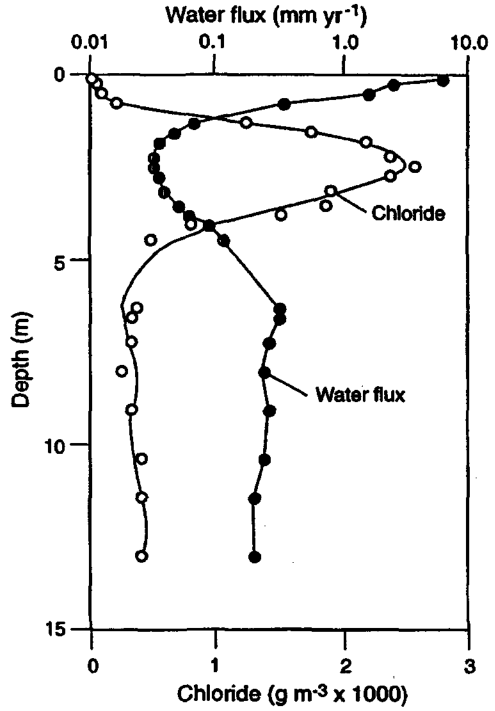

Figure 4. Typical example of inverse relationship between pore water chloride concentrations and estimated water fluxes. Adapted from *Scanlon* [1991, Figure 2] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands.

of piston-like flow has been questioned at many sites. Because chloride input to the system is continuous, chloride profiles are generally insensitive to preferential flow, or nonuniform downward movement of water, in which some water moves rapidly along preferred pathways such as roots or fractures. Piston-like and preferential flow are discussed in more detail in section 5. Evidence of preferential flow is generally provided by the distribution of bomb pulse tracers in the vadose zone such as bomb pulse ^{36}Cl and ^{3}H. Although tritium data at a fractured-chalk site in the Negev Desert indicate preferential flow, chloride profiles at this site are smooth, as would be expected at a site without preferential flow [*Nativ et al.*, 1995].

Bulge-shaped chloride profiles at many sites in nonfractured sediments could result from preferential flow [*Nativ et al.*, 1995], diffusion to a shallow water table [*Cook et al.*, 1989], or transient flow [*Scanlon*, 1991; *Phillips*, 1994] (Figure 5). Chloride profiles at many of these sites look similar, and interpretation of the bulge shape generally relies on additional information. Evidence of preferential flow in the Negev site was provided by deep penetration of ^{3}H [*Nativ et al.*, 1995]. The shape of some profiles in Australia are attributed to diffusion to a shallow water table because of the differences in chloride concentration between unsaturated and saturated zones (Figure 5) [*Cook et al.*, 1989]. Bulge-shaped chloride profiles in the southwestern United States,

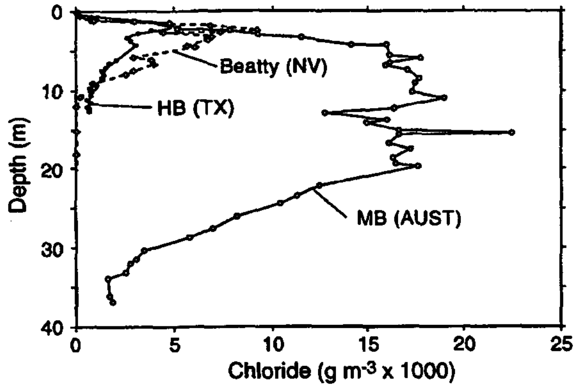

Figure 5. Bulge-shaped chloride profiles from vegetated dunes in the Murray Basin, South Australia (MB, profile BVDO1 [*Cook et al.*, 1989]), and from various southwestern U.S. settings (Hueco Bolson (HB), Texas, [*Scanlon*, 1991]; Beatty, Nevada [*Prudic*, 1994]). HB and MB plots reproduced from *Scanlon* [1991, Figure 3] and *Cook et al.* [1989] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands.

where the water table is generally much deeper (≥100 m), are attributed to higher water fluxes during the Pleistocene, when the climate was cooler and wetter [*Scanlon*, 1992a; *Phillips*, 1994; *Tyler et al.*, 1996]. Additional evidence on the effect of paleoclimate on water movement is provided by stable isotopic data [*Tyler et al.*, 1996]. In areas where the chloride concentration below the chloride peak is very low, such as at Beatty, Nevada [*Prudic*, 1994], preferential flow cannot be used to explain the reduction in chloride because preferential flow refers to enhanced water movement along localized preferred pathways, which does not include complete leaching (Figure 5). Because chloride profiles represent net liquid water flux over long time periods, the chloride at depth at these sites is a relic of past climate conditions and does not represent current conditions. In Australia, on a much smaller timescale (~100 years), transient flow conditions resulted when native mallee vegetation, characterized by deep-rooted (~20 m) eucalyptus trees, was replaced by crops and pasture [*Cook et al.*, 1994].

The chloride mass balance method provides an estimate of liquid water flux, which is important in evaluating the movement of nonvolatile solutes. Because liquid water flux may move downward and vapor flux and net water flux may move upward, estimates of liquid flux based on chloride data alone may provide inaccurate estimates of net water flux.

3.2.2. Chlorine 36. Chlorine 36 (half-life of 301,000 years) is produced in the atmosphere by cosmic ray spallation of ^{36}Ar and neutron activation of ^{35}Cl [*Bentley et al.*, 1986]. Chlorine 36 can provide estimates of liquid water residence time (1) over the past ~40 years by means of bomb pulse $^{36}Cl/Cl$ ratios, (2) over the past 70–80 kyr by means of variations in cosmogenic production of ^{36}Cl, and (3) from 50 to 1000 kyr by means of radioactive decay of ^{36}Cl (Table 3).

Nuclear weapons tests conducted between 1952 and 1958 resulted in ^{36}Cl concentrations in precipitation as much as 1000 times greater than natural fallout levels [*Bentley et al.*, 1986] (Figure 3). In nonfractured sediments, water fluxes have been estimated from the ^{36}Cl center of mass [*Cook et al.*, 1994]. The amount of water in the profile above the center of mass of ^{36}Cl is equal to the flux during the time period since the center of mass of the fallout occurred. Annual water flux is generally calculated by dividing this total flux by time in years. In many areas where bomb pulse ^{36}Cl has been used to estimate water flux, the center of mass of the bomb pulse is still in the root zone [*Gifford*, 1987; *Norris et al.*, 1987; *Phillips et al.*, 1988; *Scanlon*, 1992a] (Figure 6). Occurrence of the bomb pulse in the root zone indicates that water fluxes at these sites are extremely low, which is important for waste disposal. Because much of this water in the root zone is later removed by evapotranspiration, water fluxes estimated from tracers within the root zone overestimate water fluxes below the root zone by up to several orders of magnitude [*Tyler and Walker*, 1994]. High $^{36}Cl/Cl$ ratios have been found to depths of 440 m at Yucca Mountain, Nevada [*Liu et al.*, 1995], suggesting preferential flow along fractures. Variations in cosmogenic production of ^{36}Cl during the past 60–70 kyr could complicate the use of bomb pulse $^{36}Cl/Cl$ ratios. Some of the measured $^{36}Cl/Cl$ ratios considered to be bomb pulse, particularly at Yucca Mountain, fall within the range estimated as a result of variations in cosmogenic production of ^{36}Cl (J. Fabryka-Martin, personal communication, 1995) and may not be bomb related. Because the ratio of ^{36}Cl to chloride rather than the ^{36}Cl concentration is measured, high chloride concentrations in pore water could reduce the effectiveness of $^{36}Cl/Cl$ ratios to estimate preferential flow.

Variations in cosmogenic production of ^{36}Cl can also be used to date water during the past 70–80 kyr [*Phillips et al.*, 1991; *Plummer and Phillips*, 1995]. Production rates of meteoric ^{36}Cl vary inversely with the strength of the magnetic field and increased by as much as a factor of 2 during periods of reduced magnetic field strength [*Plummer and Phillips*, 1995]. Comparison of reconstructed ^{36}Cl production with variations in ^{36}Cl in pore water has been used to estimate ages of water at the Nevada Test Site [*Tyler et al.*, 1996]. Because variations in cosmogenic production increase the background ratio by only as much as a factor of 2, such variations may not be readily preserved in the unsaturated zone because of diffusion and dispersion.

Radioactive decay of ^{36}Cl has also been used to date very old pore water in the unsaturated zone at Yucca Mountain [*Fabryka-Martin et al.*, 1993]. Use of radioactive decay of ^{36}Cl is complicated at this site because contributions of "dead" Cl (having no ^{36}Cl) from rock away from the main flow regime result in greater apparent ages.

3.2.3. Tritium. Tritium (^3H; half-life of 12.4 years), produced by cosmic ray neutrons interacting with

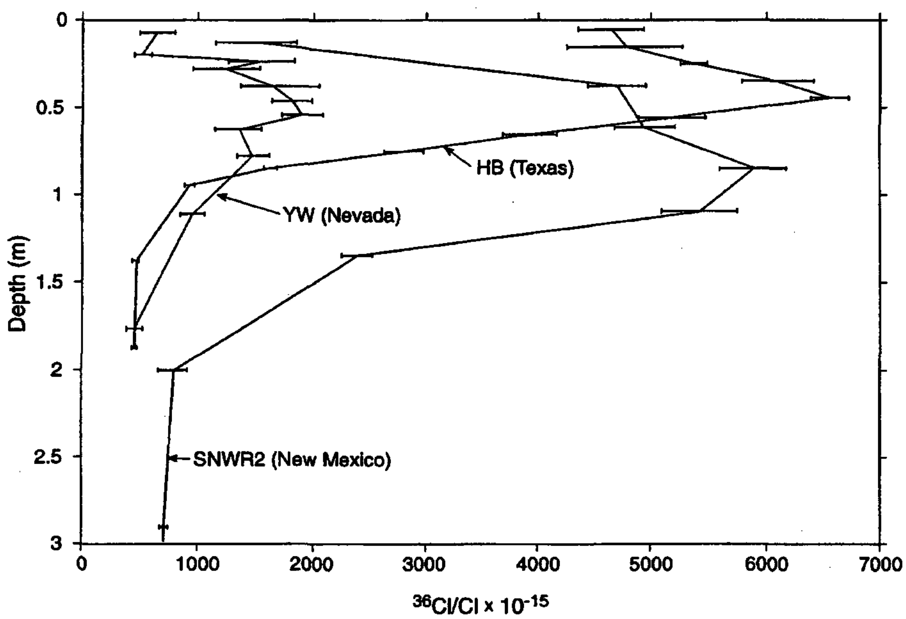

Figure 6. Profile of $^{36}Cl/Cl$ ratios from the Chihuahuan Desert (Hueco Bolson (HB) [*Scanlon*, 1992a]. Yucca Wash, Nevada (YW [*Norris et al.*, 1987]); and Sonoran Desert, New Mexico (SNWR2 [*Phillips et al.*, 1988]). Bars represent 1 standard deviation in the $^{36}Cl/Cl$ ratios. YW plot reproduced from *Norris et al.* [1987, Figure 1] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands.

nitrogen in the upper atmosphere, typically results in 5–10 tritium units (TU) in precipitation. Tritium concentrations increased from 10 to ≥2000 TU during atmospheric nuclear testing [*International Atomic Energy Agency* (*IAEA*), 1983] that began in 1952 and peaked in 1963–1964 (Figure 3). Because tritiated water exists in both liquid and vapor phases, tritium is a tracer for liquid and vapor water movement. The distribution of bomb-pulse tritium in the vadose zone can be used to estimate water fluxes and to evaluate preferential flow, a procedure similar to that described for ^{36}Cl.

In tritium analysis, pore water can be extracted directly from cores by means of toluene distillation or cryodistillation. Alternatively, gas samples can be extracted from boreholes and water condensed from the gas for tritium analysis. Large gas volumes are required to detect the trace amounts of tritium found at some sites that lead to uncertainties in the volume and depth interval of the unsaturated section that is sampled. Contamination in gas sampling procedures may occur because of the potential for air flow along well casing and leaking gas lines. Problems in interpreting very low tritium levels in Ward Valley, California, a proposed low-level radioactive waste disposal facility, are thought to result from poor sampling procedures and from the absence of procedural blanks for evaluating possible contamination [*NRC*, 1995]. General problems with analysis of low tritium levels in the unsaturated zone, particularly those close to the detection limit, may reflect our lack of experience with environmental tritium sampling and our inability to collect reliable samples.

To analyze water samples for tritium, various techniques have been used that depend on the amount of water available for analysis and accuracy required. Direct liquid scintillation generally requires ~20 mL of water, and the detection limit is ~6 TU (C. Eastoe, personal communication, 1995). The detection limit is greatly reduced when electrolytic enrichment is used; however, the amount of water required is greater. A minimum sample size of 275 mL, an electrolytic enrichment factor of ~80, and a counting time of 300 min by means of gas proportional counting result in a detection limit of 0.1 TU at the University of Miami Tritium Laboratory [*Ostlund and Dorsey*, 1977]. Longer counting times (≤1000 min) can be used for smaller samples.

Researchers recently analyzed tritium using the helium 3 "in-growth" method [*Schlosser et al.*, 1989; *Solomon and Sudicky*, 1991). Tritium decays to ^{3}He. Pore water from the unsaturated zone is degassed of all He, sealed, and stored to decay to ^{3}He, allowing much higher precision and lower detection limits than do standard counting techniques. For example, a 20-mL water sample that is allowed to decay for 6 months would result in a detection limit of ~0.2 TU (R. Poreda, personal communication, 1995). The ^{3}He in-growth method for analyzing ^{3}H in unsaturated pore water samples should be distinguished from the ^{3}He in-growth dating method, which applies strictly to the saturated zone. Dating water using $^{3}H/^{3}He$ requires isolation of the ^{3}He from the atmosphere, which occurs only below the water table and provides the age of the water since it became isolated from the atmosphere [*Solomon et al.*, 1992]:

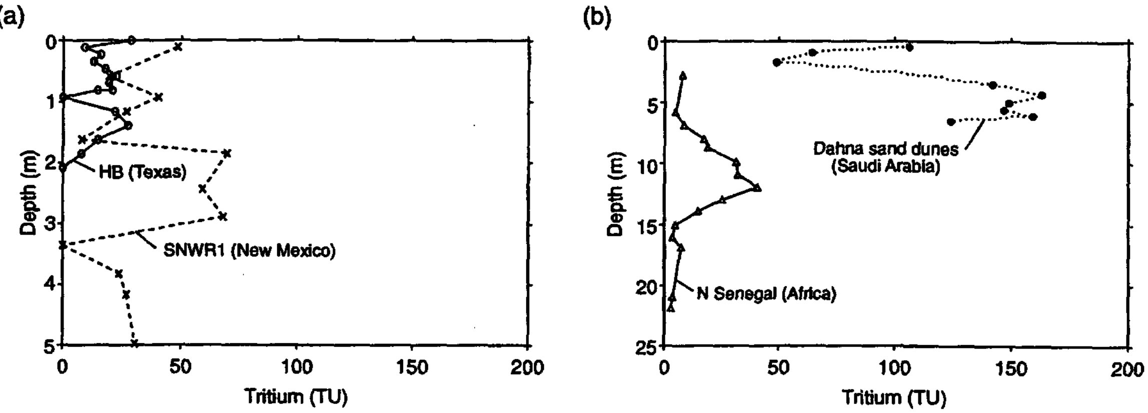

Figure 7. Profiles of ^3H concentrations (a) from the Chihuahuan Desert (Hueco Bolson (HB) [*Scanlon*, 1992]) and Sonoran Desert (SNWR1 [*Phillips et al.*, 1988]) and (b) from northern Senegal [*Aranyossy and Gaye*, 1992] (with permission from Gauthier-Villars Editeur) and Dahna sand dunes, Saudi Arabia (replotted from *Dincer et al.* [1974, Figure 11] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands).

$$t_{^3\mathrm{H}/^3\mathrm{He}} = \lambda^{-1} \ln\left(\frac{^3\mathrm{He}}{^3\mathrm{H}} + 1\right) \tag{12}$$

where $t_{^3\mathrm{H}/^3\mathrm{He}}$ is the ^{3}H/^{3}He age and λ is the ^{3}H decay constant.

At many arid sites, although the tritium bomb pulse within the root zone provides evidence of very low water fluxes [*Phillips et al.*, 1988; *Scanlon*, 1992a], accurate estimates of deep percolation below the root zone cannot be obtained from these data (Figure 7a). Deep penetration of the bomb pulse has also been found in sandy soils in arid settings [*Dincer et al.*, 1974; *Aranyossy and Gaye*, 1992] (Figure 7b). Comparison of ^{3}H and ^{36}Cl data from some arid sites showed deeper penetration of ^{3}H relative to ^{36}Cl, results that were attributed to enhanced downward movement of ^{3}H in the vapor phase [*Phillips et al.*, 1988; *Scanlon and Milly*, 1994]. Diffusion of ^{3}H in the vapor phase is limited if equilibration between liquid and gas phases occurs because the concentration of ^{3}H in the vapor phase is 5 orders of magnitude less than in the liquid phase, reflecting the different densities of water molecules in the two phases [*Smiles et al.*, 1995]. The liquid phase, in this case, acts as a large sink for tritium.

The method used to estimate water flux from bomb pulse tracer distributions is based on an assumption of steady downward advective flux, implying that the penetration depth of ^{36}Cl and ^{3}H increases linearly with time. Recent analytical studies by *Milly* [1996] suggest that the shallow distribution of these bomb pulse tracers can be attributed to episodic downward liquid flow and seasonal temperature gradients without invoking any mean vertical downward or upward water flux. The presence of ^{36}Cl and ^{3}H near the surface indicates little or no water flux below the root zone. High ^{3}H values (e.g., 1100 TU at 24-m depth, $\leq$ 162 TU at 109-m depth) have been found adjacent to the Beatty site, Nevada, that cannot readily be explained by liquid or combined liquid and vapor transport [*Prudic and Striegl*, 1995; *Striegl et al.*, 1996]. Because disposal practices at Beatty varied in the past and included disposal of as much as ~2000 m^3 of liquid waste, further research in ^{3}H movement at Beatty is warranted.

In some locations, bomb pulse ^{3}H has been found at depths greater than those initially expected. For example, bomb pulse ^{3}H was found as deep as ~450 m (105 TU; UZ-16 borehole) in Yucca Mountain (I. C. Yang, personal communication, 1995) and ~12 m (8.4 TU, RT18 borehole) in the Negev Desert [*Nativ et al.*, 1995]. These depths of ^{3}H migration, much greater than predicted by chloride mass balance data at these sites, may be attributed to preferential flow along fractures.

4. DIRECTION AND RATE OF WATER MOVEMENT

Although direction of water movement is a basic issue, it is not easily resolved at some sites, primarily because the water fluxes under consideration have a magnitude close to the errors inherent in measuring or in calculating these water fluxes. Second, a variety of driving forces in water movement may be important in arid settings, including water potential, gravitational potential, pneumatic potential, osmotic potential, and temperature. Third, the direction of water flux is likely to be spatially and temporally variable.

In this section we examine the various driving forces that can control the direction of water movement. Sediment heterogeneity also affects the direction of flow and is discussed later.

4.1. Liquid Flux

An initial examination of the simple system in which liquid flow is dominant shows that liquid water flux q_l is described by Darcy's law under steady flow conditions

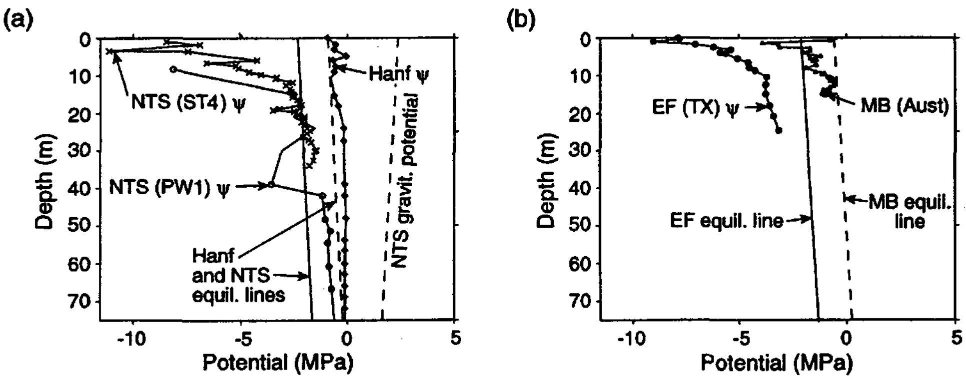

Figure 8. Evaluation of the direction of water movement according to the relationship between water potential profiles and the equilibrium line. Data are (a) from Hanford, Washington (Hanf; data from *Brownell et al.* [1975] as plotted by *Gee and Heller* [1985, Figure 4]), and Nevada Test Site, Nevada (NTS; profiles ST4 (shallow) and PW1 (deep) [*Estrella et al.*, 1993]), and (b) from Eagle Flat, Texas (EF111 [*Scanlon et al.*, 1997b]), and Murray Basin, South Australia (MB [*Jolly et al.*, 1989]). Equilibrium line refers to equilibrium matric potential that balances gravitational potential (Nevada Test Site data shown as an example).

according to equation (6). Evaluation of flow direction requires information on the hydraulic head (sum of matric and gravitational potential heads) gradient. Because matric potentials in natural interfluvial settings in arid systems are generally low, tensiometers cannot be used and thermocouple psychrometers are required that measure water potential (sum of matric and osmotic potential; see Tables 1 and 2 and Figure 3). The osmotic component of the water potential is generally negligible because zones where the magnitude of the osmotic potential is high in near-surface sediments generally correspond to zones where the magnitude of the water potential is also high [*Scanlon*, 1994]. Except in the shallow subsurface after rainfall, water (pressure) potentials measured in interfluvial settings in desert soils generally decrease (become more negative) toward the surface [*Jolly et al.*, 1989; *Fischer*, 1992; *Detty et al.*, 1993; *Scanlon*, 1994]. This upward decrease in water potentials suggests an upward driving force for liquid water flow.

One can also estimate the direction of water flow under steady flow conditions by comparing the measured matric or water potentials with the equilibrium matric potentials (Figure 8). If the vertical space coordinate z is taken as positive upward and zero at the water table, the equilibrium matric potential heads are the negative of the gravitational potential heads because matric and gravitational potential heads are balanced under static equilibrium (no flow) and their sum is a constant (0 in this case) (Figure 8). Under steady flow conditions, matric potentials that plot to the right of the equilibrium matric potential line indicate downward flow, and matric potentials that plot to the left of the equilibrium line indicate upward flow. At a site in Hanford, Washington, *Brownell et al.* [1975] (Figure 8a) found that measured water (pressure) potentials (approximately equal to matric potentials) plot to the right of the equilibrium line, indicating drainage. At several sites in Australia and in the southwestern United States, water (pressure) potentials plot to the right of the equilibrium line, indicating net upward water movement [*Jolly et al.*, 1989; *Fischer*, 1992; *Estrella et al.* 1993; *Scanlon*, 1994] (Figure 8b). At the Nevada Test Site this zone of net upward water movement is restricted to the upper 20–40 m (Figure 8a) [*Detty et al.*, 1993; *Sully et al.*, 1994]. Below 20–40 m, water potentials plot to the right of the equilibrium line, suggesting that liquid water at depth may be draining at this site.

4.2. Vapor Flux

Under dry conditions characteristic of arid settings, vapor flow may be significant. If the air phase is assumed to be static, vapor flux q_v is given by

$$q_v = q_{\mathrm{I}v} + q_{\mathrm{T}v} = -D_{\mathrm{I}v}\nabla h - D_{\mathrm{T}v}\nabla T \qquad (13)$$

where $q_{\mathrm{I}v}$ is the isothermal vapor flux, $q_{\mathrm{T}v}$ is the thermal vapor flux, $D_{\mathrm{I}v}$ is the isothermal vapor diffusivity, $D_{\mathrm{T}v}$ is the thermal vapor diffusivity, h is matric (pressure) potential head, and T is temperature. Isothermal vapor flux is driven by the matric (pressure) potential gradient and is unaffected by the temperature gradient, in a way similar to that of the liquid flux. Thermal vapor flux is driven by the temperature gradient and is unaffected by the matric potential gradient. Thermal vapor flux, resulting from variations in saturated vapor pressure according to temperature, is generally considered much more important than isothermal vapor flux. A temperature difference of 1°C at 20°C results in a greater difference in vapor density (1.04×10^{-3} kg m^{-3}) than does a 1.5-MPa difference in matric potentials from −0.01 MPa to −1.5 MPa (0.17×10^{-3} kg m^{-3}) [*Hanks*, 1992, p. 95]. The effects of temperature enter directly through temperature gradients and indirectly through temperature dependence of the matric (pressure) potential, hydraulic conductivity, and vapor diffusivity [*Scanlon and Milly*, 1994]. Thermally driven liquid flow is generally negligible under the low water contents characteristic of interfluvial arid settings [*Milly*, 1996].

Seasonal reversals in temperature gradients from upward movement in the winter to downward movement in the summer in the 2- to 12-m zone result in a net downward thermal vapor flux [*Fischer*, 1992; *Scanlon*, 1994] (Figure 1). Net downward thermal vapor fluxes are attributed to higher thermal vapor diffusivities as a result of higher temperatures in the summer when the gradients are downward. Below the zone of seasonal temperature fluctuations, the upward geothermal gradient provides an upward driving force for thermal vapor movement (Figure 1). Estimated values of local geothermal gradients are 0.06°C m^{-1} (Beatty site [*Prudic*, 1994]), 0.013°C m^{-1} (Nevada Test Site [*Tyler et al.*, 1996]), and 0.046°C m^{-1} (Hanford [*Enfield et al.*, 1973]). Calculated upward thermal vapor fluxes resulting from the upward geothermal gradient range from 0.02 mm yr^{-1} at the Nevada Test Site [*Sully et al.*, 1994] to 0.04 mm yr^{-1} at the Hanford site [*Enfield et al.*, 1973].

So far in our analysis we have considered vapor diffusion resulting from water (pressure) potential and temperature gradients only, but volatile contaminants may also diffuse as a result of concentration gradients. In addition to diffusion, advection may occur in the gas phase. Factors resulting in advective transport include barometric pressure fluctuations, density, wind, and temperature. In homogeneous, permeable media, *Buckingham* [1904] showed that the effect of barometric pressure fluctuations was small in relation to that of molecular diffusion. In fractured, permeable media, advective fluxes resulting from barometric pressure fluctuations may be orders of magnitude greater than diffusive fluxes and could result in upward movement of contaminated gases into the atmosphere [*Nilson et al.*, 1991]. A gas tracer experiment described by *Nilson et al.* [1992] confirms the importance of barometric pumping in causing upward gas movement in fractured tuff from a spherical cavity (depth ~300 m) created by underground nuclear tests at the Nevada Test Site. In areas of steep topography such as at Yucca Mountain, temperature- and density-driven topographic effects result in continuous exhalation of air through open boreholes at the mountain crest in the winter, as cold dry air from the flanks of the mountain replaces warm moist air within the rock-borehole system [*Weeks*, 1987]. Wind also results in air discharge from the boreholes that is ~60% of that resulting from temperature-induced density differences [*Weeks*, 1993]. Open boreholes greatly enhance the advective air flow at this site; numerical simulations indicate that water fluxes resulting from advective air flow under natural conditions (0.04 mm yr^{-1}) are 5 orders of magnitude less than those found in the borehole [*Kipp*, 1987] and similar in magnitude to estimated vapor fluxes as a result of the geothermal gradient (0.025 to 0.05 mm yr^{-1} [*Montazer et al.*, 1985]). These processes could cause drying of fractured rock uplands and could expedite the release of gases to the atmosphere [*Weeks*, 1993].

4.3. Water Flux

Water includes liquid and vapor phases. Analysis of data from several sites in the southwestern United States indicates that net water flux often occurs upward in the upper 20- to 40-m section of the unsaturated zone because water potentials plot to the left of the equilibrium line and total potential (matric [pressure] + gravitational) gradients are upward (Figure 8). In the zone of seasonal temperature fluctuations (2–12 m deep), upward liquid and isothermal vapor fluxes exceed downward thermal vapor fluxes (Figure 1). Upward water potential and temperature gradients at greater depths result in upward liquid and vapor fluxes (Figure 1).

Below the 20- to 40-m section, water potentials at the Nevada Test Site plot to the right of the equilibrium line [*Detty et al.*, 1993], indicating downward liquid and isothermal vapor flux under steady flow conditions, and upward thermal vapor flux due to the geothermal gradient (Figure 1). At this site, the upward thermal vapor flux (0.02 mm yr^{-1}), almost balanced by the downward liquid flux (0.03 mm yr^{-1}), results in a statistically insignificant net downward water flux of 0.01 mm yr^{-1} [*Sully et al.*, 1994]. At the Hanford site the upward thermal vapor flux (0.04 mm yr^{-1}), less than the downward liquid flux (0.30 mm yr^{-1}), results in a net downward water flux of 0.26 mm yr^{-1}. The larger flux at the Hanford site is attributed to higher water potentials (−0.1 MPa) relative to those at the Nevada Test Site (−0.6 MPa) [*Sully et al.*, 1994]. In the upper part of the unsaturated zone, different directions of liquid and vapor fluxes can therefore be important for evaluation of the transport of volatile and nonvolatile substances.

