Photographs on cover:

Upper left: View upstream from the outflow end of a furrow irrigated field in southern Idaho. The furrow stream on the right was treated with 10 mg/L anionic polyacrylamide (PAM) during stream advance and the furrow on the left was untreated--PAM nearly eliminated runoff sediment losses in treated furrows compared to controls. Photographer: Rick Lentz

Upper right: PAM/sediment layer on top of the soil at completion of the column experiments of measuring saturated hydraulic conductivity. The layer has been disturbed to show contrast between the PAM/sediment layer and the darker sand beneath. Picture courtesy of Ernesto Moran

Bottom left: Research conducted by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) National Soil Erosion Research Laboratory in West Lafayette, Indiana, on a 3:1 slope embankment showed significant erosion control benefits of using PAM (P) and PAM plus gypsum (PG) as compared to the untreated control (C), after 7 inches of simulated rainfall. PAM rate used here was 72 lbs/Acre and gypsum rate was 2.6 tons/Acre. Photo credit: Kiran Chaudhari and Dennis Flanagan

Bottom right: Addition of granular PAM to the Rocky Ford Highline Canal, CO. Picture courtesy of Delbert Smith

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Polyacrylamide (PAM) is a broad family of polymers that have historically been used in industries such as food packaging, paper manufacturing, and wastewater treatment. It has only been over the last 10 to 15 years that PAM has seen increasing uses in environmental applications. In agriculture, PAM has been used to reduce irrigation-induced erosion and to enhance infiltration by stabilizing furrow soils. The water quality of agricultural runoff has also been noted to improve as flocculation induced by the addition of PAM can reduce nutrient and sediment concentrations. More recently, PAM has been used to control erosion at construction sites, accelerate sediment and nutrient deposition in urban runoff detention basins, and reduce seepage from unlined water delivery canals. The use of PAM in canals not only promotes water conservation, but can provide canal managers with a greater flexibility in the timing and magnitude of their water delivery to end-users. Seepage reduction has the potential to improve crop yields and to reduce the load of salt returned to rivers in areas either susceptible to shallow groundwater tables or comprised of easily leachable marine shale, respectively.

For these environmental uses, a subset of anionic PAM was selected over other polymers and alternatives because it was easy to use, had a low risk of toxicological impacts, and was effective when used in low concentrations. Specifically, the subset of PAM chosen was a food-grade anionic PAM containing less than 0.05 percent of the residual acrylamide monomer (AMD). The AMD monomer is a cumulative neurotoxin and a suspected human carcinogen and the incidental release of residual AMD, even at these low concentrations, presents potential risks. However, research has shown that AMD is quickly bio-degraded and that the exposure to AMD during current environmental applications is several orders of magnitude lower than exposure levels required to cause neurotoxic or carcinogenic effects in humans. Despite the low likelihood of risk associated with the incidental release of AMD, there is still a perceived risk by some, whether justified or not, in the release of PAM into the environment.

Although they share use of the same polymer, the risks and benefits of PAM use manifest themselves differently depending on if PAM is used as a soil amendment, to reduce irrigation-induced erosion, or as a canal sealant. For example, the inherent transport associated with PAM application to water delivery canals entails a potentially greater risk to downstream water-users compared to the other uses where the transport of PAM out of the treatment zone can be more tightly controlled. The concept of this workshop was to bring together these diverse users to discuss the current state of PAM for each type of use, issues surrounding incidental AMD release, the status of potential PAM alternatives, and to delineate future research, regulatory, and training needs. The PAM and PAM Alternatives Workshop was held in Albany, California, on February 26-27, 2008, and attempted to:

I. Define current uses, benefits, and issues associated with using PAM to reduce seepage in water delivery canals, and improve on-farm soil and water efficiency for irrigated agriculture.

II. Define the needs for alternative products that can effectively achieve these benefits, and be considered environmentally “green,” and without human health risks.

III. Define a research and development plan designed to meet these needs that utilizes collaborative participation from federal agencies, the agricultural community, industry, and state and local interests.
The workshop involved approximately 50 participants, including federal and state government agency staff, researchers, water managers and users, and PAM industry representatives. To frame the discussion of this diverse group, presenters and panelists were asked to consider several questions prior to the workshop, including: 1) their perspective on the challenges in managing water delivery and/or soil conservation in irrigated agriculture; 2) their desired use for PAM or PAM alternatives; 3) their perspective on the benefits and risks associated with using PAM for soil and water conservation purposes; 4) desirable characteristics that an alternative to PAM should have for water and soil conservation purposes; 5) additional knowledge needed to develop and implement a PAM alternative with these characteristics; and 6) type of state and federal regulatory support toward the development and implementation of PAM alternatives for these uses.

Although addressed by speakers from a number of perspectives, several common issues were apparent through the talks and audience discussion. These were more fully elucidated during the final group discussion (Session Nine) and are summarized as follows:

1. **Research Needs:** Although much research has been conducted, additional studies are needed to address the perceived risks in the current use of PAM as well as more basic research to find alternatives that are as effective as PAM when used at similar, low concentrations. There needs to be a clear, integrated direction on how to coordinate these studies between participating federal and state agencies, universities, and researchers. The favored approach would be to develop a formal structure and/or consortium of key agencies and key partners that can coordinate research across the different uses (on-farm, canal, soil amendment) and arrive at a common ground on both benefits and risks of PAM and/or PAM alternatives.

2. **Regulation, Certification, and Training:** The current regulatory process regarding the environmental use of PAM needs to be clarified, as the current options are not well understood. Current National Science Foundation (NSF) International guidelines only certify food-grade PAM products resulting in the need for another regulatory group or agency to certify applicators and application methods. There is also a need for well-trained government agency personnel who can instruct end-users on the proper protocols and techniques that maximize benefits and reduce potential risks associated with PAM usage.

3. **Education/Publication:** The current knowledge regarding PAM use needs to be disseminated to interested agencies and stakeholders, including technology transfer to companies.

4. **Application Technology:** Current guidelines to apply PAM safely and effectively need to be continually refined as new application devices, forms of PAM, and/or PAM alternatives are used.

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On behalf of the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS), Pacific West Area, I welcome you to the **PAM and PAM Alternatives Workshop**. In particular, we welcome the U.S. Bureau of Reclamation (Reclamation) and look forward to working with Reclamation during this conference and in the future on critical issues related to water management and delivery. I look forward to a very interesting and timely workshop covering the use of polyacrylamide (PAM) and alternatives to PAM in agriculture.

The Pacific West Area (PWA) is one of eight USDA-ARS Areas located in the major farm and rangeland ecosystems throughout the United States and overseas, comprised of 26 research locations and work sites distributed among eight states – Alaska, Arizona, California, Hawaii, Idaho, Nevada, Oregon, and Washington. Of about 1,300 employees in the PWA, one-fourth are scientists and engineers; the rest provide critical support. The Area Director has responsibility for scientific and administrative management of the PWA and provides leadership for scientific quality, relevance, and impact of research programs.

Research performed at USDA-ARS falls under umbrella groups known as “National Programs.” Of particular note to this work is the National Program, **Water Availability and Watershed Management**, which develops practices and technologies to manage the Nation's agricultural water resources. Research focus areas include optimizing water delivery during irrigation, developing methods to reuse degraded water, increasing water use efficiency, and enhancing water availability to mitigate impacts of drought. This National Program works closely with multiple other Programs toward optimizing water use within optimal cropping systems.

Researchers at multiple PWA research locations have been particularly active in work related to PAM and alternatives to PAM, some of whom are here to make presentations at this meeting. Research locations include:

1. Northwest Irrigation and Soils Research Laboratory (NWISRL), Kimberly, ID. Scientists at the NWISRL engage in an array of related research areas such as water quality during irrigation, optimal irrigation management, soil resource management during irrigation, and manure management. They began the
Polyacrylamide (PAM) Research Project in 1991, which has evolved into a wide-ranging study on use of PAM in agriculture and beyond. The following is a link to a NWISRL PAM web-page with a broad range of public information: [http://www.nwisrl.ars.usda.gov/research/PAM](http://www.nwisrl.ars.usda.gov/research/PAM)

2. Water Management Research, San Joaquin Valley Agriculture Science Center, Parlier, CA. Research is focused on developing methods and practices to increase water use efficiency and improve productivity, reducing negative environmental impacts of irrigated agriculture in semi-arid and arid areas. PAM work there has included studies on variations in water infiltration during irrigation with PAM.

3. U.S. Salinity Laboratory, Riverside, CA. Their mission is to promote the sustainability of irrigated agriculture, and to prevent degradation of surface- and ground-water resources by salts, toxic-elements, pesticides, and pathogens.

4. Bioproduct Chemistry & Engineering, Western Regional Research Center, Albany, CA. Studies have been conducted on alternatives to PAM, such as biopolymers and ag-derived chemicals, for application in erosion control during irrigation as well as for use in an array of other commercial applications.

Again, we welcome your participation in this exciting workshop and look forward to a productive meeting.
We are going to spend a day and a half talking about flocculents and new substances that can reduce canal seepage. As the U.S. Bureau of Reclamation (Reclamation), we store and deliver a large amount of water in the west for irrigation and hydropower generation. We are always interested in making the delivery of water to the farm and on the farm more efficient. We supply water to very productive lands in the West and have approximately 13,000 miles of unlined earthen canals, which represents a significant amount of water lost through seepage. This is part of Reclamation’s infrastructure. Over the last three years, our folks have been looking hard at the use of polyacrylamide to reduce canal seepage. Del Smith has been leading a number of field studies for Reclamation with the assistance of Rick Susfalk and Michael Young of the Desert Research Institute (DRI) testing the efficacy of polyacrylamide (PAM) to reduce canal seepage, as well as investigating the fate and transport of PAM and acrylamide (AMD). We have also been working with Tim Gates from Colorado State University, and with irrigation districts, like Dan Henrich’s Rocky Ford High Line Canal Company out of Pueblo Reservoir, to reduce canal seepage. This has been the springboard for decisions that Reclamation has made to not support the use of PAM in our facilities and at the same time pursue other products that may work just as well. We know the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) and their industrial partners have been working steadily in this direction and we are eager to join that effort.

We are happy to have folks like Joyce Donohue from the U.S. Environmental Protection Agency (EPA) to help us think about the whole regulatory side of this business and make sure we have a clear path forward if we develop a new flocculent for canal uses.

Particular thanks go to the USDA-ARS folks for offering their expertise in the area of technology transfer, Martha Steinbock’s group, in particular. Chuck Hennig from Reclamation put together a three-year agreement with the USDA-ARS just a few months ago to provide technology transfer support to Reclamation. We have a fair bit of technology development within Reclamation but lag in our understanding and use of all the instruments that are available to us to move inventions and discoveries out to the public. We are delighted to have this working arrangement with ARS and will benefit greatly from it. Half of the discussion today will be about technology transfer and how we move it through industry and out into the public.

In addition to Martha Steinbock, I want to thank Bill Orts and Dave Nicholson for helping organize the workshop on the ARS side. We are delighted to be here and look forward to a very interesting day and a half. Thanks for being here today.
The U.S. Department of Agriculture (USDA) maintains an active Technology Transfer Office to encourage, promote, and facilitate the application and commercialization of technology resulting from USDA Agricultural Research Service (USDA-ARS) research and to foster cooperation between outside parties and ARS. Recently, we have been fortunate to create a formal working partnership with the U.S. Bureau of Reclamation (Reclamation) that promotes their Technology Transfer programs and potentially facilitates further partnerships with ARS scientists. I see this meeting on PAM and PAM Alternatives as an example of means toward this further partnership between Reclamation, USDA, and their stakeholders.

The Office of Technology Transfer (OTT) is responsible for the USDA-ARS Technology Transfer Program, Patent Program, Patent Licensing Program, and National Agricultural Pesticide Impact Program.

USDA-ARS has a successful history of partnering with commercial firms to transfer the fruits of agricultural research to U.S. farmers and consumers. The Federal Technology Transfer Act of 1986 dramatically changed how the federal government does business, allowing federal laboratories and industry to form commercial partnerships that enhance the development of new technologies and move them into the marketplace. ARS is a leader in the federal government in transferring and marketing new technologies developed from its research and has formed numerous partnerships using cooperative agreements. The OTT facilitates and coordinates these partnerships using different agreements and partnering tools. These include:

- **Confidentiality Agreements (CAs)**: USDA-ARS scientists enter into a CA with cooperators outside the agency when they want to discuss confidential information or data that may have patent potential. Confidentiality Agreements are also used when a company needs to discuss confidential information with ARS scientists.

- **Material Transfer Agreements (MTAs)**: MTAs are used when ARS scientists want to provide material to someone outside ARS but want to maintain control over the material and avoid public disclosure. MTAs can also be used to bring material into ARS from outside partners for research purposes.

- **Cooperative Research and Development Agreements (CRADAs)**: A CRADA is appropriate for a commercial firm seeking to further develop and commercialize an USDA-ARS invention, merge USDA-ARS technology with its own technology, or jointly discover and develop a new technology. CRADAs provide the cooperator the right to negotiate an exclusive license to inventions made under the agreement, providing confidentiality for information generated under the agreement.

- **Other Types of Agreements**: USDA-ARS enters into other strategic partnerships with federal, state, and private organizations to help deliver new technologies to the public. These varied partnerships include Trust Fund Cooperative Agreements, Reimbursable Cooperative Agreements, Non-funded Cooperative Agreements, and grants. Trust Agreements and Reimbursable Agreements are similar to CRADAs but lack the provision for negotiating an exclusive license and complete assurances of confidentiality.

The USDA-ARS OTT administers the USDA’s technology licensing program. The USDA-ARS technology licensing program grants licenses to qualified businesses and individuals who wish to commercialize USDA-ARS technologies. Licenses may be exclusive, nonexclusive, or partially exclusive, and foreign patent rights are available in some cases. Licensing federally owned inventions is done in accordance with federal regulations (37 CFR 404), which are described at www.ars.usda.gov/Business/Business.htm. Businesses or individuals who want to commercialize an USDA-ARS invention must submit a patent license application. USDA patent licenses are royalty bearing and include provisions for license execution fees, annual license maintenance fees, and patent cost reimbursements. License fees and royalty rates are negotiable.
USDA-ARS continues to foster relationships with many businesses throughout the United States and, in so doing, creates new job and economic opportunities. Several USDA-ARS technologies have resulted from fruitful partnerships or have paved the way for new partnerships.

Many small businesses have built new industries based on USDA-ARS research and products. These companies have helped bolster local, state, and national economies. Through such partnerships, the USDA-ARS OTT helps deliver innovative technologies to a growing world.
What is polyacrylamide (PAM)?

Polyacrylamide (PAM) is a synthetic organic polymer derived from petroleum. It is an industrial flocculent used worldwide in several industries. For example, one international manufacturer of PAM markets 31 percent of its PAM product to the municipal potable and waste water treatment industry, 18 percent to paper production, 17 percent to industrial water treatment, 13 percent to oil production (enhanced oil recovery), 9 percent to mining, and the remaining 8 percent to agriculture, animal feed, and cosmetic industries. Since agriculture is a relatively small market, the polymer manufacturers commit only limited resources toward developing or improving agricultural polymer products. This is why the research conducted by the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) and others toward developing PAM technologies has been crucial to growing its potential and useful application in irrigated agriculture. The PAM used in furrow irrigation erosion control is a water soluble, anionic, high molecular weight, 12 to 15 Mg mol$^{-1}$ (i.e., >150,000 repeating units) polymer with moderate charge density (~18 % of the repeating units are negatively charged). This PAM is also referred to as water soluble PAM (WSPAM) or linear anionic PAM (LAPAM). This long, single-chain polymer can be dissolved in water, where it forms a hydrated random coil structure. The size of the PAM hydrated coil increases with increasing molecular weight and charge density, and decreasing salt concentration in the water. Loops and tails of the hydrated polymer extend out into the water. Negatively charged sites on the polymer form electrostatic bonds with negatively charged sites on soil particles through intervening positively charged cations, Ca$^{2+}$, Mg$^{2+}$, and others. Thus, the polymer can bind soil particles together via a so-called cationic bridge, which is one of the main mechanisms by which PAM interacts with soil.

Polyacrylamide can be obtained in several forms. The granular form consists of white table-sugar-sized crystals and includes between 75 and 97 percent active ingredient (AI), 3 to 10 percent water, and a maximum 0.05 percent acrylamide monomer content (for food-grade products recommended for agricultural use). Granular PAM may also include 0 to 10 percent dissolution aids (e.g., urea) and/or enhancers (Ca$^{2+}$, Mg$^{2+}$). Aqueous PAM solutions may be available in some locations, but viscosity limits their AI content to a maximum of about 3 percent (w/w). Polyacrylamide can also be obtained as an emulsion. Emulsions contain 25 to 50 percent AI (w/w), 5 to 30 percent water, 30 percent mineral oil, and 5 to 10 percent surfactants, emulsifiers and inverters. The acrylamide monomer content in PAM emulsions potentially can be much less than 0.05 percent.

Users should be aware that anionic PAM can be obtained in a cross-linked form, which, unlike the linear molecule, is not soluble in water. The linear PAM molecules are bound to one another via chemical bonds, creating a massive molecule that is able to absorb 60 to 600 times its weight in water, depending on water quality.

PAM Research at Kimberly

PAM research at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID, began in 1991 as a cooperative effort with Dr. Isaac Shainberg, then a visiting scientist at the USDA-ARS Soil Erosion Laboratory, West Lafayette, IN. He had observed that water-soluble PAM reduced sediment loss in a laboratory rill study and asked interested researchers at Kimberly if PAM might have an application in irrigation furrows. We set up some field experiments to test the concept and the study produced dramatically successful results. At that point, PAM research at Kimberly accelerated (Appendix A). One research thrust refined application strategies for erosion control. Several studies examined application strategies for reducing sediment and/or increasing infiltration: 1) the influence of application technique, timing, and PAM concentration was determined, and 2) the effects of PAM charge type, charge density, and molecular weight were studied. One experiment examined the
interactions between PAM application and the presence of straw residue in furrows. Two PAM application methods were validated in above studies. One consistently successful application amends inflow irrigation water with 10 mg L\(^{-1}\) PAM only during furrow advance, completing the irrigation with untreated water. The second, commonly called the patch method, spreads 15 to 30 g PAM in the furrow at the inflow-end. It produces a continuous PAM application with 2 to 7 mg L\(^{-1}\) PAM dissolved in the furrow stream early in the irrigation and 0.2 to 2 mg L\(^{-1}\) PAM at later times. Still other research developed PAM applications for sprinkler irrigation.

A second research thrust examined PAM application effects on water quality. Experiments showed how PAM influences furrow stream and tailwater phosphorus and nitrate concentrations, chemical oxygen demand, and water temperature. Polyacrylamide effects on microorganism and weed seed concentrations in irrigation runoff were also investigated. Other studies were concerned with the effects of PAM treatment on percolation water and leaching of phosphorus, nitrate, ammonia, dissolved organic carbon, and some herbicides through soil profiles.

A third thrust delved into PAM interactions with soil microorganisms. Experiments showed how PAM affects microorganism populations in treated soil and how microorganisms can utilize PAM as a substrate.

A fourth research thrust focused on PAM effects on surface soil structure under sprinkler irrigation. Experiments were conducted to explore PAM’s potential for reducing soil crusting and improving seedling emergence, particularly for small seeded crops such as sugarbeet.

A fifth research thrust sought to ascertain the fate of PAM that was applied to furrow irrigation water. This effort included developing a method for analyzing dissolved PAM concentrations in irrigation water. A subsequent mass-balance study tracked dissolved PAM loads in furrow and tailwater streams.

A sixth research thrust focused on the fate of the residual acrylamide monomer (AMD) present in the applied PAM product. The studies determined whether AMD was incorporated into harvested crop tissues, and if AMD was prone to leach below the crop root zone (see later discussion).

**PAM: A Tool for Irrigated Agriculture**

As a result of the extensive research conducted at the laboratory, Kimberly researchers concluded that PAM was an effective tool for irrigated agriculture. Research has conclusively shown that PAM applied in irrigated furrows:

1. Reduces soil loss 94 percent (80 to 99 percent)
2. Increases infiltration 15 percent (0 to 57 percent)
3. Increases lateral-wetting 25 percent
4. Decreases P- and chemical oxygen demand (COD)-losses approximately 75 percent
5. Reduces weed seed transport 81 percent
6. Reduces microbe transport 61 to 68 percent

**Environmental Aspects**

Research reported in the literature and conducted at the Kimberly laboratory indicates that, at concentrations used in furrow applications, PAM is nontoxic, degrades slowly in the soil to form H\(_2\)O and CO\(_2\), and has variable effects on soil microorganisms, producing mainly proportional adjustments in individual populations relative to others. The concentration of PAM dissolved in furrow irrigation streams declines with travel downstream because PAM molecules adsorb to sediment and settle out. Since AMD occurs in small amounts in PAM products, it also is present in treated furrow streams. With respect to residual AMD present at concentrations less than 0.05 percent in PAM products, Kimberly research and that of others has documented the following: at recommended PAM product application rates, AMD in furrow irrigation streams should not exceed approximately 5 µg L\(^{-1}\). While AMD is a neurotoxicant and suspected carcinogen in terrestrial mammals, it has low toxicity to aquatic organisms, degrades rapidly in soil and water streams, does not appear to accumulate in crop tissue, and does not leach beyond the root zone in medium-textured soils.

Many years of laboratory and field studies have resulted in a thorough documentation of the benefits and effectiveness of PAM for erosion control and infiltration management in irrigated agriculture. These results also provide strong evidence that PAM applied at recommended dosages in field irrigations has minimal negative
environmental consequences. Polyacrylamide is one of several important tools available to farmers for reducing erosion and improving runoff water irrigation quality and should continue to be considered as part of a thoughtful management plan.

Appendix A: Contributors to Original PAM Research at the ARS Kimberly Laboratory

1991-1992:
- Carter, D.L. (Ret.)
- Lentz, R.D.
- Sojka, R.E. (Ret.)

1993-1994:
- Lentz, R.D.
- Sojka, R.E. (Ret.)
- Trout, T.J.

1995-1996:
- Kincaid, D.C. (Ret.)
- Lehrsch, G.A.
- Lentz, R.D.
- Sojka, R.E. (Ret)
- Trout, T.J.
- Westermann, D.T. (Ret.)

1997-1998:
- Aase, J.K. (Ret.)
- Bjorneberg, D.L.
- Kincaid, D.C. (Ret.)
- Lehrsch, G.A.
- Lentz, R.D.
- Robbins, C.W. (Ret.)
- Sojka, R.E. (Ret)
- Trout, T.J.
- Westermann, D.T. (Ret.)

1999-2003:
- Aase, J.K. (Ret.)
- Bjorneberg, D.L.
- Entry, J.A.
- Koehn, A.C.
- Lentz, R.D.
- Sojka, R.E. (Ret)
- Westermann, D.T. (Ret.)

2004-2008:
- Koehn, A.C.
- Lentz, R.D.
- Sojka, R.E. (Ret.)

Dr. Rodrick (Rick) D. Lentz is a soil scientist at the USDA-ARS Northwest Irrigation and Soils Research Laboratory in Kimberly, ID, where he has worked since 1991. He holds a B.S. degree in Biology from Portland State University; an M.S. in Soil Science from Oregon State University; and a Ph.D. in Soil Science from the University of Minnesota. During the last 16 years, his research has developed and evaluated various polyacrylamide applications for irrigated agriculture. His current research goals include 1) improving water quality of surface water and groundwater under irrigated agriculture; 2) conserving water resources by developing management practices to increase water application uniformity and reduce irrigation associated seepage losses; 3) enhancing our soil resources; and 4) increasing our ability to understand, describe, and predict irrigation furrow processes. Email: rick.lentz@ars.usda.gov; phone: 208-423-6531.
Introduction

To identify or develop alternative polymers, which may successfully replace polyacrylamide (PAM) as a reservoir or canal sealant, it is important to understand the nature of the sealing processes in earthen irrigation water structures and how PAM interacts with those processes to alter water seepage. The purpose of this paper is to review mechanisms that influence water infiltration into unlined irrigation canals and ponds and consider how PAM interactions with soils may alter these processes.

Sealing Mechanisms

Sediment

It is known that sediment in ponded and flowing water can reduce infiltration and seepage losses (Trout et al., 1995; Bouwer et al., 2001). Three types of sediment-derived seals have been identified: thick-layer, thin-layer, and wash-in seals (Lentz and Freeborn, 2007).

Thick-layer Deposit. Gravitational settling of suspended and bedload sediment produces a horizontally extensive depositional layer several centimeters to tens of centimeters thick above the original soil surface. This layer is subject to compressive forces from the soil layer’s own mass and that of overlying water (Behnke, 1969; Bouwer and Rice, 1989; Bouwer et al., 2001). The sediment particles in these deposits can vary widely in size. In ponds, incoming sediment composed of various particle sizes produced a graded depositional layer that was less permeable than that formed by uniform sediment (Bouwer et al., 2001).

Thin-layer Seal. Infiltration inhibition by the thick layer relies upon the force of gravity to cause the deposition, accumulation, and adherence of thick sediment layers onto the original soil surface. Sealing produced by very thin sediment deposits has also been reported. Suspended sediment carried to the wetted perimeter in flowing water, and to a limited extent by gravitational settling, can form a thin (0.1 to 2 mm), continuous, low-conductivity depositional seal on the original soil surface (Shainberg and Singer, 1985; Brown et al., 1988; Segeren and Trout, 1991).

In comparison to thick-layer deposition, in which substantial sediment accumulates and adheres to the stream bottom under force of its mass, the particles comprising a thin seal are held in place and consolidated, along with adjacent soil below, by negative water pressure below the soil surface (Brown et al., 1988; Segeren and Trout, 1991). This explains why fine soil particles that would otherwise remain suspended in the water stream adhere to the wetted perimeter upon contact. Consolidation under negative pressure causes additional conductivity reductions (Trout, 1990). Thin-layer seals can form within minutes after flow initiation (Brown et al., 1988; Segeren and Trout, 1991). The nature of the suspended sediment influences seal development. Dispersed fines produce high bulk density surface deposits with oriented clay layers, while flocculated fines form a more porous seal, owing to the random orientation of the particles (Shainberg and Singer, 1985; Southard et al., 1988).

Wash-in Seal. Unlike the previous two, the third mechanism does not require that a continuous depositional layer form over the soil surface. Instead, infiltrating water sweeps suspended particles into surface soil pores. Gravitational forces cause the particles to be deposited on the upper surfaces and ledges of soil particles within the matrix, filling in crevices and concavities on the particles (Ives, 1989). Dispersed clays suspended in infiltrating water can move as much as 5 mm into loamy soils, forming oriented clay deposits that plug finer pores (Southard et al., 1988). This mechanism, referred to as “wash in” or “interstitial straining” (Behnke, 1969), has been
identified in sands (Hall, 1957) and soils subject to raindrop impact (McIntyre, 1958) and ponding of turbid water (Shainberg and Singer, 1985; Houston et al., 1999).

Several of these sealing processes may be active in some flow regimes, while certain mechanisms may dominate in others. For example, a thin-layer seal may be relatively more important in irrigation furrows or during initial filling of irrigation canals, when soils are drier and soil water potential gradients are steep. Some of the major factors that influence the complex sediment sealing process are the size distribution of solids present in the water and soil, the concentration of the sediment in the water, and the velocity of water moving vertically toward the soil surface (Behnke, 1969; Trout et al., 1995).

Organic Particulates

Organic particulates present in secondary effluent, industrial wastewaters, or wastewaters produced by confined animal feed operations can act via similar physical mechanisms to reduce seepage through soil at the wetted perimeter. Larger organic particles tend to be deposited as a mat over the soil surface, particularly over finer-textured soils (DeTar, 1979; Houston et al., 1999), while smaller organic particles (relative to the sizes of soil pores in the seepage face) pass through or are trapped in the upper few centimeters of the soil (Barrington and Madramootoo, 1989). DeTar (1979) and Cihan et al. (2006) found that seal efficacy was more sensitive to the amount of organic solids present than to the saturated hydraulic conductivity of the untreated soil. Organic solids tend to seal finer-textured soils more rapidly than coarser soils (Rowsell et al., 1985).

Microorganisms

Applied organics can also stimulate soil microorganism growth. Large accumulations of bacteria and algae (McCalla, 1945; Gupta and Swartzendruber, 1962; Vandevivere and Baveye, 1992, Ragusa et al., 1994) or their long-chained, high-viscosity polysaccharide exudates (Avnimelech and Nevo, 1964) have also been shown to reduce seepage through soil linings.

Processes Opposing Sealing

Any process that scours sediment previously deposited on the canal or reservoir wetted perimeter attacks the thin depositional layer that has formed over an infiltrating surface, perforates the infiltration-inhibiting layer created near the soil surface, or alters macropore structure may increase infiltration and enhance seepage losses. In some cases, these processes allow stored or transported water to contact newly exposed, deeper soil strata whose original pore structure is intact (Lehrs and Kincaid, 2006). Erosive processes are more likely to occur in channeled flows than in static ponds.

Channel downcutting may occur in response to a change in the channel hydraulics, such as velocity or shear stress, or to a change in sediment load (Leopold et al., 1964; Lentz and Freeborn, 2007). Thus, channel scour and fill processes may arise at the same channel location at different times (Leopold et al., 1964). Erosion and abrading of stream beds alter channel surface morphology, disrupt previously formed seals, expose new soil surfaces, and increase seepage. Channel wall erosion and sloughing are important processes in channelized flow (Lentz and Freeborn, 2007; Smith and Dragovich, 2008) and are responsible for exposing new soil surfaces to inundation and infiltration.

Animal disturbance caused by burrowing animals such as rodents and worms penetrate any surface seals that may have formed and is an important avenue for seepage flow (Kemper and Trout, 1987; Kahlown and Kemper, 2004). The hooves of livestock tracking through irrigation canals and ponds can perforate existing surface seals and increase seepage potential.

Macropore flow can develop in continuous pores formed from old root channels or insect burrows, which are open to the soil surface. Poiseuille’s law describes laminar water flow through a cylindrical soil pore (Hillel, 1998) as

\[ Q = \frac{(\pi r^4 \Delta P)}{(8\eta L)} \]

where \( Q \) = water flux through a cylindrical pore, \( r \) = pore radius, \( \Delta P \) = change in hydraulic head, \( \eta \) = viscosity of the fluid, and \( L \) = pore length. Because the water flux in the pore is directly proportional to the fourth power of the pore radius, infiltration through a few large pores substantially increases seepage losses. In silty soils under relatively large hydraulic heads, the velocity of flow through macropores can be sufficient to cause erosion and enlargement of the pore’s cross section. The resulting piping greatly increases seepage losses. In some cases,
macropores develop in depositional seals along the channel perimeter and enhance seepage losses. Such pores may result from entrapped air escaping from the soil and be only a few millimeters deep, but are sufficient to penetrate the thin depositional seal and provide a pathway for surface water to rapidly infiltrate (Lentz and Freeborn, 2007).

**Aqueous Pam Interactions with Soil**

In furrow irrigation applications, PAM is commonly dissolved in flowing water at concentrations of 1 to 10 mg L\(^{-1}\) using brief, or continuous, applications (Lentz and Sojka, 2000). Polyacrylamide-soil interactions even at these dilute concentrations are substantial.

**Flocculation of Suspended Sediments**

Polyacrylamide flocculates sediment suspended in the water stream, increasing the mean diameter of soil particles entrained and deposited in downstream reaches (Ben-Hur and Keren, 1997; Lentz _et al._, 2002). However, as the polymer concentration increases relative to sediment load, PAM reverses its activity, and instead functions as a particle dispersant (Figure 1).

**Stabilizing Soil Structure and Porosity**

Polyacrylamide stabilizes soil structure and pores (Mitchell, 1986; Sojka _et al._, 1998b); wet aggregate stability percentages of amended soil increase with increasing treatment PAM concentration from 0 to 50 mg L\(^{-1}\) (Helalia and Letey, 1989; Nadler _et al._, 1996). This stream channel stabilization helps maintain soil structure and pore integrity, inhibits soil dispersion and entrainment, and delays or prevents depositional seal formation over the wetted-perimeter, resulting in higher infiltration rates than that in untreated channels (Lentz _et al._, 1992; Lentz and Sojka, 1994; Trout _et al._, 1995). Conversely, if sediment-laden waters are treated with PAM, the flocculated sediment may be deposited over the stabilized surface layer, negating the latter’s infiltration enhancements.

**Viscosity Effects on Soil Water Flow**

Increasing PAM concentration from 0 to 25 mg L\(^{-1}\) in water slightly increases the solution’s viscosity when measured by a Cannon-Fenske-type viscometer, but relative viscosity increases are greater as PAM concentrations rise above 25 mg L\(^{-1}\) (Lentz, 2003). These determinations were derived from flow measurements made in 0.25- to 1-mm-diameter tubes. Polymer solution viscosity is more sensitive to PAM concentration changes when measurements are made through smaller-diameter pores like those common in soil (Malik and Letey, 1992). This increased sensitivity has been attributed to extensional viscosity effects (Song _et al._, 1996) and dynamic adsorption-entanglement processes (Grattoni _et al._, 2004). Since flow in soil pores is inversely proportional to water viscosity (Equation [1]), PAM amendment tends to reduce infiltration and conductivity of treated water through soil (Mitchell, 1986; Malik and Letey, 1992; Falatah _et al._, 1999; Lentz, 2003; Ajwa and Trout, 2006).

**Other PAM-Soil Interactions**

Polyacrylamide-treated soils may show a slightly enhanced soil wettability compared with untreated soils, although this may vary with soil texture (Hartmann _et al._, 1976). It is also known that dilute concentrations of high molecular weight polymers reduce fluid drag in turbulent pipe flow (McCormick _et al._, 1990). In soils, drag reduction effects would likely be restricted to flow in larger soil pores or macropores. Larger pores may experience turbulent flow regimes, whereas laminar water flow tends to prevail in smaller soil pores (Hillel, 1998).
Effects of Polymer Characteristics on PAM Activity

The magnitude of the PAM effect on soil stabilization, flocculation, or water viscosity generally increases with increasing size of the hydrated PAM molecule in solution, which increases with its molecular weight and charge density (Kulicke et al., 1982; Nadler et al., 1996; Falatah et al., 1999), and decreases with increasing salt concentration in the water (Tam and Tiu, 1993). However, the hydrated PAM radius at which maximum flocculation occurs can differ depending on sediment characteristics and sediment and polymer concentration (LaMer and Healy, 1963; Hocking et al., 1999).

PAM Effects on Sealing Processes

**Thick-layer Deposit.** If suspended sediment is present in irrigation canals and reservoirs, the addition of PAM will promote settling of suspended sediment present in the water column. If the sediment supply is continuous, a prolonged PAM application could result in extensive thick-layer sediment deposits. The PAM amendment may make these accumulations more cohesive, stabilizing them against flow velocity changes that may otherwise tend to scour such deposits (Lentz and Freeborn, 2007).

**Thin-layer or Depositional Seals.** Polyacrylamide research at the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) laboratory in Kimberly, ID, addresses sealing mechanisms directly because surface sealing of their silt loams is the main process that reduces infiltration during furrow irrigation. Polyacrylamide’s ultimate effect on furrow infiltration results from its combined influence on pore integrity, seal formation, and water viscosity (Sojka et al., 1998a; Ajwa and Trout, 2006). For example, when Lentz and Sojka (2000) applied PAM continuously to furrow stream inflows, a 2 mg L⁻¹ PAM application effectively stabilized soil and reduced seal formation (99 percent reduction in sediment loss relative to controls), whereas the 0.5 mg L⁻¹ PAM treatment less successfully stabilized furrow soils (75 percent sediment loss reduction), yet produced an infiltration gain equal to that of the 2 mg L⁻¹ treatment (Figure 2). The difference in soil stabilizing power of the two treatments apparently was offset by viscosity effects.

However, the infiltration benefit was not realized 1) if soil structure was degraded prior to PAM application by wheel traffic or repeated irrigations (Sojka et al., 1998b; Lentz et al., 2000), or 2) for inherently stable soils with large pores and not susceptible to depositional seal formation (Trout and Ajwa, 2001; Ajwa and Trout, 2006).

Thin-layer depositional seals formed by flocculated sediments are more permeable than those formed by nonflocculated particles (Southard et al., 1988; Sojka et al., 1998a), which suggests that PAM treatment of sediment-bearing flows in unlined channels should result in greater infiltration and seepage losses than for untreated flows. Compared to controls, deposition seals in furrows treated with medium and high molecular weight PAM contained greater numbers of flow-conducting pores with diameters of less than 0.30 mm and less than 0.75 mm (Figure 3).

**Wash-in Seal.** Polyacrylamide can influence the wash-in process through its effect on stabilizing surface structure and porosity and by altering the number and size of suspended particles in the water. Polyacrylamide preserves large surface pores. While water flux through a simple cylindrical pore is directly proportional to the fourth power of its radius (Equation [1]), the pore’s wall area is directly proportional to the pore radius. Thus, in larger pores, the influx of water and sediment in proportion to the pore wall area is far greater than that in small pores. As a consequence, larger-diameter pores may be more susceptible to wash-in than small pores.

![Figure 2. Influence of concentration on net infiltration increase obtained using continuous PAM applications (Lentz and Sojka 2000).](image-url)
Polyacrylamide also flocculates sediment suspended in the water stream, increasing the mean diameter of soil particles present in the water (Ben-Hur and Keren, 1997; Lentz et al., 2002). Lentz and Freeborn (2007) reported that clay floccules created by PAM ranged in size from 50 to 400 µm depending on the concentration ratio of PAM to sediment in the water. In contrast, silt flocs were only 20 to 30 µm in diameter. For particles suspended in streamflow to enter surface pores, their horizontal momentum must be overcome by forces originating in the flow of downward-moving water draining through the pore. Since a particle’s horizontal momentum is proportional to its mass, the larger particles are less likely to be redirected into the surface pores with infiltrating water. In addition, the larger soil floccules created by PAM will be too large to enter some soil pores. If the larger floccules dominate the system, then wash-in processes may be active only in a relatively small number of the greatest-sized pores. Thus, PAM’s effect on wash-in seal processes may vary depending on several factors related to PAM and sediment concentration and suspended soil particle size.

### Influence of Sediment Type

The type of sediment suspended in the flowing stream also influences how PAM affects seepage rates. Lentz and Freeborn (2007) measured seepage loss from mini-flume channels for PAM-treated inflows containing either silt or clay-sized sediment (Figure 4). Note that sealing was immediate with clay, but more gradual for silt, especially at higher silt concentrations. Also, the effect of increasing sediment content on seepage loss differed for clay and silt particles.

### Effect of PAM Application

The effect of PAM on seepage rates can differ depending on how the polymer is applied. In a silt loam soil column study, a 0.1 percent (wt/wt) PAM solution was applied immediately before water was ponded on the surface (wet treatment) or applied and allowed to dry for 24 h before inundation (dry treatment). This was done with or without sediment additions to the ponded water. Sediment was mixed into the ponded water during the first 6 h of the test and measurements were continued for several days thereafter. The effect of treatment method on seepage rate was similar for sediment and no-sediment treatments. Early in the seepage test, the wet treatment had a lower seepage rate than the dry (Figure 5). Later, however, the wet treatment produced greater seepage losses than the dry. The addition of sediment tended to reduce seepage rates. When the experiment was repeated with a sand soil column for the sediment treatment, there was no difference between the wet and dry treatments (Figure 6). Thus, soil structure and/or texture appear to interact with application method in controlling seepage rates.

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**Figure 3.** PAM molecular weight effects on water infiltration through semi-consolidated furrows and depositional seals at water tensions of 40 and 100 mm. (From Lentz et al., 2000).

**Figure 4.** Effect of inflow clay (A) or silt (B) concentration on channel seepage loss rates for inflow PAM concentration of 0.4 mg L⁻¹ at 2-, 6-, and 22-h sampling times.
Cost Effectiveness

One way to evaluate the economic value of seepage control treatments is to examine the cost of irrigation water saved by the treatment, relative to its value to the producer (Lentz and Kincaid, 2008). One assumes that the seepage treatments are applied to irrigation canals and reservoirs during droughty periods when water is in shortest supply. The value of the saved water can be determined from the increase in production expected from each millimeter of additional water supplied to a deficit irrigated crop. Lentz and Kincaid (2008) made these calculations for water-soluble PAM applied at a rate of 0.016 kg m\(^{-2}\), cross-linked PAM applied at a rate of 0.2 kg m\(^{-2}\), and a 36-mil membrane-geotextile treatment. In spite of its presumed shorter treatment lifetime, the extra water made available by the water-soluble PAM (WSPAM) application cost less per unit water saved than that provided by the longer-lasting membrane-geotextile treatment (Table 1). Furthermore, the value of water saved in terms of increased crop yield was 7 to 44 times greater than the cost of WSPAM needed for application. This analysis underscores the potential value of the PAM seepage control solutions to producers.

Conclusions

PAM can substantially influence seepage processes in earthen canals and ponds; however, to maximize seepage reduction, it is important to understand how the polymer interacts with soil to affect infiltration. The relative complexity of these PAM-soil interactions likely explains why seepage reduction obtained from treatments tested in the field are often lower than those obtained from equivalent laboratory tests. More study is needed to better understand the character and dynamic nature of processes affecting seepage in canals and reservoirs. Polyaacrylamide can be a cost-effective seepage-reduction tool, especially when untreated water supplies cannot provide the entire crop needs and where short-term seepage control is desired.
Table 1. Estimated costs and benefits of water-soluble PAM (WSPAM) and cross-linked PAM (XPAM) treatments in comparison to a membrane-lined pond (Lentz and Kincaid, 2008).

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Expected treatment lifespan†</th>
<th>Water saved over treatment lifespan ‡</th>
<th>Cost of combined product §</th>
<th>Cost of water saved over treatment lifespan ¶</th>
<th>Estimated yield increase due to additional water #</th>
<th>Value of increased crop yield due to additional water ††</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2 XPAM + NaCl</td>
<td>2</td>
<td>2.3</td>
<td>$7 - $12 kg⁻¹</td>
<td>1.23 to 2.10</td>
<td>152 to 259</td>
<td>0.0033</td>
</tr>
<tr>
<td>WSPAM</td>
<td>2</td>
<td>2.3</td>
<td>$8.80 kg⁻¹</td>
<td>0.12</td>
<td>15</td>
<td>0.025</td>
</tr>
<tr>
<td>36-mil polyethylene membrane + geotextile cover</td>
<td>17</td>
<td>70.2</td>
<td>$8.18 m²</td>
<td>0.22</td>
<td>27</td>
<td>0.0125</td>
</tr>
</tbody>
</table>

† Lifespan of PAM treatments was limited to length of monitoring, actual duration may be longer. Lifespan of membrane treatment is mean of estimated range.
‡ Based on two seepage zones in the reservoir: side slope positions (50% of total area, total seepage water saved equal to that in control plots, 19.6 m per 2-y period), and reservoir bottom position (50% of total area, with seepage water saved equal to 3.2 m per 2-y period).
§ Membrane treatment was assumed to have a 90% percent seepage reduction efficiency.
¶ Price of XPAM ranges more widely than WSPAM due to variable supply and demand conditions. Cost of membrane treatment includes $0.11 m⁻² yearly maintenance fee. Estimate does not include installation costs.
# Reported from the literature for corn (Payero et al., 2006) and wheat (Ali et al., 2007).
†† Based on current local corn price of $209 Mg⁻¹ ($5.32 bu⁻¹) and wheat price of $257 Mg⁻¹ ($7 bu⁻¹).

References


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The Bureau of Reclamation (Reclamation) and others have been investigating and testing methods to reduce seepage losses from irrigation canals for over 50 years. Many chemical sealants have been proposed and tested, but none is in common use. Polyacrylamide (PAM) is the most recent material to show promise for reducing seepage losses. Polyacrylamide floculates sediments in the water so that particle weights increase and the sediment settles to the channel perimeter and forms a low permeability seal.

To predict the effect of PAM or alternative flocculents on canal seepage, it is important to understand the mechanisms at work: the chemistry, mechanics, and hydraulics that affect sediment transport, flocculation, and deposition; the effect of the deposited sediment flocs on infiltration; and the factors that may disrupt and decrease the effectiveness of the seal.

Past studies have shown that water chemistry (ion composition) impacts the effectiveness of ionic flocculents such as PAM. The flow hydraulics (shear velocity) will affect the particle sizes in suspended and bed transport and the settling rate of flocs. Aggregates, and especially flocs, will have lower densities than primary particles, which will reduce their settling rate. Upstream conditions will determine the amount and particle sizes of the sediment load.

The particle sizes, aggregation, density/packing, and thickness of the sediment deposits determine the permeability of the seal. Some have claimed that flocs pack with lower density than other sediments. The hydraulic gradient that is created across a seal is probably important in densifying and stabilizing the seal. The effect of the seal on reducing seepage depends on the permeability of the seal relative to the limiting permeability of the canal perimeter soils, and whether the seepage is in hydraulic contact with the groundwater.

Gravity causes most sediment to deposit on the bed of the channel. Unless held in place by a hydraulic gradient, sediment that settles on channel sides tends to roll or slide to the bed. It is likely that channel sides have higher permeability than beds, due to the lack of benefit of past deposition, and more macropores from plant roots and insect, worm, and rodent burrows. Some studies have shown that most of the seepage through the perimeter of “mature” channels is from the sides near the water surface where bio-activity is highest and deposition is least. Sediment deposition from flocculent application will likely be concentrated primarily on the channel bed and may not substantially reduce channel side seepage.

Canal seals can be ruptured by high water shear (flow surges or turbulence). Canal seals may also be ruptured by soil drying, shrinkage, and cracking. To the extent that hydraulic gradients help hold seals in place, seal ruptures reduce this gradient and may create an unstable condition in which the seal can be stripped away over a large area. This process may be important in the observed formation of head cuts in rills and irrigation furrows. The benefit of PAM may be much less in intermittently used channels that are allowed to dry or that experience high shear velocities during refilling.

PAM has been shown to have an effect on infiltration in the absence of sediment deposition or perimeter stabilization. This effect is often called an “apparent viscosity” effect because it appears to be a water property, although it is likely the result of the interaction of water with PAM and small soil pores. The relative importance of this property depends on the effect of PAM on seal formation. It may be critical in channels with primarily bed load or coarse perimeter soils. It is not known how long this effect might persist, although it is unlikely to persist beyond a drying cycle. It is important to understand the “effective viscosity” effect of alternatives relative to that of PAM.

I encourage better understanding of the processes above to predict the effectiveness of flocculents on canal seepage. Testing of flocculent efficacy under a wide range of conditions is difficult, so understanding the
processes helps guide the choice of materials and application methods and conditions, and improves the predictability of the results.

Since side-by-side tests in canals of alternative flocculents are very difficult, I suggest that testing protocols be established that can be done in the laboratory. These could include flocculent tests with waters of varying ionic composition, varying suspended sediments, and possibly varying turbulence (a “stirred” test?). A second useful laboratory test might be a soil column infiltration test using a range of soils, sediments, hydraulic gradients, and stirring rates. Such tests could indicate the materials, rates, and conditions that have the highest probability of reducing seepage losses, and probable effectiveness relative to PAM.

The desirable characteristics of PAM alternatives include:

- Flocculates over range of sediment/water properties
- Is effective at low rates to reduce material handling costs
- Reduces seepage in the absence of sediment (“viscosity” effect)
- Is low cost
- Is easy to transport, handle, and apply
- Is environmentally friendly/non-toxic/biodegradable

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Using soil amendment for erosion control has been a research focus at the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) National Soil Erosion Laboratory over the past 18 years. The work was initiated in 1990 when Dr. Isaac Shainberg of Israel spent a one-year sabbatical in the laboratory and promoted the polyacrylamide (PAM) research his group was doing. Two significant results of Shainberg’s research at West Lafayette are the: 1) development of a simple laboratory mini-flume procedure for measuring rill erodibility parameters; and 2) finding that low PAM application, i.e., 0.4 kg/ha, prevented rill erosion at high flow shear stress, i.e., 0.5 L min\(^{-1}\) flow at 30 percent slope (Shainberg et al., 1994). The mini-flume allows rapid measurement of rill erodibility with the advantage of needing a minimal amount of soil, and savings in equipment, time, and labor as compared to traditional rainfall simulation and flow injection in the field. With the help of ARS National Program Leader Dr. Doral Kemper in 1990, Shainberg was able to initiate interests from ARS colleagues in Idaho and California to test PAM in furrow irrigation fields, hence beginning extensive efforts on PAM research in the western U.S.

After Shainberg’s visit, the focus of the laboratory shifted toward the combined use of gypsum (an abundantly available power plant by-product) and PAM. For more than 10 years, research on soil amendment included laboratory and field studies using simulated rainfall, added inflow, and natural storms on soils ranging from normal farm fields to constructed steep embankments. Flanagan et al. (2003) gives a very detailed summary of these different studies and the main findings are: 1) PAM is found to be effective in controlling erosion, but it affected rill detachment processes more than interrill detachment processes, and therefore can greatly decrease rill formation and detachment rates; 2) PAM applied in liquid form and allowed to dry had better results than dry PAM granules in controlling erosion from a large storm event; and 3) combined gypsum and PAM treatments showed a synergistic effect, which was more effective in erosion control than any one treatment alone. In a study conducted at the large outdoor flume at the ARS Spillway Experiment Station in Stillwater, Oklahoma, PAM was able to control detachment from flows of water up to 760 L min\(^{-1}\) (200 gpm) in an earthen channel, indicating that it may be able to be used to control erosion in ephemeral gullies, newly established grass waterways, and other concentrated flow channels.

In addition to runoff and sediment measurements from soil amendments, we also started examining runoff water quality. One recently completed laboratory rainfall simulation study focused on using dissolved PAM in wastewater from animal production facilities during land application (Flanagan and Canady, 2006a,b). Swine wastewater from a third-stage anaerobic lagoon was mixed with high molecular weight PAM at concentrations of 0, 10, and 20 ppm and then surface applied to a silt loam soil packed in erosion boxes. Under various levels of slope and cover treatments, PAM use reduced NH\(_4\)-N loss from 34 percent to 92 percent and reduced ortho-P loss from 31 percent to 71 percent. Polyacrylamide treatment was also effective in reducing particulate nutrient losses, including reductions of 22 percent to 72 percent for total P. These results indicate that PAM can be used for controlling surface nutrient losses in runoff in the time period immediately following land application of agricultural wastewater. Effects of gypsum application on runoff water quality showed that although the concentrations of soluble nutrients and pesticides were not affected, the total loads were significantly reduced from the reduced runoff.

One recent development is the pelletizing of PAM and gypsum together. This solves the problem of using two vastly different application rates and makes its application as easy as routine granular fertilizers. Field testing has begun with this new product.
Another development that may have potential impact in changing the agricultural landscape is growing crops for fiber production, as the current wood-based fiber sources diminish. The challenge is to find out to what extent the biomass can be harvested without impacting soil quality, both short and long term. The designed fiber-harvesting machine takes the raw plant material, extracts the fiber, and produces the plant juices as ‘waste’. As there is no chemical additive except water, the waste is essentially a natural organic material that may have potential uses. Nevertheless, we would like to find out whether some portion of the juice needs to be returned to the soil to maintain its quality for sustained production. A trial test was conducted using the corn juice. We obtained approximately 4 kg of corn juice from corn plants harvested from 0.001 acre (~4 m²) area. We applied 2 mm of different dilutions of the corn juice to the test boxes, allowed surfaces to dry for two weeks, and then applied simulated rainfall for 1 h at 60 mm/h. The reductions in runoff, compared to the control (i.e., no corn juice, only water was applied) for 5, 10, 25, and 50 percent of the original concentration were 7, 17, 36, and 59 percent, while the total sediment reductions were 47, 53, 63, and 87 percent, respectively. This result is encouraging because only a small amount (in this case 5 percent) of the waste juice can reduce sediment loss by almost 50 percent. The remaining juice can either be processed for other uses or stored for additional soil applications when needed. The persistence of the plant juice in runoff and sediment reduction and the long-term effects of fiber harvesting are yet to be studied.

References

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The mission of the U.S. Bureau of Reclamation (Reclamation) is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public. By its mere presence and ownership of facilities, Reclamation directly influences water use and supply patterns in most major Western river basins. Reclamation owns 348 reservoirs, which store 245 million acre-feet of water, providing $9 billion in agricultural benefits. More than 90 million people each year visit 308 public recreation areas. Reclamation owns 254 diversion dams and approximately 16,000 miles of canals that deliver water for irrigation, and for municipal and industrial uses by more than 31 million people. This makes Reclamation the largest municipal water wholesaler in the United States. Six million homes are powered by 58 hydropower facilities and more than $12 billion in flood damages have been avoided since 1959.

**Problem** - A 1978 study (USDOI, 1978) indicated 30,300 miles of western “off-farm” canals seeped as much as 1.1 million acre-feet each year. Reclamation has approximately 14,000 miles of unlined canals. A desired benefit from a PAM alternative that Reclamation seeks for our project beneficiaries is a less-expensive alternative to reduce seepage losses in water delivery canals. Traditional seepage control measures typically cost $9 to $18 per square yard.

**How Does polyacrylamide (PAM) Reduce Canal Seepage?** It flocculates sediment entrained in canal waters, forming a seepage reduction barrier along the canal invert. The seepage reduction effectiveness has been measured between 0 and 90 percent and depends on the following site-specific factors:

- Amount of sediment in the water
- Water temperature
- Amount of PAM
- Application method
- Porosity characteristics of the canal invert

The duration of seepage reduction has been measured to last the entire irrigation season or as short as one month. Natural settling of sediments has been measured to reduce canal seepage, but it is typically more gradual and not as long lasting.

**Where do canal seepage losses go?** Not all canal seepage is a loss to the watershed; some of it recharges groundwater and may return to the downstream surface waters. Canal seepage is a loss of beneficial use to the water right. Other impacts to reducing seepage are site specific but can:

- Reduce groundwater supplies
- Reduce downstream return flows
- Make wetlands less “wet”
- Flush less salts from the soils

**Human Health Concerns** - Water delivery canals, directly or indirectly, are a source of water for human use. It is not good to throw anything potentially toxic into water used for human consumption, or for swimming, in the absence of regulation or product labeling for such uses. Polyacrylamide contains acrylamide monomer (AMD), which U.S. Environmental Protection Agency (EPA) classifies as a class B2 animal carcinogen, and is a known
neurotoxin and genotoxin. Studies of fate and transport of PAM and AMD in the environment indicate a rapid degradation. However, degradation by-products are not well understood.

In March 2004, the U.S. Department of Health and Human Services convened an expert peer-review panel that documented AMD as having potential human reproductive and developmental effects. The Food and Drug Administration in March 1994 developed an action plan for AMD in food. The World Health Organization in June 2002 started evaluating the health implications of AMD in food. This year (2008), EPA is updating a risk analysis of AMD. The European Union, academia, and others scientific entities are evaluating the human health effects of AMD.

Recent and ongoing studies to further evaluate AMD risks in food and form sensible public health advice are proving difficult. More studies and investigations are needed to better understand human risk, uncertainties, and risk management considerations.

**Public Perception and Exposure to Litigation** – In the absence of regulations and environmental studies, it is difficult for water managers to protect themselves from perceived risks. Applicators wearing protective clothing including eyewear and dusk masks indicate to the public that what is being applied is dangerous. There is also the risk that what is being applied may be potentially toxic to aquatic species. The methods to manage risk for applications of PAM do not yet exist like they do for applications of herbicides and pesticides used in canal environments. These are regulated by the EPA and individual states and are labeled accordingly for specific applications to waters. Where PAM is used in drinking water treatment, application takes place in a controlled engineering environment by trained personnel, where there is a well-defined risk-risk tradeoff.

How could the risk of using PAM in canals be appropriately managed?

- Implement customized and proven application protocols.
- Have a regulatory entity implement and administer application protocols.
- Train and certify applicators.

What are some of the associated challenges?

- Protocols based on risk characterization, not a detailed risk analysis, using available information and limited testing.
- Lack of controlled setting (i.e., there exists a wide and unpredictable range of site-specific physical, environmental, human, and institutional factors across Reclamation’s 14,000 miles of unlined canals).
- Equipment being used for applications is not designed to facilitate consistent applications.
- Easy to overdose – so little product is needed that it is easy to overdose canals. It is also not cost-prohibitive to overdose, which introduces the temptation to add more for good measure.

**Bureau of Reclamation Decision, March 2007 Memorandum** - In the absence of a regulatory framework or product labeling for PAM applications to reduce canal seepage, Reclamation will not support or allow the use of PAM in Reclamation-owned facilities.

Reclamation will continue to actively explore improved ways to reduce canal seepage losses by:

- Collaborating with the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS), and industry, to pursue the development of alternative biodegradable flocculents (i.e., green alternatives to PAM).
- Using new methods to more accurately measure and locate seepage so that spot treatments using conventional alternatives such as concrete and geotextiles are more practical and effective.

**Reference**

Chuck Hennig has been Deputy Director of Research and Development for the Bureau of Reclamation since 2000. He graduated from Colorado State University in 1978 with a degree in Civil Engineering. His career with the Bureau of Reclamation includes 10 years as a design engineer responsible for the hydraulic and structural design of dams and water delivery infrastructure, and 9 years as the Deputy Chief of the Dam Safety Office. As Deputy Director of Research and Development, Chuck develops and implements programmatic research objectives in support of Reclamation’s mission of managing water in the West.
Since 1935, the Natural Resources Conservation Service (NRCS) (originally called the Soil Conservation Service) has provided leadership in a partnership effort to help America's private land owners and managers conserve their soil, water, and other natural resources.

As such, the NRCS works primarily on private lands and with private landowners. The NRCS involvement with polyacrylamide (PAM) has been largely from a soil conservation standpoint and has developed standards for this use.

We are going to hear in more detail from Clarence Prestwich, a water management engineer with NRCS in its West National Technology Support Center, in Portland, Oregon, about PAM use on private lands.

In the State of Colorado, the NRCS has also experimented with the use of PAM to reduce canal seepage in unlined canals, specifically in some small-scale applications in the Arkansas Valley of southeast Colorado, and on a larger scale in the Grand Valley of western Colorado. An interim State of Colorado standard was developed but it has subsequently expired. John Andrews, Colorado State Conservation Engineer with U.S. Department of Agriculture (USDA)-NRCS, describes this in more detail in his write-up for these proceedings.

**Del Smith** has worked as a hydraulic engineer for the Bureau of Reclamation for 17 years. His area of expertise is evaluating surface water and shallow groundwater systems. Most of his time with Reclamation has been focused on environmental issues related to irrigation drainage water quality and endangered species. Del has led multiple interdisciplinary teams that included colleagues from the U.S. Fish and Wildlife Service and U.S. Geological Survey in planning, designing, and constructing remediation measures as part of the National Irrigation Water Quality Program. In addition to his work with Reclamation, he has worked on the design and construction of groundwater drinking water supply systems in northern Thailand and eastern Kenya. Email: dsmith@do.usbr.gov; phone: 303-445-2516.
Traditional methods of controlling canal seepage include concrete lining, compacted clay, and geomembrane lining. These proven methods of reducing canal seepage are effective but often cost-prohibitive for most water districts and canal companies. In the late 1990s, The Uncompahgre Valley Water Users Association (UVWUA) started experimenting with the flocculent polyacrylamide to reduce canal seepage. They worked with U.S. Bureau of Reclamation’s (Reclamation) Western Colorado Area Office to conduct bench-scale tests in wooden test troughs. After seeing initial success, they expanded their applications to small canal laterals that were known to have high seepage losses. By 2003, there was a significant number of polyacrylamide (PAM) applications occurring in western Colorado largely being encouraged by anecdotal evidence of seepage effectiveness and support by the Natural Resources Conservation Service.

Reclamation made a decision that this new application of PAM needed to be thoroughly evaluated on several fronts, including, in addition to water savings, potential human health and environmental effects. The following represents why Reclamation is concerned about what is put in our waters:

“Reclamation is the largest water wholesaler in the country, providing 10 trillion gallons of water to more than 31 million people and irrigating 10 million acres that produce 60 percent of the nation’s vegetables and 25 percent of its nuts and fruits.”

Reclamation collaborated with the Desert Research Institute (DRI) to provide answers to the following seven questions:

1. What are the ecological and human risks of PAM and any trace substances in PAM formulations, particularly acrylamide monomer (AMD), when used in unlined earthen canals for seepage control?
2. Does PAM degrade to the monomer, AMD? If so, does the amount present a significant risk for contamination of surface water or groundwater?
3. What is the relative significance of residual AMD in the original polymer versus AMD as a PAM degradation product (if it is generated)? Are there other potential or known degradation products of PAM that are of toxicological concern?
4. What is the fate (including biodegradation) and transport of AMD (and/or PAM, and product components) in surface water, soil, and groundwater systems? What data gaps exist specific to this application?
5. How do field application practices (e.g., application of PAM to dry soil versus water in a flowing ditch) affect the risk of use of PAM? What field practices can be used to reduce risks of PAM application?
6. If residual PAM is released into receiving waters, what are the ecological risks and issues associated with PAM in surface water (e.g., armoring channel morphology, bioaccumulation, etc.)?
7. Are there any other issues regarding the human and ecological risk of use of PAM that should be considered?