5. HOW IMPORTANT IS PREFERENTIAL FLOW?

Traditionally, piston-like flow, implying displacement of initial water by infiltrating water, was thought to be the dominant flow mechanism in the unsaturated zone. In the strict sense, piston flow refers to uniform displacement of solute or water without any mixing. True piston flow never occurs because of mixing due to molecular diffusion and microscopic water velocity variations. We therefore use the term "piston-like flow" instead of "piston flow" to represent predominantly matrix flow, or uniform flow, through the unsaturated matrix, in contrast to preferential flow, which bypasses much of the unsaturated zone. Data from many arid sites, particularly interfluvial settings that have unconsolidated sediments, suggest predominantly piston-like flow. Differences in velocities of solute (V_s) and wetting fronts (V_{wf}) in South Australia after vegetation clearing (Figure 9) could be predicted by the following equation, which assumes piston flow:

$$\frac{V_s}{V_{wf}} = \frac{\theta_f - \theta_i}{\theta_f} \tag{14}$$

where θ_f is the final water content and θ_i is the initial water content [*Jolly et al.*, 1989]. Similar results were found in large field tracer experiments conducted in Las Cruces, New Mexico [*Young et al.*, 1992]. In these experiments the lag between the solute and the wetting front increased with depth, consistent with piston-like displacement of original pore water. Increases in initial water content resulted in increased lag between solute and wetting fronts. Single peaks in bomb pulse tracer distributions such as ^{36}Cl at sites in the Chihuahuan Desert site [*Scanlon*, 1992a], the Nevada Test Site [*Norris et al.*, 1987], and the Sonoran Desert site [*Phillips et al.*, 1988], are also consistent with piston-like flow (Figure 6). Although the aforementioned data suggest predominantly piston-like flow, they are not sensitive to small-scale preferential flow.

Preferential flow has received more emphasis in recent studies. With preferential flow the cross-sectional area of flow is reduced, and water bypasses much of the unsaturated medium, leading to corresponding increases in velocity and reduced sorption. Preferential flow was generally considered to become damped with depth; however, more recent studies suggest that this is not always true. Preferential flow can be divided into funneled flow, unstable flow, and macropore flow [*Steenhuis et al.*, 1994]. These three types of preferential flow are not mutually exclusive because unstable flow can occur in macropores (as will be described later). Funneled flow, occurring at textural interfaces, was extensively documented in glacial outwash deposits in Wisconsin

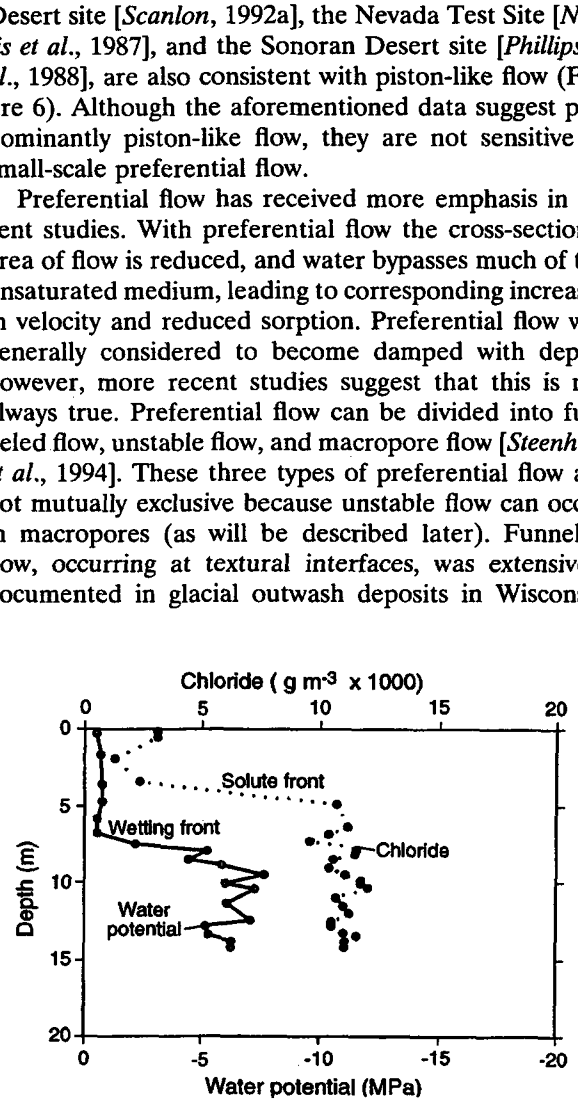

Figure 9. Piston-like flow evidenced by the lag between the wetting front and the solute front (modified from *Jolly et al.* [1989, Figure 2] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands). The zone from the soil surface to the solute front represents water that infiltrated after the vegetation was cleared, the zone between the solute and wetting front represents displaced "preclearing" water, and the zone below the wetting front represents initial "preclearing" water.

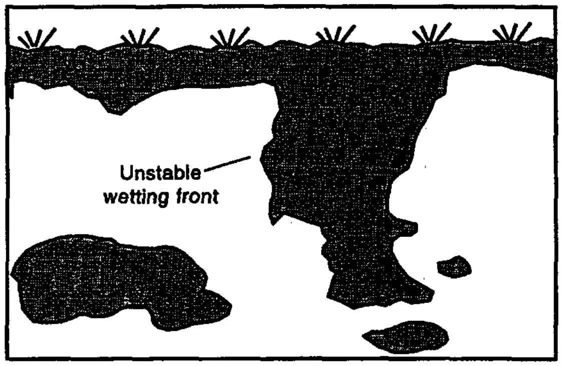

Figure 10. Example of unstable flow in water repellent soils after rainfall in the Netherlands (modified from *Hendrickx and Dekker* [1991]).

under unsaturated conditions [*Kung*, 1990a, b; *Miyazaki*, 1993]. Laboratory experiments showed that when water application rates were ≤2% of the saturated hydraulic conductivity of the finer material, water flowed along the surface of the coarser layer [*Kung*, 1993]. Although funneled flow has not been found in arid settings, lateral flow in geologically layered materials resembles funneled flow where inclined beds and natural capillary barriers result in lateral flow. Such lateral flow along geologically layered materials has been hypothesized for Yucca Mountain, Nevada, on the basis of analytical solutions and numerical simulations [*Ross*, 1990; *Oldenburg and Pruess*, 1993].

Unstable wetting fronts have been found in several field sites [*Starr et al.*, 1978, 1986; *Glass et al.*, 1988; *Hendrickx and Dekker*, 1991; *Selker et al.*, 1992; *Hendrickx et al.*, 1993] (Figure 10). *Chen et al.* [1995] provided an overview of instability and fingering in porous and fractured media. Important factors in the development of unstable flow in porous media include layering of sediment [*Hillel and Baker*, 1988; *Glass et al.*, 1989b], air entrapment [*Glass et al.*, 1990], and water repellency [*Hendrickx and Dekker*, 1991; *Ritsema et al.*, 1993; *Dekker and Ritsema*, 1994]. The absence of unstable wetting fronts in dune sands in an arid region of New Mexico led *Yao and Hendrickx* [1996] to evaluate conditions required for wetting-front instability. Many of the studies document that unstable wetting fronts were found in sandy, water-repellent soils because water repellency always results in unstable flow [*Hendrickx and Dekker*, 1991; *Ritsema et al.*, 1993; *Dekker and Ritsema*, 1994; *Ritsema and Dekker*, 1995]. Water tables are also shallow at many of these sites (0.5–1.5 m [*Ritsema et al.*, 1993]). *Hendrickx and Yao* [1996] subdivided infiltration rates into three regimes: low, medium, and high. Gravity-driven instabilities do not occur under low infiltration rates, where capillary and adsorptive forces are much greater than gravitational forces. Under high infiltration rates, wetting fronts remain stable if the infiltration rate approximates field-saturated hydraulic conductivity. Un-

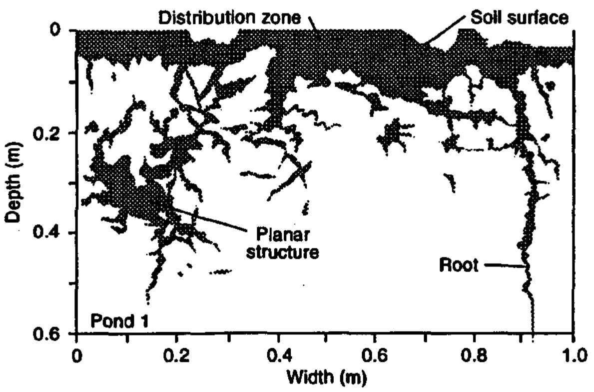

Figure 11. Example of preferential flow along roots as shown by FD&C dye [*Scanlon et al.*, 1997a].

der medium infiltration rates, stable wetting fronts are found when the total amount of infiltrating water is less than the amount of water required to wet a surface distribution layer. Additionally, the distribution layer has stable flow, and the thickness of this layer can be predicted by the same equation used by *Glass et al.* [1989a] to predict finger diameter [*Hendrickx and Yao*, 1996]. Application of these criteria to dune sands in New Mexico showed that all 2- and 10-year, and some 100-year return interval precipitation events were in the stable flow regime [*Hendrickx and Yao*, 1996]. Thus precipitation records and information on water repellency, water retention, and hydraulic conductivity of sediments at a site can be used to evaluate the potential for unstable flow.

Macropore flow refers to flow along noncapillary-size openings such as fractures, cracks, and root tubules (Figure 11). Important factors in evaluating macropore flow include sediment texture and structure and boundary conditions [*Flury et al.*, 1994]. Previous studies have shown that macropore flow is much greater in structured, fine-grained sediments than in structureless coarse-grained sediments [*Steenhuis and Parlange*, 1991; *Flury et al.*, 1994]. Whereas finger and funneled flow are eliminated under saturated conditions, it was previously thought that ponded conditions were required for macropore flow. Water ponds episodically in playas (ephemeral lakes) in arid systems. Detailed studies of playas have been conducted in the Southern High Plains of Texas, and preferential flow is inferred from the multipeaked character of a ^{3}H profile beneath a playa [*Scanlon et al.*, 1997a; *Scanlon and Goldsmith*, 1997] (Figure 12). Although ponding greatly enhances the potential for flow along macropores, such flow occurs under natural rainfall and sprinkler conditions also. Because water flow in noncapillary size pores occurs only when saturation is approached, macropore flow has been found mostly in humid sites that have higher precipitation [*Gish and Shirmohammadi*, 1991] or in arid settings subjected to ponding.

Much of the evidence for macropore flow in arid settings has been restricted to fractured media, such as tension fractures beneath fissured sediments in the Chihuahuan Desert [*Scanlon*, 1992b], fractured tuff in Yucca Mountain [*Fabryka-Martin et al.*, 1993], and fractured chalk in the Negev Desert [*Nativ et al.*, 1995]. Many fracture studies are based on laboratory experiments [*Nicholl et al.*, 1994]. *Glass et al.* [1995] proposed a "thought" experiment that may explain how preferential flow along fractures could transmit water over long distances, as seen at the Nevada Test Site [*Russell et al.*, 1987] and Yucca Mountain [*Fabryka-Martin et al.*, 1993; *Liu et al.*, 1995]. According to their thought experiment, gravity-driven fingers in inclined fractures are expected to persist over time. These fingers originate from point connections with water sources either at the surface or at a depth where perched zones occur. Water flow in the fractures should be only negligibly affected by water moving from the fracture into the matrix because of (1) the reduced flow area within the fractures (due to fingering and air entrapment), (2) reduced matrix storage capacity (most fractured rocks at Yucca Mountain are at or near satiated water content, i.e., near saturated with some entrapped air, at depth while still at low matric potential), and (3) vertical capillary barriers provided by surrounding fractures within the network that reduce conduction of water from one matrix block to another. With depth, fingers are expected to focus into a smaller number of stronger flow paths at the contact of larger aperture fractures, a concept contrary to prevailing ideas that preferential flow dissipates at depth when water moves into the matrix.

The continuity of preferred pathways, critical in macropore flow, depends on pathway type. Rock fractures can extend to great depths, whereas desiccation cracks and root tubules are generally fairly shallow. Although macropores are generally thought to provide pathways for enhanced downward liquid flow, macropores also provide pathways for gas and vapor move-

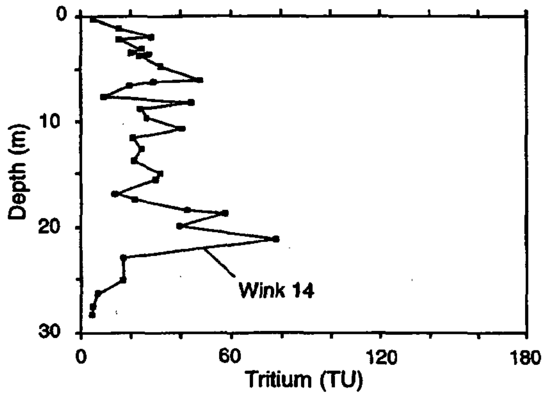

Figure 12. A deep multipeaked ^{3}H profile beneath a clay rich playa, indicating preferential flow (Wink 14 [*Scanlon et al.*, 1997a]).

ment and may enhance upward movement of volatile contaminants, as was suggested by *Weeks* [1993].

The type of contaminant helps determine the significance of preferential flow. Preferential flow is much more important for contaminants that exceed health standards in the parts-per-billion range, such as pesticides, than for contaminants that exceed health standards in the parts-per-million range, such as nitrate [*Steenhuis and Parlange*, 1991]. Nitrate contamination requires movement of the bulk of the pore water, which is much greater than the generally smaller water volume transported along preferred pathways. Arrival of the first 1% of the chemical at the groundwater is more readily accommodated by preferential flow than is the transport of the bulk of the mass.

Many of the studies evaluating preferential flow were either conducted in humid sites or performed on the basis of laboratory studies or theoretical analysis. Field evidence of preferential flow in arid settings has been found mostly in fractured rocks [*Fabryka-Martin et al.*, 1993; *Liu et al.*, 1995; *Nativ et al.*, 1995] and in fissured sediments [*Scanlon*, 1992b]. Bomb pulse tritium found at depths of ~12 m in an arid region in South Australia was attributed to preferential flow along the annular regions of eucalyptus roots [*Allison and Hughes*, 1983]. Few field studies show evidence of preferential flow at great depths in porous media in interfluvial arid settings, which may reflect (1) the absence of preferential flow in these settings, (2) the limited ability of various techniques to detect preferential flow in deep vadose zones, or (3) the difficulties of intercepting vertical preferred pathways by means of vertical boreholes.

6. CONTROLS ON WATER MOVEMENT

Water fluxes in arid regions have been shown to range widely both within and between various regions (Table 4). We can evaluate controls on unsaturated flow on the basis of comparisons of results from these studies. Primary controls such as pressure and temperature are discussed in the section on the direction of water movement. In this section we evaluate controls such as vegetation, climate, texture, and topographic setting.

6.1. Vegetation

Vegetation may be the most important control on water movement in desert soils. Uniformity in chloride profiles throughout the arid regions of the southwestern United States was attributed by *Phillips* [1994] to the ability of desert vegetation to control water fluxes regionally. Although annual precipitation and soil type varied widely among the sites examined by *Phillips* [1994], the chloride profiles were remarkably uniform. Because vegetation in arid regions is opportunistic, when the water application rate is increased, plant growth increases to use up the excess water. The opportunistic nature of desert vegetation is shown by higher concentrations of vegetation in areas of increased water flux, such as in ephemeral streams and in fissured sediments. When water supply is limited, plant activity decreases until water supply rates increase. Field studies have shown the importance of vegetation on local scales. Lysimeter studies in Hanford, Washington, and Las Cruces, New Mexico, showed deep drainage ranging from 10 to >50% of the annual precipitation in bare, sandy soils [*Gee et al.*, 1994]. The presence of plants at other sites at Hanford also greatly reduced deep drainage. Studies in Cyprus have found highest recharge rates in areas of sparse vegetation and lowest recharge rates in areas of bush vegetation [*Edmunds et al.*, 1988] (Table 4). Influence of vegetation is most clearly seen in areas where the vegetation cover has changed. In Australia, replacement of native mallee vegetation (deep-rooted eucalyptus trees) with crops resulted in an increase in recharge rates of at least an order of magnitude (from 0.1–0.9 mm yr^{-1} for native mallee regions to 4–28 mm yr^{-1} for pasture regions [*Cook et al.*, 1994]). Types of vegetation differ in how effectively they transpire water. In Hanford, Washington, water fluxes estimated in a grass site were much greater than water fluxes in nearby areas that had shrub vegetation [*Prych*, 1995]. Natural wildfires had resulted in replacement of shrubs with grass at this site. The effectiveness of vegetation in removing water from the subsurface was demonstrated in a lysimeter study at the Hanford site, where a lysimeter that had been bare for 3 years accumulated 150 mm of water in storage. The lysimeter subsequently became vegetated by deep-rooted plants (Russian thistle) that removed the excess water within a 3-month period to a depth of ~3 m [*Gee et al.*, 1994].

6.2. Climate and Paleoclimate

Although average annual precipitation is used to assess the potential for unsaturated flow, it is generally not a very good indicator of the rate of water movement. Data from various settings show little or no relationship between annual precipitation and water flux (Table 4). Seasonal distribution in precipitation is a better indicator of water flux in desert soils than is mean annual precipitation. Winter precipitation percolates through the soil more effectively than summer precipitation because evapotranspiration is low in the winter and the nature of precipitation varies seasonally. Winter precipitation in many parts of the world results from low-intensity, long-duration, frontal storms that are more likely to infiltrate in contrast to summer precipitation, which results from high-intensity, short-duration, convective storms. Snowmelt in the winter in some areas remains on the land surface longer, too, and infiltrates more readily.

As long-term mean annual precipitation rate decreases, variability in annual precipitation generally increases, and desert sites may experience many years of below-average precipitation followed by 1 or 2 years of normal or above-average precipitation. Because deep

TABLE 4. Water Fluxes in Various Arid Settings Throughout the World Estimated on the Basis of Different Measurement Techniques

Location	*Authors*	*Precipitation, mm yr⁻¹*	*Method*	*Water Flux, mm yr⁻¹*	*Topography/Texture/Vegetation*
S. Australia	*Allison et al.* [1985]	~300	chloride	>60	sinkholes
S. Australia	*Allison et al.* [1985]	~300	chloride	0.06–0.17	vegetated sand dunes
S. Australia	*Cook et al.* [1994]	260	chloride	0.1	sands, native vegetation
			chlorine 36	0.9	
S. Australia	*Cook et al.* [1994]	340	chloride	4–28	sand dunes, cleared vegetation
			chlorine 36	2–11	
			tritium	8–17	
Saudi Arabia	*Dincer et al.* [1974]	80	tritium	23	sand dunes
N. Senegal	*Aranyossy and Gaye* [1992]	395	tritium	22–26	sand dunes
Sudan	*Edmunds et al.* [1988]	225	chloride	0.25–1.28	interfluve sandy clay
Cyprus	*Edmunds et al.* [1988]	406	chloride	33–94	Fine-grained sands, sparse vegetation
			tritium	22–75	
			chloride	10	Fine-grained sands, bush vegetation
Israel	*Nativ et al.* [1995]	200	tritium	16–66	fractured chalk
			bromide	30–110	
Hueco Bolson, Texas, U.S.A.	*Scanlon* [1991]	280	chloride	0.01–0.7	ephemeral stream, silt loam
			chlorine 36	1.4	
			tritium	7	
Southern High Plains, Texas, U.S.A.	*Wood and Sanford* [1995]	460	tritium	77	playa, clay underlain by sand
New Mexico, U.S.A.	*Phillips et al.* [1988]	200	chloride	1.5–2.5	sandy loam to sand
			chlorine 36	2.5–3	
			tritium	6.4–9.5	
New Mexico, U.S.A.	*Stephens and Knowlton* [1986]	200	Darcy's law (unit gradient)	7–37	sand loam to sand
New Mexico, U.S.A.	*Stone* [1984]	385	chloride	0.8	cover sand
				4.4	sand hills
				≥12	playa clay
Las Cruces, New Mexico, U.S.A.	*Gee et al.* [1994]	230	lysimeter	87	loamy fine sand and silty clay loam, bare
Beatty, Nevada, U.S.A.	*Prudic* [1994]		chloride	2 (>10 m depth)	coarse texture, creosote bush
Nevada Test Site, U.S.A.	*Detty et al.* [1993]	125	liquid flux	0.03	Darcy's law depth 75–180 m
			vapor flux	0.02	
			net flux	~0	
Nevada Test Site, U.S.A.	*Tyler et al.* [1992]	125	tritium	600	subsidence crater, coarse sediment
Yucca Wash, Nevada, U.S.A.	*Norris et al.* [1987]	170	chlorine 36	1.8	ephemeral stream
Ward Valley, California, U.S.A.	*Prudic* [1994]	117	chloride	0.03–0.05 (>10 meter depth)	alluvial fan
Hanford, Washington, U.S.A.	*Prych* [1995]	160	chloride	0.01–0.3	shrub, sand
			chloride	0.4–2.0	grass, sand
			chlorine 36	5.1	grass, sand

percolation may occur only in the years of above-average rainfall, desert soils may be characterized by episodic flow. Although many researchers report water fluxes annually, for general purposes of comparing different techniques or for convenience, this method of reporting fluxes may be unrealistic. Long-term monitoring of physical parameters is required to evaluate episodic flow; however, such records are unavailable at most sites. Monitoring of water content in ~100 boreholes in Yucca Mountain from 1984 through 1993 showed that water content remained low during a 6-year drought but increased beginning in the winter of 1991 through 1993 as a result of increased precipitation [*Flint and Flint*, 1995]. Because monitoring of physical parameters represents only the monitoring period, evaluating how representative this time period is with respect to long-term climate is important for predictive purposes.

Distribution of environmental tracers has been used for evaluating water fluxes over a much longer timescale. Low chloride concentrations at depth in the southwestern United States (Figure 5) have been attributed to higher water fluxes during the Pleistocene, when the climate was cooler and wetter [*Scanlon*, 1991; *Phillips*, 1994; *Tyler et al.*, 1996]. Higher water (pressure) potentials at depth in these arid regions may be attributed to drainage of older, Pleistocene water [*Scanlon*, 1994; *Tyler et al.*, 1996]. Chloride and water potential data suggest that deep vadose zones in arid regions may reflect Pleistocene climate and that the shallower zone may have been drying since the Pleistocene. The deep vadose zone is therefore not in equilibrium with the current surface climate. Numerical simulations of long-term climate changes at Yucca Mountain suggest that the upper 75 m may have been undergoing long-term drying for the past 3000 years [*Flint et al.*, 1993]. The cyclic climate inputs are damped with depth, and simulations suggest steady state conditions at depths ≥250 m.

Another factor of importance with respect to climate change and waste disposal is that sites that are now arid may not always be arid. A NAS panel evaluated the impact of climate change on high-level radioactive waste disposal at Yucca Mountain [*NRC*, 1995]. The Earth is currently in an interglacial phase. Although the Earth will probably not return to a glacial climate in the next few hundred years, the possibility cannot be ruled out [*NRC*, 1995]. A return to glacial conditions is probable within a 10,000-year time frame, which is the time required for high-level radioactive waste to be isolated from the accessible environment in the United States. A cooler, wetter climate associated with glacial times would result in increased water fluxes through the unsaturated zone. The ~300-m-thick unsaturated section overlying the proposed high-level radioactive waste disposal repository at Yucca Mountain would result in a large time lag of the order of hundreds to thousands of years between surface climate change and water fluxes at the level of the repository [*NRC*, 1995]. Climate changes of the order of hundreds of years would therefore be damped out at the depth of the proposed repository.

Although the time period required for isolation of low-level radioactive waste (1000 years) is much shorter than that required for high-level radioactive waste, low-level radioactive waste is buried at shallow depths; therefore the effects of damping of climate changes would be less for shallow burial sites. Environmental tracers such as chloride provide some indication of potential increases in water fluxes associated with glacial climates. A review of chloride profiles at several sites in the southwestern United States suggests that water fluxes would increase by a factor of ~20 [*Phillips*, 1994]. The highest water fluxes estimated during glacial times at these sites were ~3 mm yr^{-1}, which is still low. Thus the effect of climate change on water flux should be considered in siting the disposal facilities.

6.3. Sediment Texture

Texture of surficial sediments can greatly affect water movement in the unsaturated zone. Fine-grained surface soils provide a large storage capacity and retain infiltrated water near the surface, where it is available for evapotranspiration. As was discussed earlier, macropore flow is much more common in highly structured, fine-grained sediments [*Flury et al.*, 1994; *Bronswijk et al.*, 1995]. Coarse-grained sediments allow water to penetrate more deeply into the soil, commonly below the zone from which it can be evapotranspired. For example, the estimated water flux was high in a sand dune area in Saudi Arabia according to tritium data (23 mm yr^{-1} [*Dincer et al.*, 1974]; see Figure 7b and Table 4), representing ~30% of the long-term mean annual precipitation (80 mm yr^{-1}). *Cook et al.* [1992] noted an apparent negative correlation between clay content in the upper 2 m and the recharge rate. The concept of fine-grained surficial sediments providing large storage capacities is also employed in engineered barrier design. At the Hanford site, the texture and thickness of the sediment in an engineered barrier were chosen to provide storage capacity sufficient for 3 times the long-term mean annual precipitation [*Wing and Gee*, 1994]. Thickness of surficial unconsolidated sediments on top of fractured rock is also an important control on water fluxes. At Yucca Mountain, water penetration and environmental tracer distribution indicated minimal water fluxes in areas of thick alluvial cover over fractured tuff [*Fabryka-Martin et al.*, 1993]. Similarly, the thickness of loess on fractured chalk in the Negev Desert greatly reduced water fluxes through the chalk [*Nativ et al.*, 1995].

Heterogeneity and layering of sediments are also important in controlling water movement. Textural heterogeneity occurs at a variety of scales; small-scale, local heterogeneity may not be very important in extremely dry sediments, typical of interfluvial settings in arid regions, because most water is adsorbed to grain surfaces, and much of the water flux may occur in the vapor phase. In areas of ponded surface water, however, small-scale variations in sediment texture may have a greater effect on flow.

Layering of sediments reduces water fluxes. Where fine-grained sediments overlie coarse-grained sediments, a capillary barrier is formed, and water will not flow into the coarse layer until the overlying fine layer is close to saturation. Where interfaces between the different layers are sloped, lateral flow can occur. Capillary barriers occur in the natural system at a variety of scales. Studies by *Kung* [1990a, b] indicate that sloping layers can result in unstable flow at the downstream end when sufficient water accumulates in the fine-grained material to flow into the underlying coarse material [*Steenhuis et al.*, 1991]. One of the conceptual models developed for Yucca Mountain suggests that the layered nonwelded tuff units may act as capillary barriers beneath the welded fractured units [*Montazer and Wilson*, 1984]. The capillary barrier concept is also used in engineered-barrier design to maximize evapotranspiration, minimize deep percolation, and (where such layers are sloped) allow lateral drainage [*Wing and Gee*, 1994].

Where fine-grained layers underlie coarser layers, perched water conditions can occur. Numerical simulations indicate that for perching to occur, downward water flux should exceed saturated hydraulic conductivity of the perching layer by an order of magnitude [*Schneider and Luthin*, 1978]. Perched water has been found in the vadose zone at Yucca Mountain [*Burger and Scofield*, 1994] and beneath ephemeral lakes (playas) in the Southern High Plains [*Mullican et al.*, 1994].

6.4. Topography

Topographic setting may also play an important role in controlling unsaturated flow. Measurement of physical parameters and environmental tracer distributions in various topographic settings at Yucca Mountain showed that water fluxes were highest in active channels where surface runoff occurs [*Flint and Flint*, 1995]. In South Australia, because sinkholes focus surface water, much higher water fluxes were found beneath sinkholes (≥60 mm yr^{-1}) than in surrounding vegetated topographic settings (0.06–0.17 mm yr^{-1} [*Allison et al.*, 1985]; see Table 4). Ephemeral lakes or playas in the Southern High Plains of Texas and New Mexico also focus recharge, and estimated water fluxes range from ≥12 mm yr^{-1} [*Stone*, 1990] to 77 mm yr^{-1} [*Wood and Sanford*, 1995]. Fissured sediments in the Chihuahuan Desert of Texas concentrate surface runoff, and water fluxes are much higher beneath these fissures than in surrounding areas [*Scanlon*, 1992b]. Nuclear subsidence craters at the Nevada Test Site are also characterized by high water fluxes (~600 mm yr^{-1}) as evidenced by high tritium concentrations and high water (pressure) potentials relative to profiles 207 m from the crater center [*Tyler et al.*, 1992].