Measuring Canal Seepage
To accurately measure canal seepage in flowing canals is not an easy task and to improve the accuracy, the following are necessary, from our experience:

- Collect frequent stage data
- Measure between diversions
• Conduct measurement during steady-state flow
• Have a long enough reach (typically 2+ miles)
• Have good cross sections/canal geometry

The site selection we used incorporated the following:
• Magnitude of seepage loss (needs to be sufficiently high)
• Controllable or stable inflows
• Minimum number of turn-outs
• Length of canal
• Presence of an upstream control reach
• Presence of background data
• Ability to collect downstream water chemistry

**Canal Application**

From 2005 to 2007, Reclamation, DRI, and Colorado State University (CSU) conducted 17 linear anionic PAM (LA-PAM) field application experiments. The 2005 and 2006 applications can be summarized as providing excellent data on short-term seepage loss and LA-PAM release into the water column, but difficult to evaluate seasonal seepage. The 2007 studies focused on obtaining significant background data and gaining a better understanding of naturally occurring changes in seepage. Polyacrylamide was applied in dry granular form at a rate of approximately 10 lbs/acre based on wetted perimeter, moving upstream in flowing water.

The concentration of PAM applied was based on the Phase II Rule National Primary Drinking Water Regulations issued by the U.S. Environmental Protection Agency (EPA) (40 CFR §141.111), which asserts an acrylamide polymer maximum use level of 1.0 mg L\(^{-1}\) and an AMD concentration of 0.05 percent in the polymer, or equivalent, for a carryover of not more than 0.5 \(\mu\)g L\(^{-1}\) of AMD into the finished water.

We sought to apply LA-PAM to achieve a canal water concentration of less than 1.0 mg L\(^{-1}\).

Variables that control effectiveness of seepage reduction:
• Travel time
• Hydration time
• Suspended solids concentration in water
• Water temperature
• Water velocity
• Water chemistry
• Ability to hit target reach
• Mixing

**Seepage Reduction**

Seepage reduction ranged from 0 percent to 99 percent, but where the conditions were favorable, the range was typically 30 percent to 90 percent and lasted throughout the irrigation season, up to five months. Follow-up measurement during successive years indicates that PAM would need to be reapplied on canals that are allowed to dry out over the winter.

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**Del Smith** has worked as a hydraulic engineer for the Bureau of Reclamation for 17 years. His area of expertise is evaluating surface water and shallow groundwater systems. Most of his time with Reclamation has been focused on environmental issues related to irrigation drainage water quality and endangered species. Del has led multiple interdisciplinary teams that included colleagues from the U.S. Fish and Wildlife Service and U.S. Geological Survey in planning, designing, and constructing remediation measures as part of the National Irrigation Water Quality Program. In addition to his work with Reclamation, he has worked on the design and construction of groundwater drinking water supply systems in northern Thailand and eastern Kenya. Email: dsmith@do.usbr.gov; phone: 303-445-2516
Introduction and Objectives

There is little doubt that seepage from unlined water delivery canals occurs on a local and regional scale and that losses may be significant in particular areas. In a 1978 report, the U.S. Department of Interior (USDOI, 1978) estimated that 37 percent of the 1.1 million ac-ft yr⁻¹ of water transported within 30,000 mi of unlined canals was lost to seepage in the western United States. The U.S. Geological Survey (USGS, 1990) has estimated that as much as 50 percent of water carried by unlined irrigation canals is lost through seepage. Some of this loss could be reduced through traditional seepage-abatement technologies such as compacted earth, reinforced or unreinforced concrete, and buried geomembranes. However, these treatments are characteristically used in situations shown to have high seepage rates and where the projected water savings offset their high construction and maintenance costs. As water resources become further constrained in the arid western United States, there is a need for alternative seepage reduction technologies that are cost-effective and can be used in locations where traditional methods are not suitable or cost-prohibitive.

The granular form of linear anionic polyacrylamide (LA-PAM) has been identified as one such technology. Granular LA-PAM is one specific member of a broader family of polyacrylamides that have a variety of uses, including as a flocculant in wastewater treatment, in food packaging, and paper manufacturing. Over the last decade, polyacrylamides have found increased use as an agent to reduce erosion and sediment transport from crop fields and construction sites (Wallace and Wallace, 1986; Lentz and Sojka, 1994; Lentz et al., 2001; Al-Abed et al., 2003; Soupir et al., 2004; Hayes et al., 2005; Orts et al., 2007).

When used properly, LA-PAM provides canal operators with a cost-effective tool to manage undesirable seepage from unlined water delivery canals. Benefits can include the ability to deliver a greater amount of water further down the canal and a reduction in the amount or an alteration of the timing of water diverted into the canal. In some situations with finite water supply, the length of the irrigation season can be extended. In addition to these more local water savings, cost-effective seepage reduction technologies can also be used to address regional-scale problems. In the Lower Arkansas River Valley (LARV) of eastern Colorado, for example, canals have contributed to a productive agricultural economy, but have also contributed to the presence of shallow water tables that have dropped crop yields by 10 to 15 percent through water logging and increased salt concentrations through evaporative concentration (Burkhalter and Gates, 2006; Gates et al., 2006). In some situations this has also increased groundwater return flows that dissolve and assimilate salts and metals from marine shales and residuum as they make their way back to the river system (USDOI, 2003; Mueller Price and Gates, 2008). This is of acute concern in the Grand Valley of western Colorado, where managers consider the reduction of salt and selenium
loadings to the Colorado River through decreased deep percolation of canal seepage as a higher priority than for water conservation.

In 2005, the Desert Research Institute (DRI), in collaboration with the U.S. Bureau of Reclamation (Reclamation), initiated a series of field and laboratory studies to assess the benefits and risks of LA-PAM used as a method to reduce seepage from unlined water delivery canals. The primary objectives of this research were to: 1) quantify potential seepage reduction benefits, water savings, and typical application costs; 2) address potential risks of LA-PAM use emphasizing the downstream transport and fate of LA-PAM, the release and fate of the residual acrylamide (AMD) monomer, and the potential impacts on aquatic organisms; and 3) gain a better understanding of how LA-PAM achieves seepage reduction in water delivery canal systems and how various environmental factors affect the ability of LA-PAM to reduce seepage.

A number of diverse studies were initiated to provide a better understanding of the benefits and risks of using LA-PAM for water conservation in unlined water delivery canals. Topics included a characterization of the risk of LA-PAM application to water delivery canals for water conservation purposes (Young et al., 2007a), application guidelines that promote seepage reduction benefits while reducing environmental exposure of LA-PAM (Susfalk et al., 2007), laboratory studies investigating flocculation, resuspension, and the impacts of LA-PAM on hydraulic conductivity, and the development of models describing the transport of PAM and AMD within the canal prism and the potential transport of AMD into groundwater. The environmental impact of LA-PAM application was investigated through studies utilizing benthic macroinvertebrates and Daphnia as indicators, and through a series of studies that assessed the breakdown of PAM and AMD through microbial and ultraviolet degradation. Preliminary results from some of the laboratory-based studies have already been reported (Young et al., 2007b) and other reports are forthcoming. Further information regarding DRI's various studies can be found online at http://pam.dri.edu.

Seepage reduction benefits were investigated utilizing studies at both the furrow and field scales. Field-based studies were conducted along 17 canal reaches in the Grand Valley of western Colorado, the Yellowstone River Valley in Montana, and the LARV of eastern Colorado in conjunction with Colorado State University. Susfalk et al. (2008) report the results from these studies, including a discussion of application costs and observed seepage reduction benefits, factors that contributed to an application of LA-PAM being successful, and potential risks involved with LA-PAM use. Here, we present an overview of the factors that we found contributed to successful applications, as well as an overview of several potential risks associated with LA-PAM application.

Factors Contributing to a Successful LA-PAM Application

Granular LA-PAM was applied to specific canal reaches at a rate of approximately 11 kg ha\(^{-1}\) (10 lbs ca\(^{-1}\)) based on the average wetted perimeter of each canal. Short-term measurements indicated that LA-PAM reduced seepage rates between 28 and 87 percent in 8 of 11 experiments. Seepage reduction was not effective in the remaining three experiments due to inadequate field conditions necessary to promote flocculation between the polymer and suspended sediment. Based on our findings, we believe that to be successful, granular LA-PAM should only be added to canal water having a suspended sediment concentration (SSC) of approximately 150 mg L\(^{-1}\) or greater, and a total dissolved solids concentration (TDS) of approximately 200 mg L\(^{-1}\) or greater. Of the two, the lack of sufficient SSC was the most common limiting factor found during field trials. This was alleviated in many canal systems by timing the application of LA-PAM with elevated turbidity events resulting from seasonal snowmelt or summer thunderstorms. Granular LA-PAM should not be used in canal systems that are chronically devoid of suspended sediment and/or are characterized by low TDS levels that suppress the formation of PAM-sediment flocs. The practice of artificially increasing SSC through dredging the canal bottom or the addition of canal tailings should also be avoided for several reasons, including the difficulty in timing sediment addition so that it is available at the same time LA-PAM has hydrated enough to react with it.

The failure to follow the above requirements, the application of excessive LA-PAM, and/or the poor choice of application methods and techniques can increase potential environmental exposure through the downstream transport of LA-PAM in the water column. The most critical factor in reducing exposure was the use of an LA-PAM application rate that was related to the level of suspended sediment in the water column and not simply the wetted perimeter, as traditionally done. Our results suggest that a nominal application rate of 11 kg ha\(^{-1}\) (10 lbs ca\(^{-1}\)) typically resulted in an over-application of LA-PAM to smaller canals (< 2.8 m\(^3\) s\(^{-1}\) or < 100 cfs) while sometimes resulting in the under-application to larger canals. This was based on the observation that higher LA-PAM concentrations were typically observed in smaller canals that had less water per unit area and lower
suspended sediment loads relative to larger canals. The formation of PAM-sediment flocs was optimized when LA-PAM concentrations were between 1 and 2 mg L\(^{-1}\) in the water column and higher polymer concentrations were found to provide little additional benefit. The Clear Zone Index (CZI) was developed to be used as a simple diagnostic aid to assess if the mass of LA-PAM exceeded the assimilative ability of suspended sediment present in the canal (Table 1). A partially developed CZI was desired, indicating the formation of PAM-sediment flocs and the full utilization of added polymer. A fully developed CZI should be avoided, as it indicated exhaustion of suspended sediment and a greater likelihood that excess LA-PAM remained mobile in the water column. It is strongly advised that current application guidelines based on a canal’s wetted perimeter be depreciated in favor of the development of application rates based on the concentration or load of suspended sediment in the water column.

Other environmental factors must also be taken into account to properly manage the application of LA-PAM. The interaction of water temperature and water velocity, for example, will determine how far LA-PAM will travel downstream before it hydrates and reacts with suspended sediment. For the sites studied, LA-PAM traveled between 196 m (643 ft) and 2,149 m (7,050 ft) downstream from the point of application prior to flocculation and development of a clear zone. The time needed for flocculation to occur in the field was not entirely temperature dependent, indicating other site-specific factors such as water mixing, water chemistry, suspended sediment concentration, and particle size may also play an important role. Therefore, granular LA-PAM must be applied at greater distances upstream of the target reach under conditions of slow hydration rates and fast water velocities, such as typical of snowmelt-fed canals during the early water season.

Table 1. Diagnostic features of the Clear Zone Index. The clear zone develops after LA-PAM reacts with a sufficient load of suspended sediment in the canal.

<table>
<thead>
<tr>
<th>Extent of Clear Zone Development</th>
<th>Potential Seepage Reduction</th>
<th>Potential Risk of Availability and Downstream Transport</th>
<th>Result</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>No Development</strong></td>
<td>Low</td>
<td>High</td>
<td>PAM-sediment flocs did not form.* Suspended sediment and dissolved solids (cations) may not be sufficient to promote flocculation.</td>
</tr>
<tr>
<td>(No change in turbidity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Some Development</strong></td>
<td>Low to Moderate</td>
<td>Low</td>
<td>PAM-sediment flocculation occurred; however, LA-PAM application rate may be too low.</td>
</tr>
<tr>
<td>(Small drop in turbidity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Partial Development</strong></td>
<td>High</td>
<td>Low</td>
<td>Significant PAM-sediment flocculation occurred. Excess suspended sediment remaining in the water column reduces the likelihood of downstream LA-PAM transport.</td>
</tr>
<tr>
<td>(Significant drop in turbidity)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Full Development</strong></td>
<td>High</td>
<td>Moderate to High</td>
<td>LA-PAM was applied in excess of the suspended sediment available in the water column. The application rate should be reduced or the application postponed until higher loads of suspended sediment are available.</td>
</tr>
<tr>
<td>(Water becomes clear or nearly clear)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* The clear zone may not be noticeable if suspended sediment concentrations are extremely high.

**Risks of LA-PAM Application**

The application of LA-PAM to unlined water delivery canals carries several potential risks related to the application and release of the polymer and the residual AMD monomer that remains occluded in the polymer. When LA-PAM was applied in excess of ambient suspended sediment conditions, LA-PAM concentrations were found to exceed 1 mg L\(^{-1}\) for up to four to nine hours depending on the time it took to physically apply the...
polymer. Excess LA-PAM beyond that needed to react with suspended sediment typically remained in the water column and travelled significant distances downstream where it had the potential to be inadvertently used by unsuspecting stakeholders, such as being diverted to farms for use on crops, or be consumed by livestock, for example. Excess polymer can also negatively impact the aquatic community. The response of benthic macroinvertebrates (BMIs) to LA-PAM was relatively minor in canal systems because these BMI communities were tolerant of the naturally harsh conditions present in these types of systems. In natural surface water systems, however, BMI species are more sensitive and were found to respond negatively to the presence of LA-PAM. The primary approach for mitigating these risks is to reduce or eliminate the transport of polymer downstream of the treatment zone by applying LA-PAM in a manner that assures it is quickly removed from the water column, as discussed above. These requirements may delay the use of LA-PAM until sufficient sediment levels are present or rule out its use completely if there is a possibility that natural surface waters may be impacted.

The most likely human health risk was to persons applying LA-PAM, either through inhalation, accidental eye contact, or from slipping on the slick polymer as it hydrated. These risks were significantly reduced through the proper use of protective gear (NSF/ANSI Standard 60 and ANSI/AWWA B453-06) and application guidelines (Susfalk et al., 2007). The incidental release of the AMD monomer, a cumulative neurotoxin and a suspected human carcinogen, also presents potential human health and environmental risks. Unlike the polymer, AMD is a small, mobile molecule that can enter groundwater. The potential risks of AMD release associated with LA-PAM applications to canal systems were more fully discussed in Young et al. (2007a). In the field, AMD concentrations in canal water were observed to be orders of magnitude below the chronic levels needed to impact human health. In addition, there was some evidence that higher concentrations of AMD were linked to high concentrations of LA-PAM, suggesting that the methods discussed above to eliminate excess polymer addition should also reduce the potential for elevated monomer concentrations. The successful formation of a PAM-sediment-induced seal will also decrease the likelihood of AMD entry into groundwater through the reduction of the seepage rate. Model results suggest that AMD entering groundwater was diluted by both canal water and groundwater, with a dilution of up to four orders of magnitude observed using an AMD surrogate at one site. Acrylamide released into the environment was found to be susceptible to microbial degradation, with an estimated half-life of 30 to 42 hours. Finally, conservative transport models indicated that AMD concentrations 10 times greater than actually measured in canal water would be undetectable within 25 m of the canal due to microbial degradation and dilution processes. Therefore, the contamination of groundwater by AMD associated with the application of LA-PAM to water delivery canals using the methods of Susfalk et al. (2007) was considered to be unlikely.

Conclusions
Granular LA-PAM is a cost-effective tool that has been shown to reduce seepage rates from unlined water delivery canals when used properly. The rates and methods used during the application of LA-PAM were critical to minimize potential environmental impacts. This includes: 1) the selection of the proper type of linear and anionic PAM for use in canals; 2) prior determination that the water chemistry will encourage PAM-sediment flocculation; 3) an application rate that considers the ambient concentrations of suspended sediment; 4) an application plan that minimizes worker contact and accounts for the downstream travel time during hydration; and 4) an assessment of the potential risks to adjacent and downstream users, and the potential for LA-PAM-treated water to reach receiving waters. Stakeholders and/or agencies responsible for the use of granular LA-PAM must assess if potential site-specific risks outweigh the benefits of using LA-PAM for water conservation purposes.

References


**Dr. Susfalk** is an Associate Research Scientist in the Division of Hydrologic Sciences at the Desert Research Institute, a campus of the Nevada System of Higher Education. His diverse interests include water conservation, surface water quality and quantity, watershed hydrology, forest hydrology and water chemistry. For the past three years, Dr. Susfalk has taken a leading role in the field investigations on the application of linear anionic PAM to water delivery canals for seepage reduction purposes. This work has included assessing the risks and benefits of PAM application to field-scale canals and smaller scale troughs, and through bench top studies. He is particularly interested in how application methods and ambient field conditions affect PAM flocculation and how these factors impact the risks and benefits of using PAM. Several of Dr. Susfalk’s other projects relate to how anthropogenic impacts and urbanization affect nutrient and suspended sediment transformations and loads in streams and rivers, including investigations of how the water clarity of Lake Tahoe’s near-shore zone is affected by on-shore, terrestrial processes. Before joining DRI, Dr. Susfalk was a Post-Doctoral assistant at the University of California, Santa Cruz and he obtained his Doctoral degree from the Graduate Program of Hydrologic Sciences at the University of Nevada, Reno. Previous to that, he received his Masters Degree in Chemistry at the University of California, Santa Barbara and his Bachelors Degree from Occidental College in Los Angeles, CA.

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There are over 600 million irrigated agriculture acres in the world; 55 million are in the USA. According to the last irrigation survey done in 2003, almost 27 million acres are irrigated by sprinkler and 23 million by surface irrigation. Of those 27 million acres, 21 million are irrigated by center pivot and roughly a half of that is on land with slope steep enough to cause erosion problems. Of the 21 million surface irrigated acres, almost 12 million are irrigated by furrow. That gives us 22 million acres that have a high potential for erosion. The last published erosion survey indicated that the USA has over 10 million acres with serious erosion between 15 and 160 tons per acre. This results in an estimated $16 billion annually in off-site damages caused by sediment and additional billions lost through reduction of productivity and repair of existing infrastructure. The 2003 irrigation survey also indicates that polyacrylamide (PAM) is used on just a little less than 400,000 acres. Industry estimates are a bit higher at 2 million acres, but even so, that leaves between 8 and 20 million acres contributing to erosion.

The Natural Resources Conservation Service (NRCS) with the help of the U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) developed a practice standard for the use and application of PAM. From the research and work that was done in development of this standard, we feel that we understand the risks from the use of PAM and that by following this standard, unintended effects and risks can be anticipated and avoided. The potential benefits from reducing erosion and seepage warrant the use of PAM. When NRCS released its standard, the use of PAM also became eligible for cost share under the EQIP program. This program allows land owners to receive incentive payments for applying PAM to prevent erosion. Over the last 10 years, requests for payment have decreased due to the fact that land owners have seen the benefits of using PAM and are applying the practice on their own.

The NRCS envisions a PAM product or PAM alternative that is off the shelf, readily available, and consistent; reduces 60 to 80 percent of the sediment yield and movement; and can be applied in multiple forms and manners. Currently, PAM can be applied in tablet, power, and liquid form. The material needs to be used in sprinklers or furrows.

Polyacrylamide strengthens soil cohesion, preserves surface roughness, and reduces particle detachment. It reduces sediment transport by flocculating suspended solids, and maintains higher infiltration in most soils. The NRCS would require any alternative to do similar.

Clarence Prestwich is a water management engineer with the U.S. Department of Agriculture, Natural Resources Conservation Service, West National Technology Support Center in Portland, Oregon.
**Background**

Jim Valliant should be credited with initiating the interest in use of polyacrylamide (PAM) for reducing canal seepage. While employed as an Extension Engineer with Colorado State University, he reported the results of field trials conducted during a period from 1998 to 2000 in the proceedings of the February 2002 Central Plains Irrigation Association Conference. The primary goal was to reduce damage caused by saline seeps adjacent to canals. This work had a significant influence in creating interest among ditch companies, farmers, and others in exploring the potential use of PAM for canal seepage reduction, and occurred at a time when the use of PAM to reduce furrow erosion control was already proven by U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) researchers and the erosion control practice had gained the general acceptance of farmers and conservationists alike. Subsequent to Jim Valliant’s work, a number of water users in Colorado began to experiment with PAM in canals.

By 2004, PAM was readily available due to its use for erosion control, and there were many irrigation water suppliers looking for help during a long period of drought. Water management specialists from the NRCS Grand Junction Field Office and the Bureau of Reclamation (Reclamation) Grand Junction Area Office had been involved in some field trials, and had observed both remarkable successes and failures of PAM canal treatments. They requested that the Natural Resources Conservation Service (NRCS) prepare an interim standard to establish some consistency in planning and applying PAM canal treatments and to advocate application practices that would minimize or eliminate any perceived environmental concerns.

**Development**

Colorado issued its interim practice standard in May 2005. The basis for the application rate and methodology criteria was the experience of the NRCS and Reclamation water management specialists who observed numerous field trials, and the recommendations from research scientists from the ARS Northwest Irrigation and Soils Research Laboratory (NWISRL), in Kimberly, Idaho.

Issuance of the interim standard was not made without due consideration and evaluation of potential environmental concerns associated with injecting PAM into canals. Significant time and effort was spent during preparation of the interim standard to review the relevant literature that characterized the environmental risks. The NRCS believes the application protocols advocated in the interim standard are sufficient to eliminate the potential for any adverse effects of the use of PAM.

**Current and Future use of the Standard**

To date, there have been many antidotal reports of successful use of the standard, and Colorado NRCS has received inquires about its use from almost every state in the western U.S. The majority of reports indicate the practice is successful in reducing canal seepage. However, only one Colorado NRCS field office has certified applications of the practice in NRCS’ progress reporting system. Agency policy assigns a three-year life to interim standards. At the end of this period in May 2008, the agency will evaluate what was learned during the interim period, and decide whether or not it should include PAM canal treatment as a practice in the National Handbook of Conservation Practices. Regardless of the efficacy of the practice, this apparent lack of use by agency conservationists makes it debatable whether or not the interim practice standard will be continued after it expires in May 2008.
At the same time the NRCS issued its interim standard, the Reclamation funded important peer-reviewed research efforts related to the use of PAM for canal seepage reduction. The results of this work are to be discussed by others at the Albany, CA, conference. Colorado NRCS believes the results as described in reports from the Desert Research Institute (DRI) support the continued use of PAM for canal seepage control. The work helps define the circumstances related to successful use of the practice and refines protocols for preventing any unintended and adverse effects. Colorado State University also has conducted field-scale experiments in southeastern Colorado. The summaries of both works will form the basis for revisions to the NRCS practice standard if the agency decides to continue this practice standard in the future.

The likely water conservation role for PAM canal treatment is to enhance maintenance efforts of field ditches and small canals where accomplishing some water conservation benefit, or reducing damage of adjacent cropland, is desired. I believe PAM canal treatment will not likely be considered the preferred alternative for instances where significant long-term seepage reduction is needed to achieve significant water conservation benefits, or where necessary to ensure the structural integrity of canal banks or protect high-value properties adjacent to canals.

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**PAM & PAM Alternatives Workshop**  
**Session Five: ARS Expertise and Research – PAM Alternatives, Status, Progress?**  

**Polymer Applications to Control Soil Run-off During Irrigation**  
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**Introduction**

In the past decade, water-soluble polyacrylamide (PAM) has been identified as a highly effective erosion preventing and infiltration enhancing polymer when applied in furrow irrigation water at 1 to 10 g m⁻³, i.e., 1 to 10 ppm (1-9). Various polymers and biopolymers have long been recognized as viable soil conditioners because they stabilize soil surface structure and improve pore continuity. The new strategy of adding the conditioner, such as PAM, to irrigation water, rather than to the entire soil surface, saves polymer. The soil structure is improved in the 1- to 5-mm-thick layer at the soil/water interface, i.e. treating only the all-important 25 to 30 percent of field surface that contacts the flowing water (7).

The term polyacrylamide and acronym "PAM" refer to a broad class of acrylamide-based polymers varying in chain length, charge type, charge concentration, and the number and types of side-group substitutions. Polyacrylamide for erosion control is typically a charged copolymer with one in five acrylamide chain segments replaced by an acrylic acid entity. Molecular weights of PAM used for irrigated agriculture range from 12 to 15 million g/mole, which is a relatively large polymer.

**Pam Erosion Control**

The main agricultural application of PAM is to reduce erosion-induced soil losses. Lentz and Sojka (2) reported a 94-percent reduction in runoff sediment loss over three years using the National Resource Conservation Service (NRCS) application standard (10). The 1995 NRCS standard calls for dissolving 10 ppm (or 10 g m⁻³) PAM in furrow inflow water as it first crosses a field, typically the first 10 to 25 percent of an irrigation duration, then halting PAM dosing when runoff begins. Alternatively, applying PAM continuously at a lower dose rate, typically 1 to 2 ppm for the full irrigation cycle, can be equally effective (7).

Considering that PAM is one of the more economical technologies for reducing soil-runoff and controlling dust, PAM use has branched into a wide range of applications (11) including stabilization of construction sites and road cuts, reduction of dust at helicopter landing pads, and control of canal seepage. These applications require higher levels of polymer application than required for erosion control during irrigation.

**Environmental Impact of PAM**

During PAM application to control irrigation loses, the overriding environmental impact of PAM is reduced erosion-induced sediment runoff (1, 2), with corresponding reductions in entrained chemical residue reaching riparian waterways. Specifically, during erosion, toxic pesticides and herbicides are entrained with soil sediment and carried to open waterways. Polyacrylamide prevents yearly topsoil runoff of up to 15.8 tons ha⁻¹, so it prevents a corresponding spread of agricultural chemicals beyond the field (12). Polyacrylamide was also shown to
sequester biological and chemical contaminants of runoff, providing significant potential for reduced spread of phytopathogens, animal coliforms, and other organisms of public health concern (13).

The main environmental concerns in PAM use revolve around polymer purity, and issues related to biodegradation and/or accumulation. Polyacrylamide biodegrades very slowly, and its long-term effects on organisms is unknown. Arguably, PAM accumulation is insignificant at the application recommended in the NRCS standards. Sojka and Lentz (7) showed that only 1 to 3 percent of applied PAM leaves fields in runoff and that this is quickly adsorbed by entrained sediment or ditch surfaces. Barvenik (14) noted that anionic PAM is safe for aquatic organisms at surprisingly high concentrations, with an LC$_{50}$ that is 10 times the inflow dosage rates.

Care must be taken by PAM suppliers, however, to ensure that polymer purity is carefully maintained, since the acrylamide monomer (AMD) used to synthesize PAM is a highly toxic tetratogen, carcinogen, and neurotoxin. Suppliers are generally required to supply PAM with AMD concentrations of less than 0.05 percent to ensure that minimal amounts of monomer are released into the environment (14). Reportedly, the first step in the biodegradation of PAM is early removal of the amine group from the polymer backbone (15-20), with reversion to AMD thermodynamically unfavorable. Polyacrylamide has been used for decades as a soil conditioner, in food processing, and in potable water treatment processes; presumably, the risk of monomer presence is not insurmountable in these applications.

**Biopolymer Alternatives to Pam**

Polyacrylamide’s successful use in irrigation water to reduce erosion and improve infiltration has raised questions of whether it is the “best” polymer for the application and has raised the need for PAM alternatives for organic farming consideration. Recent studies with biopolymers such as charged polysaccharides (21-24), whey (25), and industrial cellulose derivatives (21, 25) introduce potential biopolymer alternatives to PAM. Biopolymer alternatives to PAM would generally degrade more rapidly and provide marketing advantages due to the relative safety of natural compounds.

Cellulose and starch xanthates were among the first industrial biopolymers shown to stabilize soil. Orts *et al.* (21) added cellulose xanthate to the irrigation water of lab-scale mini-furrows, and reduced erosion 80 percent when xanthate was applied at concentrations of 80 ppm or greater, which is well above the standard PAM application rate of 5 to 10 ppm. Chitosan, the biopolymer derived from crab and shrimp shells, was shown to reduce erosion losses as effectively as PAM in lab-scale mini-furrows at concentrations of 20 ppm. In field tests, chitosan reduced erosion-induced soil losses by roughly half of the control, but far less effectively than PAM. Such poor comparative results, however, do not mean that chitosan had no effect on the irrigation (26). Observations of the furrows treated with chitosan revealed remarkable results in the first, roughly, 20 meters of the furrow. In fact, chitosan acted as such an effective flocculating agent that it removed fine sediments, and even algae from the irrigation water. Chitosan bound so readily with sediment that it flocculated out of solution near the top of the furrow.

Innovium, a small company based in St. Louis, MO, has developed a series of PAM alternatives, an array of novel biopolymers (25) for wide-ranging commercial applications, including water clarifiers, flocculating agents, and erosion control. They have shown that natural and modified polysaccharides, as well as polyamino acids, represent a family of novel biopolymers that exhibit efficacy similar to commercial PAM with less concern about the environmental impact of AMD (monomer composition) of PAM. These polymers have been used to treat suspended soils in agricultural waters, waste streams from animal husbandry operations like dairy, pig, poultry, and fish farms, waste, and process streams in the paper industry.

**Summary**

The success of PAM in agricultural erosion control opens the possibility to explore other uses for PAM, as well as the need to find alternatives to PAM. For example, modified polysaccharides, especially modified starch and cellulose, cheese whey, and amino acids all provide efficacy similar to PAM in stabilizing soil and treating water.