These studies suggest that local zones of high water flux, typical of arid settings, are generally found in topographic depressions where surface water collects, such as washes, playas, excavations, and sinkholes. Whereas the total surface area occupied by these features may be extremely small (e.g., 2% in the case of active channels in Yucca Mountain [*Flint and Flint*, 1995]) high flows beneath these features may be critical for transporting contaminants rapidly. Use of areally averaged recharge rates to predict contaminant transport would greatly underestimate the transport rates in these areas.

Paleotopography may also have affected the response of different sites to wetter climatic conditions during previous glacial periods. Low chloride concentrations deeper than 10 m at a site in the Amargosa Desert, Nevada, are attributed to increased precipitation and more frequent flooding of the Amargosa River at this site [*Prudic*, 1994]. Studies at the Nevada Test Site show much higher water fluxes in an area where surface runoff concentrated from the surrounding mountains during previous glacial maxima [*Tyler et al.*, 1996].

7. NUMERICAL MODELING

The complexity of flow in the shallow unsaturated zone of desert systems requires the use of numerical models to evaluate flow processes and to analyze interactions and feedback mechanisms between various controlling parameters. A variety of codes are available to simulate flow and transport. Simulation of flow in very dry unsaturated systems can be computationally difficult, however. Conservation of mass was a problem with traditional head-based codes, but it has been overcome with the mixed formulation of Richards' equation, which uses water content in the time derivative and head in the space derivative [*Celia et al.*, 1990]. Large execution times were also a problem that has been reduced by transformations of Richards' equation [*Kirkland et al.*, 1992; *Pan and Wierenga*, 1995]. Representation of water retention functions is also important for dry systems. Traditionally, residual water content was treated as a fitting parameter in water retention functions; however, resultant water contents were commonly greater than initial water contents in simulations in arid settings [*Hills and Wierenga*, 1994]. More realistic water retention functions have been developed recently that incorporate the full range of water content from saturation to air-dry conditions [*Milly and Eagleson*, 1982; *Rossi and Nimmo*, 1994; *Fayer and Simmons*, 1995].

The performance of various codes in simulating field-tracer experiments conducted in Las Cruces, New Mexico, was evaluated as part of the International Cooperative Project on Validation of Geosphere Transport Models (INTRAVAL), which represented an international study of validation of models for flow and transport. An extensive database characterized the hydraulic properties at this site and included ~600 measurements of bulk density, saturated hydraulic conductivity, and water retention. Two-dimensional models that assumed a heterogeneous porous medium performed no better than one-dimensional models that assumed a homogeneous porous medium [*Hills and Wierenga*, 1994]. The experiments at Las Cruces were conducted on bare soil and excluded evaporation. Detailed simulations of flow in a natural system require nonisothermal liquid and vapor flow, atmospheric forcing, and water uptake by roots. Very few codes incorporate all these features. Because simulation of preferential flow is extremely complicated, new codes need to be developed to address this issue. A code developed by *Nieber* [1996] successfully simulates unstable flow. Several investigators are simulating flow in fractured rock on the basis of data from the Yucca Mountain site, and some of these studies attempt to reproduce the tracer data that suggest preferential flow [*Wolfsberg and Turin*, 1996].

Previous studies that included numerical simulations provide valuable insights into unsaturated-flow processes. Simulations of flow in a bare soil show net downward thermal vapor flux in response to seasonal temperature gradients in the shallow subsurface [*Scanlon and Milly*, 1994]. Results of flow simulations of engineered barriers agree with field data from lysimeters at the Hanford site, Washington [*Fayer et al.*, 1992]. This study shows that hysteresis is important in simulating break-through of capillary barriers. Numerical modeling of flow at Yucca Mountain evaluated the effect of long-term climatic change on net infiltration and showed that amplitude and frequency of climate change are important factors [*Flint et al.*, 1993]. Below 250 m, climatic changes having a frequency ≤50,000 yr were damped out.

Evaluation of potential sites for disposal of waste, such as low- and high-level radioactive waste, requires performance assessment to develop a quantitative understanding of system behavior. For high-level nuclear waste disposal in the United States, performance assessment is required for time periods of 10,000 years or more. Although performance assessment of many sites includes rigorous parameter uncertainty analysis, the main source of uncertainty generally results from conceptual model uncertainty. Performance assessment has used spatially and temporally invariant upper boundary conditions, even though the long time and space scales considered in performance assessment require the use of spatially and temporally varying upper boundary conditions that relate to topography and climate. If one is trying to predict future behavior of a 10,000-year time period, future climatic changes should be incorporated into the performance assessment. Whereas the U.S. Nuclear Regulatory Commission is promoting a probabilistic approach to performance assessment, a recent NAS panel on Yucca Mountain suggested that if compliance is met in bounding estimates that are based on upper or lower limits of parameters that result from conservative assumptions, more complex analysis is not needed [*NRC*, 1995]. This does not preclude performance monitoring to evaluate whether simplistic models of flow and transport are valid.

8. IMPLICATIONS FOR CONTAMINANT TRANSPORT RELATED TO WASTE DISPOSAL

The natural characteristics of a site are important for long-term (≥ decades) disposal of waste because the natural system is ultimately relied on to minimize waste migration. The attributes of the natural system are difficult to characterize, however, because of the low water fluxes and limitations of monitoring instruments, as discussed earlier. To overcome some of these problems, multiple independent lines of data are required to increase confidence in results. Despite the difficulties in characterization, a larger margin of error can be tolerated in arid settings than in humid settings because of the naturally low water fluxes in porous media in interfluvial arid settings in porous systems. Important attributes of the natural system include direction and rate of water movement and the spatial and temporal variability in water fluxes. The type of medium (porous or fractured) is very important because of the higher potential for preferential flow in fractured systems. The vegetative cover is also important because it removes much of the infiltrated water from the subsurface.

Engineered designs and disposal practices are critical for developing a reliable disposal system. Although much information exists on site characteristics, our knowledge of the performance of engineered systems is generally limited. Ideally, an engineered system should mimic the natural system as much as possible, and the performance of various design elements of engineered systems should be rigorously tested in arid regions. Detailed studies of a capillary barrier system are being conducted at Hanford, Washington [*Wing and Gee*, 1994]. Trench-cap demonstration units will also be constructed at Ward Valley, California, to evaluate the performance of these systems [*NRC*, 1995]. Past disposal practices have often greatly enhanced the likelihood of contamination at various sites. Disposal of liquid wastes at the Beatty site (~2000 m^3 between 1962 and 1975), for example, may have resulted in the large tritium concentrations found near that disposal site [*Striegl et al.*, 1996]. Future disposal practices of low-level radioactive waste will therefore be restricted to solid wastes. Restriction of waste to a solid form does not necessarily preclude contamination because water percolating through the unsaturated zone could dissolve the waste. Critical components of near-surface engineered systems include the vegetative cover to remove water by evapotranspiration, the storage capacity of surficial sediments to hold water in the shallow zone, where it can be readily evapotranspired, and biointrusion barriers to limit human, animal, and plant intrusion into the waste. Capillary barriers not only increase the storage capacity of surficial sediments but also serve to limit biointrusion.

Monitoring of these engineered systems will be important to ensure that they perform as designed and to provide data for performance assessment. Although monitoring of low-level radioactive waste disposal facilities is required for at least 30 years, the life span of many of the monitoring instruments, such as the thermocouple psychrometer, is much shorter than 30 years. Many systems are currently available for monitoring disposal facilities, such as the Science and Engineering Associates for the Membrane Instrumentation and Sampling Technique (SEAMIST) system, which consists of an impermeable membrane that is turned inside out (everted) under pressure and that can be used to pull various logging tools through tunnels below the waste or in the cover system [*Keller*, 1991]. This system has the advantage of being readily able to incorporate newly developed technologies.

9. IMPORTANT AREAS OF FUTURE RESEARCH

Our review suggests that although within the last couple of decades considerable progress has been made in our understanding of unsaturated-flow processes in arid regions, areas exist where future research should be directed. With respect to techniques that can be used to quantify unsaturated flow, additional research should be done to evaluate the effects of instrument installation on the monitoring data. Such research could include numerical simulations or laboratory or controlled field experiments to address this issue. Most techniques used to monitor the energy status of pore water are not very robust and have a limited life span. Because regulations for waste disposal, including low-level and high-level radioactive waste disposal, require monitoring for decades, efforts should be made to develop robust instrumentation that can be used for monitoring energy potentials over long time periods. Use of time domain reflectometry in arid regions is not very widespread now, but TDR is a promising tool for detailed monitoring near the land surface atmosphere boundary, and it will most likely provide valuable information on this critical boundary as well as integrate easily with remote-sensing studies. Because unsaturated hydraulic conductivity is the most uncertain parameter, considerable effort should be directed toward developing better techniques of quantifying or estimating this parameter. The applicability of traditional methods of estimating unsaturated hydraulic conductivity from capillary bundle models should be critically evaluated for arid systems where film flow may be dominant. Although noninvasive monitoring techniques have only recently been used in vadose zone studies, they should be the focus of future studies to quantify relationships between geophysical response and water fluxes in various settings.

Establishing the direction of water movement in arid settings is extremely difficult because of the complex interaction of forces. Because it has been 40 years since *Philip and de Vries* [1957] established the theoretical framework for liquid and vapor flow, it should be revisited in light of all the work that has been conducted since then. The importance of preferential flow in arid regions should be critically examined as well. Although field studies in a number of regions demonstrate preferential flow in fractured media, field studies of preferential flow in porous media in deep vadose zones in arid settings are extremely limited. The idea that macropore flow in shallow, unsaturated, porous media can be extrapolated to great depths in arid regions has not been shown in the field, nor has it been thoroughly studied. Likewise, indiscriminate extrapolation of results of preferential flow studies that have been conducted in humid regions that have shallow water tables should be avoided. The extent to which preferential flow persists or dissipates with depth is important in thick, unsaturated, layered systems. Techniques used to evaluate unsaturated flow should therefore be critically examined to ensure that the presence or absence of preferential flow is not simply an artifact of the measurement process. Preferential flow is an issue critical in the siting of waste disposal facilities in arid regions and in the evaluation of contaminant transport and remediation.

Vegetation may be the dominant control on water fluxes in arid settings, however, and various aspects of this issue should be examined from laboratory, field, and numerical modeling perspectives. The effect of climate and paleoclimate on water fluxes should also be intensively studied to help predict unsaturated flow thousands of years into the future, as required by the high-level radioactive waste disposal program at Yucca Mountain.

10. CONCLUSIONS

Much of the work in unsaturated-zone hydrology has been conducted in humid regions; however, fundamental differences between humid and arid regions restrict the applicability of results from humid sites to arid sites. In addition, a wider variety of techniques are required to quantify unsaturated flow in the much drier unsaturated systems in arid regions.

Many arid area studies suggest that using environmental tracers to quantify unsaturated flow is more appropriate than physical approaches because hydraulic conductivity can vary over orders of magnitude. Both approaches should be used, however, because physical data provide information on current processes, whereas environmental tracers provide information on longer term, net water fluxes. A variety of environmental tracers should also be used because some are restricted to liquid phase flow, whereas others are found in liquid and vapor phases. Noninvasive techniques, such as electromagnetic induction, should be further investigated, particularly for evaluation of contaminated sites. Multiple independent lines of data are required to increase confidence in conceptual models of flow and transport in arid regions.

Low water fluxes and inaccuracies in techniques for quantifying such fluxes make it difficult to resolve basic issues such as direction and rate of water movement. The direction of water movement is difficult to evaluate in many arid sites because unsaturated systems are commonly extremely dry and because water flows in liquid and vapor phases in response to water potential, gravitational potential, pneumatic potential, and temperature gradients that are temporally and spatially variable. Temporal variability in water flow occurs at a variety of scales, including diurnal, seasonal, decadal, and millennial intervals, all of which are commonly controlled by climate. Short-term climatic fluctuations are preserved in the shallow subsurface, whereas longer-term paleoclimatic fluctuations are preserved over the thick unsaturated sections found in many arid settings. At many sites, water fluxes were much higher during previous glacial periods.

Vegetation may be the most important control on unsaturated water movement, as is shown by high rates of water movement in areas of coarse, bare soil and by negligible water movement in vegetated areas. Surface topography also plays an important role in controlling water movement by focusing unsaturated flow in topographic depressions that pond frequently. Increasing the thickness of unconsolidated sediments on fractured media in arid regions greatly decreases unsaturated water fluxes, as is shown by studies at Yucca Mountain, Nevada, and the Negev Desert, Israel.

Field evidence of preferential flow in arid regions has generally been restricted to fractured media, as evidenced by deep penetration of bomb pulse tracers in fractured tuff at Yucca Mountain and in fractured chalk in the Negev Desert. Although many studies suggest predominantly piston-like flow in porous media in interfluvial arid settings, some of the techniques used may not be sensitive to small percentages of preferential flow. Recent studies suggest that unstable flow, which is driven by gravity, should be negligible in porous media in many arid regions because of the dominance of capillary and adsorptive forces over gravity forces in these areas. Evaluation of preferential flow is much more difficult in arid regions than in humid regions because the thickness of the unsaturated section is greater and short-term applied tracer experiments cannot be used in the thick vadose zones typical of many arid regions.

Because of (1) many uncertainties in determining water fluxes in arid areas, (2) extensive spatial and temporal variability in properties, (3) vegetation, and (4) precipitation, generalized conclusions about recharge rates at a specific site are difficult to make. Detailed investigations are required to determine the nature, magnitude, and direction of water fluxes at specific locations.

GLOSSARY

Advection: movement of solute with the flowing fluid; movement of gas in response to total pressure gradient.

Capillary barrier: layer of fine sediment underlain by layer of coarse sediment that restricts downward movement of water because of the difference in the size of the capillaries. Water enters the underlying coarse layer when the matric potential in the fine layer increases sufficiently to overcome the water entry potential of the coarse layer.

Diffuse flow: movement of water into the unsaturated zone over large areas, as opposed to focused or concentrated flow.

Diffusion: movement of a substance, such as solute or vapor, along a concentration gradient.

Electromagnetic induction: technique to measure apparent electrical conductivity by electromagnetically inducing currents in the ground. Under low values of induction number, the secondary magnetic field is a linear function of conductivity.

Funneled flow: form of preferential flow that occurs when textural interfaces cause lateral water flow and accumulation of water in low regions.

Gravitational potential: change in energy per unit volume of water associated with change in the position of a body in the Earth's gravitational field. The reference state is generally defined as the land surface or the water table. Gravitational potential energy decreases with depth.

Heat dissipation probe: device used to measure matric potential in the unsaturated zone on the basis of variation in the rate of dissipation of a thermal pulse with water content. The probe is calibrated at different matric potentials.

Hydraulic conductivity: ability of material to conduct water; proportionality constant between water flux and hydraulic head gradient in Darcy's law.

Hydraulic head: sum of matric and gravitational potential heads.

Infiltration: rate of water movement from the surface to the subsurface.

Lysimeter: device for measuring water loss from soil and plants into the atmosphere. There are nonweighable and weighable lysimeters. Nonweighable lysimeters measure water storage changes indirectly (i.e., with a neutron probe and from inflow-outflow analysis), whereas weighable lysimeters measure storage changes gravimetrically.

Macropore flow: form of preferential flow in which water flows along noncapillary-size openings such as fractures, cracks, and root tubules.

Matric potential: change in energy per unit volume of water that results from the attraction of water to the solid matrix material.

Neutron probe: instrument used to monitor water content in the unsaturated zone.

Percolation or drainage: penetration of water below the shallow subsurface, where most evapotranspiration occurs.

Performance assessment: evaluation of future performance of a system on the basis of a quantitative understanding of system processes. Performance assessment generally includes long-term numerical simulations of system performance that incorporate uncertainties in conceptual models and in system parameters.

Piston-like flow: uniform downward movement of water through the unsaturated zone that displaces existing water without bypassing it.

Pneumatic potential: energy per unit volume of water resulting from changes in air pressure.

Potential energy: energy resulting from position of a body in a force field, such as gravitational, capillary, and osmotic force fields. Differences in potential energy can be used to determine the direction of water movement under isothermal conditions because water flows from regions of high to regions of low total potential energy. Potential energy is generally expressed as energy per unit volume (joules per cubic meter, equivalent to pressure units of newtons per square meter or pascals).

Preferential flow: nonuniform downward water movement along preferred pathways that bypasses much of the matrix and includes funnel flow, unstable flow, and macropore flow.

Recharge: addition of water to the aquifer.

Solute potential: equivalent to osmotic potential, change in energy per unit volume of water associated with the addition of solutes to pure, free water.

Suction lysimeter: device used to extract pore water from unsaturated media for chemical analysis.

Thermocouple psychrometer: device that measures relative humidity of water vapor in the sediment or rock sample, which is related to water potential ψ (energy per unit volume) through the Kelvin equation (equation (3)).

Time domain reflectometry: technique used to measure water content in unsaturated material on the basis of variation in the dielectric constant of the material with water content.

Unsaturated zone: zone in which pore spaces contain both water and air.

Unstable flow or fingering: form of preferential flow used to describe downward water movement in columns that may result from sediment layering, air entrapment, or water repellency.

Vadose zone: zone between land surface and regional water table.

Water activity: thermodynamic activity of water; relative humidity.

Water activity meter: device that measures water activity (relative humidity) of water vapor in sediment or rock samples and which is related to water potential through the Kelvin equation (equation (3)).

Water content: amount of water in unsaturated media; can be expressed gravimetrically (mass of water per mass of dry unsaturated material) or volumetrically (volume of water per volume of unsaturated material).

Water flux: volume of water flowing per unit cross sectional area per unit of time.

Water potential: pressure potential, sum of matric and osmotic potentials, can be measured by thermocouple psychrometers or water activity meter.

Water retention function: relationship between matric potential and water content.

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Factory seam fabrication, under controlled conditions, is done by a precise combination of heat and pressure. Field seaming uses a bodied solvent adhesive following a pre-wash to give equally reliable results under the varying weather conditions encountered during installation. After installation, a surface cross-linking develops which produces a stronger, tougher and more weather resistant liner.

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Low Density Polyethylene

This is a semi rigid material used for ponds, lagoons, canal liners, fire ponds, mine trailing ponds, waste water ponds, leachate collection ponds, brine ponds, cargo covers, interim landfill caps. Excellent protection from UV rays and harsh weather conditions. No plasticizers added. High elongation with tremendous tear resistance and bursting strength. Minimum carbon black content of 2.5%. Virgin resins. This is a fish safe material.

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This is a light weight film mono-layer membrane material consisting of a blended medium density polyethylene. Minimum carbon black content of 2.5% provides excellent protection from UV rays and harsh weather conditions. Puncture and tear strengths far exceed common polyethylene or vinyl films. This product is used mostly for ponds, including lagoons, canal liners, fire ponds, remediation liners, cargo covers, oil field pit liners, silage covers, outdoor covers, brine ponds, mine trailing ponds, interim landfill caps, leachate collection ponds. This is not a fish safe material.

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Importance and Use of Plants in Evaluating Water Flow and Contaminant Transport in Arid Environments
by B.J. Andraski, M.W. Sandstrom, R.L. Michel, J.C. Radyk, D.A. Stonestrom, M.J. Johnson, and C.J. Mayers
Based on a poster presented at the American Geophysical Union's Fall 2002 Meeting, December 6-10, 2002
ABSTRACT (Published Abstract)
Improved understanding of soil-plant-atmosphere interactions is critical to water-resource and waste management decisions. Multiple-year field studies of soil-water movement at the Amargosa Desert Research Site (ADRS) identified plants as the primary control on the near-surface water balance. The boundary conditions imposed by plant activity in the uppermost soil layer also result in episodic, deep drying below the root zone during periods of below-average precipitation. The findings help to explain evidence for negligible recharge and upward flow that has been inferred from environmental-tracer and soil-physics-based studies of deep unsaturated zones at undisturbed, arid sites.
Studies at the ADRS also are using plants to investigate tritium transport away from a low-level radioactive waste disposal area. Soil-gas sampling results indicated that tritium has moved as much as 300 m from the disposal area, and that transport primarily occurs in the gas phase with preferential transport through coarse-textured sediment layers. The need for an efficient means of gathering plume-scale data led to the development of a method that uses plant water to identify tritium contamination. Tritium concentrations in plant water determined with the new method did not differ significantly from those determined with the standard (and more laborious) toluene-extraction method or from concentrations in root-zone soil-water vapor. The new method provides a simple and cost-effective way to identify plant and soil contamination. Although work to date has focused on one desert plant, the approach may be transferable to other species and environments.

Figure 1. Location of Amargosa Desert Research Site, Nevada .
BACKGROUND
Arid environments often are considered ideal for waste isolation because the natural environment has features that can minimize the risk of waste migration to the underlying water table (e.g., low precipitation, high evapotranspiration, thick unsaturated zone). The processes influencing the transport of water and contaminants in deserts, however, are not well understood and can be affected in dramatic ways by temporal and spatial changes in precipitation, vegetation, and soils.
The objective of research at the Amargosa Desert Research Site (ADRS) is to develop a fundamental understanding of hydrologic conditions and contaminant-transport processes in arid environments. The ADRS is located about 17 km south of Beatty, Nevada (fig. 1) and is adjacent to a disposal facility for low-level radioactive and hazardous waste. Precipitation during 1981-2001 averaged 108 mm/yr. The surface soil layer was formed by eolian deposition and cumulative soil development beneath a desert pavement. The underlying sediments are fluvial deposits. Depth to the water table is about 110 m. Vegetation is sparse; Larrea tridentata (creosote bush), an evergreen shrub, is the dominant species. The rooting depth of Larrea at the ADRS is about 0.75-1 m.

WATER BALANCE AND FLOW

Water-balance data show that plants typically contribute to the annual depletion of water that accumulates in the root zone (fig. 2). The small net increase in water storage for vegetated soil in December 1998 occurred in response to increased precipitation during the 1997-98 El Niño cycle. Storage decreases for vegetated soil are due to evapotranspiration. Storage decreases for devegetated soil are due to bare-soil evaporation and percolation. Water-potential data show that plants also contribute to episodic, deep drying of sediments well below the root zone during years with below-average precipitation (e.g., 1989-90; fig. 3).

Figure 2. Cumulative changes in soil-water storage for the 0- to 1-m depth interval relative to initial (fall 1987) values (Data from Andraski, 1997; Johnson and others, 2002).

Figure 3. Sub-root-zone soil-water potentials and precipitation. (Data from Andraski, 1997)

These findings help to explain evidence for negligible recharge and upward flow that has been inferred from studies of the deep unsaturated zone at undisturbed, arid sites. For example, chloride-concentration profiles at the ADRS indicate that percolation past the 10-m depth has been negligible for the past 16,000 yr (fig. 4A). In addition, water-potential data indicate upward driving forces for water movement in the upper 60 m (fig. 4B). As a result, new conceptual models have been developed to incorporate the influence of desert vegetation in analyses of paleo- to present-day water fluxes in deep unsaturated zones (Walvoord and others, 2002a, 2002b; Scanlon and others, 2003).

Figure 4. (A) Chloride mass-balance age and (B) soil-water potential profiles. (Data from Prudic, 1994 (A); Stonestrom and others, 1999 (B))

DETECTORS OF CONTAMINATION

A simplified method was developed to identify tritium contamination in plants and soil. The method entails sample collection and solar distillation (8 hours) of plant water from foliage; distillate is collected by pipet (fig. 5). Plant water then is filtered and passed through a graphite-based, solid-phase-extraction (SPE) column to adsorb scintillation-interfering constituents (fig. 6). A 2-g-carbon-SPE column was found to be necessary and sufficient for accurate determinations of known tritium concentrations in Larrea water.

Figure 6. (A) Batch filtration and SPE-column apparatus showing (a) syringe-less filters, (b) SPE columns, and (c) 15-ml sample bottles. (B) Bottles of untreated and treated solar-distilled Larrea water.

Tritium concentrations in plant water determined with the new method did not differ significantly from those determined with the standard, and more laborious, toluene-extraction method or from concentrations in root-zone soil-water vapor (fig. 7). Although work to date has focused on one desert plant, the approach may be transferable to other species and environments after site-specific investigations establish its efficacy elsewhere. Two main sources of uncertainty that can affect the accuracy of the solar distillation-SPE method and warrant further study are: (1) the exact mechanisms that interfere with liquid-scintillation counting and (2) the effects of isotopic fractionation on solar-distilled tritium concentrations.

Figure 7. Relation between tritium concentrations in (A) solar-distilled,

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MEMORANDUM

4-5-04 Ron was asked by Dave C + Nee to review pit rules — He didn't want to send this to Gov without you know

Date: **April 1, 2004**

To: **Charles Lundstrom**

Through: **Jerry Shoeppner**

From: **Christine D. Bynum, Baird Swanson**

cc: **File**

Re: **Review of NM Oil Conservation Division Pit and Below Grade Tank Guidelines (March 16, 2004)**

At your request, we have reviewed the document referenced above, relative to its level of protectiveness to ground water, and offer the following comments:

1. Section V. Closure Site Assessment, A. General Site Characteristics, 1. Depth to Ground Water- The guidelines do not require wells and allow pit operators to estimate the depth to ground water. The guideline does not define "local" water well information, thus data used could be from a distance that might not provide accurate data. Since the guidelines later use depth to ground water as part of its scoring of sites, this is a real weakness. Guideline should also specify logging depth to water encountered during the drilling of well, if possible.

2. 2. Section V. Closure Site Assessment, C. Ground Water Quality – In the case of a release, a monitoring well is required if ground water is encountered during site characterization. In the following paragraphs, the guidelines indicate that if there is a reasonable probability of ground water contamination based upon soil concentrations beneath the pit, then a ground water monitoring well may be required. In areas where information is uncertain, at least three ground water monitoring wells surrounding the pit area would be required to establish ground water gradient. If there is a confirmed release from an impoundment, NMED would require a nature and extent assessment and likely one or more monitoring wells, unless the depth to ground water is very large and the potential for contamination seems negligible.

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3. Section V. Closure Site Assessment. First Paragraph. The text says that "sites shall be assessed for the severity of contamination and potential environmental and public health threats using the risk based ranking system described in Sections V and VI." The ranking system in Section VI is not risk based. It is arbitrary, inflexible and unlikely to provide sufficient information to determine if a threat exists. The U.S. EPA has published risk based screening guidelines, as has NMED (PSTB, HWB, VRP) that can be used to identify if soils are a threat to ground water. One of these methods should be used and not this ranking system. For example, 50 PPM of BTEX may or may not be a threat to ground water depending upon the distance to ground water and type of geologic material, however, this concentration would be a significant threat for direct exposure if left in place in the upper few feet of soil.

4. Section V. Pit construction C.3. Synthetic liners E. Should specifically state that pits constructed from caliche shall be lined/covered with topsoil or sand to prevent membrane rupture or puncture.

5. Section V Site Characteristics A. Wellhead protection. The guidance states that the nearest wells & springs should be measured, but does not set forth a minimum radial distance in which the survey must be conducted. Water sources should be located within the nearest ¼ mile.

6. Section V Site Characteristics A. 3. Nearest surface water body sources should also be located within a ¼ mile radius.

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April 8, 2004

Mr. Bill Olson
Hydrogeologist
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RE: Comments on NMOCD Draft Guidance Document entitled "Pit and Below Grade Tank Guidelines"

Dear Mr. ~~Olson:~~ Bill,

New Mexico Oil and Gas Association (NMOGA) appreciates the opportunity to provide comments on the draft guidance document referenced above.

During the time Bob Manthei represented NMOGA on the Stakeholders committee, the NMOCD indicated that adequate time would be given to the development of Pit and Below Grade Tank Guidelines.. For the pit and below grade tank rule, NMOCD allowed considerably more time and a more participative process for all parties to provide comment and technical input into the rule. NMOGA is concerned that the expedited comment period for the guidance document is far too abbreviated and could lead to poor policy. Further, a concern exists about the lack of some complete scientific research and data, which is critical to developing this guideline document.

NMOGA stated that during the rulemaking that the subject guidelines should be a guide for industry's use in expediting approval of permits. To better assure the proper design and closure of pits and below grade tanks, these minimum guidelines need to be based on documented scientific research and peer reviewed data. Further, these guidelines should not replace the rulemaking process.

Where the NMOCD intends for minimum standards to be met to assure protection of ground water, public safety and the environment, then NMOCD has the responsibility and the obligation to enact such requirements through a formal rulemaking and not to use the guidelines as a mechanism to avoid the rulemaking process.

Provided below are specific issues of concern to NMOGA with respect to the above referenced guideline:

1.) INTRODUCTION: The following specifications SHALL be used as a guide...

NMOGA have concerns that the guidelines shall be used. This implies that the guidelines are required and not suggested indicating that the NMOCD is trying to circumvent the rulemaking process. This effort is further enforced by the rule requiring the Operator to use the C-144 form and certify that they have adhered to the guidelines for construction and closure. Consequently, it appears the guidelines now have the same status as a regulation without being subject to a formal rulemaking process.

2.) PERMITTING PROCEDURES: The guideline calls for formal approval of all drilling, workover, and completion pits.