**References**


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The history, current status, and environmental safety of polyacrylamide use for agricultural and land management was thoroughly reviewed recently (Sojka et al., 2007). Included was a review of biopolymers, whose application in this area is only now emerging as a possibility, and for which there is only scant documentation in the scientific literature. Polyacrylamide (PAM) and a number of related synthetic polymers have been used extensively since the 1940s for soil structural management, sewage dewatering, paper manufacturing, a variety of mining, drilling and industrial applications, as well as potable water treatment, in food processing, in animal feed mixtures, and in certain pharmaceutical preparations. This summary focuses essentially on large molecular weight (12 to 15 Mg/mole or larger) anionic formulations of water soluble (i.e., linear or non-crosslinked) PAM, formulated to contain less than 0.05 percent free acrylamide monomer (AMD). These PAMs are widely recognized as being the least problematic (least toxic) in environmental applications. This paper will not address gel-forming (cross-linked, or super-water absorbent) PAMs. There is growing interest in gel-forming PAMs, particularly as a sealant material, but review of their history and use would require separate consideration for adequate coverage.

In agricultural and environmental applications, two PAM properties have drawn the most interest. These, or derivative properties, are largely driving research and application development. The first is its ability to bind small mineral and organic particles, which provides both for flocculation enhancement in aqueous suspensions and soil structural stabilization. The second is its ability to change the infiltration of water into soil or other porous media (positively or negatively, depending upon application strategy and properties of the soil or sediment). These two properties result from the physico-chemical attributes of the molecule (mainly molecular weight or chain length, charge type, and charge density). The expression of these attributes in managed processes varies depending on product formulation attributes (granular, emulsion, concentrated aqueous solutions or suspensions), aqueous concentration, water quality (electrolyte species and concentration), and site-specific application scenarios.

In irrigated agriculture, PAM has been very successful at reducing irrigation-induced erosion in both furrow and sprinkler irrigation when dissolved in irrigation water at rates of 1 to 10 ppm. The 1 ppm application rate is generally used as a continuous application strategy, whereas the 10 ppm rate is usually only added in the initial phase of an irrigation event. Space limitations prevent detailed examination of the differences, but, in general, 1 ppm continuous application tends to result in more total PAM use and slightly less effective erosion control, especially early in the irrigation; the 10 ppm strategy tends to improve erosion control and reduce total PAM use (Lentz and Sojka, 2000). In all irrigation scenarios, the per acre application rate is generally 1 to 2 lbs per acre (approximately 1 to 2 kg per hectare) per treated irrigation, with seasonal application totals usually in the range of 10 lbs per acre (approximately 10 kg per hectare). Total application amount varies considerably depending crop type, season length, and number of irrigations requiring treatment, and the 10 lb per acre rate is a subjectively estimated median number based on 15 years of field experience with a wide range of crops and crop cultural scenarios. In addition to dissolved application, PAM is frequently applied on dry soil as a powder “patch” at the inflow point in furrow irrigation before irrigation begins. Water flowing over the powder patch slowly dissolves the PAM and doses the flow, providing performance comparable to the dissolved application method in most situations (Sojka et al., 2003). Experiments have demonstrated that PAM losses in return flows are usually in the range of 1 to 3 percent, and that where return flows combine with sediment laden flows from non-treated...
neighboring fields, the PAM floculates the encountered sediment such that PAM is effectively removed completely from the collective return flow in a few hundred meters (Lentz et al., 2002).

When PAM is added in this fashion, the usual result on recently tilled soil (freshly formed furrows or following cultivation) is maintenance of a slightly higher infiltration rate for several irrigations with PAM treatment than in the absence of PAM treatment. The increases are typically in the range of 15 percent and can be more or less, depending on soil properties and surface conditions at the time of treatment. This has been seen both for furrow irrigation and for sprinkler irrigation. As time goes on, after repeated irrigations, the infiltration advantage eventually decreases. The decline is reliably delayed with small additions of PAM in subsequent sprinkler irrigation, because it helps prevent detachment caused by droplet impact; however, with furrow irrigation, this is less consistent. Use of PAM on course-textured soils (sandy soils, especially uniformly graded sands) usually provides less erosion reduction and either no increase in infiltration or slight decreases in infiltration (Trout and Ajwa, 2001). This is because few fines are detached by shear forces in coarse textured soils, and the slight increase in water viscosity (as well as possible PAM structural effects on water flowing in soil pores) impedes water entry into soil pores. The effects on furrow infiltration provide expanded furrow irrigation management options to farmers, which can improve water application efficiency and spatial uniformity if properly managed (Sojka et al., 1998a,b). Again, space limits complete coverage of this aspect, but it is fully reviewed in Sojka et al. (2007).

Effectiveness of PAM as a flocculating agent is not limited to soil mineral or organic particles. Polyacrylamide reduces the amount of microorganisms and weed seeds in runoff water (Sojka et al., 2003; Sojka and Entry, 2000). This is an important side benefit that reduces the vectoring and epidemiology of weeds and soil-borne diseases. This is true both within an individual farm field and where return flows are collected and reused by down-stream irrigators, resulting in benefit on an irrigation district scale. The reduction in vectoring can be assumed to result in reduced need for pesticide and herbicide application.

Because PAM used for irrigation erosion control has typically prevented 10 to 20 tons per acre of sediment loss to return flows in the Pacific Northwest, with similar effectiveness in other areas, there has also been significant reduction of nutrients, pesticides, and biological oxygen demand (BOD) deliveries to rivers and other riparian waters in return flows. Since PAM is used for irrigation-induced erosion control on upwards of a million acres, total annual sediment reduction is estimated to total more than 20 million tons. This also means prevention of thousands of tons of nutrients and hundreds of pounds of pesticides from entering rivers and other riparian waters via return flows.

Polyacrylamide degradation in soil is not easy to determine because of the difficulty of separating sorbed PAM from soil, and because of the difficulty of discriminating PAM from naturally occurring soil organic matter once added to soil. Recently, Entry et al. (2008) used natural isotope abundance ratios of carbon and nitrogen to determine degradation rate of PAM in several soils. Their findings confirmed earlier estimates that PAM degrades at a minimum of about 10 percent per year. Since PAM additions for agricultural uses typically involve only 10 to 20 pounds of PAM per acre annually, PAM buildup in soil is negligible, in view of the fact that an acre six inch slice of soil has a mass of approximately 2 million pounds.

Several reports have also determined that PAM applications at agricultural rates have little or no significant effect on soil microbial populations, function, or community structure. Even when PAM was added at rates of up to six tons per acre (three orders of magnitude greater than agricultural rates), the effects on microbial population, function, and community structure were minor, and not consistently significant (Sojka et al., 2006).

Perhaps the chief concern of skeptics regarding PAM use for environmental protection and management has been related to product contamination with acrylamide monomer (AMD). The U.S. Department of Agriculture, Agricultural Research Service (USDA-ARS) and Natural Resources Conservation Service (NRCS), have specified use of specific PAM formulations for erosion control and infiltration management. The PAMs specified are anionic, 12 to 15 Mg per mole or larger molecular weight containing no more that 0.05 percent AMD. These are the same PAMs used for food processing and drinking water treatment. Acrylamide monomer is rapidly decomposed in biologically active soil and water, with half life values reported in tens of hours. Acrylamide monomer uptake by harvested plants grown in PAM-treated soil could not be detected in corn, potatoes, or dry beans (Bologna et al., 1999). Polyacrylamide does not degrade to AMD at temperatures and pressures common in the natural terrestrial environment. Recent reports quantifying AMD content in common baked and cooked foods make it clear that human exposure risk to AMD within the general population is far more likely either via ingestion or dermal exposure from these food sources than through human exposure to treated soil, treated irrigation water, or raw harvested food grown with exposure to PAM containing these low levels of AMD.
Acrylamide monomer exposure risk to individuals applying PAM is also very low if precautions common to application of all agrichemicals are adhered to. The low health risk of AMD contamination when following common safety measures has been confirmed via safety studies in the PAM manufacturing industry. A legitimate scientific question remains as to some of the potential breakdown products of PAM or of AMD in the natural environment. These questions, however, should be weighed in the context of our experience with PAMs. After over 40 years of ubiquitous use of PAMs for the numerous sensitive applications noted earlier, often with overland disposal of solid residuals containing high levels of sorbed PAM, there has been little if any substantiation of significant problems arising from controlled processes and proper application rates. Currently, PAM use for erosion and infiltration management represents less than 1 percent of total PAM consumption globally.

Because the most common raw materials used for synthesis of the chemical precursors of PAM are natural gas and petrochemicals, concerns regarding future pricing and future availability of these raw materials have arisen. Furthermore, environmental and safety perceptions (founded or unfounded) of PAM as an applied synthetic chemical have made some individuals and some water and agricultural regulatory authorities wary of embracing PAM-based environmental protection strategies. These factors have prompted a growing interest in identifying naturally occurring polymers, or bio-based polymers, that perform all or some of the same functions of PAM. To date, there has been only limited success in identifying compounds that work as effectively as PAM at similar application rates.

Potential advantages of biopolymer chemistries could include the possibility of turning certain organic waste streams into value-added products, conceivably the ability to produce them in bio-reactors, and potentially compounds that breakdown more completely in the environment via known benign pathways. Among the more promising categories of biopolymers examined to date are polysaccharides, starches, chitins, proteins, and cellululosic micro-fibrils. The results of a series of tests (Orts et al., 1999, 2000, 2001, 2002, 2006; Sojka et al., 2005) demonstrate that many of the same constraints on PAM efficacy also impact biopolymer efficacy. One of the greatest challenges in synthesizing biopolymers of comparable efficacy is the ability to polymerize chain lengths comparable to high molecular weight PAMs. For example, when creating large chain polysaccharides, aqueous solubility and molecular stability in storage become problematic. The larger amount of materials needed for comparable erosion and infiltration results in studies to date have commonly been six to 10 times the amount of PAM for comparable results. This may not be a problem for pricing, however, it could present a handling and application challenge. Experiments conducted to date have also shown that bench-top tests of flocculation effectiveness and mini-rill erosion prevention have not translated well to field results. This suggests that fundamental differences in these organic molecule conformations may interact with soil and water in large-scale dynamics differently than what has been possible with PAM and related chemistries.

In conclusion, PAMs and biopolymers have a very robust potential for use in creating highly effective and user-friendly technologies that safely protect water quality and improve water quantity management in the environment. Specific technical implementation hurdles, safety issues, and environmental concerns identified by farmers, water managers, and environmental stewards have been and continue to be rigorously and comprehensively investigated. A formidable body of refereed scientific literature has consistently shown little if any verified risk to the environment or to humans from anionic PAMs applied for erosion control, pond clarification, soil stabilization, and infiltration management when using molecular weights of 12 to 15 Mg per mole or larger and containing 0.05 percent AMD or less, when applied according the NRCS guidelines. While there are some systematic differences when using PAM for canal and pond sealing, the data to date (some presented by others in this forum) have not identified significant evidence of substantive or consistent new environmental or health problems from this emerging new PAM use. While biopolymers should be explored as potential additional new tools for these same uses, we must recognize that development of biopolymer-based techniques is decades behind the existing potential for environmental benefit currently available through responsible use of PAM. In making judgments of environmental and health risks from the use of PAM to accomplish the benefits described in this paper, it is incumbent upon the regulatory community to make full system comparisons of the environmental impacts of the alternative technologies they would substitute for PAM. These should include whether competing technologies provide comparable water quality improvements, whether the production, transportation, and on-site application of the technologies have equal or greater negative environmental impacts (including construction damage to ecosystems and as regards such issues as human fatalities associated with production, transport, and application of alternate materials, and in the case of cement linings, carbon footprints from the transport and curing of the cement, as well as examination of potentially toxic exudates from alternative lining materials – issues that have received scant if any analytical attention), and finally whether the higher cost of the conventional alternative
technologies, which limits the range, extent, and speed of their deployment for environmental benefit, should be in and of itself factored as a further environmental risk.

The PAM manufacturing and retail industries have an enlightened self interest in enabling independent analytical work to quickly resolve remaining questions regarding safety and/or relative risk from PAM and AMD breakdown byproducts in these environments. They should be strongly encouraged to robustly communicate and partner with the public sector to overcome any regulatory hurdles. Possibly the simplest first step could be seeking an economical means of limiting AMD in the manufacturing process by at least another order of magnitude below the current 0.05 percent level, or less if possible. The growing importance of water quality and water supply issues in the U.S. and globally in the coming decades provides strong societal motivation to overcome the hesitation associated with wider and more rapid deployment of proven PAM technology. The six hundred million acre current extent of irrigated land globally, and the concomitant extent of unlined water delivery canals servicing this irrigated landscape speaks loudly to the potential market for delivery of this new technology. The devastating droughts seen in the U.S., Australia, and Africa in recent years also speak to the urgency of having the ability to deploy a rapid, simple, and effective technology capable of the typical 10 to 40 percent seepage loss reductions measured in tests with PAM sealant to date. All will benefit by moving forward decisively to resolve the few remaining barriers to full acceptance and enthusiastic promotion of this technology by environmental and agricultural regulatory authorities. With coordination and cooperation among commercial and public sector entities having a stake in the potential benefits to be derived from the perfection and prudent deployment of these PAM agricultural, environmental, and water resource management applications, remaining questions can be quickly resolved and significant public benefit can be derived at substantial cost and time savings. Put another way, taxpayers stand to benefit both from greater efficacy of water quality and water quantity stewardship implemented at a much reduced cost compared to conventional alternatives.

References


Dr. R.E. Sojka is a retired soil scientist. In January 2008, he retired from the USDA Agricultural Research Service after nearly 30 years with the agency, where he spent the previous four and a half years as the director and research leader of the Northwest Irrigation and Soils Research Laboratory in Kimberly, ID. He is the author or coauthor of 250 scientific papers. He is a Fellow of the American Society of Agronomy and Soil Science Society of America. He has received research awards from the Soil Science Society of America, American Society of Agricultural and Biological Engineers, The Federal Laboratory Consortium, The International Erosion Control Association and from the Agricultural Research Service. Dr. Sojka led a team effort in the 1990s to develop use of food-grade polymers, including PAM and several new biopolymer formulations, to halt irrigation-induced erosion, improve runoff water quality, and improve infiltration management. Dr. Sojka and colleagues have continued research to expand PAM and biopolymer technology for use with sprinkler and drip irrigation. Address: 2506 Laurie Lane, Twin Falls, ID, 83301; Email: bluejaye@cableone.net.
Innovium LLC is a St. Louis-based chemical company developing new products from renewable raw materials using patent pending “green” chemistry. By combining chemistry with nature, Innovium is able to transform polysaccharides and amino acids into high-performance products, which can be used in a number of industries.

In cooperation with the U.S. Department of Agriculture-Agricultural Research Service (USDA-ARS), Innovium developed its first product, SoilSentry™ (see www.soilsentry.com) to prevent erosion, improve infiltration and improve water utilization in irrigation farming. SoilSentry™ is a green alternative to high molecular weight linear anionic polyacrylamide (LA-PAM). In comparative field studies performed by USDA-ARS in Kimberly, Idaho, the product performed well against PAM in both furrow and sprinkler irrigation trials. The product was commercially launched in fall 2006 in Imperial Valley, California, and has been successfully applied to over 7,000 acres over the past two years.

SoilSentry™ exploits a synergy discovered between polyacrylamide and a heat-modified polysaccharide. By combining the two ingredients, Innovium is able to get a similar dosage response to LA-PAM in a formula that contains 83 percent polysaccharide and 16 percent LA-PAM. The product has a favorable environmental footprint, is readily biodegradable, and reduces exposure to the acrylamide monomer, which is present in all polyacrylamides. The product is sold in solid form to a distributor who puts it into solution for ease of handling and improved dosing consistency, allowing it to be dispensed through simple battery box technology.

Innovium has developed a second-generation formulation that has 92 percent polysaccharide and 8 percent polyacrylamide, which has similar performance to PAM, but because it was slightly more costly to produce and the market was indifferent about the need for reduced PAM, the work was put on the shelf. In addition, Innovium was working on a completely PAM-free product, and produced several viable candidates, but again shelved the work as a result of market indifference. With the proper support, these programs could be re-initiated to produce a completely biodegradable PAM-free product.

SoilSentry™’s mode of action is the same as PAM. It acts as a strong soil flocculation agent, attracting small soil particles, which have been disaggregated, to it and forming larger stable aggregates, which eventually settle out of the water. In this respect, it redistributes fine particles, making them into larger aggregates. By preventing these small particles from percolating into the soil, the interstitial spaces created by cultivation are preserved and the soils are able to take on more water. Both PAM and SoilSentry™ reduce the rate of infiltration loss, however, SoilSentry™ has demonstrated an added benefit in both laboratory and field trials by increasing the rate of water uptake by the soils. This has the effect of slowing the advance rate across the field, under equivalent water flow conditions, which is not necessarily desirable. To compensate for this, slightly higher water flow rates are recommended when using SoilSentry™ to allow the field to be more evenly watered.
In comparative commercial field trials, SoilSentry™ was applied to one 70-acre field planted with sugar beets. In a second, adjacent 70-acre field of sugar beets PAM was applied. Irrigation on the field on which PAM was applied had been underway for a day when a severe thunderstorm hit the valley. One inch of rain fell over a two-hour period in an area that gets about two inches of rain annually. The soil was a medium heavy soil with a relatively high clay content. The farmer was concerned that he would lose his crop, as these types of rains cause the soil to seal and crust over when the sun comes out. SoilSentry™ was applied to the field over the next 72 hours with the irrigation water to promote plant germination. Both the field that had the PAM application and the field with the SoilSentry™ application had a normal stand and the yields were equivalent. Both SoilSentry™ and PAM kept the fields from crusting over so the plants germinated normally. The farmer was pleased with the results, as he thought he would have to plow both fields under and replant because of the rain.

In another comparative field trial, SoilSentry™ was applied to an alfalfa field in the Imperial Valley of California, after it was initially watered via sprinklers to germinate the crop and establish the stand. The soil was very light and sandy, and very prone to cutting and channeling with the high-velocity water flow applied to the field. Approximately 3.5 to 5 cubic feet of water per second containing SoilSentry™ was applied to the field directly out of the head ditch. Ultimately, with SoilSentry™ in place, there were no visible signs of erosion, no channeling between borders, and no erosion on the borders.

Via sprinkler irrigation, SoilSentry™ was applied to a lettuce field to improve bed stabilization and prevent collapsing and separation along the seed line. The soil was a light sandy mix, which makes it difficult to maintain bed integrity. When the furrows collapse, separation occurs along the seed or transplant line, exposing roots. If not corrected, this can eventually lead to an uneven stand, nonuniformity of the produce, as well as loss of yield. In the end, SoilSentry™ worked to minimize collapsing problems and stabilize the bed.

Mark A. Hochwalt is President and CEO of Innovium LLC. He has worked in the specialty chemical, agricultural, and pharmaceutical industries for 32 years in various capacities for Monsanto, Solutia, and ValuGen LLC. He has held P&L responsibility for three global specialty chemical businesses while at Solutia. He has founded and launched a successful consulting practice that focuses on manufacturing improvement and strategic marketing in the manufacturing sector. He is an industry advisor for biomaterials for the European EpoBio initiative. Mark has launched businesses involving amino acids, odor control, and metal working fluids. He designed and built plants supplying key raw materials supporting the Nutrasweet® and Roundup® businesses while working for Monsanto. He has broad knowledge and experience in the global chemical industry with particular emphasis in the areas of amino acids and related compounds. He has a B.S. in chemical engineering from the University of Cincinnati.

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Introduction

Gunasekaran and Roa-Espinosa have developed an inexpensive process to make a strong, nontoxic, biodegradable adhesive from slaughter house animal blood; a patent application for this invention is being filed by Wisconsin Alumni Research Foundation (Gunasekaran and Lin, 2007, ‘Glue from slaughterhouse animal blood,’ U.S. patent pending). Aicardo Roa-Espinosa (Soil Net LLC) has developed a biodegradable acrylamide polymeric binder for dust and mulch control and for other applications. In preliminary trials, Gunasekaran and Roa-Espinosa have discovered that a blend of these two polymers is a superior binder, both in quality and in cost, for various applications. Therefore, Gunasekaran and Roa-Espinosa are actively pursuing different applications for the combined adhesive. Gunasekaran and Roa-Espinosa have identified several applications where there is a tremendous demand for inexpensive and biodegradable binders. The binder strength characteristics provide an excellent alternative for applications in:

a) irrigation and drainage channels, b) park trails, nature walks, and bike paths, c) fertilizer binder, and d) mulch binder.

Objectives

The objective of this work is to develop a low-cost binder for soils, sand, gravel, mulch, and fertilizer pelletizing applications. The goals are to:

1. Blend blood-based adhesive and acrylamide binder (P500) and characterize the blend properties such as bonding strength, moisture resistance, storage stability, etc.
2. Develop suitable protocols for end-use application of the new binder (i.e., quantity used, duration of application, drying temperature and time, etc.).
3. Test the effectiveness of the binder in comparison with existing alternatives such as melanine urea formaldehyde (MUF), urea formaldehyde (UF), polyvinyl alcohol (PVA), for moisture resistance, UV resistance, and durability of the glue line with time.

Materials and Methods

Six adhesives were investigated: PVA, phenol formaldehyde (PF), G-Bond (A, B, and C), and Soil Net S-500-PD. The PVA and PF were chosen to validate the method used to age the samples. This PVA behavior was known to be highly variable under conditions of temperature and humidity.

The PF, PVA, G-Bond, and S-500-PD bonded the sugar maple wood strips that were cured in a hot-press. The adhesives were used to bond 5-mm-thick, 5-mm-wide, 100-mm-long plywood sticks, cardboard, and cardboard strips. Standards were used to test the method for shear strength properties of adhesive bonds by compression loading. To avoid deformation and maintain the stress during the compression test, a metal plate was glued to the surface of the sample.

G-bond, PVA, and PF are affected by water, but not the S-500-PD. The maple strips and the cardboard strips were tested by submerging them in water for 24, 48, and 72 hours. The duration of the test in water was one week, with conditions where the maple wood strips were submerged in water. The hygromechanical properties of the adhesive indicate that the wood components fail or separate. High moisture content also can induce fatigue of the joint wood.
Figures 1, 2, and 3 show the experimental G- Bond, the maple wood strips, and the cardboard. The shear strength of the adhesive was measured dry; the shear strength of the wet wood strips was also measured.

Results and Discussion
Tables 1 and 2 present the results of the adhesive after the drying cycle. The results are also illustrated in Figures 1, 2, and 3. It is important to note that the wetting cycle had modified the hygroscopic equilibrium of the samples. The measurement of the shear strength in Table 1 compares the dry with the wet conditioning cycles.
The adhesives evaluated in this study show small differences in initial shear strength. The shear strength values show that the S-500 PD is a much better adhesive, the natural combination of the G-Bond and S-500 PD produces a binding adhesive with better strength than the PVA at a much lower price.

In Tables 1 and 2, three trends can be observed: G-bond, the PF, and S-500 PD appear to have different behaviors from each other. The statistical analysis confirmed these differences with a significant ([alpha] = 0.01) interaction between the type of adhesive and the impact PF water and humidity on the shear strength.

Table 1. Shear strength of strips of hardwood pale with PVA.

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>S-500 PD</th>
<th>Control PVA (polyvinyl alcohol)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength (Dry in N)</td>
<td>1,050 ± 58</td>
<td>1,107 ± 89</td>
<td>1,012 ± 108</td>
<td>7,800 ± 23</td>
<td>600 ± 69</td>
</tr>
<tr>
<td>Shear strength (Wet in N)</td>
<td>380 ± 37</td>
<td>630 ± 24</td>
<td>490 ± 33</td>
<td>4,800 ± 46</td>
<td>fell apart in water</td>
</tr>
</tbody>
</table>

Phenol formaldehyde and the G-bond behaved as expected. A significant decreasing relation was observed, showing a linear loss of shear strength as glue. The PF and G-Bond are affected by water; the water reduces the adhesive power to one third of the dry shear strength values. The PF and the G-Bond adhesives had a behavior similar to the PVA adhesive, except for the initial shear strength value. The initial shear strength was found to be significantly different. This indicates an overall weaker performance for PVA when compared to the PF and the G-Bond. The shear strength linearly decreased with the water and humidity. The relationship between the adhesives dry and in water was significant.

The S-500 PD showed a difference in behavior when compared with PF and the G-Bond. When S-500 PD was immersed in water, the shear strength decreased only to half, which means that the S-500 PD was more efficient as a glue. The S-500 PD, when immersed in water, decreased the shear strength due to the hydrolyzation process. In the present study, the water affected the adhesive by contact in the composite material. Since the PF resin and G-Bond process blood had an identical behavior (Table 2), it is believed that water in the sample hydrolyzed the glue line of the strips. The shear strength decreases due to changes in the conditions of the glue. The S-500 PD adhesive showed no shear performance decrease when submerged in water (Figures 4 and 5). This means that over the span of the wettings and dryings, this adhesive had a better performance than the PF and G-Bond.
The presence of water on the wood induces glue-joint fatigue. Water decreases hydrolyzation of the adhesives, which amplifies wood shrinkage and expansion. After the glue sticks were set in water, the glue line was tested for shear strength and the results showed that the four adhesives could be classified on the basis of their performance. Shear strength differences between the PF, G-bond, and the PVA adhesives were significant. The S-500 PD was the strongest, followed by PF and G-Bond, while PVA was the weakest. The tests revealed that, with PVA, PF, and G-Bond, the shear strength of the glue line declined to one third. On the contrary, the performance with the S-500 PD adhesive declined to half. A classification of these adhesives would therefore be: PVA is the least resistant to moisture conditioning, followed by PF and G-Bond, with the S-500 PD exhibiting the highest and most constant performance. Actually, the S-500 PD showed resistance to water degradation.

Aicardo Roa-Espinosa received his PhD in 1986 from the University of Wisconsin-Madison. His area of specialization is soil and water engineering. He is currently President of Soil Net LLC, a polymer solutions company. He is also a Visiting Professor of Biological System Engineering at the University of Wisconsin. Soil Net LLC provides polymer and polymer solutions and technology for fertilizer and equipment companies for slow-release fertilizer, fertilizer binders, and conversion of any byproduct into fertilizer. Soil Net has formed alliances to build a “World Center of Bioprocess” of any byproduct from ethanol, sugar, coffee, cassava, beer, paper sludge, or municipal waste at the Center for Tropical Agriculture in Cali, Colombia (CIAT). The alliance formed includes the largest paper mill in Latin America and four large sugar mills in Colombia. This sugar mill crushes 40,000 tons/day and produces a waste of 500,000 gallons/day of molasses spillage. Soil Net has also formed an alliance with South Crown Industries and Commerce of China to provide polymer technology to Southeast Asia.
The Southeastern Colorado Water Conservancy District comprises approximately 250,000 acres of scattered irrigated land along the Arkansas River basin, from near the headwaters to the Kansas border. The District wholesales water that is imported by the Fryingpan-Arkansas Project from the Colorado River watershed. This water goes to agriculture and communities that serve a population approaching one million people. The communities served include Colorado Springs, Pueblo, and numerous other smaller towns and cities near the Arkansas River and Fountain Creek. Traditionally, these communities have accounted for approximately 25 percent of water use, while agricultural use accounted for 75 percent of water use. Following the drought that began in 2001, municipal entities began requesting more water and storing it in Project facilities.

Various tools have been implemented by farmers and canal companies to increase water efficiency. These improvements include, but are not limited to, tailwater return flow systems, center pivots sprinkler systems, canal and lateral lining, using buried pipe to replace open ditches, and gated.

In short, many approaches have been tried, including the use of polyacrylamide (PAM). Some of the major canal companies have cooperated with the Bureau of Reclamation using PAM to reduce seepage from their canals. These improvements not only save water, but also save labor.

In trying to conserve water, however, the farmers in our district now face a new issue due to the Kansas/Colorado Compact. Improvements to irrigation systems must not violate the compact. The Water Division 2 Engineer, whose office regulates the waters of the Arkansas River, has released Draft Rules that basically state that all saved water must be returned to the river system and, essentially, be sent downstream to be in compliance with the Arkansas River Compact. The use of PAM is considered by the State of Colorado to be a structure as defined in the compact.

Robert (Bob) Hamilton is a Registered Professional Engineer, and since 2001, the Director of Engineering and Resource Management of the Southeastern Colorado Water Conservancy District, which is headquartered in Pueblo, Colorado. Bob is responsible for the allocation of Fryingpan-Arkansas Project water sold to the District by the U.S. Bureau of Reclamation. He is also responsible, with the Division Engineer, for the Winter Water Storage Program on the Arkansas River. Prior to coming back to Southeastern Colorado, for 14 years, Bob was Utilities Manager for the Cambria Community Services District in San Luis Obispo County, California. As Utilities Manager, he was responsible for the District water conservation plan. After graduating from Cal Poly, San Luis Obispo, with a BA in Agricultural Engineering, Bob worked for Foxley Cattle Co. in southeastern Colorado. At Foxley, he was responsible for the delivery of water to the 30,000 acres that Foxley owned. In this capacity, he was responsible for making improvements to the irrigation systems. These improvements include the design and construction of tailwater recovery systems, underground pipe systems and center pivot sprinkler systems. He was also a Board member of the Southeastern Colorado Water Conservancy District for whom he currently works.
The Coachella Valley Water District (VWD) in southern California is responsible for water, wastewater, irrigation, and flood control in a 1,000 mi² valley. The valley receives 3 inches of rain annually, and annual water use is about 700,000 acre-ft. Water is imported from watersheds approximately 120 mi to 400 mi distant. The water delivery system at Coachella VWD is described as efficient—canals are lined, plastic tubing has been put in place, and water is delivered to crops by drip system. Within this system, no return flow (“tail-water”) is collected, i.e., passed down the ditch, so-to-speak, and there is little “escape” water. Water issues at Coachella VWD appear to be somewhat different from those at other irrigation districts presented at the workshop. Seepage does not seem to be as pervasive as in other water districts. There are small, perched aquifers of brackish water, which will likely be harvested, desalinated, and introduced to the system as agricultural water. Saline water brines resulting from the desalinization process will be released to the Salton Sea.

Panel questions posed and discussed by the Coachella VWD include: challenges in managing water delivery for irrigated agriculture—do more with less; desired uses for polyacrylamide (PAM alternative: replace concrete liners; benefits and risks associated with PAM: cost reduction balanced against liability; desirable characteristics for PAM alternative: inert, impermeable, inexpensive; additional knowledge for PAM alternative: fate and transport; state and federal regulatory support needed: assume liability.