NMOGA provided extensive testimony regarding this issue and there was tacit understanding and agreement by the NMOCD representatives in the workgroup that there was no need for a formal, detailed approval process for temporary drilling, workover, and completion pits. NMOGA felt that these temporary types of pits were in fact authorized by the rule and did not require the redundancy of permitting. NMOCD representatives indicated that they merely wanted a general description on the existing APD (i.e., form C101 or Sundry Form C-103)) regarding whether a pit was going to be constructed, a general description of the pit construction, and how closure was anticipated.

Although NMOGA suggested language was not accepted by NMOCD in the final rule, the intent was achieved by the final rule language that stated in part "A separate form C-144 is not required." By incorporating the C-144 form into the form C101 and Form C-103, NMOCD has in fact required the C-144 form and required the more extensive detail that NMOCD representatives agreed was not necessary. NMOGA vigorously objects to this approach to require approval for temporary drilling, workover, and completion pits.

3.) **<u>DESIGN AND CONSTRUCTION:</u> The guideline calls for at least a 12 mil liner as acceptable for drilling and workover pits except in the circumstances where salt based drilling fluids, hydrocarbon fluids, or other contaminants that have the potential to contaminate fresh water and where the operator intends to encapsulate the pit contents in place upon completion of drilling and workover activities.**

First, NMOGA wishes to clarify that a lined pit is not always required and unlined pits are allowed in areas so specified in the rule (19.15.2.50 Section C, Paragraphs (g)(ii) and (g)(iii). Hence, NMOGA believes that the guidance document should reference that the liner guideline applies as required by rule.

Second, NMOGA disagrees that either the 12 mil or 20 mil synthetic liner is the exclusive design standard. A suitable clay liner with equivalent permeability may be appropriate. NMOGA understands that it is common industry practice to use a synthetic liner but where local clays may be available; it should be acceptable to construct an equivalent clay liner, where appropriate. Additionally BLM Conditions of Approval for drilling reserve pits in the southeast area of the state containing all fluid types stipulate that 6 mil synthetic liners are adequate. NMOGA believes as a minimum, that 6 mil synthetic liners are adequate for "fresh water based drilling fluids".

Third, NMOGA disagrees with the requirement that a 20 mil liner is required where salt based, oil based, or other contaminants have the potential to contaminate fresh water and where the operator intends to bury the pit contents in place. Technical documentation is attached indicating that mil thickness is not a factor in maintaining the integrity of a synthetic liner when buried. "Thicker is not better". NMOGA believes that as a minimum the commonly used 8-mil liner is technically sufficient in most of these cases. Unless NMOCD has specific and justified concerns for a given location, it can be specified in the approval that a 20-mil liner be required.

Fourth, NMOGA is concerned about the general reference to "Salt Based Drilling Fluids". In the Southeast area of the state naturally occurring salts are found in most of the fresh water. NMOGA believes that "Salt Based" needs to be defined. For the Northwest area of the state, salt based and oil based drilling fluids are not used but the term "other contaminants" is not specific enough for proper interpretation. NMOGA recommends that the wording be changed to require a 10 mil liner for salt based, oil based, or other contaminants specified by the NMOCD that have the potential to contaminate fresh water and where the operator intends to encapsulate the pit contents in place.

Fifth, NMOGA would like to reiterate that there is only one documented closed case, and one disputable case of ground water contamination by a temporary drilling, reserve, workover or completion pit in the State's files.

4.) <u>DESIGN AND CONSTRUCTION:</u> The guideline requires the markings be required on the liner to indicate freeboard.

Again, NMOGA would reiterate the comments above that unlined pits are allowed in certain areas; therefore, this marking would not be practical in that circumstance. Furthermore, it seems unreasonable and unnecessary to require such markings on lined temporary drilling, workover, and completion pits. From our experience, one can readily determine whether the 2-foot freeboard is met without such markings. NMOGA would suggest that this guideline be applied to pits constructed for long-term (more than 180 days) continuous use.

5.) <u>BELOW-GRADE TANKS:</u> The guideline requires that below grade tanks be of strong corrosion resistant construction, resistant to sunlight, installed on 1 inch of gravel, have visibility of the entire tank, and have a liner that is attached to the tank above grade.

NMOGA has numerous concerns about this section of the guideline. NMOGA disagrees that strapping a 40-mil synthetic liner to the tank is the exclusive design standard. The guidelines do not allow for any manufactured double walled tanks. The corrosion resistant construction requirement seems inappropriate since this could be misinterpreted to mean stainless steel or more exotic materials. NMOGA believes that a simple statement that the material must be compatible with the anticipated fluids seems more appropriate. The resistant to sunlight requirement seems inappropriate as well. NMOGA assumes that NMOCD's concern is with fiberglass or other plastic materials, and that this guideline is a holdover from the 1993 guidelines. Fiberglass, PVC, and other plastic materials manufactured today typically have UV inhibitors incorporated into the resins so NMOGA questions the need for this specification. Would an operator need to have proof of UV inhibitors and keep this on record to meet this guideline? If NMOCD still has a concern about tank materials, then a better statement would be that the materials must be suitable for outdoor exposure.

Another concern is the requirement to set tanks located below ground surface on 1 inch of gravel. NMOGA believes that utilizing I-beams to situate tanks off the ground, sand, or other suitable material is as an

acceptable design standard without requiring the exclusive use of gravel.

Finally, for tanks installed below the ground surface in an open excavation, the guideline states that the entire tank shall be exposed to visually detect leaks. According to the definition of a below grade tank as developed for the Pit Rule, they are defined as vessels where any portion of the sidewalls are not visible. Hence, NMOGA recommends that this wording be changed to correspond with the matching regulatory definition.

6.) **FENCES, SIGNS, AND NETTING: The guideline requires that fencing be around the perimeter of the facility, that a sign not less than 12" x 24" with lettering not less than 2"shall be posted on the fence, that the fencing not be constructed on berms, and the location on of the facility be identified by quarter-quarter section, township, and range.**

NMOGA believes that the intent of preventing livestock from access is the key point so the prescriptive nature of this requirement is not necessary. If a fence around a pit or below grade tank is effective in preventing livestock access, then that is sufficient evidence of good design.

With regard to the signs, NMOGA objects to the need for an additional sign on the location since all locations are already required to have a sign designating the same information as listed in the guideline. NMOGA believes that location identification allowing the use of a Unit Letter in lieu of providing ¼ ¼ section, as specified in rule 19.15.3.103 section F.4. is sufficient. If another company adds a pit to a location as part of a co-located well or gathering system pit, then they must too post a sign designating their operation. Consequently, this requirement seems redundant and unnecessary.

7.) **NOTIFICATION: The guideline requires that notification be given to NMOCD for installing all liners or leak detection systems.**

According to the Pit Rule, notification only should be given to NMOCD for installing a leak detection primary liner. Hence, NMOGA respectfully requests that the guideline be changed to correspond to the Pit Rule language and the as built documentation be limited to the installation of leak detection.

8.) **CLOSURE SITE ASSESSMENT: The guideline requires a general site assessment for all pits.**

First, nothing in the Pit Rule required such an assessment for drilling, workover, and completion pits and it is unreasonable and unnecessary to require such an assessment. When an APD or Sundry is prepared for a given well, a general site assessment has already been prepared, fully acknowledging any established groundwater sensitive area, wellhead protection area, or surface water body. Hence, this section seems only applicable to existing or new storage or disposal pits at the point of reaching closure.

Second, the guideline in Section V.A.2. Wellhead Protection Area requires the operator to determine the horizontal distance to all private, domestic fresh water wells or springs used by less than five households for domestic stock watering purposes and all other fresh water wells and springs. A question exits to the radius from the pit this information should be obtained. Is it assumed that the ranking criteria are the radius? For example, the wellhead protection area is <200 feet from a private domestic fresh water well or spring or <1000 feet from any other fresh water well or spring. In the absence of any specifics in the guideline regarding a required radius, we would proceed with our data collection based upon the ranking criteria. Consequently, it may be of value to clarify the intent and include the radii of the information requested. Further, the word "known" should be inserted before "private, domestic fresh water wells or springs... It is not uncommon to have difficulty identifying these, particularly if the wells have not been registered or the landowners are unwilling to disclose the information. NMOGA recommends that the operator only determine distance to the extent of the ranking criteria.

Third, the guideline in Section V.A.3, Distance To Nearest Surface Water Body, requires the operator to determine the horizontal distance of all wetlands, playas, irrigation canals, ditches and perennial and ephemeral watercourses. As with the comment above, we are assuming, using the risk ranking criteria, which between 200' and 1,000' is the radius of concern for accumulating this data. Again, including the radius, suggested from the ranking criteria, would help clarify the expectation of the assessment. NMOGA recommends that the operator only determine distance to the extent of the ranking criteria.

9.) **<u>SOIL/WASTE CHARACTERISTICS:</u> The guideline states that soil testing is not required for lined drilling and reserve pits and that waste sampling is necessary for all drilling and reserve pits.**

NMOGA believes that lined workover and completion pits are of the same nature as drilling and reserve pits and that they should be excluded from the requirement of soil sampling. NMOGA and NMOGA

provided extensive testimony that testing of any drilling, reserve, or workover pit was unnecessary unless a breach of that pit occurred. Given the fact that not all drilling, workover, and completion pits require liners, it should be further stated that unlined pits do not require soil testing as well.

With regard to wastes that will remain within the pit for closure, there is no reason to test such pits where oil based and salt based muds have not been used. NMOGA also believes that since the location of the pit will be documented and process knowledge of the drilling fluids will exist, sampling should be limited to cases when its value can be demonstrated.

10.) <u>OIL AND WATER REMEDIATION LEVELS:</u> The guideline requires chlorides in the soil be remediated to 250 mg/kg, and ground water contaminated in excess of WQCC standards be remediated.

First 250 mg/kg is the WQCC standard for water, not soil. NMOGA believes that remediation of chlorides should consider background levels. There are many instances in the southeast area of the state where back ground levels are much higher than 250 mg/kg. Remediation could be prescribed when no contamination has occurred.

Second, in the "UNLINED SURFACE IMPOUNDMENT CLOSURE GIDELINES" dated February 1993 ground water contamination in excess of NM WQCC ground water standards or natural background water quality will require remediation. NMOGA believes that in the southeast area of the state, where water in excess of NM WQCC ground water standards is naturally occurring, that the 1993 original wording be retained to avoid situations requiring remediation when no contamination has actually occurred.

Third, NMOGA would like the data developed from the NMOGA TPH and Chlorides workgroup be considered when establishing remediation levels. NMOGA would also like the API Chloride Study be considered as a valid method of determining the reasonable probability to contaminate ground water or surface water in excess of the standards in 19.15.1.19.B. (2) NMAC and 19.15.1.B. (3) NMAC through leaching, percolation, or other transport mechanisms.

11) <u>SOIL And WATER SAMPLING PROCEDURES</u>: The guideline requires in Section C. 4.(a), that the monitoring wells shall be purged a minimum of three well volumes of ground water ... in order to ensure the sample represents the quality of ground water in the formation and not stagnant in the wellbore.

It is important to note that it is not always possible to acquire three well volumes of ground water from a monitoring well. There are cases where the nature of a given aquifer will not yield three well volumes during a sampling episode. A suggestion would be to insert the words "To the extent hydraulically possible, monitor wells shall be purged...".

12) <u>SOIL AND WASTE MANAGEMENT OPTIONS</u>: The guideline calls for the contents of drilling and workover pits drilled or worked over with salt water that are to be encapsulated onsite be capped with either a 1-foot thick clay cap compacted to ASTM standards, or a 40 mil minimum thickness synthetic liner meeting ASTM standards that is designed to be resistant to the material encapsulated and when the bottom of the pit is located at least 50 feet above a source of fresh water.

NMOGA disagrees that capping with clay or a 40 mil synthetic liner is the exclusive design standard to prevent migration of contaminants. Technical documentation is attached indicating that mil thickness is not a factor in maintaining the integrity of a synthetic liner when buried. "Thicker is not better". A technical document "Hydrologic issues in arid, unsaturated systems and implications for contaminant transport" is attached. In this recent work, at a site in Arizona, the USGS (Andraski et. al, 2002) (<u>http://toxics.usgs.gov/pubs/agu_poster/</u>) reports "chloride-concentration profiles indicate that percolation past the 10-m depth (approximately 33 feet) has been negligible for the past 16,000 years".

NMOGA would recommend that NMOCD consider using 10 meters or 33 feet instead of 50 feet. Other current and ongoing scientific research has indicated that there are other methods that are as effective or better in preventing the migration of chlorides. One study indicated that a current practice, similar to the prescribed guideline, could enhance the migration of chlorides to the surface. NMOGA would again emphasize that the API Chloride Study, and the recent USGS work, be used to allow other designs that would be technically acceptable.

13.) <u>SURFACE RESTORATION:</u> The guideline requires successful re-vegetation of the area.

According to the Pit Rule, within one year of the completion of closure of a pit, the operator shall contour the surface where the pit was located to prevent erosion and ponding of rainwater. Hence, NMOGA respectfully requests that the guideline be changed to correspond to the rule language. Re-vegetation could be considered to include non-native species and noxious weeds which is obviously not the intent.

14.) <u>CLOSURE REPORTS:</u> The guidelines require a separate closure form be filed.

The Pit Rule allows for the filing of a general permit for a class of like facilities and requires the proposed disposal method of drilling fluids and cuttings to be described on the application. NMOGA believes that when the general plan is approved and the closure is within the allowed 180 days, the application and closure report are one in the same. When an APD or Sundry is prepared for a given well, a general site assessment has already been prepared, fully acknowledging any established groundwater sensitive area, wellhead protection area, or surface water body.

In closing, NMOGA appreciates the opportunity of providing the following comments on this guideline. However, we want to reiterate our recommendation that more time should be given to study and comment on this guideline using a collaborative approach. By doing so, a better final product will result that achieves the intended goal of the document. NMOGA would gladly participate in such an approach if given the opportunity.

Respectfully,

Bob Gallagher

Bob Gallagher
President, NMOGA

Bob Manthei

Bob Manthei, BP
Chairman, NMOGA Pit Committee

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HYDROLOGIC ISSUES IN ARID, UNSATURATED SYSTEMS AND IMPLICATIONS FOR CONTAMINANT TRANSPORT

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Abstract. Analysis of unsaturated flow and transport in arid regions is important, not only in water resource evaluation but in contaminant transport as well, particularly in siting waste disposal facilities and in remediating contaminated sites. The water fluxes under consideration have a magnitude close to the errors inherent in measuring or in calculating these water fluxes, which makes it difficult to resolve basic issues such as direction and rate of water movement and controls on unsaturated flow. The purpose of this paper is to review these issues on the basis of unsaturated zone studies in arid settings. Because individual techniques for estimating water fluxes in the unsaturated zone have limitations, a variety of physical measurements and environmental tracers should be used to provide multiple, independent lines of evidence to quantify flow and transport in arid regions. The direction and rate of water flow are affected not only by hydraulic head gradients but also by temperature and air pressure gradients. The similarity of water fluxes in a variety of settings in the southwestern United States indicates that vegetative cover may be one of the primary controls on the magnitude of water flow in the unsaturated zone; however, our understanding of the role of plants is limited. Most unsaturated flow in arid systems is focused beneath topographic depressions, and diffuse flow is limited. Thick unsaturated sections and low water fluxes typical of many arid regions result in preservation of paleoclimatic variations in water flux and suggest that deep vadose zones may be out of equilibrium with current climate. Whereas water movement along preferred pathways is common in humid sites, field studies that demonstrate preferential flow are restricted mostly to fractured rocks and root zones in arid regions. Results of field studies of preferential flow in humid sites, generally restricted to the upper 1–2 m because of shallow water tables, cannot be applied readily to thick vadose zones in arid regions.

1. INTRODUCTION

In the past, unsaturated-zone studies in arid settings were conducted primarily for water resource evaluation. During the past 2 decades, however, emphasis has shifted from water resources to waste disposal and contaminant transport. In addition to remediation of contaminated sites in arid regions, arid areas are also being proposed for low-level and high-level radioactive waste disposal [*Montazer and Wilson*, 1984; *Scanlon*, 1992a; *Prudic*, 1994]. Water resource evaluation studies generally assume uniform rates of water movement throughout a study area because that assumption may not greatly affect resource estimates. In contrast, application of uniform rates of water movement to contaminant transport analyses in areas of spatially variable water movement could invalidate estimated rates of contaminant transport. Knowledge of spatial variability in unsaturated flow is therefore critical for realistic assessment of transport rates because such spatially variable rates could allow contaminants in some areas to migrate rapidly, essentially bypassing the buffering capacity of much of the unsaturated zone.

Low precipitation rates and high evapotranspiration rates should result in low rates of water movement in arid settings. The book *Deserts as Dumps* by *Reith and Thomson* [1992] evaluates many issues related to waste disposal in arid regions. Groundwater contamination in many arid settings such as Hanford, Washington [*Dresel et al.*, 1996], Sandia, New Mexico [*Crowson et al.*, 1993], and the Negev Desert, Israel [*Nativ et al.*, 1995], has resulted in considerable debate about the suitability of arid settings for waste disposal. In the past, National Academy of Science (NAS) panels suggested that arid sites are unsuitable for radioactive waste disposal because of limited information on flow processes in arid regions [*National Research Council (NRC)*, 1957, 1966]. The findings of a recent NAS panel suggest, however, that interstream settings in arid regions should be suit-

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able for waste disposal [*NRC*, 1995]. Does this shift in opinion reflect an increased understanding of unsaturated flow and transport processes in arid settings?

Much research on unsaturated-zone hydrology has been conducted in humid sites; however, fundamental differences between humid and arid regions limit the applicability of techniques developed at humid sites to arid sites. Such fundamental differences include thickness of the unsaturated zone, which can be as much as several hundred meters in arid regions but commonly is only meters thick in humid sites. Water fluxes and water content of unsaturated media also have a much greater range in arid sites than in humid sites. Greater thickness of the unsaturated zone and lower water fluxes in many arid settings result in much longer timescales being represented by unsaturated sections in arid regions (up to thousands of years) than in humid regions (up to tens of years). Because of these differences the results of studies conducted in humid regions should not be applied directly to arid regions.

Questions about the suitability of arid settings for waste disposal may result from limited understanding of unsaturated-flow processes, in turn reflecting the limitations of various techniques for quantifying the extremely low water fluxes typical of interfluvial settings in many arid regions. As a result of low water fluxes and the limitations of various techniques to quantify flow, basic issues such as (1) direction and rate of water movement and (2) mechanisms and controls of water flow are difficult to resolve. The purpose of this paper is to examine some of the basic issues related to unsaturated flow by reviewing unsaturated-zone studies in arid settings. Some of the issues that will be considered are as follows:

1. What are the difficulties inherent in various techniques used to evaluate flow and transport?
2. What are the direction and rate of water movement?
3. How important is preferential flow in arid regions?
4. What are the most important controls on water flow and transport?
5. What is the role of vegetation in controlling water flow?
6. What effect do potential climate changes have on unsaturated flow?
7. How can we numerically simulate flow in arid settings?

An understanding of these issues is important for evaluation of water resources in arid regions and also for analysis of contaminant transport related to municipal, hazardous, and radioactive waste disposal.

Although arid regions occur throughout the world, unsaturated-zone studies have been conducted primarily in the western United States and in Australia; limited studies have been conducted in Africa, Israel, and Saudi Arabia. Results of studies of these arid settings are evaluated in this paper to provide insights into some of the basic issues described above.

Most of the studies referenced in this paper were conducted in the western United States. These studies include remediation of contaminated areas such as at Hanford, Washington [*Dresel et al.*, 1996] and Sandia (near Albuquerque), New Mexico [*Crowson et al.*, 1993], and at several uranium mill tailings sites [*Reith and Thomson*, 1992]. In addition, arid sites have been proposed for low-level radioactive waste disposal (from medical and research activities, and power plants) in Ward Valley, California, and Eagle Flat, Texas. Commercial facilities for disposing of low-level radioactive waste include Richland, Washington, and Beatty, Nevada (1962–1992). Deep (~300 m) geological disposal in the unsaturated zone at Yucca Mountain, Nevada, is proposed for high-level radioactive waste, which includes spent fuel from nuclear power plants and material from the nuclear weapons industry. Because much of the waste remains radioactive for a long time, we are concerned not only with flow and transport in the natural system, which can serve as a long-term (hundreds to thousands of years) barrier, but also with how we can engineer systems so as to minimize water fluxes.

To evaluate flow processes in the unsaturated zone, we need detailed information at small scales (~0.3 m); however, results from small-scale studies may have implications for much larger areas. Timescales of interest range from days to thousands of years, depending on the problem being evaluated. Arid systems are generally characterized by episodic flow that can occur in days in response to a sequence of precipitation events. In contrast, the period of time required for high-level nuclear waste to remain isolated from the accessible environment is ~10,000 years [*NRC*, 1995].

First we evaluate various techniques for quantifying unsaturated flow that use both hydraulic and hydrochemical approaches. Then we discuss the various driving forces for water movement that control the direction of water flow. Next we review preferential flow and how important it is in desert systems. The controls on unsaturated flow, including vegetation, climate, texture, and topography, are evaluated with reference to published studies. Recent improvements in numerical modeling that apply to simulations of flow and transport in arid regions are discussed, and results of case studies are presented. We close the discussion with some implications for waste disposal in arid settings and a brief overview of important areas for future research.

2. TERMINOLOGY

The glossary at the end of this paper should help the reader understand many of the terms used in unsaturated-zone hydrology. Some of these terms are discussed in more detail below.

"Unsaturated zone" refers to the zone in which the pore space contains at least two phases, water and air. "Vadose zone" refers to the zone between land surface and the underlying aquifer. Although the terms "unsaturated zone" and "vadose zone" are generally used interchangeably, "unsaturated zone" may not be strictly accurate in some cases where perched water (which includes saturated zones) accumulates above impeding layers in an otherwise unsaturated zone. The more general term "vadose zone" may be preferred in these cases, or "variably saturated" can be used to overcome this problem.

Some classifications of arid/semiarid/humid regions have been based on mean annual precipitation (hyperarid, 0–50 mm; arid, 50–200 mm; semiarid, 200–500 mm; and humid, >500 mm [*Lloyd*, 1986]), whereas others classify regions on the basis of precipitation/evaporation ratios [*Potter*, 1992] (arid, <0.5; semiarid, 0.5–1.0; and humid, >1.0). These classifications give some idea of what is meant by "arid" and "semiarid." The term "recharge" has been generally used to describe downward water movement in the unsaturated zone; however, in thick unsaturated sections where water is moving slowly, it may be impossible to determine whether downward moving water in the upper 10–20 m will recharge the aquifer at depths ≥100 m. To avoid this problem, we use "infiltration" to refer to water movement from the surface into the subsurface and "percolation" or "drainage" to refer to penetration of water below the shallow subsurface, where most evapotranspiration occurs. "Recharge" is restricted to situations where it is likely that the water reaches the water table (shallow water table or high water flux). Although the terms "percolation" and "recharge" imply downward water movement, determining the direction of water movement is often difficult. In these situations, "water flux" is better because it implies no particular direction.

3. TECHNIQUES FOR EVALUATING WATER FLOW

Because many reviews of techniques for evaluating water flow in arid regions exist [*Edmunds et al.*, 1988; *Allison et al.*, 1994; *Phillips*, 1994], this section is not a comprehensive review of techniques. Many issues related to unsaturated flow in arid systems result from limitations of techniques used to evaluate flow; therefore a review of the limitations and assumptions associated with these techniques is important.

Techniques that are used to quantify water fluxes can be generally subdivided into physical and chemical tracer techniques. Most studies are restricted to application of one of these techniques, and although few studies apply both, use of physical and tracer methods together can provide a more comprehensive understanding of water flow. The physical approach provides an understanding of current processes, whereas chemical tracers provide information on current and long-term net water flux. Because of inherent difficulties in quantifying low water fluxes that are characteristic of many arid sites, it is important to use multiple, independent lines of data to examine unsaturated-flow processes.

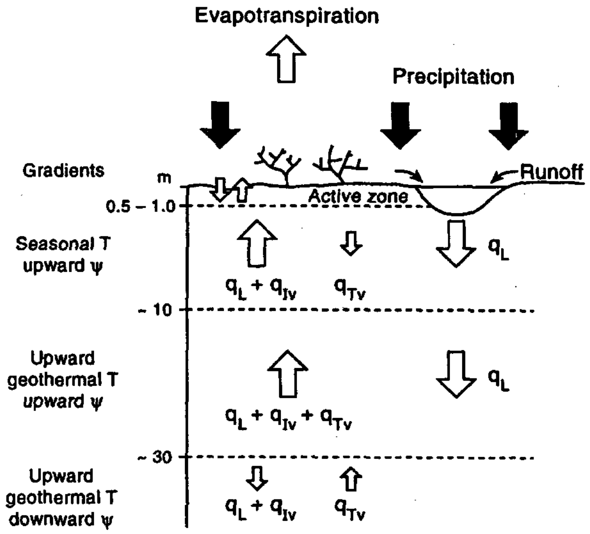

Figure 1. Schematic of unsaturated water fluxes in relation to different driving forces with depth. T is temperature, ψ is water potential, q_L is liquid water flux, q_{Iv} is isothermal vapor flux, and q_{Tv} is thermal vapor flux.

3.1. Physical Techniques

Physical techniques include water budgets to estimate water fluxes. The water balance equation can be represented by

$$D = P - R_0 - ET_a - \Delta S \qquad (1)$$

where D is drainage or percolation, P is precipitation (includes rain and snow), R_0 is surface runoff, ET_a is actual evapotranspiration, and ΔS is change in water storage (Figure 1). ET is used to describe the combined processes of evaporation (conversion of water to vapor) from the soil and transpiration from the plants. Significant improvements have been made in measuring evapotranspiration [*Malek et al.*, 1990; *Nichols*, 1994; *Albertson et al.*, 1995]; however, measurements of the different components of the water budget are generally too imprecise (±5% for P; ± 10% for ET_a) to allow confidence in calculating the difference between numbers of nearly equal value (such as precipitation and evapotranspiration) to estimate drainage as shown by *Gee and Hillel* [1988].

Lysimeters, used to measure components of the water budget, have an artificially enclosed volume of unsaturated material [*Brutsaert*, 1982; *Allen et al.*, 1991; *Young et al.*, 1996]. Traditional lysimeters generally consist of round or square tanks that range from 1 to 5 m^2 in area and from 1 to 4 m in depth that are filled with disturbed or undisturbed soil that may be vegetated. Nonweighable lysimeters simply measure the drainage rate or amount of water percolating from the base of the lysimeter. Water storage changes can be estimated in these lysimeters by monitoring water content with a neutron probe or other device. Precipitation can be measured with a rain gauge. Most lysimeters have a rim around the surface to prevent runoff. Weighable lysimeters measure precipitation, storage changes, and drainage directly, and in this way evapotranspiration may be calculated over time spans as short as 15 min. Lysimeter measurements are considered to provide the best determination of actual evapotranspiration and are used to compare other techniques.

Lysimeter data provide valuable insights into the effects of vegetation and sediment on water movement at different sites [*Gee et al.*, 1994; *Wing and Gee*, 1994]. Deep (18 m), nonweighable lysimeters at the Hanford, Washington, site measured drainage below the root zone [*Gee et al.*, 1994]. To overcome the problem of limited areal extent associated with the individual lysimeters just described, large-pan lysimeters (92–322 m^2) were installed beneath engineered cover systems at the Hanford site to monitor drainage with a precision of ± 2 mm [*Tyler et al.*, 1997]. Disadvantages of lysimeter studies include expense of construction, time required for maintenance, limited areal extent, boundary effects, and disturbance of the natural system. The large-pan lysimeters overcome the areal limitation, however, and when they are installed to evaluate engineered cover systems, disturbance of the natural system is not an issue.

3.1.1. Water content. Water content of sediment or rock samples can be measured readily in the laboratory by weighing samples before and after oven drying (the gravimetric method) [*Gardner*, 1986]. Because samples are destroyed during processing, this technique is generally used for collecting baseline data, for one-time routine measurements, and for calibration of other methods. It is used generally for evaluating spatial variability in water content, but not as readily for examining temporal variability. Traditionally, water content has been monitored with a neutron probe (Figure 2a) [*Gardner*, 1986], which is placed in an access tube that is installed horizontally or vertically. The neutron probe emits high-energy neutrons that collide with hydrogen nuclei and are slowed and reflected back to the probe, where they are counted. Neutron probes are calibrated against laboratory-measured water content of sediment or rock samples taken around neutron probes in the field. Calibrations are stable, and neutron probes are robust (both important for long-term monitoring). Disadvantages of neutron probes include health hazards associated with a radioactive source, time required for monitoring (generally done manually), and difficulty of monitoring the near-surface zone (top 0.15 m). Long-term (9 years) monitoring of water content was conducted in the Chihuahuan Desert, New Mexico, to evaluate spatial and temporal variability in water content [*Wierenga et al.*, 1987]. Results of the monitoring show that in 8 of the 9 years, all precipitation was taken up by plant roots in the upper 1.3 m and lost by evapotranspiration back into the atmosphere.