The Coachella VWD will not be applying PAM for three main reasons: PAM is used with the best of intentions, with very little data on health risks, and because the liability of its use is unclear. Available data on health risks for PAM mention bioaccumulation and bring up questions as to degradation, which raise a red flag for its use at Coachella VWD. Additionally, the Coachella VWD manages a single basin, so it also functions as a steward of the local groundwater. If there is potential for PAM use in water delivery canals to cause unintended negative consequences to other water resources, its use cannot be supported at Coachella VWD.

In further explaining why PAM will not be applied, the Coachella VWD draws parallels to the use of methyl tertiary butyl ether (MTBE). Initially, MTBE was used with best of intentions, with uncertainties to the fate, transport, and breakdown, with little data on health risks, and undefined liability if something went wrong. For instance, MTBE was used for cleaner air and PAM would be used to increase water efficiency. Though PAM is used as a floc-aid in the drinking water industry, it is used in a tightly controlled setting and the monomer is viewed as a hazard. The acrylamide monomer (AMD) is difficult to test for, and cannot be done at low levels. In the future, further testing may reveal it is hazardous at levels we could not previously test for. If birth defects are caused by the monomer, there will be significant problems.

Legal issues surrounding the use of PAM were raised and re-iterated by the Coachella VWD. Presently, it is undefined who retains the liability of PAM use. For instance, if AMD is found to be causing adverse health effects in the Coachella VWD, though the Coachella VWD is not using PAM, it will be necessary to address the source of the monomer. The Coachella VWD would be willing to trace the monomer to the upstream source and hold the user responsible for downstream damages. This example shows that the decision to use PAM must be delegated. The decision must be made by the farmer, the polymer vendor, and/or the federal government. In this case, a follow-up must also be delegated. Finally, it is unclear as to who has the money to take care of problems, should any occur.

Some closing suggestions were made for future research. First, more legal research should be done on PAM use and liability. Next, natural alternatives to PAM should be investigated. If and when these alternatives are released into the environment, it would be valuable to know what nature does with them. Also, the effects of PAM use on invasive species (such as the zebra and quagga mussels) inhabiting canals should be evaluated.
Finally, it was noted that the drinking water industry was not represented. Perhaps the American Water Works Association or a similar agency should be represented as a stakeholder. In all likelihood, they are the impacted party if there are unintended negative consequences.

Mark D. Beuhler is Assistant General Manager of the Coachella Valley Water District. Coachella provides water, wastewater, and stormwater services to urban and agricultural customers in a 1,000-square-mile service area, with total water consumption of roughly 700,000 acre-feet annually and a staff of over 500. Previously, Mr. Beuhler was in charge of Water Quality for the Metropolitan Water District of Southern California, responsible for all aspects of water quality source protection, treatment, and maintenance for the majority of the water used by the 17 million people within Metropolitan’s service area. He has 26 years of experience, including work as an engineering consultant and for a large wastewater agency. He received his Bachelor’s degree in Engineering from Tulane University and his Master’s in Environmental Engineering from the University of North Carolina at Chapel Hill. He is also a registered Civil Engineer and a Grade V Water Treatment Plant Operator.
The problem of seepage loss was readily apparent at the High Line Canal during the 2002 drought. At that time, seepage losses resulted in very little flow in the canal for end-users and those farmers faced potential crop loss. The High Line is an 87-mile canal that cannot reasonably be cement-lined. Plastic tubing, placed in areas of high seepage, has been helpful but is prone to damage from cattle. If the canal were to be cemented, some local wells may not have water.

The problem of increasing salinity of groundwater was exacerbated after thousands of pumping wells were ordered to stop (result of a lawsuit with Kansas). Water that was previously lifted and removed now remains, and seepage adds to it. Crops are essentially waterlogged.

Given these scenarios, the risks of applying polyacrylamide (PAM) may be small in light of the benefits for the High Line Canal. Polyacrylamide, or a similar product, may be needed, but more testing of canal waters and additional research on PAM and PAM alternatives must be done. The end result would be more consistent, better application methods. A simple, specific application methodology needs to be developed.

What products can be used when there is no turbidity present in the canals? In and around the community of Pueblo, CO, dams are being installed to clarify water, so it appears “pristine.” This leaves irrigators without the turbidity necessary for PAM use for seepage reduction. Alternative products would be very helpful.

Dan Henrichs is Superintendent for the High Line Canal Company, whose office is located in Rocky Ford, Colorado. The Canal was built in the 1890s, is 87 miles long, and it begins near Boone, Colorado. It flows southeast past Fowler and Manzanola, and then on south of Rocky Ford. The company has seven different water rights on the Arkansas River, and have the number 4 right of 40cfs of 1861. Their full decree is 1890 for 368 cfs for a total flow of 504cfs. Dan received his first hands-on experience in irrigation at the end of a shovel for a Dairy Farmer in Pueblo, CO. In November 1992, Dan was hired by the Bessemer Ditch Company of Pueblo, CO, as a ditch rider. He preformed those duties for seven and a half years, until being hired by the High Line Canal Company in June 2000. Dan and his wife Cindy own a small cattle ranch in Avondale, where they raise hay for their livestock. They also have two children, Zach, a senior, and Jacque, a sophomore. Both attend Pueblo County High School. Email: henrichscattle@prodigy.net; phone: 719-469-4107.
The clear need to enhance water quality and conserve water, while maintaining crop productivity and rural communities, will require structural and management interventions that include improvements in both conveyance and application efficiencies. The necessity that such interventions be cost effective poses a particular challenge to an industry that already is financially strapped.

Based upon my research experience, one of the most substantial benefits of polyacrylamide (PAM) is in lessening recharge to shallow ground-water tables via the reduction of seepage from canals. This is especially important in irrigated areas characterized by already high ground-water levels and/or by underlying geology that is high in soluble salts and metals. For example, in Colorado’s Lower Arkansas River Valley, the more than 1,000 miles of contour earthen canals that have made a productive agricultural economy possible have also contributed to saline shallow ground-water tables. One detrimental result of shallow water tables is a 10 to 15 percent drop in crop yields due to waterlogged soils and increased salt concentrations associated with evaporative upflux and concentration (Burkhalter and Gates, 2005; Gates et al., 2006). Secondly, high water tables also drive increased ground-water return flows that dissolve and pick up salts and metals (selenium and uranium) from marine shales and residuum as they make their way back to the river system (Mueller Price and Gates, 2008). Finally, shallow water tables that extend under adjacent naturally vegetated and fallow land result in substantial loss of water to non-beneficial consumptive use due to evaporative upflux (Halberg et al., 2008). Modeling studies have shown that if canal seepage can be substantially reduced, water tables can be lowered, resulting in increased crop productivity, reduced salt and metal loading to tributaries and the river, and water conservation through reduced upflux under non-cultivated land (Burkhalter and Gates, 2006; Gates et al., 2006).

An added benefit of PAM is its flexibility. It allows selective control of the timing and intensity of canal seepage. For example, in years where diversions to canals are expected to be relatively large during the early season but lower later on, it may be desirable to preserve a degree of seepage early on so as to build up ground-water storage for later use. Also, seepage may need to be controlled to provide specific targeted levels of moisture to sustain desirable wetlands or habitat. Achieving this level of management in the timing and intensity of seepage is difficult, if not impossible, with conventional lining techniques.

In addition to being environmentally less risky, such an alternative must rival PAM in its (1) effectiveness in seepage reduction, (2) ease of application, (3) flexibility, and (4) cost. From the research results that I have seen to date, I am not convinced that PAM is too risky to avert its continued use. In addition to laboratory study, such an alternative must be evaluated under actual field conditions.

At this time, it is unclear what type of state and federal regulatory support would be helpful toward the development and implementation of PAM alternatives for these uses.

References
Timothy K. Gates is a water resources systems engineer and a Professor of Civil and Environmental Engineering at Colorado State University. Prof. Gates has taught academic courses in open-channel flow, fluid mechanics, hydraulic engineering, hydraulic structures/systems, hydrology, groundwater engineering, and solid dynamics. His research has focused on analysis, design and operation of open-channel flow systems; stochastic simulation and optimization of water resources systems; modeling and analysis of shallow ground-water flow and salt transport; management and modeling of water quality (especially salinity and selenium); drainage of salinity-affected regions; multi-objective river basin planning; and monitoring and evaluation of irrigation and drainage systems. Prof. Gates has directed or co-directed numerous research projects over the last 20 years, including leading an extensive research effort involving field data collection and modeling of the irrigation-stream-aquifer system of the Lower Arkansas River Valley in Colorado for the last nine years. He has served as an independent consulting engineer with the United States Agency for International Development; the United Nations Development Program; Camp, Dresser & McKee, Inc.; Keller-Bliesner Engineering; D'Appolonia Environmental Services; Denver Water Department; Governance Committee of the Platte River Cooperative Agreement; Devon Energy; Pennaco; ARCADIS & GM; Riverside-Allen Ditch Company; Greg Lewicki and Associates; and Wastewater Department of the City of Pueblo on a variety of water resources and irrigation projects. He has designed and conducted numerous short courses and special training programs in open-channel flow, irrigation and drainage engineering, and groundwater. Prof. Gates spent a total of about four years in Egypt working on various irrigation projects, and has consulted in India, Sri Lanka, and Australia on irrigation projects. Email: tkg@engr.colostate.edu; phone: 970-491-5043.
Background

The federal regulations that apply to water quality are the Clean Water Act and the Safe Drinking Water Act. There are no specific portions of either act that apply directly to the use of polyacrylamide (PAM) or other coagulant materials in controlling soil erosion or to application to irrigation canals for seepage control. However, both of these uses raise concern for possible contamination of receiving surface water and for contamination of ground water in the areas of application. There are also potential impacts of the PAM monomer on human health as well as aquatic life, and domestic and wild animal populations.

Risk Concerns

The health and/or ecological concerns associated with the application of PAM or other coagulant materials to agricultural lands or irrigation canals relate to the coagulant materials and all associated contaminants, including monomers, adjuvants, and/or reaction byproducts found in the materials as sold. Health risks associated with decomposition products formed in the environment must also be considered when evaluating environmental risks. This means that the risk assessment for each proposed use and each potential coagulant is complex and requires toxicity data on all components of potential concern in addition to the primary coagulant material.

The U.S. Department of Agriculture (USDA) and Bureau of Reclamation (Reclamation) have both conducted scientific evaluations of the use of PAM as a coagulant to control soil erosion and canal seepage. Both agencies have taken steps to minimize environmental risks by requiring that the product applied meet prescribed specifications and be certified against American National Standards Institute/National Science Foundation (ANSI/NSF) International Standard 60 as a drinking water treatment chemical. In doing so, USDA and Reclamation have minimized environmental impact concerns because the certification process involves formulation, toxicological, and analytical evaluation of each product to ensure that the levels of product and all associated impurities, including confidential materials, fall below levels of human toxicological concern when applied under conditions specified on the product label.

Standard 60 requirements for toxicological data apply to humans as the target receptor and evaluate risk based on the at-the-tap exposure anticipated for each certified product use. Exposure levels for all analytes with at-the-tap concentrations greater than the threshold for toxicological evaluation (3ppb; ANSI/NSF, 2002) require experimental data to demonstrate a lack of genotoxicity (chemical-induced change to DNA or chromosomal structure), along with a battery of toxicological data to support development of a benchmark that is estimated to be safe for humans including sensitive populations. For those chemicals that are genotoxic, animal studies of carcinogenicity are also required. Product use levels are set to minimize lifetime risk to humans based on a tap water intake of 2 liters/day and considering other potential routes of exposure.

Standard 60 does not require consideration of receptors other than humans when establishing acceptable product use levels for potable water. Thus, reliance on use of certified materials in agriculture and/or irrigation canals should consider the possible impact on plants, aquatic vertebrates, and invertebrates, as well as domestic animals and wild life. Research on some of these receptors has been conducted for the canal application scenario.

Issues of environmental fate and persistence become more important with applications to agricultural lands and to irrigation canals than for drinking water, where the coagulant and materials it coagulates are removed from the finished product before it is delivered to the user. In the case of coagulants that remain in the environment, data
that address impact on ecosystem diversity, a variety of target species, endocrine effects, and genomic stability are increasingly important.

**Polyacrylamide Coagulants**

Polyacrylamide products certified against Standard 60 have been evaluated for their contribution of acrylamide, acrylic acid, acrylonitrile, 3-hydroxypropanenitrile, and other product-specific contaminants. Product samples are collected as part of annual audits of production plants and analyzed to ensure that the analyte levels remain below their established health-based benchmarks. Standard 60 also restricts the use levels of PAM found in certified well drilling muds and PAM well sealants based on the purity of the polymer product.

In the case of acrylamide monomer, a National Primary Drinking Water Regulation specifies that the level of polymer used as a coagulant in drinking water treatment cannot exceed 1 mg/L (ppm) and the acrylamide monomer level in the polymer must be 0.05 percent or lower (ANSI/NSF, 2002). Restriction of the levels of acrylamide monomer in the polymer products is based on its ability to cause peripheral neuropathies in humans and animals at low doses and its classification as a likely genotoxic carcinogen based on animal studies. The current U.S. Environmental Protection Agency (EPA) acrylamide risk assessment was completed in 1987. This assessment is presently being updated by the Agency. The draft revised assessment is available at: http://cfpub.epa.gov/ncea/cfm/recordisplay.cfm?deid=187729. It was peer reviewed by experts external to the Agency on February 20, 2008. Once peer review comments have been received by the Agency, they will be posted at this same internet site and the draft assessment will be revised to address the peer review comments.

**Other Coagulants**

To protect the environment and human health, it will be important to require a comparable level of toxicological scrutiny to alternatives to PAM for both human and ecological health. Standard 60 has certified other materials for use as coagulants. Table 1 is a summary of the certified coagulants, their use levels established for potable water treatment, and the analytes specified by the Standard. When compared to PAM, none of the other certified materials appears to have properties that would make them to be superior for the proposed use. Cationic and neutral PAM products do not carry the anionic charge that promotes coagulation with soil particles. Anionic emulsions, although potentially easier to apply require consideration of the ecological impact of the surfactants, oils, and emulsifying agents they contain. The emulsified PAM products are not included in Table 1. The required analytes for the emulsified products are the same as those for the dry PAMs.

Knowledge of the mode of action that promotes coagulation of soil particles in both canal sealing and furrow treatment offers the potential to develop new materials that would have the characteristics of anionic PAM yet be more ecologically friendly. Each alternative, however, should be evaluated for its efficacy for the proposed use in laboratory and field studies as was done for PAM. It will be important to establish product specifications and application guidelines that maximize efficacy and minimize health and environmental risks. Education of the applicators and other groups impacted by the proposed uses will be equally important. Applicators, farm families, and nearby residents should be informed when coagulants are to be applied. Risk communications materials should make clear the risks associated with the misuse of the coagulant materials and promote an understanding of how the prescribed application guidelines were crafted to minimize health and environmental risks.
<table>
<thead>
<tr>
<th>Coagulant</th>
<th>Use Level</th>
<th>Contaminants of Concern</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bentonite</td>
<td>200 mg/L</td>
<td>Regulated metals</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radionuclides</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base/neutral/acid scan</td>
<td></td>
</tr>
<tr>
<td>Hectorite</td>
<td>200 mg/L</td>
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<td></td>
<td></td>
<td>Radionuclides</td>
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<tr>
<td></td>
<td></td>
<td>Base/neutral scan</td>
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</tr>
<tr>
<td>Montmorillonite clay</td>
<td>200 g/L</td>
<td>Regulated metals</td>
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<tr>
<td></td>
<td></td>
<td>Radionuclides</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Base/neutral/acid scan</td>
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</tr>
<tr>
<td>Polyacrylamide/</td>
<td>1 mg/L</td>
<td>Acrylamide</td>
<td></td>
</tr>
<tr>
<td>acrylic acid*</td>
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<td>Acrylic acid</td>
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<td></td>
<td></td>
<td>Acrylonitrile</td>
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<tr>
<td></td>
<td></td>
<td>3-hydroxypropane nitrile</td>
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<tr>
<td></td>
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<td>Isobutane nitrile</td>
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</tr>
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<td></td>
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</tr>
<tr>
<td>Polyacrylamide cationic*</td>
<td>1 mg/L</td>
<td>Acrylamide</td>
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<tr>
<td></td>
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<td>Cationic monomer</td>
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<td></td>
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<td>Acrylonitrile</td>
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<tr>
<td></td>
<td></td>
<td>3-hydroxypropane nitrile</td>
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<td></td>
<td></td>
<td>Isobutane nitrile</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Product specific</td>
<td></td>
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<tr>
<td>Hydrolyzed polyacrylamide*</td>
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<td>Acrylonitrile</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>3-hydroxypropane nitrile</td>
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<td></td>
<td></td>
<td>Isobutane nitrile</td>
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<td></td>
<td></td>
<td>Product specific</td>
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<tr>
<td>Non-ionic polyacrylamide*</td>
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<td>(anionic)</td>
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<td>Acrylonitrile</td>
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<tr>
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<td></td>
<td>3-hydroxypropane nitrile</td>
<td></td>
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<td></td>
<td></td>
<td>Isobutane nitrile</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Product specific</td>
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<td>Polyamines (polyepichlorohydrin/ Dimethylamines)</td>
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<td>Maximum of 1 ppm polymer with a 0.05% monomer concentration</td>
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<tr>
<td></td>
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<td>1,3-dichloro-2-propanol</td>
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<td>1,2-dichloro-3-propanol</td>
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<td></td>
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<td>Glycidol</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Dimethylamine</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Ethylenediamine if used as a branching agent</td>
<td></td>
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<tr>
<td>Polydiallyldimethyl ammonium chloride</td>
<td>25 mg/L</td>
<td>Dimethylallyl ammonium chloride monomer</td>
<td>Limitation on residual polymer = 0.05 mg/L</td>
</tr>
<tr>
<td></td>
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<td>dimethylamine</td>
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<td>Polyethyleneimine</td>
<td>10 mg/L</td>
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<td></td>
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<tr>
<td></td>
<td></td>
<td>Epichlorohydrin</td>
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</tr>
<tr>
<td></td>
<td></td>
<td>Glycidol</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,3-dichloro-2-propanol</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>1,2-dichloro-3-propanol</td>
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<tr>
<td>Sodium silicate</td>
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<td>Regulated metals</td>
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<tr>
<td></td>
<td></td>
<td>Na₂O(SiO₂)ₙ; typically n=3</td>
<td></td>
</tr>
<tr>
<td>Starch (anionic)</td>
<td>10 mg/L</td>
<td>Regulated metals</td>
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The table does not include the emulsified polyacrylamide family of coagulants.

* If nitrogen-containing initiators are used, the product will be evaluated for the initiator and initiator byproducts.

Reference

Joyce Donohue, Ph.D. works in the Health and Ecological Criteria Division in the Office of Science and Technology at the U.S. EPA Office of Water. She has a background in biochemistry and nutrition and over 25 years of experience in assessing the toxicological properties of contaminants in drinking water. During her career she has authored toxicological profiles of chemicals for U.S.EPA, NSF International, The United States Department of Agriculture (USDA), the Agency for Toxic Substances and Disease Registry (ATSDR) and the Department of the Army. Email: Donohue.Joyce@epa.gov; phone: 202-566-1098.
The Montana Department of Natural Resources funds water conservation measures, including polyacrylamide (PAM). Montana has yet to face some of the issues that are being discussed at the conference. The irrigation canals do not typically deliver domestic water. As time goes on, however, subdivisions are likely to encroach and domestic wells will be drilled closer to the canals. Thus, now is a good time to begin considering the future of PAM in Montana. The product will be used because it is needed, but careful use will be emphasized. Regulatory state agencies to be considered are the Department of Agriculture, the Department of Environmental Quality, and the Department of Natural Resources. In ensuring careful use of PAM, it is possible that the user may need training as to product use and application.

Pat Riley is the Director of Irrigation Development for the Montana Department of Natural Resources.
SNF, Inc., was formed in 1978, and is one of the world’s largest water-soluble polymer manufacturers. Their main plant is located in Riceboro, GA. As a privately-held company, SNF feels that it is able to attend to customer needs and modify products, as necessary. Organic flocculants and polyacrylamide (PAM) are the main products. The company is certified by the International Organization for Standardization (ISO).

SNF has 700 products to choose from, and can specially blend products for unique performance. SNF also manufactures acrylonitrile, a cationic monomer, acrylamide, polyacrylamide, and powders and emulsions. Manufacture of all these products is tied to oil and oil prices. By 2012, polymer production is anticipated to double. SNF would like to be the only seller of polymers, so it keeps costs low in an attempt to discourage competition.

Main users of SNF products are industries related to potable water, wastewater (these two represent 55 percent of the business), textiles, paper, and oil. The oil industry is the single largest user of PAM in the world.

The traditional process of manufacturing acrylamide from acrylonitrile uses a copper catalyst. Conversion is approximately 94 percent. This copper process results in unreacted acrylamide and a copper contaminant. The process occurs under high temperature and pressure and requires many people to operate. More recently, the company has switched to a biological process. Conversion is 100 percent. The process uses enzymes and occurs under low temperature. No copper and no residuals occur. Bacteria are incinerated. With this process, polymers with higher molecular weight and better structure can be made.

Production at the Riceboro plant includes enzymatic acrylamide, monomers, emulsions, and powders. There is also an application equipment division, which develops the appropriate equipment for polymer use. Visitors are encouraged in Riceboro. Application training classes are conducted by Dr. Tichenor at Riceboro, or can be arranged at other locations. Correct application is stressed and some specific points are discussed. For instance, dry spreading of polymer should not be compared with solution addition. Dry polymer should be made into solution. Additionally, polymer dissolution time and mixing energy is critical. Finally, convenience should not replace safe usage practice. With correct application, dosage is lowered, as is cost, and there is less product in the environment.

Scott Ramey is the Director of Business Development at SNF, Inc.
**Introduction**

The goal of Marine Wing Support Squadron (MWSS) 272 was to develop a new formulation for multiple uses in helicopter landing and other areas where helicopters operate. Sand less than 1 mm silt and clay becomes airborne when the turbulence delivered by the propellers of the helicopters hits the ground. The larger the helicopter, the greater is the torque of the propellers and the turbulence that causes the soil particles to become airborne. This causes dust clouds that impact the visibility of the area where the helicopters operate or need to land in the theater of operations. Due to the air turbulence, the silt and clay that are electrically charged are suspended in the air; due to the static electricity charge, the dust particles will remain suspended in the air for long periods of time, making the visibility of the landings more difficult.

**Objectives**

Based on the experience acquired in the theater of operation and knowledge of the different dust abatement products, the following objectives were set during this field test:

1. The product must be easy to apply.
2. The volume of water must not exceed 500 gallons of water (maximum load of the dust-abatement vehicle).
3. The landing zone of 150 ft by 150 ft (22,500 sq ft) will be treated with 500 gallons of product.
4. The penetration of the liquid emulsion should be at least 0.5 inches to form an even layer where class 2 and 4 aircraft can safely land.
5. The treated landing zone after drying must have flexibility to prevent breaking.
6. The drying time for dust abatement must be 30 minutes.
7. The drying time for a final maximum strength must be within 12 hours.

**Materials and Methods**

Soil Net LLC of Madison, Wisconsin, provided the following products:

1. **Soil Net EM-500 PD**: The EM-500 PD is a polymer mix with the following characteristics:
   - White-bluish emulsion, with a mild odor of latex. It dries as a clear coat and does not wash off after drying. It binds very well to cloth and metal surfaces, is easy to wash when fresh, and causes no irritation to the skin or eyes of the user. The EM-500 PD binds harder when in combination with Portland cement at the ratio of 10 pounds per 100 gallons of EM-500 PD mix (50 percent polymer, 50 percent water). The EM-500 PD can be compacted with a roller if a harder surface is required.
   - Highly soluble in water; self-dispersing characteristics.
   - Low foam during mixing.
• Instantaneous dust abatement capabilities.
• Quick surface drying time at temperatures above 100 °F.
• Binding capabilities above 5,000 PSI.
• Stable up to 160 °F and below minus 30 °F.
• Specific gravity of 8.9 pounds per gallon.

2. Soil Net F-Wax is highly soluble in water with the following characteristics:
• Yellow, creamy emulsion, with a mild wax odor. It dries very quickly at 90 °F, leaving a clear, moist look, easy to wash after drying. It binds very well to soil particles, and causes no irritation to the skin or eyes of the user. The Soil Net F-Wax gives flexibility when in combination with Soil Net EM-500 PD at the ratio of two parts of EM-500 PD to one part of Soil Net F-Wax.
• Highly soluble in water and self-dispersing characteristics.
• Foams during mixing.
• Instantaneous dust abatement capabilities.
• Quick surface drying time at temperatures above 100 °F.
• Binding capabilities above 500 PSI.
• Stable up to 160 °F and below minus 30 °F.
• Specific gravity of 8.9 pounds per gallon.

**Personnel**
MSgt Moore, Engineer
MSgt Meehan, Engineer
WO Ugarte, Expeditionary Airfield
GySgt Winand, Expeditionary Airfield
Sgt Mitchell
SSgt Howe, Surveyor
Sgt Hartline, Surveyor
SSgt Jones, Heavy Equipment
LCpl Calderon, Heavy Equipment
LCpl Daum, Driver
GySgt Highter, Tech Support

**Equipment**
DAV (Dust Abatement Vehicle Version #2) (photo 1)
(1) 7.5 Ton Truck MTVR (Military Tactical Vehicle Replacement)
(1) 6 CON (900 Gallon Water Container)
(1) 125 GPM Pump and 2 Hose Sections
(1) 5 K TEREX Forklift

**Results**
The test site was divided into three landing zone areas (LZ) of 22,500 sq ft, with very little vegetation. Stakes signaling the LZ were located in four corners of the LZ. Each of the LZ areas was dedicated to a specific treatment of the EM-500PD and the F-WAX individually, and the third plot was treated using the results from LZ 1 and LZ 2.

The LZ 1 was treated with 55 gallons of EM-500 PD dissolved in 445 gallons of water. The mix was delivered with the standard DAV version #2. DAV #2 has the following characteristics:
• 5 flood jet nozzles of 10 gallons per minute at 60 PSI.
• Total delivery rate of 50 gallons per minute.
• Variable pressure by controlling the RPMs with a throttle lock, and 500 gallon water tank capacity.

The test started without noticing that the flow at the predetermined pressure and speed was too high, and the entire 500 gallons were applied in five runs of 150 ft. The result of the five runs was that the polymer penetrated from 0.5 to 0.75 in. The large drops (3 to 4 mm) hit the sand and produced a powerful mixing effect that even erased the tracks of the military tactical vehicle replacement (MTVR). The final result of this application was a very hard surface, but it used a large amount of polymer and water.

After realizing that the amount of water and product did not meet the proposed target, it was decided to change the nozzles to a TJ 20 that delivers 2.5 gallons per minute and much smaller drop sizes (1 to 2 mm). The LZ 1 was finished with another 45 gallons of polymer and 205 gallons of water. The results after changing the nozzles and the angle of application were not satisfactory in penetration, and the layer of treated sand was thin compared to the first part of the application with the larger nozzles.

The drying time was quick, and 24 hours later the LZ 1 surface was completely dry with a very thin crust. According to our experience from previous applications and the results in the theater of application, it was concluded that the LZ 1 will provide dust abatement and a hard surface for landing aircraft. If the site was to be used for repeated landings, the durability would be limited. The final volume of water was 650 gallons and 100 gallons of polymer.

The LZ 2 was treated with 50 gallons of F-WAX dissolved in 450 gallons of water. The mix was delivered with the standard DAV version #2. DAV #2 has the following characteristics:
• 5 flood jet nozzles of 2.5 gallons per minute at 60 PSI.
• Total delivery rate of 12.5 gallons per minute.
• Variable pressure by controlling the RPMs with a throttle lock, and 500 gallon water tank capacity.

The results of the F-WAX by itself were not promising. The amount of product was very similar to the EM-500 PD, with more water. Dust abatement will not be effective with this formulation. For this application, the angle of the nozzles was changed to deliver a larger contact area. These changes did not produce the expected results and were abandoned for LZ 3.

Landing zone 3 (22,500 sq ft) is located in an area where continuous human traffic has occurred, and the surface is very fine with heavy sand underneath. The fines have been moved to the surface due to impact and continuous use by pedestrians during previous training exercises (photo 2)

The decision was taken to change to the bigger original nozzles, and change the angle of deposition of the flow jet to try to reach a larger overall area. The larger cover area had the effect of preventing a double pass of the tires of the MTVR. Also by this time, the MTVR operator had become more familiar with the vehicle, and with simple commands could increase or decrease the speed of the MTVR during the application. The flow rate was controlled by this mechanism. Revolutions per minute were set to a minimum, controlling the flow, but providing the application with adequate flow and larger drop sizes.

The total area covered for LZ 3 was 22,500 sq ft. Due to the results from LZ 1 and LZ 2, the two products were mixed at the following rates per each tank of the MTVR: 55 gallons of polymer, 75 gallons of F-WAX, with a total application of 260 gallons of the dust abatement products and 740 gallons of water. The total volume of water and product was 1,000 gallons in a 22,500 sq ft area.

At a follow-up inspection after two hours, it was noted by MSgt Moore that a Dodge Durango had driven over a small area of the treated LZ 3. The results were promising because although the product was still in the process of curing, the area did not crack and was partially reestablished to 0.5 inch of the original surface.

The following day after eight hours of sun, the test site was visited. During this visit, the following conclusions were reached:
• LZ 1, treated with EM-500 PD, has dust abatement capabilities and will take the landing of aircraft, but with limited durability.
• LZ 2, treated with F-WAX, did not perform well. The site has small openings caused by bubbles of air escaping through the applied layer of F-WAX. It is likely the amount of product will be large and not cost effective.

• LZ 3, treated with a combination of polymer EM-500 PD and F-WAX, was extremely hard with some degree of flexibility. Under the 0.5 inch of penetration, the sand was still moist (photos 3 and 4). This indicates that the curing is still taking place and the surface has been sealed completely. At this site two velocities were used to see the results in the application. This site still has a very hard layer. In the areas where the pressure was able to move the sand and produce a smoothing affect of the surface, ideal results were achieved. To test the hardening of this area, a Dodge Durango was driven across the entire site. In the photos (5-8), you can see the tire tracks that slowly disappear once the vehicle reaches the treated area. The Durango weighed 4,800 pounds. With fuel and passengers the total weight of the vehicle was approximately 6,000 pounds.

Conclusions

1. The application with a 10 GPM nozzle at lower pressure was better than that at 2.5 GPM.

2. The quality of the application was dependent on the pressure and the right flow per nozzle. It is very likely that the best flow rate per nozzle will be one or two sizes smaller than the actual nozzles used during initial tests. This means nozzles with a rate of approximately 5 GPM, at 60 PSI.