More recently, developments in time domain reflectometry (TDR) have led to its increased use in monitoring water content (Figure 2b) [*Dalton*, 1992]. A time domain reflectometry system consists generally of a two- or three-rod probe that is connected through a transmission line to a reflectometer, such as the Tektronix 1502B (Tektronix Inc., Redmond, Oregon), at the surface. A high-frequency pulse is applied by the reflectometer to the probe or waveguide, and reflections at the beginning and end of the probe caused by impedance changes are analyzed and displayed by the reflectometer. The time required for the electromagnetic pulse to travel along the waveguide is determined by the dielectric properties of the unsaturated medium. The TDR system measures the transit time t of the pulse along the TDR probe, and the dielectric constant ε is calculated as

$$\varepsilon = (ct/2l)^2 \tag{2}$$

where c is the velocity of light in a vacuum (3×10^8 m s^{-1}) and l is the probe length. Because of large differences in the dielectric constant of water (~80), sediment or rock (~4–8), and air (~1), the dielectric constant of the unsaturated medium is controlled largely by the water content. Although *Topp et al.* [1980] developed an empirical third-order polynomial relationship between water content and dielectric constant that applies to many different sediment textures, individual calibrations can also be developed for different sediments. The average water content along the length of the TDR probe is measured. TDR probes can be installed vertically to measure average water content to a particular depth or horizontally to monitor movement of wetting fronts. A typical probe uses 0.3-m-long rods, ~5 mm in diameter, and ~20-mm spacing between rods (Campbell Scientific Inc., Logan, Utah). The advantages of TDR systems are the absence of a radioactive source, automated water content monitoring that can be operated remotely, and the ability to monitor the near-surface zone. Although TDR has not been widely implemented in arid settings, the automated measurement of water content by TDR should lead to large databases that document water content changes in arid regions.

Remote sensing has also been used to estimate water content in the unsaturated zone [*Jackson*, 1993]. This technique is based on variations in the dielectric constant with water content in unsaturated material, which is similar to that described for TDR measurements. Passive microwave remote sensing detects water content in the upper 50 mm of the unsaturated zone at a spatial resolution of ~200 m [*Jackson et al.*, 1993]. The shallowness of the zone being evaluated and the low spatial resolution make this technique unsuitable for evaluation of unsaturated-zone water fluxes at small scales; it is generally more applicable in basin-scale studies and climate modeling.

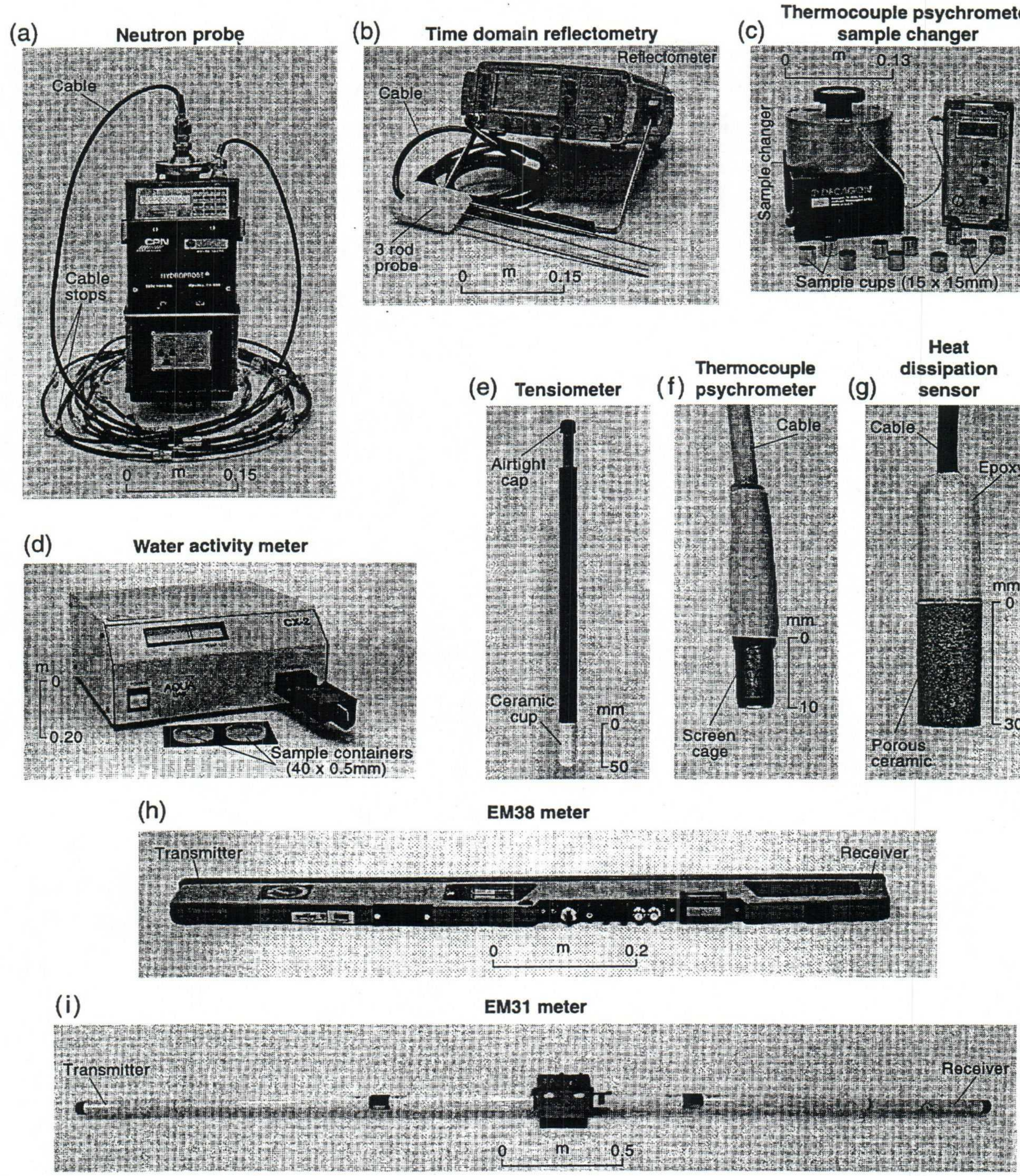

Figure 2. Instrumentation used for monitoring various parameters in the unsaturated zone: (a) neutron probe (model CPN 503DR), (b) time domain reflectometry system (reflectometer and three-rod probe), (c) thermocouple psychrometer sample changer, (d) water activity meter, (e) tensiometer, (f) thermocouple psychrometer, (g) heat dissipation sensor, (h) EM38 meter, and (i) EM31 meter.

Spatial variability in water content cannot be used to evaluate water flux in heterogeneous systems because water content varies with sediment type: clays, for example, retain more water than do sands. In contrast, temporal variations in water content can be used to evaluate the movement of water pulses through the unsaturated zone, particularly in areas of moderate to high water flux; however, in areas of low water flux, typical standard

TABLE 1. Summary of Instruments Used to Measure Various Hydraulic Parameters in Arid Systems

Parameter	*Instrument*	*Range*	*Accuracy*	*Notes*
Water content	neutron probe	0 to 100% saturation	±1%	robust, radioactive source
	TDR	0 to 100% saturation	±1%	robust, nonradioactive, automated
Matric potential	HDS	−0.01 to −1.4 MPa		not robust, automated
	tensiometer	0 to −0.08 MPa		automated
Water potential	TCP	−0.2 to −8.0 MPa	±0.2 MPa	not robust, automated
	Filter paper	−0.2 to −90 MPa		laboratory measurement
	SC10A sample changer	−0.2 to −8.0 MPa (Peltier)	±0.2 MPa	laboratory measurement affected by temperature gradients; time consuming
		−0.2 to −300 MPa (Spanner)	±0.2 MPa	
	water activity meter	0 to −312 MPa	±0.003 activity units	rapid laboratory measurement
Hydraulic conductivity	centrifuge method	$\geq 10^{-11}$ m s^{-1}	~±10%	expensive

Abbreviations are TDR, time domain reflectometry; HDS, heat dissipation sensor; and TCP, thermocouple psychrometer.

errors (~±1% for calibration curves for instruments (Table 1)) associated with water content measurements at one location over time may be too high to detect low water fluxes. Water content cannot be used to estimate water flux under steady flow conditions because water content does not vary.

3.1.2. Potential energy. In contrast to water content, which cannot be used to evaluate the direction of water movement because water content is discontinuous across the interface between different sediment textures, potential energy can be used to assess the direction of the driving force for water movement. Water flows from regions of high potential to regions of low potential. Potential energy in the unsaturated zone includes capillary, adsorptive, gravitational, solute or osmotic, and pneumatic components (Table 2). Capillary and adsorptive components combine to form the matric potential, which is the component of potential energy associated with the matrix of the unsaturated zone. The term "matrix" describes the particles and pore space that make up the unsaturated medium; "matric" is its adjectival form (Webster's Third International Dictionary). "Gravitational potential" represents the elevation of the measurement point above a reference level, such as the water table. Solute or osmotic potential results from the reduction in energy associated with addition of solutes to pore water. Matric and osmotic components are combined to form water potential. Because osmotic potential is generally neglected except in cases where high solute concentrations exist, "water potential" and "matric potential" are often used interchangeably. Pneumatic potential results from changes in air pressure in the unsaturated zone. Potential energy is generally expressed as energy per unit volume (pressure equivalent in megapascals) or energy per unit weight (head equivalent in meters).

The pore space in unsaturated media is partially filled with water, and pressures are negative. Matric potentials and water potentials are negative, whereas suction or tension, the negative of the matric potential, is positive (Table 2). The general term "pressure potential" is used in this paper, along with more appropriate, specific terms for clarity. Pressures close to 0 correspond to near-saturated conditions, and low negative pressures correspond to dry conditions. Water flows from regions of high potential, where pressures are less negative, to

TABLE 2. Various Types of Potential Energy Important for Understanding Unsaturated Flow

Potential Energy Type	*Description*
Gravitational potential	elevation above reference level (e.g., water table)
Matric potential	capillary and adsorptive forces associated with the soil matrix
Suction or tension	negative matric potential
Osmotic (solute) potential	variations in potential energy associated with solute concentration
Water potential	matric + osmotic potential
Pneumatic potential	associated with variations in air pressure
Hydraulic head	matric + gravitational potential head

Water potential approximates matric potential when osmotic potential is negligible. Tensiometers generally measure matric potential because air pressure is usually atmospheric. Heat dissipation sensors measure matric potential. Thermocouple psychrometers measure water potential. Potential energy is generally expressed as energy per unit weight of water, which is equivalent to head (meters) or energy per unit volume of water, which is equivalent to pressure (megapascals).

regions of low potential, where pressures are more negative.

Tensiometers (Soil Measurement Systems, Tucson, Arizona; Soil Moisture Equipment Corporation, Santa Barbara, California) can be used to monitor high (≥ -0.08 MPa) pressure potentials (matric and pneumatic) generally found in humid sites; however, pressure potentials in arid sites have a wide range (0 to < -200 MPa), and thus tensiometers can only be used where the vadose zone is relatively moist (Figure 2e; Table 1). Tensiometers consist of a ceramic cup connected to an airtight PVC tube that is filled with water (Figure 2e) [*Cassel and Klute*, 1986]. Water in the tensiometer equilibrates with the surrounding unsaturated medium, and a vacuum is developed that is measured by a pressure transducer.

Heat dissipation sensors (Campbell Scientific Inc., Logan, Utah) (Figure 2g), also called matric potential sensors, measure matric potential over a range (-0.01 to -1.4 MPa) greater than that of tensiometers [*Campbell and Gee*, 1986; *Phene et al.*, 1992]. Heat dissipation sensors consist of a ceramic block, a heater, and a temperature transducer. Heat dissipation sensors (1) measure the matric potential of the unsaturated medium by equilibrating a standard matrix, such as porous ceramic, with the surrounding sediments and (2) determine the water content of the sensor by measuring the rate of heat dissipation, which is a function of water content of the ceramic block. The higher the water content of the soil and the less negative the matric potential, the more rapidly the heat dissipates, and the lower the recorded voltage. The temperature change is measured with a data logger before and after application of a 30 s heat pulse. Temperature measurements are related to matric potentials through calibration curves between temperature or voltage and matric potential measured in the laboratory. Because matric potential is continuous across material types, the matric potential of the heat dissipation sensor is the same as that of the surrounding unsaturated medium [*Thamir and McBride*, 1985].

Thermocouple psychrometers (J.R.D. Merrill Specialty Co., Logan, Utah; Wescor, Logan, Utah) are required to measure much more negative water (matric + osmotic) potentials associated with typically dry sediments in arid systems. Thermocouple psychrometers measure the relative humidity of the vapor phase in the unsaturated zone, which is related to the water (pressure) potential in the liquid phase, according to the Kelvin equation

$$\psi = \frac{RT}{V_w} \ln \frac{P}{P_0} \tag{3}$$

where R is the ideal gas constant (8.314 J mol^{-1} °K), T is the Kelvin temperature, V_w is the molar volume of water (1.8×10^{-5} m^3 mol^{-1}), and P/P_0 is the relative humidity expressed as a fraction (P is the vapor pressure of the air in equilibrium with the sample, and P_0 is the saturation vapor pressure) [*Rawlins and Campbell*, 1986]. There are two basic types of thermocouple psychrometers: (1) Peltier or Spanner psychrometers (Figure 2f) and (2) Richards psychrometers (Figure 2c). Peltier psychrometers consist of a small thermocouple junction in a sample chamber such as the screen cage in Figure 2f that is cooled by the Peltier effect to condense water on it. The Richards psychrometer mechanically adds a drop of water to the thermocouple junction that is within the sample chamber (Figure 2c) and is restricted to laboratory measurements. Both systems measure temperature depression of the wet, or measuring, junction relative to a dry, or reference, thermocouple junction in the chamber. Temperature depression varies with the rate of evaporation, which is greater at lower relative humidity. A primary source of error results from temperature gradients between the reference junction and pore water in the unsaturated zone. A temperature gradient of 1°C at 20°C results in an error in measured water potentials of 13 MPa [*Rawlins and Campbell*, 1986]. Thermocouple psychrometers are calibrated with salt solutions of known osmotic potential.

In situ thermocouple psychrometers (Figure 2f) are used to monitor water potential between -0.2 and -8.0 MPa. Water potentials have been monitored in various arid settings to a maximum depth of 387 m to evaluate the direction of water movement and to estimate water fluxes [*Montazer et al.*, 1985; *Fischer*, 1992; *Scanlon*, 1994]. Significant improvements have been made in thermocouple psychrometry for monitoring water potentials in the field in recent years as a result of advances in data acquisition systems and newly developed thermocouple psychrometers for installation in deep boreholes [*Kume and Rousseau*, 1994].

One problem inherent in monitoring pressure potentials in arid systems is that the installation process may significantly affect the natural system, causing the monitoring data to be an artifact of the installation process rather than a reflection of the natural system. Although thermocouple psychrometers are generally installed in dry materials, because equilibration of the backfill sediments may take a long time, determining the true potential of the sediments may be difficult. Numerical simulations conducted to examine the effect of borehole backfill on monitored water potentials in a fractured tuff site show that backfill material could greatly disturb the natural system [*Montazer*, 1987]. Heat dissipation sensors are generally installed in wet silica flour because they require good contact with the surrounding sediment [*Montazer et al.*, 1985]; however, measured discrepancies between closely spaced thermocouple psychrometers and heat dissipation sensors suggest that the wetted sediments may not equilibrate for a long time. Because the calibration is unstable and because the instruments are not robust and have a high failure rate, thermocouple psychrometers may be unsuitable for long-term (≥ 10 years) monitoring unless they are retrievable. Installation of retrievable thermocouple psychrometers in caissons and in boreholes [*Fischer*, 1992; *Prudic*, 1994] has allowed recalibration of these instruments.

Because of the expense and difficulties of installing thermocouple psychrometers in the field, we generally obtain information on spatial variability of water (pressure) potential on the basis of laboratory measurements on disturbed samples by using a thermocouple psychrometer with a sample changer (Figure 2c) or a water activity meter (Decagon Devices, Pullman, Washington) (Figure 2d). The sample changer uses a Richards thermocouple psychrometer to measure a wide range in water (pressure) potentials (−0.2 to −300 MPa [*Rawlins and Campbell*, 1986]). Laboratory measurements of water potential made by thermocouple psychrometers are time-consuming and sensitive to the effects of temperature gradients [*Rawlins and Campbell*, 1986].

A water activity meter (Figure 2d) can also be used to measure water (pressure) potential in the laboratory. Water activity is synonymous with relative humidity. Water potential measurements made by a water activity meter are neither as time-consuming nor as sensitive to the effect of temperature gradients as are measurements made by thermocouple psychrometers [*Gee et al.*, 1992]. The measurement of water activity of a sediment or rock sample takes only a few minutes, ranging from 0.100 to 1.000 (−312 to 0 MPa water potential) with uniform resolution of ±0.003 water activity units throughout the range [*Gee et al.*, 1992]. The water activity meter uses a chilled mirror to measure the dew point of water vapor above a small sample of sediment or rock (40 mm in diameter by 5 mm thick). A Peltier cooling device controlled by a data logger is used to cool the mirror until dew forms and then to heat the mirror to eliminate the dew. Temperature of the sediment or rock sample is measured with an infrared thermometer. Vapor pressure of air is equal to the saturation vapor pressure at the dew point temperature, by definition of the dew point. Saturation vapor pressure is approximated by

$$P_0(T) = a \exp\left(\frac{bT_s}{T_s + c}\right) \tag{4}$$

where a, b, and c are constants and T_s is the surface temperature [*Buck*, 1981].

$$\begin{aligned} A_w = \frac{P}{P_0(T_s)} &= a \exp\left(\frac{bT_d}{T_d + c}\right)\left[a \exp\left(\frac{bT_s}{T_s + c}\right)\right]^{-1} \\ &= \exp\left(\frac{bT_d}{T_d + c} - \frac{bT_s}{T_s + c}\right) \\ &= \exp\left(\frac{bc(T_d - T_s)}{(T_d + c)(T_s + c)}\right) \end{aligned} \tag{5}$$

where T_d is the dew point temperature in degrees celsius. A microprocessor-controlled algorithm is used to convert the air dew point temperature and the sample temperature to water activity or relative humidity readings. The Kelvin equation (equation (3)) is then used to estimate the water potential. Temperature control is unimportant because change in water activity with temperature is generally <0.003°C^{-1}. Because the chilled mirror dew point technique is a primary measurement method of relative humidity, no calibration is required.

The filter paper method, also used to measure matric or water potentials on sediment or rock samples in the laboratory ranging from −0.2 to −90 MPa, does not require expensive instrumentation [*Greacen et al.*, 1987; *American Society for Testing and Materials*, 1994]. This method assumes that porous media in liquid or vapor contact with the filter paper will exchange water until the matric or water potentials of both are the same. The filter paper can be placed in direct contact with the sample to measure the matric potential, or it can be separated from the sample by a vapor gap to measure water potential (matric and osmotic potential). Although the time required for equilibration varies with the potential of the medium, equilibrium is generally reached within 7 days. Whatman no. 42 filter papers are generally used, and the increase in mass of the filter paper is measured and related to matric or water potential through a previously determined calibration curve. *Greacen et al.* [1987] listed calibration equations for different ranges in water potential. The greatest source of error in all laboratory measurements of pressure (water or matric) potentials is the possibility of samples drying during collection, particularly in coarse-textured material.

3.1.3. Hydraulic conductivity. Information on hydraulic conductivity is required for estimating water flux using Darcy's law under steady flow conditions or using Richards' equation under transient flow conditions. Darcy's law is empirical and was originally developed for the saturated zone. Darcy's law shows that water flux under steady flow is proportional to the hydraulic head gradient, the proportionality constant being the hydraulic conductivity. Hydraulic head is the sum of the matric (pressure) potential head and the gravitational potential head. In the saturated zone, hydraulic conductivity is constant at a point in space. Darcy's law was modified by *Buckingham* [1907] for the unsaturated zone by allowing the hydraulic conductivity K to vary with water content θ:

$$q_l = -K(\theta)\frac{\partial H}{\partial z} = -K(\theta)\left(\frac{\partial h(\theta)}{\partial z} + 1\right) \tag{6}$$

where q_l is the liquid water flux, H is the hydraulic head, and h is the matric potential head, which is a function of the water content. Richards' equation is required to predict water content or matric potential in the unsaturated zone during transient flow and combines the conservation of mass with Darcy's equation (conservation of momentum):

$$\frac{\partial \theta}{\partial t} = -\frac{\partial q_l}{\partial z} = \frac{\partial}{\partial z}\left[K(\theta)\left(\frac{\partial h(\theta)}{\partial z} + 1\right)\right] \tag{7}$$

Although unsaturated hydraulic conductivity is the least well known flow parameter, it has a great effect on estimated water fluxes because hydraulic conductivity may vary over several orders of magnitude in the range of water contents found in arid regions. Unsaturated hydraulic conductivity can be estimated from water retention and saturated hydraulic conductivity data by assuming that the unsaturated medium behaves like a bundle of capillary tubes [*Mualem*, 1976; *van Genuchten*, 1980]; however, in many arid regions, water may be adsorbed as films, and estimates of hydraulic conductivity based on capillary flow may not apply.

There are numerous field and laboratory methods for determining the unsaturated hydraulic conductivity as a function of water content. These methods are either steady state or transient and are described in detail by *Klute* [1986]. Recent developments in ultracentrifuge technology allow measurement of unsaturated hydraulic conductivity at fairly low water contents. *Nimmo et al.* [1987, 1992] and *Conca and Wright* [1992] developed steady state centrifuge methods to measure unsaturated hydraulic conductivity. Large forces (≤2000 g per unit mass) applied to the unsaturated sample result in removal of water from the sample. The magnitude of the force is controlled by the radius and speed of rotation of the centrifuge [*Kutilek and Nielsen*, 1994]. The various centrifuge methods apply water at a constant rate to the inner side of a small sediment sample or rock core either through precision pumps or through a water reservoir and porous ceramic plate. The sample generally reaches a steady state water content in a fairly short time. The steady state water flux can be described by a modified Darcy equation:

$$q_l = -\frac{K(\theta)}{g}\left(\frac{dh(\theta)}{dr} - \omega^2 r\right) \qquad (8)$$

where K is the unsaturated hydraulic conductivity, g is the gravitational acceleration, r is the radius of the sample, and $\omega^2 r$ is the centripetal force per unit mass. Assuming a negligible or unit gradient ($dh/dr = 1$), the unsaturated hydraulic conductivity is calculated by dividing the measured flux q_l by $\omega^2 r g^{-1}$. The sample is removed from the centrifuge, and the water content and/or matric potential is measured. The experiment is rerun at different flow rates to calculate the unsaturated hydraulic conductivity at different water contents or matric potentials.

3.1.4. Noninvasive techniques for estimating water content and movement. Because of the difficulties and expense of installing dedicated equipment, particularly in contaminated sites, noninvasive techniques for evaluating unsaturated water movement are highly desirable. In disposal sites, equipment installation should be minimized to maintain site integrity and to avoid creating preferred pathways for contaminants.

Electromagnetic induction (EMI) has been used to evaluate spatial variability in unsaturated flow over large regions [*Cook et al.*, 1992; *Cook and Kilty*, 1992]. EMI is a noninvasive technique that measures apparent electrical conductivity, which can be used to evaluate unsaturated flow. The theoretical basis for electromagnetic induction measurements is described by *McNeill* [1992]. The instruments (e.g., EM38 meter (Figure 2h) or EM31 meter (Figure 2i), Geonics Inc., Mississauga, Ontario) generally consist of a transmitter coil placed on the ground that is energized by an alternating current at an audio frequency. This current generates a primary magnetic field, which in turn induces small currents that generate their own secondary magnetic field. The receiver coil responds to both the primary and secondary magnetic field components. Under low values of induction number, the secondary magnetic field is a linear function of apparent electrical conductivity. The instrument can be operated with both transmitter and receiver coils lying horizontally (vertical dipole mode) or vertically (horizontal dipole mode) on the ground.

Ground-based EMI surveys can be conducted with a variety of instruments that range in exploration depth from 0.75 to 40 m (Figure 2) [*McNeill*, 1992]. Apparent electrical conductivity (EC_a) in the subsurface is related to water content, salt content, texture, structure, and mineralogy:

$$EC_a = EC_w\theta\tau + EC_s \qquad (9)$$

where EC_w is pore-water conductivity, θ is volumetric water content, τ is tortuosity, and EC_s is surface conductance of the sediment [*Rhoades et al.*, 1976]. Higher recharge generally occurs in more coarsely textured soils (lower EC_a) and results in higher relative water content (higher EC_a) and lower chloride content (lower EC_a) [*Cook et al.*, 1992]. Because of competing effects of texture, chloride, and water content on EC_a, EMI will work well only in recharge estimation where any one of these factors dominates or where two factors operate synergistically on EC_a. In an Australian study, because the correlation between recharge and EC_a was controlled by soil texture, the EMI survey mapped primarily soil texture at the site [*Cook et al.*, 1992]. Comparison of ground measurements of EC_a with recharge estimated according to unsaturated-zone chloride data at 20 sites resulted in a coefficient of determination (R^2) of 0.5. These data suggest that although EMI cannot estimate recharge directly, it may be useful in reconnaissance and interpolation between borehole measurements.

An electromagnetic meter (Geonics model EM31 (Figure 2i)) has also been used to monitor temporal variations in water content along an ~2-km transect [*Sheets and Hendrickx*, 1995]. The researchers found a linear relationship between apparent conductivity measured using the EM31 meter and water content in the upper 1.5 m of soil logged in 65 neutron probe access tubes along the transect. This technique shows promise for monitoring water content in disposal facilities, once a calibration equation has been developed.

TABLE 3. Summary of Environmental Tracers Commonly Used in Arid Regions and Their Attributes

Tracer	*Type*	*Liquid/Vapor Phase*	*Dating Period, years*	*Notes*
Chloride		liquid	≤1000s	qualitative
^{36}Cl	bomb pulse	liquid	0–40	used in evaluating water fluxes and preferential flow
	cosmogenic variation	liquid	≤70,000	small signal ≤2 × background; advection-dominated systems
	radioactive decay	liquid	50,000–1,000,000	used at Yucca Mountain, Nevada
^{3}H	bomb pulse	liquid + vapor	0–40	used in evaluating water fluxes and preferential flow

3.2. Tracer Techniques for Estimating Water Movement

It is difficult to estimate rates of water movement in unsaturated media because the rates are generally low. Physical methods that depend on Darcy's or Richards' equations are restricted by uncertainties in estimated unsaturated hydraulic conductivities. Chemical tracers can provide information on current water fluxes and long-term net water fluxes for up to thousands of years. In humid sites, applied tracers (such as bromide) are used for evaluating solute transport. Organic dyes (such as FD&C (food, drug, and cosmetics) blue dye and Rhodamine dye) have also been used in delineating preferred pathways in humid regions [*Steenhuis et al.*, 1990]. Use of applied tracers has generally been limited in arid regions to irrigated areas [*Wierenga et al.*, 1991] or localized zones of high water fluxes [*Scanlon*, 1992b]. The low water fluxes typical of many arid settings limit the penetration depth of applied tracers. In some arid settings, contaminants in the unsaturated zone can be considered long-term applied tracers. Bromide that originated in a factory that had been operating for 18 years was used to evaluate water flow and solute transport at a site in the Negev Desert, Israel [*Nativ et al.*, 1995].

A wide variety of environmental tracers exists that span different time scales (Table 3). These tracers, including ^{36}Cl and ^{3}H, are produced naturally in the Earth's atmosphere and have existed in the natural environment for millions of years. The concentration of these tracers was greatly increased by nuclear testing in the mid-1950s to early 1960s, however (Figure 3). Some tracers exist in both liquid and vapor phases (tritiated water), whereas others exist only in the liquid phase in the subsurface (Cl and ^{36}Cl). We will review some of the most widely used environmental tracers and examine the assumptions associated with these tracers and how accurately they represent the flow system.