3. The quality of the landing surface in reference to hardening and flexibility is more dependent on the right flow rate than the amount of water and product. The results show that the use of more water, as used in LZ 2, and more product did not improve greatly due to the lack of penetration of the product.

4. The results also show that a combination of three parts EM-500 PD with two parts F-WAX, mixed in 370 gallons of water, can treat an LZ of 110 ft by 100 ft, with the results expected in the photo showing the Dodge Durango. (photos 5-8).
Liquid Weed Mat Efficacy Study - Results

Objectives
1. Determine the effect of concentrate and carrier volume on suppression.
2. Determine the relative performance of the polymer with and without the addition of purified cement.

Treatment Summaries
TRT 1: Rate of concentrate applied
- [0 X]
- [0.05 X] 5 mL/m² of concentrate, approx equivalent to 32 mL per 2,000 ft²
- [0.1 X] 10 mL/m² of concentrate, approx equivalent to 32 mL per 1,000 ft²
- [0.2 X] 20 mL/m² of concentrate, approx equivalent to 32 mL per 500 ft²
- [1 X] 100 mL/m² of concentrate
- [2.5 X] 250 mL/m² of concentrate
- [5 X] 500 mL/m² of concentrate
- [10 X] 1,000 mL/m² of concentrate

TRT 2: Spray volume
- [500] 500 gal/A, equivalent to 468 mL/m²
- [1K] 1,000 gal/A, equivalent to 935 mL/m²
- [2K] 2,000 gal/A, equivalent to 1.87 L/m²

TRT 3: Formulation
- [A] SN2500
- [B] SN2500 + 0.2kg/gal purified cement premixed with water
- [C] SN2500 + 0.2kg/gal purified cement (cement added as powder)
- [D] same as [C] diluted 50:50 with water
Conclusions

Objective 1: Both concentrate and carrier volume had an effect on the suppression of plant emergence. We did not observe significant suppression below the 2,000 mL/m² carrier volume rate or below the 500 mL/m² rate of concentrate. The 1,000 mL/m² rate of the concentrate performed better than the 500 mL/m² rate (47 percent versus 64 percent). The crusts formed with the highest rate were stronger.

Objective 2: The formulations tested (A and D) demonstrated no differences in performance by formulation. We did not, however, test formulation D at the higher rates of concentrate. It is possible that it might have performed better, or worse, than formulation A at those higher rates. Although there were interesting correlations between the weeds emerging and the different treatments, in general, weed emergence behaved in the same manner as the four crops used to assess suppression (visual observation). Because we do not know the initial distribution of weed seeds, the emergence of the crop provides a more accurate picture of the potential of the polymer.

The crust formed by the polymer had reasonably high mechanical strength. On the scale of millimeters or centimeters, however, there appeared to be sufficient variation to allow weeds/crop to successfully emerge, despite the average strength being high enough to potentially prevent emergence. This small-scale heterogeneity may very well vary between different soil types or other environmental factors. However, the experiment, in combination with our prior work on other soils and in the greenhouse, would indicate it is unlikely that crusts strong enough to prevent emergence could be created with less than 100 mL/m² of the Soil Net 2500 polymer.

Table 1. Means and standard errors of the crust strength and average emergence of the four crop species as they relate to polymer formulation, rate of concentrate, and spray volume. The relationship between crust strength and emergence is shown below in Figure 1. Formulation A is Soil Net 2500, formulation D is Soil Net 2500 mixed with purified cement, diluted 1:1 with water.

<table>
<thead>
<tr>
<th>Treatment ID</th>
<th>Formulation</th>
<th>Rate of Concentration</th>
<th>Spray Volume</th>
<th>S Ave</th>
<th>S SE</th>
<th>N %</th>
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Figure 1. Comparison of the polymer crust strength to emergence (as a percentage of the control plots). The upper figure shows only the mean values, whereas the lower figure includes the standard error bars for both measures. As is apparent, the two treatments performed reasonably well. Both of those treatments were polymer formulation A (Soil Net 2500) applied at the highest carrier volume (2,000 mL/m²) with 500 or 1,000 mL/m² of concentrate.

Figure 2. Polymer crust strength was measured with a mechanical soil penetrometer (photograph on left). There is some variation in its operation due to how quickly or forcibly the operator presses down. Readings were standardized by subtracting the mean and dividing by the standard deviation within each block of the experiment. The photo on the right shows the crust itself.
Figure 3. Comparison of typical check/control plot with the best performing polymer treatment.

Aicardo Roa-Espinosa received his PhD in 1986 from the University of Wisconsin-Madison. His area of specialization is soil and water engineering. He is currently President of Soil Net LLC, a polymer solutions company. He is also a Visiting Professor of Biological System Engineering at the University of Wisconsin. Soil Net LLC provides polymer and polymer solutions and technology for fertilizer and equipment companies for slow-release fertilizer, fertilizer binders, and conversion of any byproduct into fertilizer. Soil Net has formed alliances to build a “World Center of Bioprocess” of any byproduct from ethanol, sugar, coffee, cassava, beer, paper sludge, or municipal waste at the Center for Tropical Agriculture in Cali, Colombia (CIAT). The alliance formed includes the largest paper mill in Latin America and four large sugar mills in Colombia. This sugar mill crushes 40,000 tons/day and produces a waste of 500,000 gallons/day of molasses spillage. Soil Net has also formed an alliance with South Crown Industries and Commerce of China to provide polymer technology to Southeast Asia.
The Workshop Attempted to:

1. Define current uses, benefits, and issues associated with using polyacrylamide (PAM) to reduce seepage in water delivery canals, and improve on-farm soil and water efficiency for irrigated agriculture.

2. Define the needs of alternative products that can effectively achieve these benefits, be considered “green,” and without human health risks.

3. Define a research and development plan designed to meet these needs that utilizes collaborative participation from federal agencies, the agriculture community, industry, and state and local interests.

Group Discussion—several subject areas were covered in a final workshop session, with everyone’s input. Each person present was encouraged to share what in their opinion were the top three needs related to one of four categories (1) Research and Development, (2) Regulation/Certification/Training, (3) Application, and (4) Education/Publication.

The following is a bullet list of the comments recorded, broken down by subject:

(1) Research and Development Needs

• Develop a clear direction on how to proceed with future studies that is well coordinated between the U.S. Department of Agriculture (USDA), the U.S. Bureau of Reclamation (Reclamation), and research institutions

• Consider the possibility of developing a formal structure and/or consortium of key agencies and key partners

• Coordinate research across the various uses (e.g., canal sealing and on-farm erosion reduction)

• Integrate state environmental agencies as a pathway to keep the U.S. Environmental Protection Agency (EPA) involved

• Define Outcomes and Next Steps for PAM use

• Government funding for a five- to 10-year period

• Look at new polymer alternatives, but keep working with existing PAM formulations

• If not PAM, a tool that will work like it! The alternative needs to be inexpensive and effective, like PAM

• “Greener” formulations, such as PAM without the acrylamide monomer (AMD) in it

• Continue research on soil amendments

• Price point and specifications – what it costs and how long will an application last?

• Delineate potential markets as incentive for industry to make new products

• Appoint task force to come up with a reasonable and consensus assessment of benefits and risks of PAM and/or PAM alternatives. Have to balance risks and benefits, not just one over the other

• Conduct further studies to determine where applications are safe and where they are not

• Gather additional information on long-term PAM and AMD bioconcentration

• Encourage research on alternatives and identify toxicity issues first
- Investigate the use of radio-labeled PAM to look at DNA adducts in plants and bugs – the technology exists to do this
- Investigate resources to develop new techniques and good risk assessments
- End confusion regarding PAM products. Manufacturers and resellers need to release PAM product specifications
- Develop effective PAM application methods for the various types of PAM products, not just granular forms.
- Get everyone up to speed on tools and equipment available
- Conduct additional research to know how PAM affects different soil types and under a variety of other conditions
- Conduct field-scale tests under real-world conditions
- Conduct more trials in canals with “greener” PAM formulations
- Determine application for clear water canals that do not have enough suspended sediment for granular PAM to be effective
- Gain a better understanding on how to achieve targeted levels of performance and to determine the net benefit of PAM for a given time period
- Document water savings under a wider variety of conditions
- Document the impacts that PAM application has on on-farm nutrients—what is happening to water quality?
- Continue to study the basic mechanisms of canal sealing
- Continue to find ways to better seal canals with PAM or alternatives
- Hold meetings similar to this one more often, with industry representatives present
- Have a meeting patterned after national research meetings to share knowledge of PAM-related studies

(2) Regulation/Certification/Training Needs

- Compile basic information to scope regulation information
- Conduct legal research to determine who takes responsibility if something goes wrong related to a PAM or PAM alternative application
- Clarify regulatory process – current options are not well understood
- Involve regulatory group or agency to certify products & applicators?
- Is ASTM International (originally known as the American Society for Testing and Materials) such an agency, or does a new regulatory group need to be established?
- The American National Standards Institute (ANSI) does regulations – draft materials to start discussion. This could be a working group (similar to that for pesticides)
- Natural Resources Conservation Service (NRCS) has some experience on drafting standards
- Involve EPA! It appears that the best route may be for personnel in state agencies to develop better ties with EPA
- Certify National Science Foundation (NSF) users (or use licensed applier) and require documentation
- Have better training – NSF regulations do not certify applicators
- Have well trained agency personnel (NRCS; U.S. Department of Agriculture, Agricultural Research Service [USDA-ARS]; Reclamation) who can instruct end-users
(3) Education/Publication Needs

- Get this wealth of information from current studies out to agencies and stakeholders
- Develop better technology transfer processes to regulatory agencies, as they will play an important part in the adoption of PAM alternatives. An AMD-free alternative might not be adopted if it is not competitive to PAM by both cost and ease of application.

(4) Application Technology Needs

- Continue to refine current application guidelines and extend them to other forms of PAM and PAM alternatives.
- Investigate the use of devices that can potentially simplify the application of granular PAM
- Continue to develop application procedures
- Involve water industry representatives (e.g., American Water Works Association, AQUA)
- Centralize administration/regulations
- Get field results out to stakeholders
- Organize recurring education on PAM
- Don’t lose the current knowledge
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Workshop on PAM and Alternatives to PAM

February 26-27, 2008

Andrew C. Hammond, PhD
Acting Area Director
USDA, ARS, Pacific West Area
Albany, California

About ARS
- USDA’s chief scientific research agency
- Food, feed, fiber, flowers, and fuel
- Develop and transfer solutions to agricultural problems
- 1,200 research projects
- 21 national programs
- 2,100 scientists
- 6,000 other employees
- 100 research locations

Pacific West Area
- 49 research units
- 21 locations and 10 worksites
- 400 scientists
- 1,500 total employees
- $156 M base program
- $17.5 M extramural and in kind support

ARS National Programs

<table>
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<th>Animal Production &amp; Protection</th>
<th>Nutrition, Food Safety, &amp; Quality</th>
<th>Crop Production &amp; Protection</th>
<th>Natural Resources &amp; Sustainable Agriculture Systems</th>
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<td>• Human Nutrition</td>
<td>• Plant Genetic Resources, Genomics, and Genetic Improvement</td>
<td>• Soil Resource Management</td>
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<td>• Food Safety (Animal) and Plant Products</td>
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<td>• Veterinary, Medical, and Urban Entomology</td>
<td>• Quality and Utilization of Agricultural Products</td>
<td>• Plant Diseases</td>
<td>• Global Change</td>
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<td>• Aquaculture</td>
<td>• Crop Protection and Quarantine</td>
<td>• Rangeland, Pasture, and Range Resources</td>
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<td>• Methyl Bromide Alternatives</td>
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<td>• Crop Production</td>
<td>• Manure and Bioremediation Utilization</td>
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<td>• Methyl Bromide Alternatives</td>
<td>• Water Availability and Water Management</td>
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<td>• Bioenergy &amp; Energy Alternatives</td>
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<td>• Agricultural System Competitiveness and Sustainability</td>
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</table>

Kimberly, Idaho
- Northwest Irrigation and Soils Research
Technology Transfer and Research Partnerships

David Nicholson
ARS Office of Technology Transfer

Mission of ARS

- To conduct research to develop and transfer solutions to agricultural problems of high national priority and provide information access and dissemination to:
  - ensure high-quality, safe food, and other agricultural products
  - assess the nutritional needs of Americans
  - sustain a competitive agricultural economy
  - enhance the natural resource base and the environment, and
  - provide economic opportunities for rural citizens, communities, and society as a whole.

Means of Technology Transfer

- Publications
- Seminars / Workshops
- Field Days
- Public Release of New Plant Varieties
- Dedication of new technology to the public domain
- Licensing of Intellectual Property Rights (IPR)

Licensing of IPR

- IPR, i.e., Patents
  - The right to exclude others from making, using, selling, and importing the claimed invention
  - A patent does not necessarily guarantee the right to practice the invention
  - Regulatory approval sometimes needed (EPA, FDA)

ARLS retains ownership but enters into exclusive and non-exclusive patent licenses

Federal Tech Transfer Law

- Major reorganization beginning in 1980
  - Bayh-Dole Act
  - Stevenson-Wyder Act
  - Many others...

- Universities allowed to retain patent rights for inventions flowing from government grants

- Empowered Federal Government to:
  - Form research partnerships with industry
  - Exclusively license patent rights to private companies

Office of Technology Transfer (OTT)

Mission

To facilitate research partnerships and to transfer ARS-developed technology to the private sector for broad beneficial public use.

Resources

- Forty-five personnel
- Patent agents, licensing officers, contract specialists

75
OTT as Facilitator

University Interests

ARS Mission

U.S. Company Interests

OTT’s Operating Space

Stages of Tech Transfer

- Invention
- Refinement and Adaptation
- Pilot Plant Production
- Regulatory Approval
- Manufacturing
- Distribution

ARS

Partners

Research Contracts

- Sponsored research agreements
  - CRADAs
  - Trusts
- Patent Licenses
  - Exclusive
  - Non-exclusive

Trusts

- Partner provides funds to ARS
  - Partner generally has no or limited technical expertise
- Intellectual property of secondary consideration
  - i.e. Often used for developing new methods
- Appropriate for a trade/commodity group, facing a common problem

CRADA

Cooperative Research and Development Agreement

- A joint research effort with at least one non-Federal partner
- Usually intended to create a commercial product
- Often results in intellectual property
- Possible exclusive patent license

Forming a CRADA

Partner must provide one or more of the following:

- Funding
- Equipment
- Materials
- Facilities
- Additional employees (i.e. Post-Doc)
Benefits flowing to the Research Partner

- Access to ARS technology and expertise
- Service from ARS Patent Advisors
- Right to negotiate exclusive license for any patent

Benefits to ARS

- Increased resources to augment base research program
  - Funding
  - Equipment
  - Supplies and Materials
  - Personnel (e.g., Post-Docs)
- Political support for ARS programs

CRADA Dynamics

- Funding
- Post-docs / Technicians
- Facilities
- Patents
- Political Support

Summary

- ARS has tools and resources to partner with companies, universities, and trade groups
- ARS and BoR can partner with a private company under a CRADA
- Private companies can gain exclusive rights to federally-owned technology through CRADAs and patent licenses
**Discussion Topics**

- PAM – What is it?
- Research
- A Tool for Irrigated Agriculture
- Environmental Aspects

**Common Uses of Polyacrylamide**

**Polymer Flocculants (% of Sales)**

- Municipal Potable & Wastewater - 31%
- Paper Production - 18%
- Industrial Water Treatment - 17%
- Oil Well, Enhanced Recovery - 13%
- Various Mining Applications - 9%
- Other - 8%
  
  Agriculture
  Animal Feed Thickeners & Suspending Agents
  Cosmetics

**Polyacrylamide Employed**

- Water soluble polyacrylamide
- Anionic (negatively charged)
- High molecular weight, 12-15 Mg mol⁻¹ (>150,000 repeating units)
- Moderate charge density ~ 18% of repeating units
**Acrylamide Monomer (AMD)**

\[
\begin{align*}
C = C &\quad C = C \\
\quad \text{I} &\quad \quad \text{I} \\
\text{NH}_2 &\quad \text{O}^- \quad \text{Na}^+ \\
\end{align*}
\]

**Sodium Acrylate**

\[
\begin{align*}
\text{C} = \text{C} &\quad \text{C} = \text{O} \\
\quad \text{I} &\quad \quad \text{I} \\
\text{O}^- &\quad \text{Na}^+ \\
\end{align*}
\]

**Polyacrylamide**

**Acrylamide Monomer**

- polyacrylamide (75-90%)
- water (~10%)
- acrylamide monomer, AMD (< 0.05%)
- additives (0-10%)
  - dissolution aids, e.g. urea
  - enhancers, divalent salts, Ca\(^{2+}\), Mg\(^{2+}\)
- fillers, sugar and others (0-?%)

**Dissolved PAM**

**Aqueous PAM**

- polyacrylamide (25-50% w/w)
- H\(_2\)O (~30%)
- mineral oil (~30%)
- surfactants, emulsifiers and inverters (5-10%)
- acrylamide monomer, AMD (can be << 0.05%)

**Emulsion PAM**

**PAM Emulsions**

**Water Soluble PAM in Solution**

*Blown* Solvent

*Fine* Solvent

Coil Volume

Chain Substance

**Dry Granular PAMs**
Cross-Linked Polyacrylamide (XPAM)

Cross-Linked Polyacrylamide (XPAM)

Linear PAM

Chemical Linkages

Non soluble
Highly Absorbent

“The Big Bang”

This is your irrigated furrow.

This is your furrow on PAM.

PAM Is Added To Irrigation Water Before or After It Enters the Field

Final PAM Concentration in Furrow Stream is 1 to 10 ppm

Research After the Big Bang

Application Strategies: sediment, infiltration
- Application number, timing, PAM conc.
- PAM type, charge density, mole. Wt.
- PAM-straw residue interactions
- Use in sprinkler irrigation

PAM effects on water quality
- Furrow stream and tailwater, P, NO₃, COD, temp.
- Percolation water, P, NO₃, NH₄, DOC, alachlor

PAM and soil microorganisms
- Effect on microorganism populations
- Biological degradation of PAM

Research After the Big Bang, 2

PAM effects on soil crusting
- Improve seedling emergence

Fate of PAM
- Develop method to determine PAM conc.
- PAM conc. in furrow and tailwater streams

Fate of acrylamide monomer (AMD)
- Uptake in harvested crop tissues
- Leaching losses

PAM for reducing organic solids in runoff
- Weed seed and microorganisms

The PAM Tool:
• Reduces soil loss 94% (80-99%)
• Increases infiltration 15% (0-57%)
• Increases lateral-wetting 25%
• Decreases P- and COD-losses ~ 75%
• Reduces weed seed transport 81%
• Reduces microbe transport 61-68%
PAM and the Environment

- Anionic PAM is nontoxic
- Degrades slowly in soil to form H₂O and CO₂
- Variable effects on soil microorganisms
- Dissolved conc. in the water stream declines, adsorbs to sediment and settles out

AMD and the Environment

- Acrylamide monomer is a neurotoxicant and suspected carcinogen
- Low toxicity to aquatic organisms
- Concentrations in PAM are regulated (<0.05%)
- Degrades rapidly in soil and water streams
- Does not appear to accumulate in crop tissue
- No evidence that it leaches beyond the root zone
- Concluded that PAM applications to soil at recommended dosage rates are safe
PAM in Irrigated Agriculture: Issues Related to Canal Sealing

R.D. Lentz

USDA – Agricultural Research Service
Northwest Irrigation and Soils Research Lab
Kimberly, Idaho

Irrigated Furrow and Canal or Pond Sealing Applications

- Sealing mechanisms
- PAM – Soil Interactions
- WSPAM effects on sealing mechanisms

Natural Sealing Processes

- Degradation of surface structure (Porosity)
- Sediment
  - Thick-layer deposit
  - Thin-layer seal
  - Wash-In seal
- Organic Particulates
  - Similar to sediment effects
  - Stimulates microorganism activity
- Microorganisms
  - Proliferation of bacteria and algae cells
  - Accumulation of polysaccharide exudates

Processes Opposing Sealing

- Erosive down cutting in channel
- Channel wall erosion and sloughing
- Animal disturbance
  - Burrowing (gopher, worms, etc.)
  - Livestock trespass
- Piping (silty soils, high water levels)

Aqueous PAM Interactions with Soil

- Stabilization
- Flocculation
- Enhanced soil wettability
- Water viscous effects (large vs. small pore)
- Drag Reduction (non-Darcian, turbulent flow)
Thick-Layer Deposits

Start of Season
End of Season

Thick-Layer Deposit Effects on Seepage Reduction

<table>
<thead>
<tr>
<th>SITE</th>
<th>PAM</th>
<th>SLS</th>
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<tbody>
<tr>
<td>1</td>
<td>93</td>
<td>97</td>
</tr>
<tr>
<td>2</td>
<td>19</td>
<td>44</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
<td>32</td>
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Rapid Wetting of Structured Soils in Earthen Channels

Before
After

Rapid Wetting of Non-Structured Soils

Before
After

Structure Slaking

Result of Soil Slaking

PAM Preserves Surface Pores
Thin-Layer Seal

- Thin-Layer Deposit
  Seal thickness: < 0.5 mm
  Seal adhesion force from negative soil water pressure

- Wash-In Seal
  Fines penetrate to > 1 mm depths
  Source of in-washed fines includes those suspended in water flow

PAM Effects on Semi-Consolidated Furrow Depositional Seals

Furrow PAM Treatment
- 40 mm water tension
- 100 mm water tension

Wash-In Seal

Kinematic Viscosity of WSPAM Solutions

<table>
<thead>
<tr>
<th>Concentration (mg/L)</th>
<th>Viscosity (Relative to H2O)</th>
</tr>
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<tbody>
<tr>
<td>0</td>
<td>1.00</td>
</tr>
<tr>
<td>10</td>
<td>1.02</td>
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<tr>
<td>50</td>
<td>1.30</td>
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<tr>
<td>125</td>
<td>1.86</td>
</tr>
<tr>
<td>500</td>
<td>4.00</td>
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<tr>
<td>1000</td>
<td>10.92</td>
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Effective Viscosity of WSPAM Solutions Flowing in Small Pores: Entanglement

Silt Loam Pore Size Distribution
Effect of Sediment Type and Evidence Of Multiple Processes

Cost Effectiveness

<table>
<thead>
<tr>
<th>Treatment</th>
<th>Duration of treatment</th>
<th>Water saved per annum</th>
<th>Cost of combined product</th>
<th>Costs of water saved over additional water</th>
<th>Value of increased crop yield due to additional water</th>
<th>Value of increased crop yield due to additional water</th>
</tr>
</thead>
<tbody>
<tr>
<td>XPAM</td>
<td>2</td>
<td>2.3</td>
<td>0.12</td>
<td>0.025</td>
<td>0.0033</td>
<td>0.0033</td>
</tr>
<tr>
<td>XPAM</td>
<td>2</td>
<td>2.3</td>
<td>0.12</td>
<td>0.025</td>
<td>0.0033</td>
<td>0.0033</td>
</tr>
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Based on current local corn price of $209 Mg⁻¹ ($5.32 bu⁻¹) and wheat price of $257 Mg⁻¹ ($7 bu⁻¹).
Conclusions

• PAM can act as a double edge sword with respect to seepage reduction in earthen canals and ponds.

• This likely explains why seepage reduction results can vary substantially from one application to another.

• Can be a cost effective approach especially where short-term seepage control is desired.
**Seal Calculation**

- 1 mi canal with 15 ft WP, 50 cfs flow, 200 ppm sediment
  - 5m x 1600 m = 8000 m²
  - 514 m³/hr flow x 200 ppm = 1000 kg sediment per hr
  - 0.1 mm seal per hr.
- 1 mm seal @ 100% efficiency = 10 hr
- 1 ppm PAM = 5 kg per mile (11 lb)
- 200 ppm = 10 Mg sediment (10 ton)

**Figure 2**—Cumulative infiltration (8 h) vs. average sediment concentration (initial hour) for experiments 2 (18 L/min flow rate) and 3 (22 L/min), differentiated by treatment. The best fit regression line is for the combined data.

**Sediment Seal Mechanics**

- Sediment Particle Sizes (Permeability)
- Seal Thickness & Density (Hydraulic Resistance)
  - 0.2 mm thick, 1/100 relative permeability, 50% infiltration
- Sediment Deposition
  - Density and Permeability of Flocs
  - Shear Velocity, Gravity (flocculation), Hydraulic Gradient
  - Channel bottom vs. sides
- Seal Life/Stability
  - Shear, Drying
  - PAM “Effective Viscosity”

**PAM & Flocculation**

- Emulsion PAM (Prills)
- Granular PAM (Superflo)
Sediment Seal Mechanics

- Sediment Particle Sizes (Permeability)
- Seal Thickness (Hydraulic Resistance)
  - 0.2 mm thick, 1/100 relative permeability, 50% infiltration
- Sediment Deposition
  - Density and Permeability of Flocs
  - Shear Velocity, Gravity (flocculation), Hydraulic Gradient
  - Channel bottom vs. sides
- Seal Life/Stability
  - Shear, Drying
  - PAM “effective viscosity”

Benefits and Risks - Balance

- Benefits
  - Water savings – productivity, in-stream flows, water logging, return flows
  - Reduced sediment (chemicals, pathogens, pests)
  - Channel/structure maintenance
- Risks
  - Environmental Harm
  - Human impacts (toxicology)

Desirable Characteristics

- It Works – Excellent Flocculent over range of sediment/water properties
- Reduces seepage (“viscosity” effect)
- Low Cost
- Easy to transport and apply
- Environmentally friendly / non-toxic / biodegradable

Additional Knowledge - Mechanisms

- Sediment transport vs. Seal formation
- Sediment Seal Properties vs. Effectiveness
- PAM effectiveness (flocculent, “viscosity”)
- Sediment Seal effective life
Surface sealing reduced air and water entry into the soil.

Surface sealing results in reduced infiltration, increased runoff, and increased soil erosion.

Focus of NSERL Soil Amendment Research

**Using Soil Amendments to Improve Infiltration, Reduce Runoff and Soil Erosion**

Mainly on PAM and By-Product Gypsum

- PAM molecular weight and charge density effects.
- Dry vs. wet application, in rainwater (sprinkler irrigation)
- Soil boxes, flumes, field plots (simulated and natural rain), channels, construction sites, and farm fields.
- New initiatives:
  - Testing pelletized PAM & gypsum
  - Crop ‘juice’ study

Mini-flume and PAM Research

In 1990-91, Isaac Shainberg from Israel spent one year sabbatical at W. Lafayette with an intention to bring his PAM research to US.

A mini-flume study showed .4 kg/ha PAM prevented rill erosion under 30% slope and .5 L/min flow (Shainberg et al., 1994, SSSAJ).
Flue gas desulfurization (FGD) from coal burning power plants produces large quantity of gypsum.

**FGD Process:**
Sulfur dioxide gas interacts with lime or limestone slurry to form calcium sulfite which is further oxidized into gypsum.

Rain can break up aggregates through physical impact, but since it is low in electrolytes, it can also cause chemical dispersion.

Ca/Mg Ratio has been found to be important in clay flocculation

**Fayette silty clay loam from DeWitt, Iowa.**

*PAM + By-Product Gypsum Treatment*

Field study on silt loam soil - 18 lb/A PAM

Up to inflows of 16 gallons/minute
Steep (32%) slope study

Natural Rainfall Study on 45% landfill embankment slope with silt loam soil

Stillwater (OK) large flume study
Inflows of water up to 200 gallons per minute

Gypsum-treated field near Van Wert, Ohio
No-till field treated with 1 t/A gypsum every other year

Crop ‘Juice’ Study
A Purdue professor is developing an in-situ technology to harvest fiber from agricultural crops.

Challenges:
1) How much biomass can be harvested without impacting soil quality?
2) Can the processing waste be returned to soil as a trade-off?

Since fiber harvesting only needs water, the processing waste is basically natural crop ‘juice’.

Applied 2 mm of corn juice of different dilutions. Soil dried for two weeks and rained 60 mm/h for 1 h.
Corn juice effects on total runoff and soil loss.

At 5% conc., runoff is ~7% and erosion is ~47%  
At 50% conc., runoff is ~59% and erosion is ~87%

Treated surfaces after 1 hour rain at 60 mm/h

Control Diluted to 10% 100%

SEM photos of surface aggregates after rain

Control Diluted to 10% 100%

Summary:

PAM is more effective in reducing rill erosion than interrill erosion.  
Combined PAM and gypsum treatments show a synergistic effect.  
Pelletizing PAM and gypsum overcomes the problem of different application rates and makes it feasible for broader field usage.  
Returning crop ‘juice’ to the soil during fiber harvesting may be a possible protocol.
The mission of the Bureau of Reclamation is to manage, develop, and protect water and related resources in an environmentally and economically sound manner in the interest of the American public.

348 Reservoirs
245 Million acre-foot of water storage
254 Diversion dams
16,000 Miles of canals
$9 Billion annual agricultural benefits
M&I benefits to more than 31 million people
58 Hydropower facilities powering over 6 million homes
308 public recreation areas visited by more than 90 million people each year
More than $12 billion avoided flood damages since 1959

By its mere presence and ownership of facilities, Reclamation directly influences water use and supply patterns in most major western river basins.
What are the desired benefits from a PAM alternative that Reclamation seeks for our project beneficiaries?

Less expensive alternative to reduce seepage losses in water delivery canals

Conventional Alternatives: Linings such as Concrete, Geotextiles and Compacted clay cost $9 to $18/yd

How does PAM reduce canal seepage?

Flocculates sediments entrained in canal waters. Forms a seepage reduction barrier along the canal invert

How well does it work?

~ 0 to 90 % seepage reduction

Depends on site specific factors:
- Amount of sediments in the water
- Water temperature
- Amount of PAM
- How it is applied
- Porosity characteristics of the canal invert

How long does the seepage reduction last?

Not sure…. varies based on site specific factors…. but 1 to 5 months observed during field tests.

Does natural settling of sediments reduce canal seepage?

Yes…. but is a more gradual process and effectiveness depends on site-specific factors

Where do canal seepage losses go?

- Not an overall loss to the watershed
- Seepage charges the groundwater and also may return to the downstream surface waters
- Lost beneficial use to the water right

What are second party impacts of reducing canal seepage?