3.2.1. Meteoric chloride. The chloride mass balance approach uses chloride concentrations in pore water to estimate liquid water fluxes for up to thousands of years at many arid sites [*Allison and Hughes*, 1983]. Chloride from precipitation, dry fallout, or irrigation may concentrate in the root zone as a result of evapotranspiration [*Gardner*, 1967]. Chloride transport through the unsaturated zone is described by

$$q_{Cl} = q_l c_{Cl} - D_h \frac{\partial c_{Cl}}{\partial z} \tag{10}$$

where q_l is the volumetric liquid water flux below the root zone (L T^{-1}), q_{Cl} is the chloride deposition flux at the surface (M L^{-2} T^{-1}), c_{Cl} is the pore water chloride concentration (M L^{-3}), and D_h is the hydrodynamic dispersion coefficient (L^2 T^{-1}), a function of θ (volumetric water content) and v (average pore water velocity). The first term on the right represents the chloride flux that results from advection, and the second term represents the flux from hydrodynamic dispersion. The mechanical dispersion coefficient D_m and the effective molecular diffusion coefficient D_e compose the hydrodynamic dispersion coefficient. Mechanical dispersion is the mixing that occurs as a result of variations in pore water velocity due to (1) the parabolic velocity distribution within a pore, (2) different pore sizes, and (3) the effects of tortuosity or branching of pore channels. Molecular diffusion results from the thermal or kinetic energy of particles. Mechanical dispersion is assumed to be negligible because flow velocities are generally <7 m yr^{-1}, which *Olsen and Kemper* [1968] specified as the water velocity below which mechanical dispersion can be ignored. The effective molecular diffusion coefficient differs from the diffusion coefficient in pure water because of the reduced cross-sectional area in unsaturated media (represented by the water content)

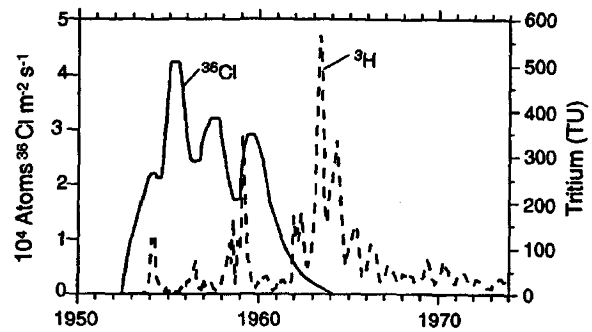

Figure 3. Temporal variations in predicted bomb ^{36}Cl fallout between 30°N and 50°N latitude [*Bentley et al.*, 1986] and in ^{3}H fallout of precipitation in the northern hemisphere [*IAEA*, 1983], decay corrected to 1989.

and the increased path length for the water (tortuosity). At low water fluxes the diffusive flux may be dominant. In many arid systems the hydrodynamic dispersion coefficient can be assumed to be negligible [*Allison and Hughes*, 1978], and equation (10) is simplified to

$$q_l = q_{Cl}/c_{Cl} \tag{11}$$

The age of the chloride and, by implication, that of the water can be calculated by dividing the integrated Cl content from the surface to the depth of interest by the annual chloride deposition flux. Chloride concentration in pore water is inversely proportional to water flux: low chloride concentrations indicate high water flux, and high chloride concentrations indicate low water flux (Figure 4).

Chloride deposition flux at a site can be estimated by (1) measuring chloride concentrations in precipitation and dry fallout or (2) dividing the natural ^{36}Cl fallout at a site, which varies according to latitude (as predicted by *Andrews and Fontes* [1991]), by the prebomb ^{36}Cl/Cl ratio (i.e., ratios before the first atmospheric nuclear explosion). An independent estimate of chloride deposition was also calculated for chloride profiles at the Hanford site, Washington [*Murphy et al.*, 1996]. Late Pleistocene floods, resulting from breaching of glacial dams, reset the chloride mass balance clock at the beginning of the Holocene. Estimates of chloride deposition that were calculated by dividing the chloride mass by the time since flooding when all chloride was flushed out of the sediments (15,000 years) agreed with estimates based on prebomb ^{36}Cl/Cl ratios. Because chloride mass balance equations are linear, uncertainties in the chloride deposition flux result in corresponding uncertainties in estimated water fluxes. If chloride concentration in precipitation is controlled (to first order) by distance from the ocean, its concentration should not vary significantly with time. Higher precipitation during Pleistocene times would result in correspondingly higher chloride deposition. Chloride deposition from dry fallout of dust and salts is of the same magnitude as that from precipitation in Nevada [*Dettenger*, 1989]. The contribution of dry fallout from saline lakes can be examined by measuring prebomb ^{36}Cl/Cl ratios because saline lakes have signatures markedly different from those of modern precipitation [*Phillips et al.*, 1995]. The prebomb ^{36}Cl/Cl ratios refer to ^{36}Cl/Cl ratios at depth that reflect fallout that occurred before the bomb pulse. At many sites, prebomb ^{36}Cl/Cl ratios are similar (500×10^{-15} [*Scanlon*, 1992a; *Fabryka-Martin et al.*, 1993]), which suggests that the contribution of ^{36}Cl from saline lakes is negligible at these sites. In addition to rain and dry fallout, other sources of chloride include rocks at Yucca Mountain [*Fabryka-Martin et al.*, 1993] and runon or runoff that should be quantified.

The chloride mass balance approach assumes piston-like flow, or uniform downward movement of water that displaces the initial water in the profile. The assumption

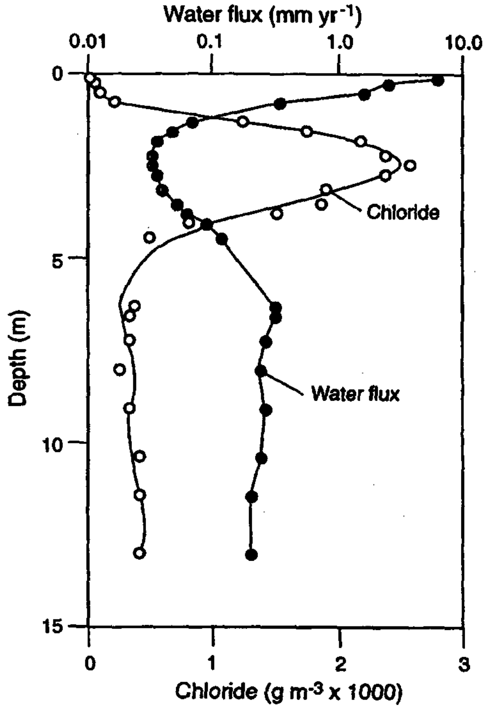

Figure 4. Typical example of inverse relationship between pore water chloride concentrations and estimated water fluxes. Adapted from *Scanlon* [1991, Figure 2] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands.

of piston-like flow has been questioned at many sites. Because chloride input to the system is continuous, chloride profiles are generally insensitive to preferential flow, or nonuniform downward movement of water, in which some water moves rapidly along preferred pathways such as roots or fractures. Piston-like and preferential flow are discussed in more detail in section 5. Evidence of preferential flow is generally provided by the distribution of bomb pulse tracers in the vadose zone such as bomb pulse ^{36}Cl and ^{3}H. Although tritium data at a fractured-chalk site in the Negev Desert indicate preferential flow, chloride profiles at this site are smooth, as would be expected at a site without preferential flow [*Nativ et al.*, 1995].

Bulge-shaped chloride profiles at many sites in nonfractured sediments could result from preferential flow [*Nativ et al.*, 1995], diffusion to a shallow water table [*Cook et al.*, 1989], or transient flow [*Scanlon*, 1991; *Phillips*, 1994] (Figure 5). Chloride profiles at many of these sites look similar, and interpretation of the bulge shape generally relies on additional information. Evidence of preferential flow in the Negev site was provided by deep penetration of ^{3}H [*Nativ et al.*, 1995]. The shape of some profiles in Australia are attributed to diffusion to a shallow water table because of the differences in chloride concentration between unsaturated and saturated zones (Figure 5) [*Cook et al.*, 1989]. Bulge-shaped chloride profiles in the southwestern United States,

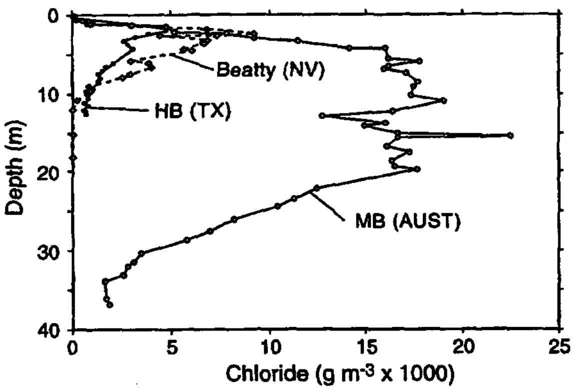

Figure 5. Bulge-shaped chloride profiles from vegetated dunes in the Murray Basin, South Australia (MB, profile BVDO1 [*Cook et al.*, 1989]), and from various southwestern U.S. settings (Hueco Bolson (HB), Texas, [*Scanlon*, 1991]; Beatty, Nevada [*Prudic*, 1994]). HB and MB plots reproduced from *Scanlon* [1991, Figure 3] and *Cook et al.* [1989] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands.

where the water table is generally much deeper (≥100 m), are attributed to higher water fluxes during the Pleistocene, when the climate was cooler and wetter [*Scanlon*, 1992a; *Phillips*, 1994; *Tyler et al.*, 1996]. Additional evidence on the effect of paleoclimate on water movement is provided by stable isotopic data [*Tyler et al.*, 1996]. In areas where the chloride concentration below the chloride peak is very low, such as at Beatty, Nevada [*Prudic*, 1994], preferential flow cannot be used to explain the reduction in chloride because preferential flow refers to enhanced water movement along localized preferred pathways, which does not include complete leaching (Figure 5). Because chloride profiles represent net liquid water flux over long time periods, the chloride at depth at these sites is a relic of past climate conditions and does not represent current conditions. In Australia, on a much smaller timescale (~100 years), transient flow conditions resulted when native mallee vegetation, characterized by deep-rooted (~20 m) eucalyptus trees, was replaced by crops and pasture [*Cook et al.*, 1994].

The chloride mass balance method provides an estimate of liquid water flux, which is important in evaluating the movement of nonvolatile solutes. Because liquid water flux may move downward and vapor flux and net water flux may move upward, estimates of liquid flux based on chloride data alone may provide inaccurate estimates of net water flux.

3.2.2. Chlorine 36. Chlorine 36 (half-life of 301,000 years) is produced in the atmosphere by cosmic ray spallation of ^{36}Ar and neutron activation of ^{35}Cl [*Bentley et al.*, 1986]. Chlorine 36 can provide estimates of liquid water residence time (1) over the past ~40 years by means of bomb pulse ^{36}Cl/Cl ratios, (2) over the past 70–80 kyr by means of variations in cosmogenic production of ^{36}Cl, and (3) from 50 to 1000 kyr by means of radioactive decay of ^{36}Cl (Table 3).

Nuclear weapons tests conducted between 1952 and 1958 resulted in ^{36}Cl concentrations in precipitation as much as 1000 times greater than natural fallout levels [*Bentley et al.*, 1986] (Figure 3). In nonfractured sediments, water fluxes have been estimated from the ^{36}Cl center of mass [*Cook et al.*, 1994]. The amount of water in the profile above the center of mass of ^{36}Cl is equal to the flux during the time period since the center of mass of the fallout occurred. Annual water flux is generally calculated by dividing this total flux by time in years. In many areas where bomb pulse ^{36}Cl has been used to estimate water flux, the center of mass of the bomb pulse is still in the root zone [*Gifford*, 1987; *Norris et al.*, 1987; *Phillips et al.*, 1988; *Scanlon*, 1992a] (Figure 6). Occurrence of the bomb pulse in the root zone indicates that water fluxes at these sites are extremely low, which is important for waste disposal. Because much of this water in the root zone is later removed by evapotranspiration, water fluxes estimated from tracers within the root zone overestimate water fluxes below the root zone by up to several orders of magnitude [*Tyler and Walker*, 1994]. High ^{36}Cl/Cl ratios have been found to depths of 440 m at Yucca Mountain, Nevada [*Liu et al.*, 1995], suggesting preferential flow along fractures. Variations in cosmogenic production of ^{36}Cl during the past 60–70 kyr could complicate the use of bomb pulse ^{36}Cl/Cl ratios. Some of the measured ^{36}Cl/Cl ratios considered to be bomb pulse, particularly at Yucca Mountain, fall within the range estimated as a result of variations in cosmogenic production of ^{36}Cl (J. Fabryka-Martin, personal communication, 1995) and may not be bomb related. Because the ratio of ^{36}Cl to chloride rather than the ^{36}Cl concentration is measured, high chloride concentrations in pore water could reduce the effectiveness of ^{36}Cl/Cl ratios to estimate preferential flow.

Variations in cosmogenic production of ^{36}Cl can also be used to date water during the past 70–80 kyr [*Phillips et al.*, 1991; *Plummer and Phillips*, 1995]. Production rates of meteoric ^{36}Cl vary inversely with the strength of the magnetic field and increased by as much as a factor of 2 during periods of reduced magnetic field strength [*Plummer and Phillips*, 1995]. Comparison of reconstructed ^{36}Cl production with variations in ^{36}Cl in pore water has been used to estimate ages of water at the Nevada Test Site [*Tyler et al.*, 1996]. Because variations in cosmogenic production increase the background ratio by only as much as a factor of 2, such variations may not be readily preserved in the unsaturated zone because of diffusion and dispersion.

Radioactive decay of ^{36}Cl has also been used to date very old pore water in the unsaturated zone at Yucca Mountain [*Fabryka-Martin et al.*, 1993]. Use of radioactive decay of ^{36}Cl is complicated at this site because contributions of "dead" Cl (having no ^{36}Cl) from rock away from the main flow regime result in greater apparent ages.

3.2.3. Tritium. Tritium (^{3}H; half-life of 12.4 years), produced by cosmic ray neutrons interacting with

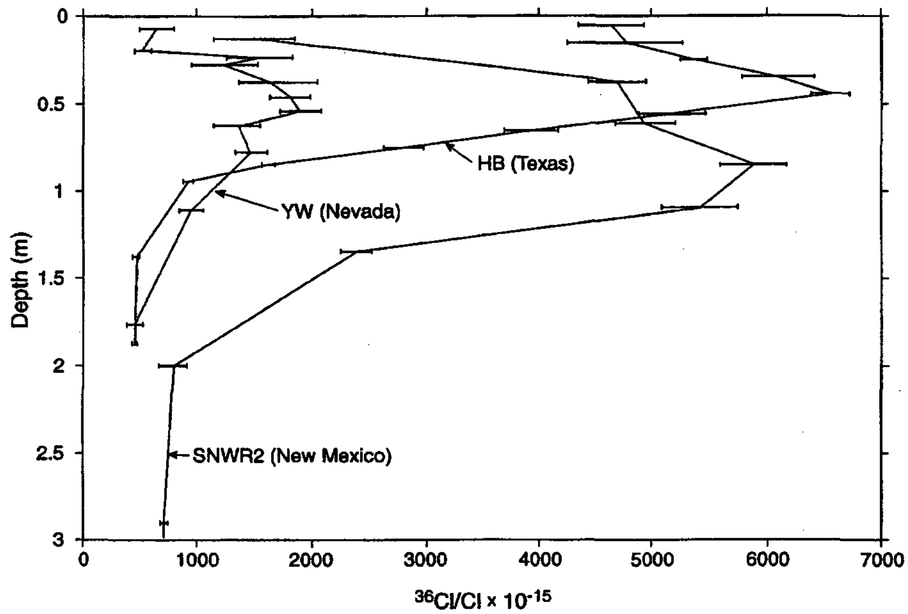

Figure 6. Profile of ^{36}Cl/Cl ratios from the Chihuahuan Desert (Hueco Bolson (HB) [*Scanlon*, 1992a]. Yucca Wash, Nevada (YW [*Norris et al.*, 1987]); and Sonoran Desert, New Mexico (SNWR2 [*Phillips et al.*, 1988]). Bars represent 1 standard deviation in the ^{36}Cl/Cl ratios. YW plot reproduced from *Norris et al.* [1987, Figure 1] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands.

nitrogen in the upper atmosphere, typically results in 5–10 tritium units (TU) in precipitation. Tritium concentrations increased from 10 to ≥2000 TU during atmospheric nuclear testing [*International Atomic Energy Agency (IAEA)*, 1983] that began in 1952 and peaked in 1963–1964 (Figure 3). Because tritiated water exists in both liquid and vapor phases, tritium is a tracer for liquid and vapor water movement. The distribution of bomb-pulse tritium in the vadose zone can be used to estimate water fluxes and to evaluate preferential flow, a procedure similar to that described for ^{36}Cl.

In tritium analysis, pore water can be extracted directly from cores by means of toluene distillation or cryodistillation. Alternatively, gas samples can be extracted from boreholes and water condensed from the gas for tritium analysis. Large gas volumes are required to detect the trace amounts of tritium found at some sites that lead to uncertainties in the volume and depth interval of the unsaturated section that is sampled. Contamination in gas sampling procedures may occur because of the potential for air flow along well casing and leaking gas lines. Problems in interpreting very low tritium levels in Ward Valley, California, a proposed low-level radioactive waste disposal facility, are thought to result from poor sampling procedures and from the absence of procedural blanks for evaluating possible contamination [*NRC*, 1995]. General problems with analysis of low tritium levels in the unsaturated zone, particularly those close to the detection limit, may reflect our lack of experience with environmental tritium sampling and our inability to collect reliable samples.

To analyze water samples for tritium, various techniques have been used that depend on the amount of water available for analysis and accuracy required. Direct liquid scintillation generally requires ~20 mL of water, and the detection limit is ~6 TU (C. Eastoe, personal communication, 1995). The detection limit is greatly reduced when electrolytic enrichment is used; however, the amount of water required is greater. A minimum sample size of 275 mL, an electrolytic enrichment factor of ~80, and a counting time of 300 min by means of gas proportional counting result in a detection limit of 0.1 TU at the University of Miami Tritium Laboratory [*Ostlund and Dorsey*, 1977]. Longer counting times (≤1000 min) can be used for smaller samples.

Researchers recently analyzed tritium using the helium 3 "in-growth" method [*Schlosser et al.*, 1989; *Solomon and Sudicky*, 1991). Tritium decays to ^{3}He. Pore water from the unsaturated zone is degassed of all He, sealed, and stored to decay to ^{3}He, allowing much higher precision and lower detection limits than do standard counting techniques. For example, a 20-mL water sample that is allowed to decay for 6 months would result in a detection limit of ~0.2 TU (R. Poreda, personal communication, 1995). The ^{3}He in-growth method for analyzing ^{3}H in unsaturated pore water samples should be distinguished from the ^{3}He in-growth dating method, which applies strictly to the saturated zone. Dating water using ^{3}H/^{3}He requires isolation of the ^{3}He from the atmosphere, which occurs only below the water table and provides the age of the water since it became isolated from the atmosphere [*Solomon et al.*, 1992]:

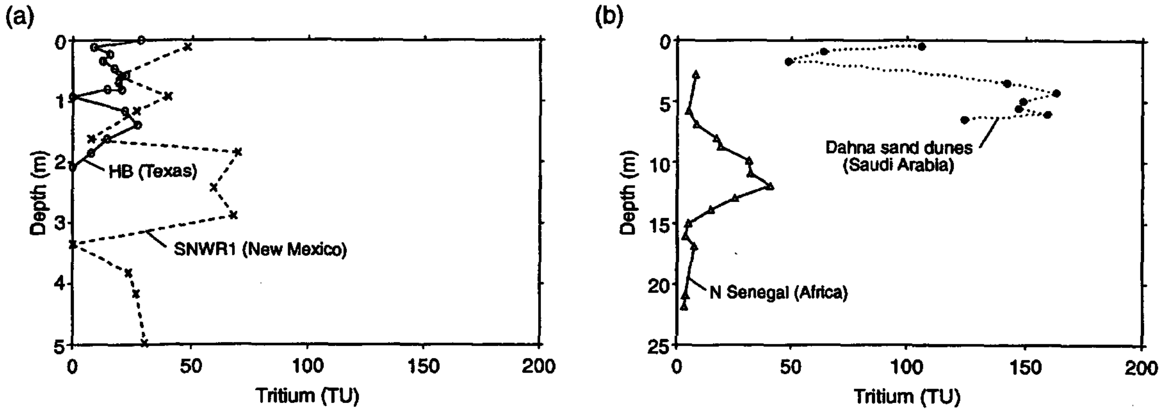

Figure 7. Profiles of ^{3}H concentrations (a) from the Chihuahuan Desert (Hueco Bolson (HB) [*Scanlon*, 1992]) and Sonoran Desert (SNWR1 [*Phillips et al.*, 1988]) and (b) from northern Senegal [*Aranyossy and Gaye*, 1992] (with permission from Gauthier-Villars Editeur) and Dahna sand dunes, Saudi Arabia (replotted from *Dincer et al.* [1974, Figure 11] with kind permission from Elsevier Science-NL, Amsterdam, Netherlands).

$$t_{^3\mathrm{H}/^3\mathrm{He}} = \lambda^{-1} \ln \left(\frac{^3\mathrm{He}}{^3\mathrm{H}} + 1 \right) \qquad (12)$$

where $t_{^3\mathrm{H}/^3\mathrm{He}}$ is the ^{3}H/^{3}He age and λ is the ^{3}H decay constant.

At many arid sites, although the tritium bomb pulse within the root zone provides evidence of very low water fluxes [*Phillips et al.*, 1988; *Scanlon*, 1992a], accurate estimates of deep percolation below the root zone cannot be obtained from these data (Figure 7a). Deep penetration of the bomb pulse has also been found in sandy soils in arid settings [*Dincer et al.*, 1974; *Aranyossy and Gaye*, 1992] (Figure 7b). Comparison of ^{3}H and ^{36}Cl data from some arid sites showed deeper penetration of ^{3}H relative to ^{36}Cl, results that were attributed to enhanced downward movement of ^{3}H in the vapor phase [*Phillips et al.*, 1988; *Scanlon and Milly*, 1994]. Diffusion of ^{3}H in the vapor phase is limited if equilibration between liquid and gas phases occurs because the concentration of ^{3}H in the vapor phase is 5 orders of magnitude less than in the liquid phase, reflecting the different densities of water molecules in the two phases [*Smiles et al.*, 1995]. The liquid phase, in this case, acts as a large sink for tritium.

The method used to estimate water flux from bomb pulse tracer distributions is based on an assumption of steady downward advective flux, implying that the penetration depth of ^{36}Cl and ^{3}H increases linearly with time. Recent analytical studies by *Milly* [1996] suggest that the shallow distribution of these bomb pulse tracers can be attributed to episodic downward liquid flow and seasonal temperature gradients without invoking any mean vertical downward or upward water flux. The presence of ^{36}Cl and ^{3}H near the surface indicates little or no water flux below the root zone. High ^{3}H values (e.g., 1100 TU at 24-m depth, $\leq$ 162 TU at 109-m depth) have been found adjacent to the Beatty site, Nevada, that cannot readily be explained by liquid or combined liquid and vapor transport [*Prudic and Striegl*, 1995; *Striegl et al.*, 1996]. Because disposal practices at Beatty varied in the past and included disposal of as much as ~2000 m^3 of liquid waste, further research in ^{3}H movement at Beatty is warranted.

In some locations, bomb pulse ^{3}H has been found at depths greater than those initially expected. For example, bomb pulse ^{3}H was found as deep as ~450 m (105 TU; UZ-16 borehole) in Yucca Mountain (I. C. Yang, personal communication, 1995) and ~12 m (8.4 TU, RT18 borehole) in the Negev Desert [*Nativ et al.*, 1995]. These depths of ^{3}H migration, much greater than predicted by chloride mass balance data at these sites, may be attributed to preferential flow along fractures.

4. DIRECTION AND RATE OF WATER MOVEMENT

Although direction of water movement is a basic issue, it is not easily resolved at some sites, primarily because the water fluxes under consideration have a magnitude close to the errors inherent in measuring or in calculating these water fluxes. Second, a variety of driving forces in water movement may be important in arid settings, including water potential, gravitational potential, pneumatic potential, osmotic potential, and temperature. Third, the direction of water flux is likely to be spatially and temporally variable.

In this section we examine the various driving forces that can control the direction of water movement. Sediment heterogeneity also affects the direction of flow and is discussed later.

4.1. Liquid Flux

An initial examination of the simple system in which liquid flow is dominant shows that liquid water flux q_l is described by Darcy's law under steady flow conditions

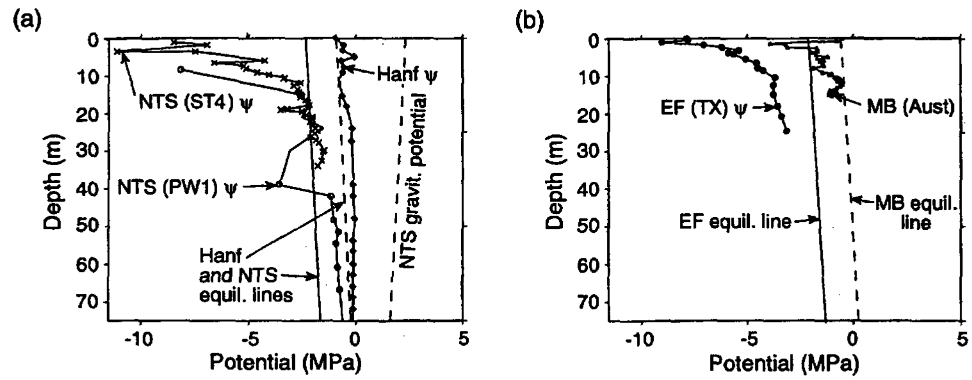

Figure 8. Evaluation of the direction of water movement according to the relationship between water potential profiles and the equilibrium line. Data are (a) from Hanford, Washington (Hanf; data from *Brownell et al.* [1975] as plotted by *Gee and Heller* [1985, Figure 4]), and Nevada Test Site, Nevada (NTS; profiles ST4 (shallow) and PW1 (deep) [*Estrella et al.*, 1993]), and (b) from Eagle Flat, Texas (EF111 [*Scanlon et al.*, 1997b]), and Murray Basin, South Australia (MB [*Jolly et al.*, 1989]). Equilibrium line refers to equilibrium matric potential that balances gravitational potential (Nevada Test Site data shown as an example).

according to equation (6). Evaluation of flow direction requires information on the hydraulic head (sum of matric and gravitational potential heads) gradient. Because matric potentials in natural interfluvial settings in arid systems are generally low, tensiometers cannot be used and thermocouple psychrometers are required that measure water potential (sum of matric and osmotic potential; see Tables 1 and 2 and Figure 3). The osmotic component of the water potential is generally negligible because zones where the magnitude of the osmotic potential is high in near-surface sediments generally correspond to zones where the magnitude of the water potential is also high [*Scanlon*, 1994]. Except in the shallow subsurface after rainfall, water (pressure) potentials measured in interfluvial settings in desert soils generally decrease (become more negative) toward the surface [*Jolly et al.*, 1989; *Fischer*, 1992; *Detty et al.*, 1993; *Scanlon*, 1994]. This upward decrease in water potentials suggests an upward driving force for liquid water flow.

One can also estimate the direction of water flow under steady flow conditions by comparing the measured matric or water potentials with the equilibrium matric potentials (Figure 8). If the vertical space coordinate z is taken as positive upward and zero at the water table, the equilibrium matric potential heads are the negative of the gravitational potential heads because matric and gravitational potential heads are balanced under static equilibrium (no flow) and their sum is a constant (0 in this case) (Figure 8). Under steady flow conditions, matric potentials that plot to the right of the equilibrium matric potential line indicate downward flow, and matric potentials that plot to the left of the equilibrium line indicate upward flow. At a site in Hanford, Washington, *Brownell et al.* [1975] (Figure 8a) found that measured water (pressure) potentials (approximately equal to matric potentials) plot to the right of the equilibrium line, indicating drainage. At several sites in Australia and in the southwestern United States, water (pressure) potentials plot to the right of the equilibrium line, indicating net upward water movement [*Jolly et al.*, 1989; *Fischer*, 1992; *Estrella et al.* 1993; *Scanlon*, 1994] (Figure 8b). At the Nevada Test Site this zone of net upward water movement is restricted to the upper 20–40 m (Figure 8a) [*Detty et al.*, 1993; *Sully et al.*, 1994]. Below 20–40 m, water potentials plot to the right of the equilibrium line, suggesting that liquid water at depth may be draining at this site.

4.2. Vapor Flux

Under dry conditions characteristic of arid settings, vapor flow may be significant. If the air phase is assumed to be static, vapor flux q_v is given by

$$q_v = q_{Iv} + q_{Tv} = -D_{Iv}\nabla h - D_{Tv}\nabla T \qquad (13)$$

where q_{Iv} is the isothermal vapor flux, q_{Tv} is the thermal vapor flux, D_{Iv} is the isothermal vapor diffusivity, D_{Tv} is the thermal vapor diffusivity, h is matric (pressure) potential head, and T is temperature. Isothermal vapor flux is driven by the matric (pressure) potential gradient and is unaffected by the temperature gradient, in a way similar to that of the liquid flux. Thermal vapor flux is driven by the temperature gradient and is unaffected by the matric potential gradient. Thermal vapor flux, resulting from variations in saturated vapor pressure according to temperature, is generally considered much more important than isothermal vapor flux. A temperature difference of 1°C at 20°C results in a greater difference in vapor density (1.04×10^{-3} kg m^{-3}) than does a 1.5-MPa difference in matric potentials from −0.01 MPa to −1.5 MPa (0.17×10^{-3} kg m^{-3}) [*Hanks*, 1992, p. 95]. The effects of temperature enter directly through temperature gradients and indirectly through temperature dependence of the matric (pressure) potential, hydraulic conductivity, and vapor diffusivity [*Scanlon and Milly*, 1994]. Thermally driven liquid flow is generally negligible under the low water contents characteristic of interfluvial arid settings [*Milly*, 1996].