Site-specific…. but can:
- Reduce groundwater supplies
- Reduce downstream return flows
- Make wetlands less "wet"
- Flush less salts from the soils
What are Human Health Concerns?

Water Delivery Canals can directly or indirectly be a source of water for human use.

Not Good to throw anything potentially toxic in water used for human consumption, or swimming in the absence of regulation or product labeling for such uses.

Human Health Concerns of using PAM to reduce canal seepage

Contains Acrylamide (AMD):
- EPA class B2 carcinogen
- Neurotoxin
- Genotoxin

Fate and transport of PAM and AMD in the environment:
- Studies indicate rapid degradation
- Fate and degradation by-products not well understood

What do others say about human risks of AMD?

- Action Plan for Acrylamide in Food, Food and Drug Administration, March 2004
- Health Implications of Acrylamide in Food, World Health Organization, June 2002
- EPA Risk Analysis Update, 2008
- Other risk evaluations common such as European Union, academia, and other scientific entities.

What are the general findings from these other references

Recent and ongoing studies to further evaluate AMD risks in food and form sensible public health advice is proving difficult.

More studies and investigations are needed to better understand human risk, uncertainties, and risk management considerations.
Public perception and exposure to litigation

Environmental Concerns of using PAM to reduce canal seepage

- Potential toxicity to aquatic species
- Potential to adversely impact aquatic habitat that supports aquatic species

Reclamation spends $$$$$ each year to restore river systems, recover T&E species, and respond to associated litigation.

Methods to Manage Risks

Water Treatment Applications to Flocculate Contaminates:
- Regulated by EPA and states
- AMD concentrations < .5 micrograms/liter
- AMD concentration in PAM < .05 percent
- Trained applicators
- Controlled, engineering environment
- PAM floc is removed from the water stream and disposed
- Considered risk-risk tradeoff
- Continue to evaluate risks

Herbicides and pesticides in water canal environments:
- Regulated by EPA and states
- Used according to product labeling

How could risk of using PAM in Canals be appropriately managed?

Implement customized, proven application protocols
Uncertainties and Limitations:
- Regulatory entity?
- Trained, certified applicators?
- Lack of a controlled setting – (i.e. Wide and unpredictable range of site-specific physical, environmental, human, and institutional factors across Reclamation’s 14,000 miles of unlined canals).
- No equipment available designed to facilitate consistent applications
- Temptation to overdose
- Protocols based on risk characterization ... not a detailed risk analysis... using available information and limited testing.

Bureau of Reclamation Decision

March 26, 2007 Memorandum:
In the absence of a regulatory framework or product labeling for PAM applications to reduce canal seepage, Reclamation will not support or allow the use of PAM in Reclamation-owned facilities.

Reclamation will continue to actively explore improved ways to reduce canal seepage losses:
- Collaborating with USDA – Agricultural Research Service, and industry to pursue the development of alternative biodegradable flocculants (i.e. green alternatives to PAM).
- Using new methods to more accurately measure and locate seepage so that spot treatments using conventional alternatives such as concrete and geotextiles is more practical and effective.
Field Applications of PAM for Canal Seepage Reduction
Del Smith, P.E.

Traditional Concrete with Sealed Joints

Traditional Compacted Clay

Traditional Buried Geomembrane

PAM and AMD

Acrylamide

Polyacrylamide
Formulation of PAM Used

- Linear Anionic (LA-PAM)
- Certified Acceptable for Drinking Water Treatment
- ANSI/NSF Standard 60
- Dry Granules (NRCS Interim Standard Specification)
- 0.05% AMD

Risks

- Aquatic Environmental Concerns
- Human Health Concerns
- Other Concerns

"Reclamation is the largest water wholesaler in the country, providing 10 trillion gallons of water to more than 31 million people and irrigating 10 million acres that produces 60 percent of the nation’s vegetables and 25 percent of its nuts and fruits.” (Reclamation, 2005)

PAM Benefits

- Seepage reduction – water savings
  - Lower seepage-induced water tables
  - Decrease in salinization of arable lands
- Improve canal operations
- Improvements in crop productivity
- Low cost relative to other methods

Seven Question Central to Risk Assessment

1. What are the ecological and human risks of the use of PAM and any trace substances in PAM formulations, particularly AMD, when used in unlined earthen canals for seepage control?

2. Does PAM degrade to the monomer, AMD? If so does the amount present a significant risk for contamination of surface water or groundwater.

3. What is the relative significance of residual AMD in the original polymer versus AMD as a PAM degradation product (if it is generated)? Are there other potential or known degradation products of PAM that are of toxicological concern?

4. What is the fate (including biodegradation) and transport of AMD (and/or PAM, and product components) in surface water, soil, and groundwater systems? What data gaps exist specific to this application?
5. How do field application practices (e.g., application of PAM to dry soil versus water in a flowing ditch) affect the risk of use of PAM? What field practices can be used to reduce risks of PAM application?

6. If residual PAM is released into receiving waters, what are the ecological risks and issues associated with PAM in surface water (e.g., armoring channel morphology, bioaccumulation, etc.)?

7. Are there any other issues regarding the human and ecological risk of use of PAM that should be considered?

Irrigation Canals

Objectives:

1. Assess downstream transport of PAM.
2. Estimate seepage reduction resulting from PAM application.
3. Assess the effect of PAM on aquatic life.

Measuring Canal Seepage

- Not Easy
- Seepage is dynamic
- Need multiple measurements
- Ponding tests or Inflow-Outflow

Inflow-Outflow Measurements

- Collect frequent stage data
- Measure between diversions
- Conduct measurement during steady-state flow
- Long enough reach
- Need Good Cross-Sections / Canal Geometry
Application Methods

- Dry on Dry
- Dry on Wet
- Wet on Dry

Laboratory Schematic – Hydraulic Conductivity
Site Selection
- Magnitude of seepage loss
- Controllable or stable inflows
- Minimum number of turn-outs
- Length of canal
- Presence of an upstream control reach
- Presence of background data
- Ability to collect downstream water chemistry

Canal Applications
- Conducted 17 LA-PAM application experiments from 2005 and 2007
- 2005 and 2006 applications
  - Excellent data on short-term seepage loss
  - Excellent data on LA-PAM release into water column
  - Difficult to evaluate seasonal seepage
- 2007 studies focused on obtaining significant background data and gaining better understanding of naturally occurring changes in seepage

PAM Application
- Granular PAM
- Rate: ~ 10 lbs/acre based on wetted perimeter
- Downstream to Upstream
Concentration of PAM Applied

- Phase II Rule National Primary Drinking Water Regulations issued by the U.S. EPA (40 CFR 141.111 asserts and acrylamide polymer maximum use level of 1.0 mg/L and an AMD concentration of 0.05% in the polymer, or equivalent, for a carryover of not more than 0.5 ug/L of AMD into the finished water.

- We sought to apply LA-PAM to achieve a canal water concentration of less than 1.0 mg/L.
Variables Controlling Effectiveness

- Travel Time
- Hydration Time
- Suspended Solids Concentration in Water
- Water Temperature
- Water Velocity
- Water Chemistry
- Ability to Hit Target Reach
- Mixing

Seepage Reduction

Estimated Seepage Reduction as Percentage

<table>
<thead>
<tr>
<th>Elapsed Time (days)</th>
<th>LAM-1</th>
<th>CAT-1</th>
<th>CAT-2</th>
<th>RFH-1</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>33%</td>
<td>99%</td>
<td>100%</td>
<td>78%</td>
</tr>
<tr>
<td>2-15</td>
<td>27%</td>
<td>NA</td>
<td>82%</td>
<td>64%</td>
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<tr>
<td>16-55</td>
<td>31%</td>
<td>90%</td>
<td>91%</td>
<td>71%</td>
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<tr>
<td>56-115</td>
<td>33%</td>
<td>89%</td>
<td>100%</td>
<td>67%</td>
</tr>
<tr>
<td>&gt;116</td>
<td>NA</td>
<td>93%</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>
Seepage Reduction from PAM

- Immediate
- 35 to 90 percent
- Lasted throughout Water Year
- Effectiveness Dependent on Multiple Factors
  - Sediment
  - Application Method
  - Temperature
  - Water Chemistry

Cost Comparison

<table>
<thead>
<tr>
<th>Type of Lining</th>
<th>Const Cost ($/ft²)</th>
<th>Durability (years)</th>
<th>Seepage Reduction</th>
<th>Conserved Water ($/AF)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Traditional</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Concrete</td>
<td>$5 - $10</td>
<td>50 yrs</td>
<td>95 %</td>
<td>$30 - $60</td>
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<tr>
<td>- Compact Clay</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Buried GM</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Cost</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Shotcrete</td>
<td>$2</td>
<td>50 yrs</td>
<td>70 %</td>
<td>$15 - $17</td>
</tr>
<tr>
<td>- Exposed GM</td>
<td>$0.80-1.50</td>
<td>10 - 25 yrs</td>
<td>90 %</td>
<td>$14 - $20</td>
</tr>
<tr>
<td>- GM+Concrete</td>
<td>$2.50</td>
<td>50 yrs</td>
<td>95 %</td>
<td>$13 - $15</td>
</tr>
<tr>
<td>PAM</td>
<td>$100 per Acre</td>
<td>1 yr</td>
<td>25 – 50 %</td>
<td>$1 - $2</td>
</tr>
</tbody>
</table>

Recommended Course of Action

- Reclamation will not support the use of LA-PAM
- Legal and Regulatory issues should be pursued
- Complete field studies and documentation
- Pursue other cost-effective canal seepage reduction alternatives
- Collaborate with USDA-ARS and industry
PAM Research Topics:
Use of Granular PAM in Water Delivery Canals

Dr. Richard Susfalk
Desert Research Institute

Seepage Reduction:
Temperature As A Tracer

Test Troughs

Flocculation: Jar Testers

PAM Transport Model

Field-scale PAM Applications
Outline

Granular PAM application to water delivery canals

I. Clear Zone Index
II. Application Methodology
III. Risks of PAM and AMD
Clear Zone

Water Chemistry (quality & quantity)
Suspended Sediment Concentration
Water Temperature
Application method
Water Velocity

Manage Benefits and Risks

“Clear Zone”

Suspended Sediment + PAM → PAM - Sediment Floc

Clear Zone Index (CZI)

- Case 1
  - No Flocculation
  - No Seepage Reduction
  - PAM Remains in Water Column

- Case 2
  - Flocculation
  - Seepage Reduction
  - No PAM in Water Column

- Case 3
  - Flocculation
  - Seepage Reduction
  - PAM Remains in Water Column

Turbidity and PAM Concentration

How much PAM do we add?
Lesson II
Application to Water Delivery Canals

Application Methodology
- Application Rate: 10 lbs/acre
- Concentration in water: 1-2 ppm PAM or less
- Application Speed

Application Methodology
Water Chemistry
Suspended Sediment Concentration
Water Temperature
Application method
Water Velocity

Lesson III
Risks of PAM and AMD
PAM Risk I
Exposure to technicians applying PAM

Use of proper application guidelines
Safety gear

PAM Risk II
Downstream transport

Macrobenthos

AMD Risk I
Entering Groundwater
(AMD sorption to soils is 0.2-4%)

- Concentrations measured were orders of magnitude below chronic levels needed to impact human health.

- AMD concentrations reduced by dilution with groundwater

AMD Risk II
Entering Groundwater

- Bacterial degradation resulted in an AMD half-life of 30 to 42 hours

 AMD Risk III
Entering Groundwater

- Transport modeling indicates that an AMD concentration 10 times that observed in the field would become undetectable within 25 m of the canal

- Worst case Scenario
  - Course-textured soil
  - AMD input via PAM enters groundwater (eg no effective rooting)

Summary I
Clear Zone Index

- Measure of the “impact” of PAM application

- Will differ by site:
  - Water chemistry
  - Suspended sediment concentration
  - Water temperature
  - Water velocity
  - Application method

- Need sufficient suspended sediment

- Application rate based on suspended sediment load NOT wetted perimeter

- Useful for any flocculation based PAM alternative
Summary II
Application Methodology

* Application rate that minimizes risk and maximizes benefits:
  * PAM: 10 lbs/acre and 1-2 ppm

* Methodology must account for site-specific issues that affect the flocculation processes
  * Target only application area
  * Minimize downstream impacts

* Useful for any flocculation based PAM alternative

Summary III
Risks of PAM and AMD

* PAM Risks
  * Human exposure
  * Downstream Impacts
  * Managed by proper application protocols

* AMD Risks
  * Contamination of groundwater
  * Contamination appears minimal due to microbial degradation and dilution by canal water and groundwater

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Smith ditch #7
Kannah Creek ditch #2
Hunty Irrigation District

Rocky Ford Highline
Culkin Canal Company
Lamar Canal Company
Fort Lyon Canal Company
Belleview Canal Company

Summary
Questions

* Is the water quality in the canal conducive to forming PAM-sediment flocs?

* Is there enough suspended sediment in the canal water to form PAM-sediment flocs?

* Based on environmental conditions, is the application rate and approach sufficient to minimize the downstream transport of hydrated LA-PAM?

Field Studies
NRCS perspective on PAM

Clarence Prestwich
Water Quantity Quality Team
West National Technical Support Center
Portland, Oregon

What are the challenges for managing soil conservation in irrigated agriculture?

Extent of Irrigated Agriculture

Worldwide Cropped Acres: 3.0 - 3.5 billion
Irrigated Cropped Acres: 600 million
Total US Irrigated Acres: 55.3 million

Irrigated Land

- Last published survey indicated that 10+ million acres of irrigated cropland have serious erosion
  - 15 to 160 tons/acre/year
Center Pivot erosion

Magnitude of erosion problem
- Agriculture can never completely eliminate soil erosion
- Off-site damages caused by sediment in North America are estimated at $16 billion annually
- Additional billions of dollars lost through reduction of productivity and repair of existing infrastructure.
- Soil erosion has caused the collapse of societies in the past

Acres by irrigation method (2003 survey)
- 26,937,835
- 2,521,465
- 23,124,131

Potential acre for PAM use
- 19,567,256
- 11,723,084
- 21,293,091
- 114
Summary

We have 11 million acres of furrow ground and roughly half of the 26 million acres of center pivot ground producing erosion and we are using PAM on maybe 2 million acres. There is still a lot of erosion potential.

Desired uses of PAM or Alternative

- Anionic PAMs: "Off the Shelf " Industrial Flocculents
  - Cosmetics
  - Paper Manufacture
  - Potable Water
  - Dewater Sewage Sludges
  - Clarify Fruit Juices & Sugar Liquor
  - Mining & Drilling Applications
  - Adhesives & Paper in Contact with Food
  - Washing & Lye-Peeling of Fruits & Veg's
  - Animal Feed Thickener & Suspending Agent

Sediment Reduction

- Research
  - Range 80 - 99 %
  - Avg. 94 %
- Farmers:
  - typically 60 - 80 %
Multiple Application methods

No PAM          PAM

PAM Blocks

PAM Tablets

Add to water - Predissolved

Applied Dry - Patch

Sprinklers
Tire tracks

Benefits vs. Risks

- The benefits warrant the use of PAM and we understand the risks sufficiently enough to craft protocols for use of PAM such that all unintended effects can be anticipated and avoided.

Desired characteristics of an alternative

What Does PAM Do?

- Strengthens soil cohesion
- Preserves surface roughness
- Increases viscosity slightly
  - Reduce particle detachment
- Flocculates suspended solids
  - Reduces sediment transport
- All these preserve pore continuity
  - Maintains higher infiltration

PAM Effects on Infiltration

- Soil dependent (texture)
  - Balances surface seal vs. viscosity effects
  - Reduces surface sealing
  - Longer advance time
- Net increases
  - 15% on silt loams
  - 50% on clays
  - 0% or slight reduction on sands
- 25% increase in lateral wetting on shallow furrows

On Average: 1 Oz PAM Halts ½ ton Erosion
PAM & Biopolymers in Perspective

- low rates small applications 3-5 lbs acre/yr
  - low/no toxicities
  - removes 94% sediment (typically 10-20 ton/acre in PNW)
  - 60-80% nutrients, pesticides, BOD, weed seed, microbes
  - Sustainability yield, environment protected
  - Economic
  - A practice farmers use where others fail, or are unwanted
PAM Structure/Function Studies: PAM Alternatives

William J. Orts
Gregory M. Glenn
Syed Imam
USDA-ARS-WRRC, Albany, CA

Robert E. Sojka
USDA-ARS-NWISRL, Kimberly, ID (retired)

Partnerships: Industrial Cooperators

PAM Furrows

PAM Structure/Function

PAM-Treated Furrow Irrigation

PAM: Calcium Effects

Molecular Weight (x 10^-6)

Soil Conc. (% of Control)

Ca^++ Concentration (mM)

Soil Conc. (% of Control)
Alternatives to PAM:

- Soil Affinity $\leftrightarrow$ Charge
- Size $\leftrightarrow$ “Large”

Dimensions

![Image of PAM structure]

180 nm

$> 12$ microns

Ionic Expansion $\sim 1/\text{Cs}$

PAM Structure/Function

- Chain bridging between charged soil particles
- Ion bridges between chains
- Charged particulate (soil)

Alternatives to PAM:

- Size $\leftrightarrow$ LARGE
- Charge $\leftrightarrow$ Calcium effect
- Environmental Impact
- Dispersible in Water

Possibilities:

- Modified starch
- Charged cellulose – Xanthate?
- Chitosan

Acid Hydrolyzed Cellulose Microfibrils

- Stiff, “large”, charged microfibrils.
- Readily dispersed in water.

Cellulose Microfibrils

Charge Microfibril

Cellulose/ Starch Xanthate

Concentration (ppm)

Soil Conc. (% of Control)

Graph showing concentration vs. soil conc. for PAM (Cytec 836A) and Cellulose xanthate (ds=1.7).
Chitosan

- Mechanism?
  ⇔ smaller than PAM

- Price = 2 x PAM

Alternatives to PAM: Lab Furrow Tests

Lab Furrow Results: (mg/mL of soil in effluent)

<table>
<thead>
<tr>
<th>Composition</th>
<th>Without Calcium</th>
<th>Calcium Nitrate (20 ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (Tap Water)</td>
<td>48.1 ± 5.1</td>
<td>1.63 ± 0.23</td>
</tr>
<tr>
<td>PAM 20ppm</td>
<td>3.47 ± 0.41</td>
<td>0.01 ± 0.004</td>
</tr>
<tr>
<td>Chitosan</td>
<td>5.48 ± 1.76</td>
<td>0.05 ± 0.009</td>
</tr>
<tr>
<td>Chitosan/Cationic Starch</td>
<td>3.51 ± 0.44</td>
<td>0.04 ± 0.008</td>
</tr>
</tbody>
</table>

Partnerships: Industrial Cooperators

Beyond Chitosan – Complex Polysaccharides
**Novel Sources of Cellulose**

**Municipal Solid Waste (MSW)**

- **Food scraps**: 36%
- **Paper**: 36%
- **Other**: 3%
- **Yard trimmings**: 12%
- **Wood**: 9%
- **Rubber, leather and textiles**: 7%
- **Plastics**: 11%
- **Metals**: 8%
- **Glass**: 5%

**Biomass Pretreatment:**

A compressed hot water treatment allows straw to be hydrolyzed relatively easily.

**Salinas Demonstration Plant:**

Crazy Horse Canyon Landfill
In operation since November 2007

**Conveyor loading MSW to autoclave**

Kevin Holtman
Dave Bozzi
Diana Franqui-Espiet
MSW inside the autoclave prior to steam treatment

MSW in the autoclave after steam treatment

Clean fiber from MSW after centrifugal cleaners

New Uses for PAM Alternatives:
- Cost
- Environmental Impact
- Dispersible in Water

Aicardo Roa:
- Construction sites
- Controlling wind erosion
- Controlling canal seepage
- Helicopter landing pads

PAM: Helicopter Landing Pads: Aicardo Roa

Before

After
Summary

- PAM is not easy to mimic
  Tested over 250 compounds.....

- PAM alternatives have been “invented”
  It’s all about the price point.....

- Partnerships are key
  Let’s talk.....
Polymers and Biopolymers for Soil & Water Management

Resistance to PAM Technology

- Snake Oil... Too Good To Be True!
- Isn't PAM Another Chemical?
- Doesn't PAM Build Up in Soil?
- Doesn't It Hinder Soil Microbes?
- Isn't AMD a Bad Contaminant?
- Isn't AMD a Breakdown Product?

Public, EPA, Court, Ethics, & Common Sense All Demand We Better Protect Our Waters

“Conventional” Conservation

- Scores of Existing BMPs
- Wide Range of Effectiveness
- Often Costly or Time Consuming
- Intrusive to Farm Operations
- 19th Century (BC?) Approaches
- Hard Sell to Irrigation Farmers
- Easy Sell to Regulators

Anionic Polyacrylamide (PAM)

- PAM is a polymer of acrylamide (AMD) monomers
- Erosion PAMs are 12 to 15 Mg/mole & >150,000 chained monomers/molecule.
- Erosion PAMs have <0.05% unreacted AMD (500 ppm)
Anionic PAMs: "Off the Shelf" Industrial Flocculents
- Cosmetics
- Paper Manufacture
- Potable Water
- Dewater Sewage Sludges
- Clarify Fruit Juices & Sugar Liquor
- Mining & Drilling Applications
- Adhesives & Paper in Contact with Food
- Washing & Lye-Peeling of Fruits & Veg's
- Animal Feed Thickener & Suspending Agent

PAM: Easily Applied & Highly Effective
Long Term Avg. 94% Reduction of Runoff Sediment
Similar Reduction of Nutrients, DOC, Pesticides, Weed Seed & Microbes

PAM Effects on Infiltration
- Soil dependent (texture)
  - Balances surface seal vs viscosity effects
  - Reduces surface sealing
  - Longer advance time
- Net increases
  - 15% on silt loams
  - 50% on clays
  - 0% or slight reduction on sands
- 25% increase in lateral wetting on shallow furrows

Infiltration Results Are Application-Protocol-Specific
- At Low Concentrations
  - Low Viscosity
  - Soil Structure (Pore) Stabilization
  - Little Detachment, Hence Few Flocs
  - Infiltration Increases
- At High Concentrations
  - High Viscosity
  - Particle Dispersion
  - Pore Blockage (particles and PAM)
  - Infiltration Decreases (Sealant)

PAM Considerations
- Water soluble (not crosslinked) PAM
  - High Mol Wt (15 M g mol⁻¹)
  - Anionic (-) charge (typically 18%)
  - < 0.05% Acrylamide (AMD) - 500 ppm
- Cost $2.50-$4.00 per lb
- 1-2 lb/acre/application
- Typically 3-5 applications/yr
- $7.50-$20.00/acre/yr
- Up to 94% Erosion Control
- Nutrient, pesticide, microbe, weed seed

PAM Costs Offset By:
- Easier irrigating, better infiltration
- Less furrow reshaping/cultivating
- Less pond construction & cleaning
- Less soil respreading
- Weed/Disease Containment
- Yield/quality improvement
Implications of Microbe Removal from Runoff

- Soil-borne plant disease epidemiology
  - Less disease spread in your field
  - Less spread downstream in return flows
  - Potentially less need for pesticides
  - Manturing less prone to coliform losses
  - Reduced hygiene threat to public waters
  - Potentially reduced water treatment need

Table 4. Seed of 6 weed species in patch or dissolved PAM-treated runoff as % of controls in 2 yrs.

<table>
<thead>
<tr>
<th>Species</th>
<th>Year 97</th>
<th>Year 98</th>
<th>Year 97</th>
<th>Year 98</th>
<th>Year 97</th>
<th>Year 98</th>
<th>Year 97</th>
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<th>Year 98</th>
<th>Year 97</th>
<th>Year 98</th>
<th>Year 97</th>
<th>Year 98</th>
</tr>
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<tbody>
<tr>
<td>Kochia</td>
<td>37.3</td>
<td>29.5</td>
<td>24.6</td>
<td>36.2</td>
<td>33.8</td>
<td>33.8</td>
<td>33.8</td>
<td>33.8</td>
<td>33.8</td>
<td>33.8</td>
<td>33.8</td>
<td>33.8</td>
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<td></td>
</tr>
<tr>
<td>Lambsquarters</td>
<td>15.5</td>
<td>15.0</td>
<td>15.5</td>
<td>15.5</td>
<td>15.5</td>
<td>15.5</td>
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<tr>
<td>Redroot Pigweed</td>
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<tr>
<td>Hairy Nightshade</td>
<td>4.3</td>
<td>6.4</td>
<td>4.3</td>
<td>6.4</td>
<td>4.3</td>
<td>6.4</td>
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<td>6.4</td>
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<tr>
<td>Barnyard Grass</td>
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<tr>
<td>Common Mallow</td>
<td>12.3</td>
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</tbody>
</table>

* Differs from control at P<0.05 for a given treatment. Data adapted from Sojka et al. (2003). Latin names, respectively: Kochia scoparia L., Chenopodium album L., Amaranthus retroflexus L., Solanum sarrachoides L. Sendtner, Echinochloa crus-galli L., Malva neglecta Wallr.
PAM Persistence in Soil

- PAM N-groups quickly consumed by microorganisms
- PAM carbon backbone more resistant, UV & mechanical shear (degrades at least 10%/yr)
- Monomer (AMD) biodegrades rapidly in soil, 18-48 hours
- PAM does not degrade to AMD

Natural Abundance of C to Determine PAM Conc in Soil

- PAM raw material is natural gas
- Natural gas has less $^{13}$C & $^{15}$N than SOM
- PAM has lighter $^{13}$C/$^{12}$C or $^{15}$N/$^{14}$N ratios than SOM
- Allows discrimination of PAM conc., based on soil natural abundance signatures
- 3x C atoms vs. N atoms in PAM molecule

Concentration of anionic polyacrylamide (PAM)

<table>
<thead>
<tr>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Added</td>
<td>6000</td>
<td>5000</td>
<td>4000</td>
</tr>
<tr>
<td>Remaining</td>
<td>1000</td>
<td>2000</td>
<td>3000</td>
</tr>
</tbody>
</table>

PAM Left in Soil After Time at Five Different Application Rates

Assuming 10% degradation per year
PAM Mobility & Fate

**During Irrigation**
- PAM is mobile while in solution
- PAM quickly adsorbs to solid surfaces
- Adsorbed irreversibly upon drying
- Field retention 97-99%

**PAM Enviro-Safety (<10ppm)**
- Anionic, 12-15 Mg/mole, <0.05% AMD
- EPA & FDA OK’d for food/water etc. uses
- An animal feed additive (not assimilated)
- No known toxicities in soil/water (even at more than 10x NRCS rates)
- No PAM accumulation in crops
- No negative plant effects at these rates
- PAM soon is a Carbon skeleton in soil
- Small AMD content safe/quickly degraded

**PAM Toxicity Considerations**
- AMD is a neurotoxin, **PAM is not**
  - AMD is reacted during PAM synthesis
  - Erosion PAMs have <0.05% AMD (safe)
  - PAM does not degrade to AMD
- **Anionic PAMs are safe to aquatic life**
  - Cationic PAMs suffocate fish (anionics do not)
  - **Erosion PAMs are ANIONIC**
  - >10 fold concentration safety factor at application
  - PAM removes itself from runoff via adsorption
  - Safe compound, low application, 1-3% loss, adsorption, dilution = VERY low aquatic risk

**AMD in Perspective**
- AMD is to PAM as glucose is to wood
- PAM cannot degrade to AMD w/o heat/Pressure
- UV degradation of PAM wavelength-dependent
- AMD purity same as food processing PAM
- AMD in fried, baked, cooked foods
  - 25 to 2300 ppb
    - Potato chips 1300 ppb
    - French Fries 540 ppb
    - Popcorn 500 ppb
  - PAMs used for irrigation erosion control
    - Product contains < 0.05% AMD (500 ppm)
    - Diluted to 1-10 ppm in Water
    - 97-99% infiltrates into soil
    - Half life <48hrs (microbial N-source)

**Anionic Erosion PAMs are FAR less toxic than**
Fungicides, Insecticides, Rodenticides, most Herbicides and even concentrated Fertilizers

**Active bacterial, fungal, and microbial biomass in soils treated with 2691 and 5382 kg ai PAM ha⁻¹.**

<table>
<thead>
<tr>
<th>Month</th>
<th>Treatment</th>
<th>ABB</th>
<th>AFB</th>
<th>AMB</th>
</tr>
</thead>
<tbody>
<tr>
<td>June</td>
<td>Control</td>
<td>9.84 a</td>
<td>10.16 a</td>
<td>19.21 b</td>
</tr>
<tr>
<td></td>
<td>2691 kg PAM ha⁻¹</td>
<td>7.29 b</td>
<td>6.97 b</td>
<td>13.97 b</td>
</tr>
<tr>
<td></td>
<td>5382 kg PAM ha⁻¹</td>
<td>7.12 b</td>
<td>7.24 b</td>
<td>14.56 ab</td>
</tr>
<tr>
<td>July</td>
<td>Control</td>
<td>5.31 b</td>
<td>10.84 a</td>
<td>15.95 a</td>
</tr>
<tr>
<td></td>
<td>2691 kg PAM ha⁻¹</td>
<td>4.86 b</td>
<td>6.64 b</td>
<td>11.51 b</td>
</tr>
<tr>
<td></td>
<td>5382 kg PAM ha⁻¹</td>
<td>5.39 b</td>
<td>7.32 b</td>
<td>10.71 b</td>
</tr>
<tr>
<td>Aug</td>
<td>Control</td>
<td>6.13 a</td>
<td>6.26 b</td>
<td>15.42 a</td>
</tr>
<tr>
<td></td>
<td>2691 kg PAM ha⁻¹</td>
<td>7.35 b</td>
<td>8.51 b</td>
<td>12.81 b</td>
</tr>
<tr>
<td></td>
<td>5382 kg PAM ha⁻¹</td>
<td>5.13 b</td>
<td>6.73 b</td>
<td>11.63 b</td>
</tr>
</tbody>
</table>

† ABB = active bacterial biomass; AFB = active fungal biomass; AMB = active microbial biomass.
‡ In each column values followed by the same letter are not significantly different as determined by the least square means test (p ≤ 0.05; n=27).
Figure 1c. Principal components analysis of substrate utilization profiles for whole-soil microbial communities exposed to various application rates of PAM and sampled in August 2001. (•, negative control; X, 2691 kg PAM ha⁻¹; ○, 5382 kg PAM ha⁻¹).