Seasonal reversals in temperature gradients from upward movement in the winter to downward movement in the summer in the 2- to 12-m zone result in a net downward thermal vapor flux [*Fischer*, 1992; *Scanlon*, 1994] (Figure 1). Net downward thermal vapor fluxes are attributed to higher thermal vapor diffusivities as a result of higher temperatures in the summer when the gradients are downward. Below the zone of seasonal temperature fluctuations, the upward geothermal gradient provides an upward driving force for thermal vapor movement (Figure 1). Estimated values of local geothermal gradients are 0.06°C m^{-1} (Beatty site [*Prudic*, 1994]), 0.013°C m^{-1} (Nevada Test Site [*Tyler et al.*, 1996]), and 0.046°C m^{-1} (Hanford [*Enfield et al.*, 1973]). Calculated upward thermal vapor fluxes resulting from the upward geothermal gradient range from 0.02 mm yr^{-1} at the Nevada Test Site [*Sully et al.*, 1994] to 0.04 mm yr^{-1} at the Hanford site [*Enfield et al.*, 1973].

So far in our analysis we have considered vapor diffusion resulting from water (pressure) potential and temperature gradients only, but volatile contaminants may also diffuse as a result of concentration gradients. In addition to diffusion, advection may occur in the gas phase. Factors resulting in advective transport include barometric pressure fluctuations, density, wind, and temperature. In homogeneous, permeable media, *Buckingham* [1904] showed that the effect of barometric pressure fluctuations was small in relation to that of molecular diffusion. In fractured, permeable media, advective fluxes resulting from barometric pressure fluctuations may be orders of magnitude greater than diffusive fluxes and could result in upward movement of contaminated gases into the atmosphere [*Nilson et al.*, 1991]. A gas tracer experiment described by *Nilson et al.* [1992] confirms the importance of barometric pumping in causing upward gas movement in fractured tuff from a spherical cavity (depth ~300 m) created by underground nuclear tests at the Nevada Test Site. In areas of steep topography such as at Yucca Mountain, temperature- and density-driven topographic effects result in continuous exhalation of air through open boreholes at the mountain crest in the winter, as cold dry air from the flanks of the mountain replaces warm moist air within the rock-borehole system [*Weeks*, 1987]. Wind also results in air discharge from the boreholes that is ~60% of that resulting from temperature-induced density differences [*Weeks*, 1993]. Open boreholes greatly enhance the advective air flow at this site; numerical simulations indicate that water fluxes resulting from advective air flow under natural conditions (0.04 mm yr^{-1}) are 5 orders of magnitude less than those found in the borehole [*Kipp*, 1987] and similar in magnitude to estimated vapor fluxes as a result of the geothermal gradient (0.025 to 0.05 mm yr^{-1} [*Montazer et al.*, 1985]). These processes could cause drying of fractured rock uplands and could expedite the release of gases to the atmosphere [*Weeks*, 1993].

4.3. Water Flux

Water includes liquid and vapor phases. Analysis of data from several sites in the southwestern United States indicates that net water flux often occurs upward in the upper 20- to 40-m section of the unsaturated zone because water potentials plot to the left of the equilibrium line and total potential (matric [pressure] + gravitational) gradients are upward (Figure 8). In the zone of seasonal temperature fluctuations (2–12 m deep), upward liquid and isothermal vapor fluxes exceed downward thermal vapor fluxes (Figure 1). Upward water potential and temperature gradients at greater depths result in upward liquid and vapor fluxes (Figure 1).

Below the 20- to 40-m section, water potentials at the Nevada Test Site plot to the right of the equilibrium line [*Detty et al.*, 1993], indicating downward liquid and isothermal vapor flux under steady flow conditions, and upward thermal vapor flux due to the geothermal gradient (Figure 1). At this site, the upward thermal vapor flux (0.02 mm yr^{-1}), almost balanced by the downward liquid flux (0.03 mm yr^{-1}), results in a statistically insignificant net downward water flux of 0.01 mm yr^{-1} [*Sully et al.*, 1994]. At the Hanford site the upward thermal vapor flux (0.04 mm yr^{-1}), less than the downward liquid flux (0.30 mm yr^{-1}), results in a net downward water flux of 0.26 mm yr^{-1}. The larger flux at the Hanford site is attributed to higher water potentials (−0.1 MPa) relative to those at the Nevada Test Site (−0.6 MPa) [*Sully et al.*, 1994]. In the upper part of the unsaturated zone, different directions of liquid and vapor fluxes can therefore be important for evaluation of the transport of volatile and nonvolatile substances.

5. HOW IMPORTANT IS PREFERENTIAL FLOW?

Traditionally, piston-like flow, implying displacement of initial water by infiltrating water, was thought to be the dominant flow mechanism in the unsaturated zone. In the strict sense, piston flow refers to uniform displacement of solute or water without any mixing. True piston flow never occurs because of mixing due to molecular diffusion and microscopic water velocity variations. We therefore use the term "piston-like flow" instead of "piston flow" to represent predominantly matrix flow, or uniform flow, through the unsaturated matrix, in contrast to preferential flow, which bypasses much of the unsaturated zone. Data from many arid sites, particularly interfluvial settings that have unconsolidated sediments, suggest predominantly piston-like flow. Differences in velocities of solute (V_s) and wetting fronts (V_{wf}) in South Australia after vegetation clearing (Figure 9) could be predicted by the following equation, which assumes piston flow:

$$\frac{V_s}{V_{wf}} = \frac{\theta_f - \theta_i}{\theta_f} \qquad (14)$$

where θ_f is the final water content and θ_i is the initial water content [*Jolly et al.*, 1989]. Similar results were found in large field tracer experiments conducted in Las Cruces, New Mexico [*Young et al.*, 1992]. In these experiments the lag between the solute and the wetting front increased with depth, consistent with piston-like displacement of original pore water. Increases in initial water content resulted in increased lag between solute and wetting fronts. Single peaks in bomb pulse tracer distributions such as ^{36}Cl at sites in the Chihuahuan Desert site [*Scanlon*, 1992a], the Nevada Test Site [*Norris et al.*, 1987], and the Sonoran Desert site [*Phillips et al.*, 1988], are also consistent with piston-like flow (Figure 6). Although the aforementioned data suggest predominantly piston-like flow, they are not sensitive to small-scale preferential flow.

Preferential flow has received more emphasis in recent studies. With preferential flow the cross-sectional area of flow is reduced, and water bypasses much of the unsaturated medium, leading to corresponding increases in velocity and reduced sorption. Preferential flow was generally considered to become damped with depth; however, more recent studies suggest that this is not always true. Preferential flow can be divided into funneled flow, unstable flow, and macropore flow [*Steenhuis et al.*, 1994]. These three types of preferential flow are not mutually exclusive because unstable flow can occur in macropores (as will be described later). Funneled flow, occurring at textural interfaces, was extensively documented in glacial outwash deposits in Wisconsin

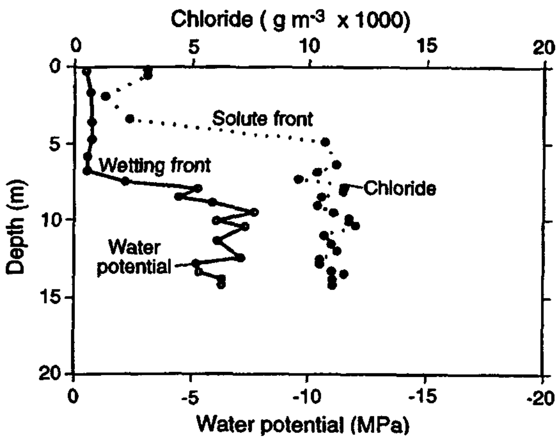

Figure 9. Piston-like flow evidenced by the lag between the wetting front and the solute front (modified from *Jolly et al.* [1989, Figure 2] with kind permission from Elsevier Science–NL, Amsterdam, Netherlands). The zone from the soil surface to the solute front represents water that infiltrated after the vegetation was cleared, the zone between the solute and wetting front represents displaced "preclearing" water, and the zone below the wetting front represents initial "preclearing" water.

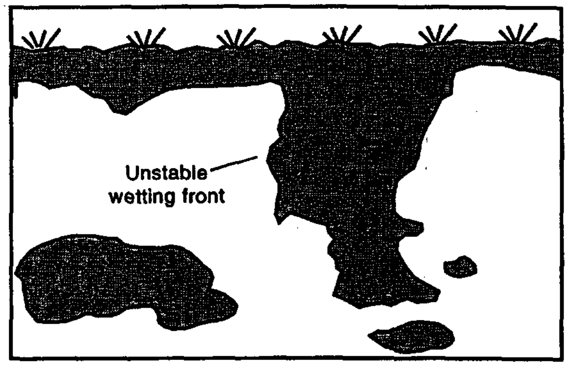

Figure 10. Example of unstable flow in water repellent soils after rainfall in the Netherlands (modified from *Hendrickx and Dekker* [1991]).

under unsaturated conditions [*Kung*, 1990a, b; *Miyazaki*, 1993]. Laboratory experiments showed that when water application rates were ≤2% of the saturated hydraulic conductivity of the finer material, water flowed along the surface of the coarser layer [*Kung*, 1993]. Although funneled flow has not been found in arid settings, lateral flow in geologically layered materials resembles funneled flow where inclined beds and natural capillary barriers result in lateral flow. Such lateral flow along geologically layered materials has been hypothesized for Yucca Mountain, Nevada, on the basis of analytical solutions and numerical simulations [*Ross*, 1990; *Oldenburg and Pruess*, 1993].

Unstable wetting fronts have been found in several field sites [*Starr et al.*, 1978, 1986; *Glass et al.*, 1988; *Hendrickx and Dekker*, 1991; *Selker et al.*, 1992; *Hendrickx et al.*, 1993] (Figure 10). *Chen et al.* [1995] provided an overview of instability and fingering in porous and fractured media. Important factors in the development of unstable flow in porous media include layering of sediment [*Hillel and Baker*, 1988; *Glass et al.*, 1989b], air entrapment [*Glass et al.*, 1990], and water repellency [*Hendrickx and Dekker*, 1991; *Ritsema et al.*, 1993; *Dekker and Ritsema*, 1994]. The absence of unstable wetting fronts in dune sands in an arid region of New Mexico led *Yao and Hendrickx* [1996] to evaluate conditions required for wetting-front instability. Many of the studies document that unstable wetting fronts were found in sandy, water-repellent soils because water repellency always results in unstable flow [*Hendrickx and Dekker*, 1991; *Ritsema et al.*, 1993; *Dekker and Ritsema*, 1994; *Ritsema and Dekker*, 1995]. Water tables are also shallow at many of these sites (0.5–1.5 m [*Ritsema et al.*, 1993]). *Hendrickx and Yao* [1996] subdivided infiltration rates into three regimes: low, medium, and high. Gravity-driven instabilities do not occur under low infiltration rates, where capillary and adsorptive forces are much greater than gravitational forces. Under high infiltration rates, wetting fronts remain stable if the infiltration rate approximates field-saturated hydraulic conductivity. Un-

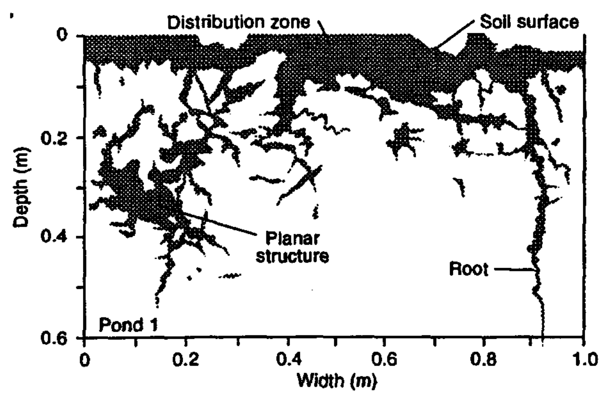

Figure 11. Example of preferential flow along roots as shown by FD&C dye [*Scanlon et al.*, 1997a].

der medium infiltration rates, stable wetting fronts are found when the total amount of infiltrating water is less than the amount of water required to wet a surface distribution layer. Additionally, the distribution layer has stable flow, and the thickness of this layer can be predicted by the same equation used by *Glass et al.* [1989a] to predict finger diameter [*Hendrickx and Yao*, 1996]. Application of these criteria to dune sands in New Mexico showed that all 2- and 10-year, and some 100-year return interval precipitation events were in the stable flow regime [*Hendrickx and Yao*, 1996]. Thus precipitation records and information on water repellency, water retention, and hydraulic conductivity of sediments at a site can be used to evaluate the potential for unstable flow.

Macropore flow refers to flow along noncapillary-size openings such as fractures, cracks, and root tubules (Figure 11). Important factors in evaluating macropore flow include sediment texture and structure and boundary conditions [*Flury et al.*, 1994]. Previous studies have shown that macropore flow is much greater in structured, fine-grained sediments than in structureless coarse-grained sediments [*Steenhuis and Parlange*, 1991; *Flury et al.*, 1994]. Whereas finger and funneled flow are eliminated under saturated conditions, it was previously thought that ponded conditions were required for macropore flow. Water ponds episodically in playas (ephemeral lakes) in arid systems. Detailed studies of playas have been conducted in the Southern High Plains of Texas, and preferential flow is inferred from the multipeaked character of a ^3H profile beneath a playa [*Scanlon et al.*, 1997a; *Scanlon and Goldsmith*, 1997] (Figure 12). Although ponding greatly enhances the potential for flow along macropores, such flow occurs under natural rainfall and sprinkler conditions also. Because water flow in noncapillary size pores occurs only when saturation is approached, macropore flow has been found mostly in humid sites that have higher precipitation [*Gish and Shirmohammadi*, 1991] or in arid settings subjected to ponding.

Much of the evidence for macropore flow in arid settings has been restricted to fractured media, such as tension fractures beneath fissured sediments in the Chihuahuan Desert [*Scanlon*, 1992b], fractured tuff in Yucca Mountain [*Fabryka-Martin et al.*, 1993], and fractured chalk in the Negev Desert [*Nativ et al.*, 1995]. Many fracture studies are based on laboratory experiments [*Nicholl et al.*, 1994]. *Glass et al.* [1995] proposed a "thought" experiment that may explain how preferential flow along fractures could transmit water over long distances, as seen at the Nevada Test Site [*Russell et al.*, 1987] and Yucca Mountain [*Fabryka-Martin et al.*, 1993; *Liu et al.*, 1995]. According to their thought experiment, gravity-driven fingers in inclined fractures are expected to persist over time. These fingers originate from point connections with water sources either at the surface or at a depth where perched zones occur. Water flow in the fractures should be only negligibly affected by water moving from the fracture into the matrix because of (1) the reduced flow area within the fractures (due to fingering and air entrapment), (2) reduced matrix storage capacity (most fractured rocks at Yucca Mountain are at or near satiated water content, i.e., near saturated with some entrapped air, at depth while still at low matric potential), and (3) vertical capillary barriers provided by surrounding fractures within the network that reduce conduction of water from one matrix block to another. With depth, fingers are expected to focus into a smaller number of stronger flow paths at the contact of larger aperture fractures, a concept contrary to prevailing ideas that preferential flow dissipates at depth when water moves into the matrix.

The continuity of preferred pathways, critical in macropore flow, depends on pathway type. Rock fractures can extend to great depths, whereas desiccation cracks and root tubules are generally fairly shallow. Although macropores are generally thought to provide pathways for enhanced downward liquid flow, macropores also provide pathways for gas and vapor move-

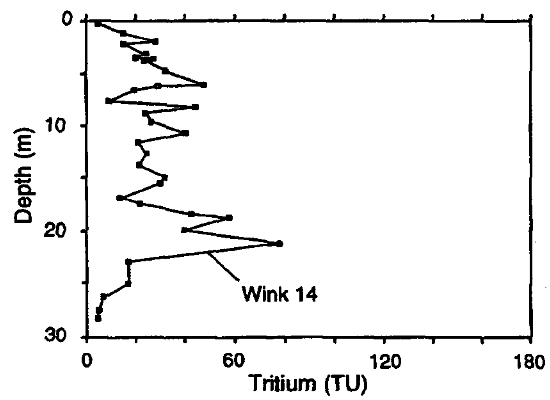

Figure 12. A deep multipeaked ^3H profile beneath a clay rich playa, indicating preferential flow (Wink 14 [*Scanlon et al.*, 1997a]).

ment and may enhance upward movement of volatile contaminants, as was suggested by *Weeks* [1993].

The type of contaminant helps determine the significance of preferential flow. Preferential flow is much more important for contaminants that exceed health standards in the parts-per-billion range, such as pesticides, than for contaminants that exceed health standards in the parts-per-million range, such as nitrate [*Steenhuis and Parlange*, 1991]. Nitrate contamination requires movement of the bulk of the pore water, which is much greater than the generally smaller water volume transported along preferred pathways. Arrival of the first 1% of the chemical at the groundwater is more readily accommodated by preferential flow than is the transport of the bulk of the mass.

Many of the studies evaluating preferential flow were either conducted in humid sites or performed on the basis of laboratory studies or theoretical analysis. Field evidence of preferential flow in arid settings has been found mostly in fractured rocks [*Fabryka-Martin et al.*, 1993; *Liu et al.*, 1995; *Nativ et al.*, 1995] and in fissured sediments [*Scanlon*, 1992b]. Bomb pulse tritium found at depths of ~12 m in an arid region in South Australia was attributed to preferential flow along the annular regions of eucalyptus roots [*Allison and Hughes*, 1983]. Few field studies show evidence of preferential flow at great depths in porous media in interfluvial arid settings, which may reflect (1) the absence of preferential flow in these settings, (2) the limited ability of various techniques to detect preferential flow in deep vadose zones, or (3) the difficulties of intercepting vertical preferred pathways by means of vertical boreholes.

6. CONTROLS ON WATER MOVEMENT

Water fluxes in arid regions have been shown to range widely both within and between various regions (Table 4). We can evaluate controls on unsaturated flow on the basis of comparisons of results from these studies. Primary controls such as pressure and temperature are discussed in the section on the direction of water movement. In this section we evaluate controls such as vegetation, climate, texture, and topographic setting.

6.1. Vegetation

Vegetation may be the most important control on water movement in desert soils. Uniformity in chloride profiles throughout the arid regions of the southwestern United States was attributed by *Phillips* [1994] to the ability of desert vegetation to control water fluxes regionally. Although annual precipitation and soil type varied widely among the sites examined by *Phillips* [1994], the chloride profiles were remarkably uniform. Because vegetation in arid regions is opportunistic, when the water application rate is increased, plant growth increases to use up the excess water. The opportunistic nature of desert vegetation is shown by higher concentrations of vegetation in areas of increased water flux, such as in ephemeral streams and in fissured sediments. When water supply is limited, plant activity decreases until water supply rates increase. Field studies have shown the importance of vegetation on local scales. Lysimeter studies in Hanford, Washington, and Las Cruces, New Mexico, showed deep drainage ranging from 10 to >50% of the annual precipitation in bare, sandy soils [*Gee et al.*, 1994]. The presence of plants at other sites at Hanford also greatly reduced deep drainage. Studies in Cyprus have found highest recharge rates in areas of sparse vegetation and lowest recharge rates in areas of bush vegetation [*Edmunds et al.*, 1988] (Table 4). Influence of vegetation is most clearly seen in areas where the vegetation cover has changed. In Australia, replacement of native mallee vegetation (deep-rooted eucalyptus trees) with crops resulted in an increase in recharge rates of at least an order of magnitude (from 0.1–0.9 mm yr^{-1} for native mallee regions to 4–28 mm yr^{-1} for pasture regions [*Cook et al.*, 1994]). Types of vegetation differ in how effectively they transpire water. In Hanford, Washington, water fluxes estimated in a grass site were much greater than water fluxes in nearby areas that had shrub vegetation [*Prych*, 1995]. Natural wildfires had resulted in replacement of shrubs with grass at this site. The effectiveness of vegetation in removing water from the subsurface was demonstrated in a lysimeter study at the Hanford site, where a lysimeter that had been bare for 3 years accumulated 150 mm of water in storage. The lysimeter subsequently became vegetated by deep-rooted plants (Russian thistle) that removed the excess water within a 3-month period to a depth of ~3 m [*Gee et al.*, 1994].

6.2. Climate and Paleoclimate

Although average annual precipitation is used to assess the potential for unsaturated flow, it is generally not a very good indicator of the rate of water movement. Data from various settings show little or no relationship between annual precipitation and water flux (Table 4). Seasonal distribution in precipitation is a better indicator of water flux in desert soils than is mean annual precipitation. Winter precipitation percolates through the soil more effectively than summer precipitation because evapotranspiration is low in the winter and the nature of precipitation varies seasonally. Winter precipitation in many parts of the world results from low-intensity, long-duration, frontal storms that are more likely to infiltrate in contrast to summer precipitation, which results from high-intensity, short-duration, convective storms. Snowmelt in the winter in some areas remains on the land surface longer, too, and infiltrates more readily.

As long-term mean annual precipitation rate decreases, variability in annual precipitation generally increases, and desert sites may experience many years of below-average precipitation followed by 1 or 2 years of normal or above-average precipitation. Because deep

TABLE 4. Water Fluxes in Various Arid Settings Throughout the World Estimated on the Basis of Different Measurement Techniques

Location	*Authors*	*Precipitation, mm yr⁻¹*	*Method*	*Water Flux, mm yr⁻¹*	*Topography/Texture/Vegetation*
S. Australia	*Allison et al.* [1985]	~300	chloride	>60	sinkholes
S. Australia	*Allison et al.* [1985]	~300	chloride	0.06–0.17	vegetated sand dunes
S. Australia	*Cook et al.* [1994]	260	chloride	0.1	sands, native vegetation
			chlorine 36	0.9	
S. Australia	*Cook et al.* [1994]	340	chloride	4–28	sand dunes, cleared vegetation
			chlorine 36	2–11	
			tritium	8–17	
Saudi Arabia	*Dincer et al.* [1974]	80	tritium	23	sand dunes
N. Senegal	*Aranyossy and Gaye* [1992]	395	tritium	22–26	sand dunes
Sudan	*Edmunds et al.* [1988]	225	chloride	0.25–1.28	interfluve sandy clay
Cyprus	*Edmunds et al.* [1988]	406	chloride	33–94	Fine-grained sands, sparse vegetation
			tritium	22–75	
			chloride	10	Fine-grained sands, bush vegetation
Israel	*Nativ et al.* [1995]	200	tritium	16–66	fractured chalk
			bromide	30–110	
Hueco Bolson, Texas, U.S.A.	*Scanlon* [1991]	280	chloride	0.01–0.7	ephemeral stream, silt loam
			chlorine 36	1.4	
			tritium	7	
Southern High Plains, Texas, U.S.A.	*Wood and Sanford* [1995]	460	tritium	77	playa, clay underlain by sand
New Mexico, U.S.A.	*Phillips et al.* [1988]	200	chloride	1.5–2.5	sandy loam to sand
			chlorine 36	2.5–3	
			tritium	6.4–9.5	
New Mexico, U.S.A.	*Stephens and Knowlton* [1986]	200	Darcy's law (unit gradient)	7–37	sand loam to sand
New Mexico, U.S.A.	*Stone* [1984]	385	chloride	0.8	cover sand
				4.4	sand hills
				≥12	playa clay
Las Cruces, New Mexico, U.S.A.	*Gee et al.* [1994]	230	lysimeter	87	loamy fine sand and silty clay loam, bare
Beatty, Nevada, U.S.A.	*Prudic* [1994]		chloride	2 (>10 m depth)	coarse texture, creosote bush
Nevada Test Site, U.S.A.	*Detty et al.* [1993]	125	liquid flux	0.03	Darcy's law depth 75–180 m
			vapor flux	0.02	
			net flux	~0	
Nevada Test Site, U.S.A.	*Tyler et al.* [1992]	125	tritium	600	subsidence crater, coarse sediment
Yucca Wash, Nevada, U.S.A.	*Norris et al.* [1987]	170	chlorine 36	1.8	ephemeral stream
Ward Valley, California, U.S.A.	*Prudic* [1994]	117	chloride	0.03–0.05 (>10 meter depth)	alluvial fan
Hanford, Washington, U.S.A.	*Prych* [1995]	160	chloride	0.01–0.3	shrub, sand
			chloride	0.4–2.0	grass, sand
			chlorine 36	5.1	grass, sand

percolation may occur only in the years of above-average rainfall, desert soils may be characterized by episodic flow. Although many researchers report water fluxes annually, for general purposes of comparing different techniques or for convenience, this method of reporting fluxes may be unrealistic. Long-term monitoring of physical parameters is required to evaluate episodic flow; however, such records are unavailable at most sites. Monitoring of water content in ~100 boreholes in Yucca Mountain from 1984 through 1993 showed that water content remained low during a 6-year drought but increased beginning in the winter of 1991 through 1993 as a result of increased precipitation [*Flint and Flint*, 1995]. Because monitoring of physical parameters represents only the monitoring period, evaluating how representative this time period is with respect to long-term climate is important for predictive purposes.

Distribution of environmental tracers has been used for evaluating water fluxes over a much longer timescale. Low chloride concentrations at depth in the southwestern United States (Figure 5) have been attributed to higher water fluxes during the Pleistocene, when the climate was cooler and wetter [*Scanlon*, 1991; *Phillips*, 1994; *Tyler et al.*, 1996]. Higher water (pressure) potentials at depth in these arid regions may be attributed to drainage of older, Pleistocene water [*Scanlon*, 1994; *Tyler et al.*, 1996]. Chloride and water potential data suggest that deep vadose zones in arid regions may reflect Pleistocene climate and that the shallower zone may have been drying since the Pleistocene. The deep vadose zone is therefore not in equilibrium with the current surface climate. Numerical simulations of long-term climate changes at Yucca Mountain suggest that the upper 75 m may have been undergoing long-term drying for the past 3000 years [*Flint et al.*, 1993]. The cyclic climate inputs are damped with depth, and simulations suggest steady state conditions at depths $\geq$250 m.

Another factor of importance with respect to climate change and waste disposal is that sites that are now arid may not always be arid. A NAS panel evaluated the impact of climate change on high-level radioactive waste disposal at Yucca Mountain [*NRC*, 1995]. The Earth is currently in an interglacial phase. Although the Earth will probably not return to a glacial climate in the next few hundred years, the possibility cannot be ruled out [*NRC*, 1995]. A return to glacial conditions is probable within a 10,000-year time frame, which is the time required for high-level radioactive waste to be isolated from the accessible environment in the United States. A cooler, wetter climate associated with glacial times would result in increased water fluxes through the unsaturated zone. The ~300-m-thick unsaturated section overlying the proposed high-level radioactive waste disposal repository at Yucca Mountain would result in a large time lag of the order of hundreds to thousands of years between surface climate change and water fluxes at the level of the repository [*NRC*, 1995]. Climate changes of the order of hundreds of years would therefore be damped out at the depth of the proposed repository.

Although the time period required for isolation of low-level radioactive waste (1000 years) is much shorter than that required for high-level radioactive waste, low-level radioactive waste is buried at shallow depths; therefore the effects of damping of climate changes would be less for shallow burial sites. Environmental tracers such as chloride provide some indication of potential increases in water fluxes associated with glacial climates. A review of chloride profiles at several sites in the southwestern United States suggests that water fluxes would increase by a factor of ~20 [*Phillips*, 1994]. The highest water fluxes estimated during glacial times at these sites were ~3 mm yr^{-1}, which is still low. Thus the effect of climate change on water flux should be considered in siting the disposal facilities.

6.3. Sediment Texture

Texture of surficial sediments can greatly affect water movement in the unsaturated zone. Fine-grained surface soils provide a large storage capacity and retain infiltrated water near the surface, where it is available for evapotranspiration. As was discussed earlier, macropore flow is much more common in highly structured, fine-grained sediments [*Flury et al.*, 1994; *Bronswijk et al.*, 1995]. Coarse-grained sediments allow water to penetrate more deeply into the soil, commonly below the zone from which it can be evapotranspired. For example, the estimated water flux was high in a sand dune area in Saudi Arabia according to tritium data (23 mm yr^{-1} [*Dincer et al.*, 1974]; see Figure 7b and Table 4), representing ~30% of the long-term mean annual precipitation (80 mm yr^{-1}). *Cook et al.* [1992] noted an apparent negative correlation between clay content in the upper 2 m and the recharge rate. The concept of fine-grained surficial sediments providing large storage capacities is also employed in engineered barrier design. At the Hanford site, the texture and thickness of the sediment in an engineered barrier were chosen to provide storage capacity sufficient for 3 times the long-term mean annual precipitation [*Wing and Gee*, 1994]. Thickness of surficial unconsolidated sediments on top of fractured rock is also an important control on water fluxes. At Yucca Mountain, water penetration and environmental tracer distribution indicated minimal water fluxes in areas of thick alluvial cover over fractured tuff [*Fabryka-Martin et al.*, 1993]. Similarly, the thickness of loess on fractured chalk in the Negev Desert greatly reduced water fluxes through the chalk [*Nativ et al.*, 1995].