Alternatives to PAM: Considerations

- **Perceptions / Cost / Availability**
- Ag Biproduct/Waste Use
- Cost (+/-)
- Enviro Impact– Manufacture & Use
- Dispersible in Water (+/-)

Possibilities:

- Modified starch
- Charged cellulose
- Polysacharides
- Chitosan
- Protein-based analogues (Whey, Animal Renderings)

Must Biopolymers Be Anionic?

- Efficacy for Intended Use
- Toxicity
- Ease of Production (Cost)
- Ease of Handling and Use

Runoff sediment conc. from lab mini-furrows for PAM vs polysaccharide derivatives.

Soil pH 7.5, exchangeable Ca 7%, ~5% organics.
10 ppm Ca(NO₃)₂ in water, for ionic bridging.
SD based on 5 reps/sample.

Alternatives to PAM: Considerations

Lab vs field furrow tests

No calcium was added to the irrigation water.

Lab Furrow Tests

- PAM vs polysaccharides (Cytec 836A)
  - Cellulose xanthate (ds=1.7)
  - Wheat starch xanthate (ds=0.54)
Alternatives to PAM: Lab Furrow Tests

Lab Furrow Results: (mg/mL of soil in effluent)
Starch/Chitosan Mixtures vs. PAM

<table>
<thead>
<tr>
<th></th>
<th>Without Calcium</th>
<th>Calcium Nitrate (20 ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control (Tap Water)</td>
<td>48.1 ± 5.1</td>
<td>1.63 ± 0.23</td>
</tr>
<tr>
<td>PAM 20ppm</td>
<td>3.47 ± 0.41</td>
<td>0.01 ± 0.004</td>
</tr>
<tr>
<td>Chitosan</td>
<td>5.48 ± 1.76</td>
<td>0.05 ± 0.009</td>
</tr>
<tr>
<td>Chitosan/ Cationic Starch</td>
<td>3.51 ± 0.44</td>
<td>0.043 ± 0.008</td>
</tr>
</tbody>
</table>

Acid Hydrolyzed Cellulose Microfibrils
(R.H. Marchessault, J.-F. Revol)

- Stiff, “large”, charged microfibrils.
- Readily dispersed in water.

Responses to PAM Resistance

- No Snake Oil, Highly Effective Flocculant
- PAM is a food grade Chemical
- PAM breaks down @ 10%/yr
- Nearly no impact on soil microbial function
- Acrylamide regulated at safe levels
- Acrylamide is not a breakdown product
- Acrylamide exposure via irrigation small vs. food

PAM & Biopolymers in Perspective

- PAMs & Biopolymers: low rates, low/no toxicities
  - 16yr research 13yr on-farm use -no evidence of damage
- 3-5 lbs PAM/acre/yr removes from runoff:
  - 94% sediment (typically 10-20 ton/acre in PNW)
  - 60-80% nutrients, pesticides, BOD, weed seed, microbes
  - reduced remediation effort, costs, positive epidemiology
- 2 million acres of erosion halted (2003 Industry Estimate)
  - Sustainability, yield, environment protected
  - A practice farmers use where others fail, or are unwanted
- Biopolymers: potential PAM surrogates / more research
PAM Use: Forward Thinking

- Safe enough for food and potable water
- Erosion PAMs are about 2% of market
  - Most are more problematic
    - Most are cationic or non-ionic (toxic)
    - Most have much more AMD
- Think Outside the Box

Thank You For Your Attention

Combining Chemistry & Nature

We Are The Technology Company With...

- Two NEW platform chemistries
- Products from natural, renewable materials
- First market entry -- Agriculture

Introducing Innovium

- Founded in St. Louis, 2002
- Use “Green Chemistry”
- Exclusive intellectual property estate
- Collaboration agreement with USDA
- Revenue generation through product sales, option and licensing agreement.

Why Green Chemistry

**The Economics:**

- Raw materials are available, inexpensive and abundant
- Little waste is generated, low environmental liability
- Favorable environmental impact - reduced long term liability

The Innovium Team

Mark A. Hochwalt, CEO
- (Monsanto, Solutia, ValuGen, Innovium)
- P&L responsibility for 3 chemical businesses – $25 million sales
- Launched 3 businesses while at Monsanto
- Built plants supporting Roundup® and NutraSweet® businesses

C. Steven Sikes, Ph.D., CSO
- Over 25 patents
- 100+ professional papers and books
- 40+ government grants, 6 agencies
- Chemical R&D commercial collaborations worldwide, 1983 to present

Science Advisory Board
- Robert Strom, Ph.D., Chairman - Retired Dow (2006), CSO Performance Chemicals
- William Ott, Ph.D. - USDA
- Geff Naber, Ph.D. - Title and Lyne
Product Overview

- New patent pending technology for erosion control, infiltration improvement, and water conservation in irrigation farming
- Improves soil characteristics by promoting soil aggregation, less crusting
- Developed in cooperation with the USDA

Laboratory Testing of SoilSentry™

Lab trials showing water outflow plus sediment in 20 ml vials

USDA Furrow Irrigation Field Trial Kimberly, ID

USDA Sprinkler Irrigation Field Trial Kimberly, Idaho

Static Infiltration Data

Dynamic Infiltration Data
Dynamic Infiltration Data

Infiltration Depth vs. Time

Infiltration Depth vs. Water Advance

SoilSentry Infiltration Summary

- Infiltration rate is approximately 25% better when using SoilSentry PL
  - More water is getting into the soil and less is running off
  - Improved watering efficiency
- Advance rate is slower while using SoilSentry PL
  - Deeper water penetration, lower erosion
- Water infiltration is faster to the same depth over the control

Product Features and Benefits

<table>
<thead>
<tr>
<th>Features</th>
<th>Benefits</th>
</tr>
</thead>
<tbody>
<tr>
<td>Halts erosion</td>
<td>Reduces top soil loss and over time it improves soil fertility</td>
</tr>
<tr>
<td>Reduces the rate of infiltration loss</td>
<td>Better water penetration, more efficient water usage</td>
</tr>
<tr>
<td>Improves soil characteristics</td>
<td>Less soil compaction, less crusting, better aeration</td>
</tr>
<tr>
<td>Reduces migration of inputs</td>
<td>Inputs stay where they are placed, reduced runoff</td>
</tr>
<tr>
<td>Easy and reliable application</td>
<td>Sodmas time and the field gets properly treated</td>
</tr>
<tr>
<td>Biofriendly and Safe to handle</td>
<td>Protects your investment for future generations</td>
</tr>
</tbody>
</table>

Dispensing Setup Furrow Irrigation

SoilSentry PL Tank

Battery Box - Place box so outflow falls into a turbulent zone

4"-10" long piece of tygon tubing attached to hose and battery box

Dispensing Setup Sprinkler Irrigation

SoilSentry is injected into the irrigation system using a metering pump

Application Dosage Recommendations

- Fields with slopes of 2% or less
  - 10 gallons of SoilSentry per acre
  - Irrigation water should contain a minimum of between 1 to 2 ppm of active
- Fields greater than 2% slopes
  - 10 to 30 gallons per acre based on soil type, field slope and rate of water application
    - Irrigation water should contain between 2 to 10 ppm of active
      - Increase application rate for fine textured, low organic content soils
      - Increase application rate for high sloping fields
      - Increase application rate or reduce water flow rate for high shear or high velocity water flow rates
Field Application Case Studies

SoilSentry Applied to 350 acres in the Imperial Valley during Fall 2005

Denotes SoilSentry Field
Denotes PAM Field
Denotes locations where SoilSentry was Applied

The Field Design

<table>
<thead>
<tr>
<th>Paved Road</th>
<th>Unpaved Road</th>
<th>Paved Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>Head Ditch</td>
<td>Head Ditch</td>
<td>Distribution Lateral</td>
</tr>
</tbody>
</table>

Application Conditions and Rates

- **Conditions**
  - Extremely Adverse
    - Product applied the day after a 1" rainfall. The area only gets 2" of rain annually
    - High water turbidity in irrigation water as a result of the rainfall
      - Large quantities of yellow clay in the water
- **Dosage Rate**
  - 1.26 to 1.55 ppm actives in the water – 8 oz per minute of SoilSentry PL as is. Average dispensing rate was 5 gallon per hour.
  - Water Flow rate - 5 cu ft per second

Flock Formation in Head Ditch

Mottled appearance Are flock pools of Yellow clay

Flocked Yellow Clay Entering the First Siphon Pond

Delta of Flocked Yellow Clay Forming in First Siphon Pond

Lateral from Head Ditch Entering Siphon Pond
Irrigated SoilSentry Field

Picture of top of field 32 hours after the start of irrigation.

End of Field and Tail Ditch

Tail ditch is clear with no turbidity. Flow off of furrow is about 20% of inflow rate. Picture taken about 25 hours after starting the irrigation.

SoilSentry Treated Beet Field 4 Weeks After Application

SoilSentry Treated Beet Field

8 weeks after initial application and 2 weeks after 2nd application.

Pam Dispenser

PAM dispenser supplied by Helena. Unit hold 50 lbs dry PAM.

PAM Irrigated Field

PAM irrigated field 30 hours after start of irrigation cycle.
PAM Treated Beet Field
4 Weeks after Application

SoilSentry Applied to Alfalfa
Lateral off of Head ditch. Flow is 3-3.5 cuft per second

SoilSentry Applied to Alfalfa
Field after water has penetrated. Note that there is no rutting

8 weeks after Initial application and 2 weeks after 2nd application
SoilSentry Applied to Alfalfa

Tail water off the end of the fields. Note the clarity.

SoilSentry Applied Lettuce

SoilSentry Applied to lettuce field to prevent bed erosion which exposes root zone

Untreated Lettuce Field

Note how the furrow has collapsed exposing the root zone along the seed line. If left untreated the crop will mature with an uneven stand affecting consistency and yield.

Treated Lettuce Field

Field right after irrigating with ¾" of water and SoilSentry. Note there is no collapsing of the bed margins into the furrow like the untreated field.

Treated Lettuce Field 4 Weeks Later

Summary

- Grower felt SoilSentry was equivalent to slightly better than the petrochemical alternative.
- Grower thought application method was more reliable
- PL is better than the petrochemical alternative at removing the yellow clay. Water less turbid in the siphon ponds and head ditch
- PL worked well in both heavy and light soils
- PL worked equally well in spray irrigation and controlled bed margin erosion
- To learn more go to www.soilsentry.com
PAM modify Effectiveness, efficiency and Impact of PAM Delivery Systems
Soil Net liquid binder is so good that it even works applied as rain.
Soil Net liquid binder application

Thickness of the crust range from ½ to ¾ of an inch

Soil Net liquid binder 12 hours after applied

Soil Net liquid binder applied

12 hours after application the sand still holds moisture on treated area

Tire tracks disappear on treated area

Tire tracks disappear on treated area
Soil Net liquid binder applied to sand and dust.

Tire tracks on treated area disappear two hours after application.
### Comparison with Poly(vinyl acetate)

**Table 1: Shear strength of strips of sugar maple**

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Control poly(vinyl acetate)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength (dry) (N)</td>
<td>1050 ± 58</td>
<td>1107 ± 89</td>
<td>1012 ± 108</td>
<td>690 ± 69</td>
</tr>
<tr>
<td>Shear strength (wet) (N)</td>
<td>380 ± 37</td>
<td>630 ± 24</td>
<td>490 ± 33</td>
<td>Fall apart in water</td>
</tr>
</tbody>
</table>

### Comparison with Phenol Formaldehyde

**Table 2: Shear strength of 5-ply aspen plywood**

<table>
<thead>
<tr>
<th>Sample</th>
<th>A</th>
<th>B</th>
<th>C</th>
<th>Control Phenol formaldehyde</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shear strength (dry) (N)</td>
<td>1874 ± 208</td>
<td>1909 ± 243</td>
<td>1651 ± 440</td>
<td>1630 ± 240</td>
</tr>
<tr>
<td>Shear strength (wet) (N)</td>
<td>510 ± 54</td>
<td>699 ± 158</td>
<td>515 ± 64</td>
<td>780 ± 90</td>
</tr>
</tbody>
</table>

Shear strength of different animal blood adhesive preparations (formulations 2 through 8) and that of control, poly vinyl acetate (c). Dry and wet refer to condition of wood samples prior to adhesive application.
Polymer crust strength was measured with a mechanical soil penetrometer. As there is some variation in its operation due to how quickly or forcibly the operator presses down, we standardized readings by subtracting the mean and dividing by the standard deviation within each block of the experiment. The lower photograph shows the crust itself.

Figure 3. Comparison of typical check/control plot with the best performing polymer treatment.

Emergence (% of Control) vs. Strength (Standardized): Points are means of three replicates, error bars represent one standard error of the mean.

Cumulative Average Sediment Concentrations (sprinkler simulator):

- Control
- EM-1000-5 kg/ha +Ca
- EM-1000-5 kg/ha +PAM-PS-5 kg/ha
- Soil Net-50-5 kg/ha (gypsum)
- TRIPAM (Ca added)
Soil Net liquid emulsion binder application

Polymer preventing penetration

PAM-12 “Soil Granules”
• Blend of water-soluble linear copolymers and particle sizes
• Contain 1.2% polyacrylamide
• Water activated to give time release of different molecular weight PAM polymers
• Pellets are weed-seed free
• Pellets made from recycled paper product
Clayuca y Soil Net introduced varieties of CASSAVA IN CHINA

CASSAVA PLANT FOR 1200 TON OF FRESH ROOTS PER DAY
Stakeholder Perspectives and Concerns on PAM

Mark Beuhler
Assistant General Manager
Coachella Valley Water District
Presented at the February 27 PAM Workshop in Albany, CA

Coachella Valley is a desert, gets three inches of rain annually (75 mm)

Annual water use of 700,000 acre-feet (870,000 megaliters)

Coachella VWD: water, wastewater, irrigation, flood Control in 1,000 sq. mi. (2600 sq. km.)

Panel Questions
- Challenges in managing water delivery for irrigated agriculture: do more with less
- Desired uses for PAM alternative: replace concrete liners
- Benefits and risks associated with PAM: cost reduction balanced against liability
- Desirable characteristics for PAM alternative: inert, impermeable, inexpensive
- Additional knowledge for PAM alternative: fate and transport
- State and federal regulatory support needed: assume liability

Parallels between PAM and MTBE
- Best of intentions initially
- Large amounts of man-made chemical added to the environment
- Uncertain fate and transport
- Uncertain breakdown products
- Likely health issues with compound or derivatives
- Undefined liability if something goes wrong
Water Use Efficiency has its Risks
Assessing Benefits of Increased Irrigation Efficiency & Reduced Canal Seepage to the Arkansas River System

Timothy K. Gates
Civil & Environmental Engineering Department
Colorado State University

What are the current water conditions in the irrigated stream-aquifer system?

How could conditions be improved?

Field Measurements
Field-Scale Modeling
Regional-Scale Modeling
Basin-Scale Modeling
Pilot Studies for Implementation

Through our Studies We Have Discovered Some Major Problems Related to Water Management, Salinity, and Selenium.

Inefficient Surface Irrigation

Average Irrigation Application Efficiency 55%

About 90% of Applied Water Infiltrates, about 30 to 40% of Infiltrated Water Percolates Downward to Recharge Water Table

Excessive Canal Seepage

Earthen Canals with High Seepage Losses (95 measurements on 8 canals): Up to 4.7 cfs per mile with Average 1.8 cfs per mile (20 to 30% total loss)
Inefficient Irrigation and Excessive Canal Seepage Contribute to:

- Shallow Saline Water Tables
- Dissolving and Movement of Salts and Selenium in Flows that Return to the River

Shallow Saline Ground Water Tables

- Upflux under cropped land causes soil waterlogging and salinity, decreasing crop yield (average 10 to 20% loss)
- Upflux under naturally-vegetated, retired, and fallow land contributes to non-beneficial consumptive use and excessive evapoconcentration

1999 - 2001 Average Water Table Depth

1999 - 2001 Average Soil Salinity

1999 - 2001 Relative Crop Yield

NonBeneficial Consumptive Use from High WT

- Two uncultivated Fields
  - One retired field and one naturally vegetated field
- Landsat5 remote sensing with RESET to obtain ET estimates
- Measure of influencing factors in the field
  - Monitoring wells + water level loggers to measure water table depths ranging from 0 to 3m
  - Soil Moisture (1, 2, 3, and 4 feet)
  - Normalized Difference Vegetation Index (NDVI)
  - Soil Salinity
  - Precipitation
  - Reference Crop ET
**Ground Water Monitoring Wells**

**ET on a Field Near Manzanola, CO**
- 15 June 2007

**NDVI**
- Estimated Upflux from Shallow Ground Water Table to ET
  (21 April – 5 October 2007):
  - 2.6 mm/day Manzanola Field
  - 3.4 mm/day Swink Field

**Estimated Losses to NonBeneficial Consumptive Use in Arkansas Valley**
- **130,000 ac-ft** per year from 218,000 ac naturally-vegetated and retired land
- **30,000 ac-ft** per year from 50,000 ac summer fallowed land
- **22,000 ac-ft** per year from 210,000 ac winter fallowed land
- **Additional losses** on 20,000 ac Tamarisk infested riparian areas

**Salt and Selenium Loads to River with Increasing Concentrations Downstream**
- Evaporative concentration of existing solutes (salts and Se)
- Dissolution and mobilization of new solutes (salts and Se) with surface and subsurface flows through marine shales and shale-derived soils

**Nonpoint Source (NPS) Se Loading Rates to River**
- 1 July 2003
- 28 July 2003
- 25 October 2003
- 12-13 January 2003
- 1 May 2004
- 3 - 4 June 2004
- 29 - 30 June 2004
- 4 August 2004
- 6 November 2004
- 12 January 2005
- 17 - 18 March 2005
- 19 August 2005

**Total NPS TDS Load to River in Upstream Reach**

**Total NPS TDS Load to River in Downstream Reach**

**Salt and Selenium Loads to River with Increasing Concentrations Downstream**

**Nonpoint Source (NPS) Se Loading Rates to River**

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Using our Field Data and Computer Models We are Trying to Discover the Best Solutions to these Problems.

**Improvement Strategies**

- Increased Irrigation Efficiency and Rotational Fallowing:
  - Reduction in Areal Recharge
- Lining/Sealing of Canals
  - Reduction in Seepage
- Subsurface Drainage
- Altered Pumping Patterns
- Combined Strategies

**Favorable Possibilities**

- Ground water table depth can be markedly increased, soil salinity can be significantly reduced, and relative crop yields increased (average 10 percentage points) by improving irrigation efficiency, reducing canal seepage, and installing subsurface drains in selected regions.

- Salt (and likely Se) loads to the river can be reduced substantially (up to 40%), & in-stream and stateline concentrations (up to 10 to 30%) can be lowered, by diminishing recharge to the saline water table by increasing recharge to the saline water table by increasing irrigation efficiency and reducing canal seepage.

We Have Discovered Some Favorable Possibilities for the Arkansas River Valley
Favorable Possibilities

Measures taken to lower the high water table may result in significant reduction in non-beneficial consumptive use under uncultivated fields and under cultivated fields during the off-season (by as much as 15,000 to 60,000 ac-ft per year in the valley).

Key Finding: The Same Strategies that Would Boost Agricultural Productivity Would Also Benefit the River Environment

Canal Seepage Reduction

Key Strategy

- L.A. PAM
- Key Method
  - Effective
  - Low Cost
  - Relatively Easy to Apply
  - Flexible

Polyacrylamide to reduce canal seepage
Current irrigation practices and prospects for increased efficiency
Water conservation and improved quality by reduced non-beneficial consumptive use
Subsurface drainage to control waterlogging and salinity
Modeling best ways to manage river to achieve prospects & comply with compact
Arkansas River GeoDSS

- GIS representation of the system (ESRI ArcMap)
- Spatio-Temporal Database
- Surface/Ground Water Flow & Quality Models with Water Law

Acknowledgements

More than 120 Arkansas Valley Growers and Ranchers
Southeastern Colorado Water Conservancy District
Lower Arkansas Valley Water Conservancy District
Bent County Soil Conservation District
Fort Lyon Canal Company
Catlin Canal Company
Rocky Ford Highline Canal Company
Amity Canal Company
Buffalo Canal Company
Lamar Canal Company
Northeast Prowers County Soil Conservation District
Prowers County Soil Conservation District
Colorado Agricultural Experiment Station
Colorado Water Resources Research Institute
Colorado Water Conservation Board
Colorado Department of Public Health and Environment
Colorado Division of Water Resources
United States Department of Agriculture (USDA)
United States Bureau of Reclamation
USDA Natural Resources Conservation Service
United States Geological Survey
USDA Farm Services Agency
Federal Water Quality Perspective

Joyce M. Donohue Ph.D.
Office of Water
U.S. EPA

Technical Issues
- Efficacy of the material
  - Agriculture
  - Canal sealant
- Potential for contamination of ground water and/or surface water used as drinking water sources
- Impact on aquatic environment
  - Ambient Water Quality Criteria
    - Aquatic organisms
    - Human health
    - Biocriteria

Risk Considerations
- Toxicity of polymer, monomers, additives and/or degradates
  - Mutagenic potential
  - Endocrine disruption
  - Reproductive and/or developmental effects
  - Adequate data to assess risk
- Persistence in the environment

Polyacrylamide
- Office of Water Approved Uses
  - Coagulant for treatment of Drinking Water
    - Anionic and cationic
    - Dry and emulsions
- Treatment Technology Limitations
  - Residual monomer ≤ 0.05%
  - 1 mg/L polymer
- Treatment Technology under review as part of the second six-year review of regulations
- Certification against NSF/ANSI Standard 60 (enforced by states)

Acrylamide
- Neurotoxin
- Mutagen
  - Glycidamide metabolite
- Likely to be carcinogenic to humans
- Germ line mutagen
- NTP studies in progress
  - Cancer studies of acrylamide and glycidamide
  - Developmental neural toxicity study of acrylamide
- EPA risk assessment status
  - Peer review February 20, 2008 reference dose increased
  - Cancer dose response based on glycidamide
    - Age specific adjustment factor for early life exposure

Other Standard 60 Certified Coagulant Polymers
- Polyamines (20 mg/L)
  - EPA limitations on epichlorohydrin and dimethyleamine
- Polyamine limitations on monomer degradates
- Polydimethylallyl ammonium chloride (25 mg/L)
  - 0.05 mg/L residual polymer
- Polyethylene amines (25 mg/L)
  - Standard 60 limitations on epichlorohydin and dimethyleamine and monomer degradates
- Anionic Starch (10 mg/L)
Standard 60 Certified Inorganic Coagulants

- Bentonite (200 mg/L)
- Hectorite (200 mg/L)
- Montmorillonite (200 mg/L)
  - Certification limitations on regulated metals, radionuclides, pesticides, herbicides
- Sodium Silicate (7.8 mg/L)
  - Certification limitation on regulated metals
SNF
LEADING MANUFACTURER OF WATER SOLUBLE POLYMERS
2008

SNF QUICK SUMMARY

- PRIVATELY HELD COMPANY
  - CREATED 1978
  - ST. ETIENNE, FRANCE
- GLOBAL SALES EFFORT
  - SALES IN 130 COUNTRIES
  - OVER 15K CUSTOMERS
- LOWEST COST PRODUCER
  - REINVESTMENT
  - MANUFACTURING DEVELOPMENT
- FOCUSED MARKET
  - POLYACRYLAMIDE
  - ORGANIC COAGULANTS

CERTIFICATIONS

- SNF is certified to ISO9001(2000)
- SNF employees are fully committed to the quality assurance system.
- Internal and External audits are carried out regularly to improve the quality of our products and the service provided to our customers.
- SNF is certified under the Responsible Care® Management Systems and Certification
  - A system designed to improve processes regarding health, safety, security and pollution prevention
  - Audits are carried out periodically to ensure performance and reliability

KEY MARKETS

POTABLE WATER
- FLOCCULANTS, COAGULANTS

WASTEWATER
- FLOCCULANTS, COAGULANTS, DECOR CONTROL, ANTIOXIDE

TEXTILE
- THICKENERS, SOFTENERS

MINING
- FLOCCULANTS, COAGULANTS, FLOTATION REAGENTS

PAPER
- RETENTION, DRAINAGE, WET & DRY STRENGTH

OIL
- EOR, DRAG REDUCTION, DRILLING MUD

Over 700 Products!
**PRODUCTION SITES**

- Paper Products
- Storage Facility
- Production Site
- Production Project
- Sales Office

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<thead>
<tr>
<th></th>
<th>2008</th>
<th>2012</th>
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<tr>
<td>Powder</td>
<td>174</td>
<td>208</td>
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<tr>
<td>Emulsion</td>
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<td>229</td>
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<td>ACM</td>
<td>130</td>
<td>230</td>
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<tr>
<td><strong>TOTAL</strong></td>
<td>460</td>
<td>750</td>
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**NORTH AMERICAN PRODUCTION**

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<tr>
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<tr>
<td>Acrylonitrile</td>
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<td>Cell Microenamer</td>
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<td>Powder</td>
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<tr>
<td>Briochener</td>
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<tr>
<td><strong>TOTAL</strong></td>
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**RAW MATERIAL CHAIN**

- Acrylonitrile
- Water
- Acrylamide
- Ion exchange resin
- Copper Effluent
- Water treatment

**UNIQUE ACRYLAMIDE**

- Conventional Copper Process
  - Acrylamide
  - Water
  - Acrylonitrile

- New Biological Process
  - Acrylamide recirculation

**MY OPINION:**

- **CORRECT APPLICATION IS KEY:**
  - Cannot compare dry spreading to solution addition
  - Dry polyacrylamide should be made into a solution
  - Dissolution time vs mixing energy is critical
  - Convenience should not replace safe usage practice

- **MORE REVIEW OF AVAILABLE PRODUCTS:**
  - Molecular weight range vs application need
  - Blending of products is key to success

- **RESULT:**
  - Lower dosage
  - Lower cost
  - Less loss of product to environment
WHAT IS NEEDED:

• COMMUNICATION!
• COME TO RICEBORO
  – See how and what we make.
  – Attend application training
  – Visit our application systems group
• WE WILL COME TO YOU!
  – Dr. Tichenor will come to your group and hold a training session.

THANK YOU!
**Objectives**

1) Evaluate the ability of new polyacrylamide formulations to reduce soil loss in laboratory scale rainfall simulations.
2) Select the most effective polyacrylamide formulation(s) based on results from laboratory tests and determine their effectiveness at low application rates to reduce soil and P loss from agricultural fields using plot-scale rainfall simulation.
3) Evaluate the longevity of the most promising polyacrylamide formulation.

**Timeline**

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<th>Year</th>
<th>Fall</th>
<th>Winter</th>
<th>Spring</th>
<th>Summer</th>
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<td></td>
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</tr>
<tr>
<td>2006</td>
<td></td>
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- Lab tests - Drip Simulator research
- Field simulations at Arlington:
- Field simulations at Arlington & Platteville
- Field simulations at Arlington & Platteville
- Lab Rainfall Simulations to evaluate PAM for Fall ’05
- Lab Rainfall Simulations to evaluate PAM for ’06

**Soil Test Properties**

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<tr>
<th>Location</th>
<th>% Sand</th>
<th>% Silt</th>
<th>% Clay</th>
<th>Classification</th>
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<tr>
<td>Arlington Agricultural Research Station</td>
<td>21</td>
<td>60</td>
<td>19</td>
<td>Silt Loam</td>
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<tr>
<td>UW-Platteville Pioneer Farm</td>
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<td>56</td>
<td>21</td>
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<table>
<thead>
<tr>
<th>Location</th>
<th>pH</th>
<th>OM (%)</th>
<th>Ca (ppm)</th>
<th>Soluble Salts (mhos x 10^-5 cm-1)</th>
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<td>7.4</td>
<td>4.0</td>
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<td>3740</td>
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<td>6.9</td>
<td>4.4</td>
<td>1770</td>
<td>381</td>
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**Initial Lab Simulations**

- Initial testing EM-1000
  - Soil properties from each location tested
  - Soil % Reduction
    - Arlington: 91%
    - Platteville: 71%

**EM-1000 Modification**

- Adsorption compensation
  - EM-1000 formulation modified to enhance adsorption to Platteville soil
  - An increased divalent cation source can significantly increases PAM sorption to soil particles (Green et al., 2000; Lu et al., 2002)

<table>
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<tr>
<th>Formulation</th>
<th>% PAM</th>
<th>% Calcium</th>
<th>% Oil, Surfactant</th>
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<td>EM-1000</td>
<td>25%</td>
<td>25%</td>
<td>50%</td>
</tr>
<tr>
<td>EM-1000-50%</td>
<td>16.5%</td>
<td>50%</td>
<td>33.5%</td>
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</table>
Lab Simulations EM-1000-50

Arlington Agricultural Research Station

Control showing penetration

Polymer preventing penetration

Soil Net liquid emulsion binder application
Figure 1.
(A) Cumulative sediment load during 60 minutes of simulated rainfall (total precip ~ 65 mm) for bare soil and lime, lime + PAM and PAM-PAM coated lime treated soils.
(B) Percent reduction in cumulative sediment load compared to bare soil for soils treated with the three different conditioners.
Figure 2
(A) Cumulative sediment load during 60 minutes of simulated rainfall (total precip ~ 65 mm) (B) for bare soil, and gypsum, PAM coated gypsum, and gypsum + PAM treated soils. Percent reduction in cumulative sediment load wrt bare soil for soils treated with the three different conditioners.
Manure flocculation and prevention in the runoff

Kurt from DNR fisheries helping to make the S-50

Soil Net liquid binder application

Soil Net liquid binder is so good that it even works applied as rain

Feeding Granules

- Blend of water-soluble linear copolymers
- Contains 1.2% polyacrylamide
- Water activated to give time release of different molecular weight PAM polymers
- Pellets are weed-seed free
- Pellets made from recycled paper product

Existing Biodiesel process

Separator

Glycerin

Biodiesel

Existing Biodiesel process

Separator

Glycerin

Biodiesel

PAM-12 “Soil Granules”

- Blend of water-soluble linear copolymers
- Contains 1.2% polyacrylamide
- Water activated to give time release of different molecular weight PAM polymers
- Pellets are weed-seed free
- Pellets made from recycled paper product

Soil Net liquid binder application

Soil Net liquid binder 12 hours after applied

Soil Net liquid binder 24 hours later

Soil Net liquid binder is so good that it even works applied as rain
## APPENDIX B
### List of Presenters and Participants

<table>
<thead>
<tr>
<th>Name</th>
<th>Organization</th>
<th>Phone</th>
<th>Email</th>
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<tbody>
<tr>
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<td>Roa-Espinosa, Aicardo</td>
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