Heterogeneity and layering of sediments are also important in controlling water movement. Textural heterogeneity occurs at a variety of scales; small-scale, local heterogeneity may not be very important in extremely dry sediments, typical of interfluvial settings in arid regions, because most water is adsorbed to grain surfaces, and much of the water flux may occur in the vapor phase. In areas of ponded surface water, however, small-scale variations in sediment texture may have a greater effect on flow.

Layering of sediments reduces water fluxes. Where fine-grained sediments overlie coarse-grained sediments, a capillary barrier is formed, and water will not flow into the coarse layer until the overlying fine layer is close to saturation. Where interfaces between the different layers are sloped, lateral flow can occur. Capillary barriers occur in the natural system at a variety of scales. Studies by *Kung* [1990a, b] indicate that sloping layers can result in unstable flow at the downstream end when sufficient water accumulates in the fine-grained material to flow into the underlying coarse material [*Steenhuis et al.*, 1991]. One of the conceptual models developed for Yucca Mountain suggests that the layered nonwelded tuff units may act as capillary barriers beneath the welded fractured units [*Montazer and Wilson*, 1984]. The capillary barrier concept is also used in engineered-barrier design to maximize evapotranspiration, minimize deep percolation, and (where such layers are sloped) allow lateral drainage [*Wing and Gee*, 1994].

Where fine-grained layers underlie coarser layers, perched water conditions can occur. Numerical simulations indicate that for perching to occur, downward water flux should exceed saturated hydraulic conductivity of the perching layer by an order of magnitude [*Schneider and Luthin*, 1978]. Perched water has been found in the vadose zone at Yucca Mountain [*Burger and Scofield*, 1994] and beneath ephemeral lakes (playas) in the Southern High Plains [*Mullican et al.*, 1994].

6.4. Topography

Topographic setting may also play an important role in controlling unsaturated flow. Measurement of physical parameters and environmental tracer distributions in various topographic settings at Yucca Mountain showed that water fluxes were highest in active channels where surface runoff occurs [*Flint and Flint*, 1995]. In South Australia, because sinkholes focus surface water, much higher water fluxes were found beneath sinkholes ($\geq$60 mm yr^{-1}) than in surrounding vegetated topographic settings (0.06–0.17 mm yr^{-1} [*Allison et al.*, 1985]; see Table 4). Ephemeral lakes or playas in the Southern High Plains of Texas and New Mexico also focus recharge, and estimated water fluxes range from $\geq$12 mm yr^{-1} [*Stone*, 1990] to 77 mm yr^{-1} [*Wood and Sanford*, 1995]. Fissured sediments in the Chihuahuan Desert of Texas concentrate surface runoff, and water fluxes are much higher beneath these fissures than in surrounding areas [*Scanlon*, 1992b]. Nuclear subsidence craters at the Nevada Test Site are also characterized by high water fluxes ($\sim$600 mm yr^{-1}) as evidenced by high tritium concentrations and high water (pressure) potentials relative to profiles 207 m from the crater center [*Tyler et al.*, 1992].

These studies suggest that local zones of high water flux, typical of arid settings, are generally found in topographic depressions where surface water collects, such as washes, playas, excavations, and sinkholes. Whereas the total surface area occupied by these features may be extremely small (e.g., 2% in the case of active channels in Yucca Mountain [*Flint and Flint*, 1995]) high flows beneath these features may be critical for transporting contaminants rapidly. Use of areally averaged recharge rates to predict contaminant transport would greatly underestimate the transport rates in these areas.

Paleotopography may also have affected the response of different sites to wetter climatic conditions during previous glacial periods. Low chloride concentrations deeper than 10 m at a site in the Amargosa Desert, Nevada, are attributed to increased precipitation and more frequent flooding of the Amargosa River at this site [*Prudic*, 1994]. Studies at the Nevada Test Site show much higher water fluxes in an area where surface runoff concentrated from the surrounding mountains during previous glacial maxima [*Tyler et al.*, 1996].

7. NUMERICAL MODELING

The complexity of flow in the shallow unsaturated zone of desert systems requires the use of numerical models to evaluate flow processes and to analyze interactions and feedback mechanisms between various controlling parameters. A variety of codes are available to simulate flow and transport. Simulation of flow in very dry unsaturated systems can be computationally difficult, however. Conservation of mass was a problem with traditional head-based codes, but it has been overcome with the mixed formulation of Richards' equation, which uses water content in the time derivative and head in the space derivative [*Celia et al.*, 1990]. Large execution times were also a problem that has been reduced by transformations of Richards' equation [*Kirkland et al.*, 1992; *Pan and Wierenga*, 1995]. Representation of water retention functions is also important for dry systems. Traditionally, residual water content was treated as a fitting parameter in water retention functions; however, resultant water contents were commonly greater than initial water contents in simulations in arid settings [*Hills and Wierenga*, 1994]. More realistic water retention functions have been developed recently that incorporate the full range of water content from saturation to air-dry conditions [*Milly and Eagleson*, 1982; *Rossi and Nimmo*, 1994; *Fayer and Simmons*, 1995].

The performance of various codes in simulating field-tracer experiments conducted in Las Cruces, New Mexico, was evaluated as part of the International Cooperative Project on Validation of Geosphere Transport Models (INTRAVAL), which represented an international study of validation of models for flow and transport. An extensive database characterized the hydraulic properties at this site and included $\sim$600 measurements of bulk density, saturated hydraulic conductivity, and water retention. Two-dimensional models that assumed a heterogeneous porous medium performed no better than one-dimensional models that assumed a homogeneous porous medium [*Hills and Wierenga*, 1994]. The experiments at Las Cruces were conducted on bare soil and excluded evaporation. Detailed simulations of flow in a natural system require nonisothermal liquid and vapor flow, atmospheric forcing, and water uptake by roots. Very few codes incorporate all these features. Because simulation of preferential flow is extremely complicated, new codes need to be developed to address this issue. A code developed by *Nieber* [1996] successfully simulates unstable flow. Several investigators are simulating flow in fractured rock on the basis of data from the Yucca Mountain site, and some of these studies attempt to reproduce the tracer data that suggest preferential flow [*Wolfsberg and Turin*, 1996].

Previous studies that included numerical simulations provide valuable insights into unsaturated-flow processes. Simulations of flow in a bare soil show net downward thermal vapor flux in response to seasonal temperature gradients in the shallow subsurface [*Scanlon and Milly*, 1994]. Results of flow simulations of engineered barriers agree with field data from lysimeters at the Hanford site, Washington [*Fayer et al.*, 1992]. This study shows that hysteresis is important in simulating break-through of capillary barriers. Numerical modeling of flow at Yucca Mountain evaluated the effect of long-term climatic change on net infiltration and showed that amplitude and frequency of climate change are important factors [*Flint et al.*, 1993]. Below 250 m, climatic changes having a frequency ≤50,000 yr were damped out.

Evaluation of potential sites for disposal of waste, such as low- and high-level radioactive waste, requires performance assessment to develop a quantitative understanding of system behavior. For high-level nuclear waste disposal in the United States, performance assessment is required for time periods of 10,000 years or more. Although performance assessment of many sites includes rigorous parameter uncertainty analysis, the main source of uncertainty generally results from conceptual model uncertainty. Performance assessment has used spatially and temporally invariant upper boundary conditions, even though the long time and space scales considered in performance assessment require the use of spatially and temporally varying upper boundary conditions that relate to topography and climate. If one is trying to predict future behavior of a 10,000-year time period, future climatic changes should be incorporated into the performance assessment. Whereas the U.S. Nuclear Regulatory Commission is promoting a probabilistic approach to performance assessment, a recent NAS panel on Yucca Mountain suggested that if compliance is met in bounding estimates that are based on upper or lower limits of parameters that result from conservative assumptions, more complex analysis is not needed [*NRC*, 1995]. This does not preclude performance monitoring to evaluate whether simplistic models of flow and transport are valid.

8. IMPLICATIONS FOR CONTAMINANT TRANSPORT RELATED TO WASTE DISPOSAL

The natural characteristics of a site are important for long-term (≥ decades) disposal of waste because the natural system is ultimately relied on to minimize waste migration. The attributes of the natural system are difficult to characterize, however, because of the low water fluxes and limitations of monitoring instruments, as discussed earlier. To overcome some of these problems, multiple independent lines of data are required to increase confidence in results. Despite the difficulties in characterization, a larger margin of error can be tolerated in arid settings than in humid settings because of the naturally low water fluxes in porous media in interfluvial arid settings in porous systems. Important attributes of the natural system include direction and rate of water movement and the spatial and temporal variability in water fluxes. The type of medium (porous or fractured) is very important because of the higher potential for preferential flow in fractured systems. The vegetative cover is also important because it removes much of the infiltrated water from the subsurface.

Engineered designs and disposal practices are critical for developing a reliable disposal system. Although much information exists on site characteristics, our knowledge of the performance of engineered systems is generally limited. Ideally, an engineered system should mimic the natural system as much as possible, and the performance of various design elements of engineered systems should be rigorously tested in arid regions. Detailed studies of a capillary barrier system are being conducted at Hanford, Washington [*Wing and Gee*, 1994]. Trench-cap demonstration units will also be constructed at Ward Valley, California, to evaluate the performance of these systems [*NRC*, 1995]. Past disposal practices have often greatly enhanced the likelihood of contamination at various sites. Disposal of liquid wastes at the Beatty site (~2000 m^3 between 1962 and 1975), for example, may have resulted in the large tritium concentrations found near that disposal site [*Striegl et al.*, 1996]. Future disposal practices of low-level radioactive waste will therefore be restricted to solid wastes. Restriction of waste to a solid form does not necessarily preclude contamination because water percolating through the unsaturated zone could dissolve the waste. Critical components of near-surface engineered systems include the vegetative cover to remove water by evapotranspiration, the storage capacity of surficial sediments to hold water in the shallow zone, where it can be readily evapotranspired, and biointrusion barriers to limit human, animal, and plant intrusion into the waste. Capillary barriers not only increase the storage capacity of surficial sediments but also serve to limit biointrusion.

Monitoring of these engineered systems will be important to ensure that they perform as designed and to provide data for performance assessment. Although monitoring of low-level radioactive waste disposal facilities is required for at least 30 years, the life span of many of the monitoring instruments, such as the thermocouple psychrometer, is much shorter than 30 years. Many systems are currently available for monitoring disposal facilities, such as the Science and Engineering Associates for the Membrane Instrumentation and Sampling Technique (SEAMIST) system, which consists of an impermeable membrane that is turned inside out (everted) under pressure and that can be used to pull various logging tools through tunnels below the waste or in the cover system [*Keller*, 1991]. This system has the advantage of being readily able to incorporate newly developed technologies.

9. IMPORTANT AREAS OF FUTURE RESEARCH

Our review suggests that although within the last couple of decades considerable progress has been made in our understanding of unsaturated-flow processes in arid regions, areas exist where future research should be directed. With respect to techniques that can be used to quantify unsaturated flow, additional research should be done to evaluate the effects of instrument installation on the monitoring data. Such research could include numerical simulations or laboratory or controlled field experiments to address this issue. Most techniques used to monitor the energy status of pore water are not very robust and have a limited life span. Because regulations for waste disposal, including low-level and high-level radioactive waste disposal, require monitoring for decades, efforts should be made to develop robust instrumentation that can be used for monitoring energy potentials over long time periods. Use of time domain reflectometry in arid regions is not very widespread now, but TDR is a promising tool for detailed monitoring near the land surface atmosphere boundary, and it will most likely provide valuable information on this critical boundary as well as integrate easily with remote-sensing studies. Because unsaturated hydraulic conductivity is the most uncertain parameter, considerable effort should be directed toward developing better techniques of quantifying or estimating this parameter. The applicability of traditional methods of estimating unsaturated hydraulic conductivity from capillary bundle models should be critically evaluated for arid systems where film flow may be dominant. Although noninvasive monitoring techniques have only recently been used in vadose zone studies, they should be the focus of future studies to quantify relationships between geophysical response and water fluxes in various settings.

Establishing the direction of water movement in arid settings is extremely difficult because of the complex interaction of forces. Because it has been 40 years since *Philip and de Vries* [1957] established the theoretical framework for liquid and vapor flow, it should be revisited in light of all the work that has been conducted since then. The importance of preferential flow in arid regions should be critically examined as well. Although field studies in a number of regions demonstrate preferential flow in fractured media, field studies of preferential flow in porous media in deep vadose zones in arid settings are extremely limited. The idea that macropore flow in shallow, unsaturated, porous media can be extrapolated to great depths in arid regions has not been shown in the field, nor has it been thoroughly studied. Likewise, indiscriminate extrapolation of results of preferential flow studies that have been conducted in humid regions that have shallow water tables should be avoided. The extent to which preferential flow persists or dissipates with depth is important in thick, unsaturated, layered systems. Techniques used to evaluate unsaturated flow should therefore be critically examined to ensure that the presence or absence of preferential flow is not simply an artifact of the measurement process. Preferential flow is an issue critical in the siting of waste disposal facilities in arid regions and in the evaluation of contaminant transport and remediation.

Vegetation may be the dominant control on water fluxes in arid settings, however, and various aspects of this issue should be examined from laboratory, field, and numerical modeling perspectives. The effect of climate and paleoclimate on water fluxes should also be intensively studied to help predict unsaturated flow thousands of years into the future, as required by the high-level radioactive waste disposal program at Yucca Mountain.

10. CONCLUSIONS

Much of the work in unsaturated-zone hydrology has been conducted in humid regions; however, fundamental differences between humid and arid regions restrict the applicability of results from humid sites to arid sites. In addition, a wider variety of techniques are required to quantify unsaturated flow in the much drier unsaturated systems in arid regions.

Many arid area studies suggest that using environmental tracers to quantify unsaturated flow is more appropriate than physical approaches because hydraulic conductivity can vary over orders of magnitude. Both approaches should be used, however, because physical data provide information on current processes, whereas environmental tracers provide information on longer term, net water fluxes. A variety of environmental tracers should also be used because some are restricted to liquid phase flow, whereas others are found in liquid and vapor phases. Noninvasive techniques, such as electromagnetic induction, should be further investigated, particularly for evaluation of contaminated sites. Multiple independent lines of data are required to increase confidence in conceptual models of flow and transport in arid regions.

Low water fluxes and inaccuracies in techniques for quantifying such fluxes make it difficult to resolve basic issues such as direction and rate of water movement. The direction of water movement is difficult to evaluate in many arid sites because unsaturated systems are commonly extremely dry and because water flows in liquid and vapor phases in response to water potential, gravitational potential, pneumatic potential, and temperature gradients that are temporally and spatially variable. Temporal variability in water flow occurs at a variety of scales, including diurnal, seasonal, decadal, and millennial intervals, all of which are commonly controlled by climate. Short-term climatic fluctuations are preserved in the shallow subsurface, whereas longer-term paleoclimatic fluctuations are preserved over the thick unsaturated sections found in many arid settings. At many sites, water fluxes were much higher during previous glacial periods.

Vegetation may be the most important control on unsaturated water movement, as is shown by high rates of water movement in areas of coarse, bare soil and by negligible water movement in vegetated areas. Surface topography also plays an important role in controlling water movement by focusing unsaturated flow in topographic depressions that pond frequently. Increasing the thickness of unconsolidated sediments on fractured media in arid regions greatly decreases unsaturated water fluxes, as is shown by studies at Yucca Mountain, Nevada, and the Negev Desert, Israel.

Field evidence of preferential flow in arid regions has generally been restricted to fractured media, as evidenced by deep penetration of bomb pulse tracers in fractured tuff at Yucca Mountain and in fractured chalk in the Negev Desert. Although many studies suggest predominantly piston-like flow in porous media in interfluvial arid settings, some of the techniques used may not be sensitive to small percentages of preferential flow. Recent studies suggest that unstable flow, which is driven by gravity, should be negligible in porous media in many arid regions because of the dominance of capillary and adsorptive forces over gravity forces in these areas. Evaluation of preferential flow is much more difficult in arid regions than in humid regions because the thickness of the unsaturated section is greater and short-term applied tracer experiments cannot be used in the thick vadose zones typical of many arid regions.

Because of (1) many uncertainties in determining water fluxes in arid areas, (2) extensive spatial and temporal variability in properties, (3) vegetation, and (4) precipitation, generalized conclusions about recharge rates at a specific site are difficult to make. Detailed investigations are required to determine the nature, magnitude, and direction of water fluxes at specific locations.

GLOSSARY

Advection: movement of solute with the flowing fluid; movement of gas in response to total pressure gradient.

Capillary barrier: layer of fine sediment underlain by layer of coarse sediment that restricts downward movement of water because of the difference in the size of the capillaries. Water enters the underlying coarse layer when the matric potential in the fine layer increases sufficiently to overcome the water entry potential of the coarse layer.

Diffuse flow: movement of water into the unsaturated zone over large areas, as opposed to focused or concentrated flow.

Diffusion: movement of a substance, such as solute or vapor, along a concentration gradient.

Electromagnetic induction: technique to measure apparent electrical conductivity by electromagnetically inducing currents in the ground. Under low values of induction number, the secondary magnetic field is a linear function of conductivity.

Funneled flow: form of preferential flow that occurs when textural interfaces cause lateral water flow and accumulation of water in low regions.

Gravitational potential: change in energy per unit volume of water associated with change in the position of a body in the Earth's gravitational field. The reference state is generally defined as the land surface or the water table. Gravitational potential energy decreases with depth.

Heat dissipation probe: device used to measure matric potential in the unsaturated zone on the basis of variation in the rate of dissipation of a thermal pulse with water content. The probe is calibrated at different matric potentials.

Hydraulic conductivity: ability of material to conduct water; proportionality constant between water flux and hydraulic head gradient in Darcy's law.

Hydraulic head: sum of matric and gravitational potential heads.

Infiltration: rate of water movement from the surface to the subsurface.

Lysimeter: device for measuring water loss from soil and plants into the atmosphere. There are nonweighable and weighable lysimeters. Nonweighable lysimeters measure water storage changes indirectly (i.e., with a neutron probe and from inflow-outflow analysis), whereas weighable lysimeters measure storage changes gravimetrically.

Macropore flow: form of preferential flow in which water flows along noncapillary-size openings such as fractures, cracks, and root tubules.

Matric potential: change in energy per unit volume of water that results from the attraction of water to the solid matrix material.

Neutron probe: instrument used to monitor water content in the unsaturated zone.

Percolation or drainage: penetration of water below the shallow subsurface, where most evapotranspiration occurs.

Performance assessment: evaluation of future performance of a system on the basis of a quantitative understanding of system processes. Performance assessment generally includes long-term numerical simulations of system performance that incorporate uncertainties in conceptual models and in system parameters.

Piston-like flow: uniform downward movement of water through the unsaturated zone that displaces existing water without bypassing it.

Pneumatic potential: energy per unit volume of water resulting from changes in air pressure.

Potential energy: energy resulting from position of a body in a force field, such as gravitational, capillary, and osmotic force fields. Differences in potential energy can be used to determine the direction of water movement under isothermal conditions because water flows from regions of high to regions of low total potential energy. Potential energy is generally expressed as energy per unit volume (joules per cubic meter, equivalent to pressure units of newtons per square meter or pascals).

Preferential flow: nonuniform downward water movement along preferred pathways that bypasses much of the matrix and includes funnel flow, unstable flow, and macropore flow.

Recharge: addition of water to the aquifer.

Solute potential: equivalent to osmotic potential, change in energy per unit volume of water associated with the addition of solutes to pure, free water.

Suction lysimeter: device used to extract pore water from unsaturated media for chemical analysis.

Thermocouple psychrometer: device that measures relative humidity of water vapor in the sediment or rock sample, which is related to water potential ψ (energy per unit volume) through the Kelvin equation (equation (3)).

Time domain reflectometry: technique used to measure water content in unsaturated material on the basis of variation in the dielectric constant of the material with water content.

Unsaturated zone: zone in which pore spaces contain both water and air.

Unstable flow or fingering: form of preferential flow used to describe downward water movement in columns that may result from sediment layering, air entrapment, or water repellency.

Vadose zone: zone between land surface and regional water table.

Water activity: thermodynamic activity of water; relative humidity.

Water activity meter: device that measures water activity (relative humidity) of water vapor in sediment or rock samples and which is related to water potential through the Kelvin equation (equation (3)).

Water content: amount of water in unsaturated media; can be expressed gravimetrically (mass of water per mass of dry unsaturated material) or volumetrically (volume of water per volume of unsaturated material).

Water flux: volume of water flowing per unit cross sectional area per unit of time.

Water potential: pressure potential, sum of matric and osmotic potentials, can be measured by thermocouple psychrometers or water activity meter.

Water retention function: relationship between matric potential and water content.

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Reservoir, Lagoon and Wasterwater Pits: Liner and Installations

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Many types of materials can be used in the lining of these large applications,
with the most commonly used materials being:

Hypalon, PVC's, XR-5, XR-3, HDPE, LLDPE, MDPE,
Clay Liners, and Polypropylene.

Hypalon
(Chlorosulfonated Polyethylene)
An extremely durable flexible pond liner/cover material. Hypalon liners are made from a special polymer that is compounded, fabricated and installed in a thermoplastic state. Field installations and accelerated aging tests by Burke Environmental Products, have demonstrated that under most conditions Hypalon liners and covers have an extremely long service life. Hypalon synthetic rubber will resist the elements better than any known material and is exceptionally resistant to oxidation and virtually immune to ozone and ultraviolet light. This material is proved to be suitable for the containment of a large variety of industrial wastes. Hypalon can also be compounded in white and attractive light colors without sacrificing its desirable properties.

Factory seam fabrication, under controlled conditions, is done by a precise combination of heat and pressure. Field seaming uses a bodied solvent adhesive following a pre-wash to give equally reliable results under the varying weather conditions encountered during installation. After installation, a surface cross-linking develops which produces a stronger, tougher and more weather resistant liner.

PVC's
(Polyvinyl Chloride)
Liners are fabricated for plating, agriculture, potable water storage, foodstuffs, crude oil & fuels, hazardous materials, mining applications, acids, earthen pits, large or small ponds, berms and sumps, with expert installation services available for storage tanks, lagoons, floor linings, sewage facilities, etc., fabricating PVC's, Hypalon , XR-3, XR-5, Urethanes and other specialized fabrics. Materials range in thickness from 20 mil to 3/16 thick and hold solutions up to 200 F.

Most PVC geomembranes are either black or shades of gray. Carbon black and titanium dioxide are used to make these colors, with carbon black being an excellent UV protector, absorbing most of the UV radiation that strikes the geomembranes, converting it to heat. Titanium dioxide reflects almost all UV radiation, so together they offer excellent UV protection. Geomembranes can be exposed for years with minimal UV degradation.

Miscellaneous raw materials that are used in geomembranes are not necessarily in every formula. These would include biocides, UV additives, process aids and impact modifiers. Biocides are added to resist any biological attack that the geomembranes may experience in the field and to meet soil burial requirements for NSF standard 54. UV additives are added to PVC geomembranes specifically designed for outdoor exposure. Impact modifiers may be added to improve low temperature resistance, for low temperature applications.

HDPE
(High Density Polyethylene)
HDPE is manufactured from microbiological resistant polyethylene resins and offers optimum chemical resistance, with weathering capabilities and stress absorption properties. HDPE offers the best dimensional stability and resistance to stress cracking, with excellent weld strength.

Field Lining Systems, Inc., has installed millions of square feet of HDPE in all types of applications and you can be assured that Field Lining Systems has the experience, knowledge and full capabilities to handle the most complex and difficult lining assignments, with HDPE being just one of Field Lining Systems specialties.
GCL's
(Geocomposite Clay Linings)

Geosynthetic Clay Liners (GCLs) are high performance needle punched environmental reinforced composites which combine two durable geotextile outer layers with a uniform core of natural sodium bentonite clay to form a hydraulic barrier. Fibers from the non-woven geotextile are needle punched through the layer of bentonite and incorporated into the other geotextile (either a woven or non-woven). This process results in a strong mechanical bond between the fabrics.

LLDPE, MDPE
(Linear Low Density Polyethylene & Medium Density Polyethylene)
Low Density Polyethylene

This is a semi rigid material used for ponds, lagoons, canal liners, fire ponds, mine trailing ponds, waste water ponds, leachate collection ponds, brine ponds, cargo covers, interim landfill caps. Excellent protection from UV rays and harsh weather conditions. No plasticizers added. High elongation with tremendous tear resistance and bursting strength. Minimum carbon black content of 2.5%. Virgin resins. This is a fish safe material.

Medium Density Polyethylene

This is a light weight film mono-layer membrane material consisting of a blended medium density polyethylene. Minimum carbon black content of 2.5% provides excellent protection from UV rays and harsh weather conditions. Puncture and tear strengths far exceed common polyethylene or vinyl films. This product is used mostly for ponds, including lagoons, canal liners, fire ponds, remediation liners, cargo covers, oil field pit liners, silage covers, outdoor covers, brine ponds, mine trailing ponds, interim landfill caps, leachate collection ponds. This is not a fish safe material.

POLYPROPYLENE

Polypro is a more flexible than the LLDPE, but not as flexible as the PVC. This can be used for large and semi large applications. Our Polypropylene contains no plasticizers that can leach out and hinder long term flexibility and performance. Outstanding resistance to environmental stress cracking even at elevated temperatures and in addition to aggressive chemical environments.

This is a good material for ponds, lagoons, canal liners, fire ponds, remediation liners, brine ponds, mine trailing ponds, landfill caps, fish hatcheries, evaporation ponds, golf course water traps and waste ponds. This product is fish safe.
XR-5 & XR-3 By Seaman Corporation
X-R5 is not a scrim supported flexible liner. It is instead, an extremely tough woven composite fabric of DuPont Dacron polyester fibers that have been molecularly coated with sophisticated compounds that are minimally degradable in adverse environments. Combined liner and coating offer a unique balance of performance features and durability.
Liner type is used in primary and secondary containment applications and is excellent for wastewater, brine, saltwater, oily wastes, manure, jet fuel, diesel, motor oil, kerosene, acids, cyanide, pulp waste, landfills, brewery waste, vapor odor barrier, sewage, sludge ponds, floating baffles, leachate ponds, substation containment, mining facilities, potable water.
X-R3 geomembrane is specifically designed for high-performance containment and storage of waste water and storm water, as well as bioremediation covers and mining applications. XR-3 has superior resistance to UV radiation and harsh weather. Holds up to long term exposure without the need to be covered. This material also has high resistance to common contaminants present in waste water. Comes in large pre-fabricated panels to help simplify installation and field seaming. XR-3 comes in reinforced and non-reinforced, with the non-reinforced stretching up to 250% without breaking.

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Importance and Use of Plants in Evaluating Water Flow and Contaminant Transport in Arid Environments

by B.J. Andraski, M.W. Sandstrom, R.L. Michel, J.C. Radyk, D.A. Stonestrom, M.J. Johnson, and C.J. Mayers

Based on a poster presented at the American Geophysical Union's Fall 2002 Meeting, December 6-10, 2002

ABSTRACT (Published Abstract)

Improved understanding of soil-plant-atmosphere interactions is critical to water-resource and waste management decisions. Multiple-year field studies of soil-water movement at the Amargosa Desert Research Site (ADRS) identified plants as the primary control on the near-surface water balance. The boundary conditions imposed by plant activity in the uppermost soil layer also result in episodic, deep drying below the root zone during periods of below-average precipitation. The findings help to explain evidence for negligible recharge and upward flow that has been inferred from environmental-tracer and soil-physics-based studies of deep unsaturated zones at undisturbed, arid sites.

Studies at the ADRS also are using plants to investigate tritium transport away from a low-level radioactive waste disposal area. Soil-gas sampling results indicated that tritium has moved as much as 300 m from the disposal area, and that transport primarily occurs in the gas phase with preferential transport through coarse-textured sediment layers. The need for an efficient means of gathering plume-scale data led to the development of a method that uses plant water to identify tritium contamination. Tritium concentrations in plant water determined with the new method did not differ significantly from those determined with the standard (and more laborious) toluene-extraction method or from concentrations in root-zone soil-water vapor. The new method provides a simple and cost-effective way to identify plant and soil contamination. Although work to date has focused on one desert plant, the approach may be transferable to other species and environments.

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CERTIFICATE OF COMPLIANCE

SUBJECT: Dura-Skrim 6BB & 8BBR

DESCRIPTION: Dura-Skrim 6BB & 8BBR consists of two sheets of high strength LLDPE (Linear Low Density Polyethylene) film laminated together with a third layer of molten polyethylene. A heavy scrim reinforcement placed between these plies greatly enhances tear resistance and increases service life.

DATE: 3/30/2004

It is here by certified that Dura-Skrim 6BB and 8BBR have been successfully used as an Oilfield Temporary Reserve Pit Liners for over 8 years. When Dura-Skrim products are used in a buried application, there are no natural degradation processes that will shorten the life of the product.

Gary M Kolbasuk

Gary Kolbasuk
New Product Development Manager
Engineered Films Division

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