OPPORTUNITIES AND SOLUTIONS, DEVELOPMENT AND GROWTH OF THE GEOMEMBRANE INDUSTRY

Gary Kolbasuk
Raven Industries, Sioux Falls, SD, USA

ABSTRACT

Polymeric or synthetic hydraulic barriers (geomembranes) have been used in civil engineering applications for over 50 years. Spurred on first by the need to contain water for agricultural and potable water use and then by the need to protect water from pollutants, geomembranes went through an initially slow developmental and acceptance process. As environmental pollution pressures grew, interest and research in geomembranes as a solution accelerated. Eventually, action by regulatory agencies such as the US EPA, brought about rapid growth in geomembrane use and technology. This paper provides a short overview of this history.

INTRODUCTION

A relatively short paper such as this cannot do justice to the history of geomembrane development and use. As with geotextiles and some other geo-materials, there is enough information to write a book. What this paper attempts to do is to give the reader a flavor of what the industry was, how it grew and what it has become today. All materials and activities are not exhaustively covered. The focus is on the major products and activities in the industry.

Because of my background, this paper has a slightly different perspective than the other papers in this symposium in that I have spent most of my career working for manufacturers of geosynthetics and have never worked in academia. Wearing a manufacturing hat, I'm sure, has colored my view of the world and causes my priorities to be a little different than those of a professor, a regulator or a practicing engineer. Based on that perspective, this paper touches on not only the technical developments of geomembranes, but also the business climate, moods of the industry and some of the monetary motivations that caused the industry to change and grow. Also, while I have spent time working in the international market, the bulk of my experience is in the North American market and the information here reflects that bias.

Geomembranes came into use as a result of a growing world population putting increasing demands on our ever more precious water resources. Man's activities were polluting those resources at an alarming rate. Natural materials such as compacted clay and man made inorganic materials such as concrete did not perform well enough and / or were too expensive to use in some applications.

ASTM's definition of a geomembrane is an essentially impermeable geosynthetic composed of one or more synthetic sheets. That bland description, while accurate, does not convey a picture of what a geomembrane is and does. In its simplest form, a geomembrane is a synthetic hydraulic barrier used to contain water and/or pollutants, keep water and/or pollutants out of a clean environment, act as a gas barrier or be a physical barrier in an aquatic environment.

Geomembranes have had a profound impact on the quality of life in developed countries and is improving the quality of life in developing countries. Society depends on geomembranes to contain hazardous waste byproducts in landfill, to control odors from industrial processing ponds, to collect gas generated in landfills, to preserve and convey potable water, to grow food in aquaculture applications, to waterproof dam faces, to control effluents in sewage treatment plants and to provide enjoyment from applications such as golf course ponds, decorative fish ponds and even the magic fountains at the Bellagio in Las Vegas.

PERIODS OR PHASES OF GEOMEMBRANE MARKET GROWTH.

Cutting up the history of geomembranes into periods is somewhat artificial in that there are no real boundaries. The periods and dates I have selected are useful only in trying to organize a picture of the market and technology developments. Others, I'm sure, would divide up the history differently. But I think this is a useful exercise in setting the stage for the rest of the paper and organizing the information.

PHASE I. EXPERIMENTING AND LEARNING.

The first phase of geomembrane history starts in the early 1950's as scientists and engineers started to explore the potential use of synthetic materials in civil engineering and agricultural applications. The research was basic in nature, finding out what these materials could do, how they could be used and how well they held up. Publications of this research made information available to a wider audience and supported acceptance and slow growth.

With some large chemical companies promoting the use of their materials and smaller fabricators, distributors and construction companies looking to make some money in a new field, a number of materials found progressive acceptance until in the late 1960's liner use became widespread. The growth in use, and lack of structure in the industry, brought about the need for standardization and specifications which opens the second period of geomembrane growth.

PHASE II, RECOGNITION AND GROWTH

The second phase begins around 1970, plus or minus a couple years. Recognition began in the form of several standards being written for lining materials including three ASTM specifications, one each for polyvinyl chloride (PVC), polyethylene (PE) and butyl sheeting for pond, canal and reservoir lining. These standards were both material specifications as well as test procedures for some of the tests.

As the recognition phase continues, these materials began to find their way into environmental applications. State and federal regulations began to require flexible membrane liners (FML's) fueling an increase in liner use. Many new manufacturers and installers entered the market.

This period draws to a close as the geomembrane manufacturers, users and regulators gathered under the umbrella of the National Sanitation Foundation to provide a much needed consensus specification for a broad range of liners, bringing legitimacy to the industry, paving the way for the next phase of growth.

PHASE III, GEO-ERA, TECHNOLOGY AND PROSPERITY

Of any of the dates for the beginning and ending of a phase of geomembrane history, for me, 1983 is the most solid. This is the start of the Geo-Era. 1983 is the year that Joe Fluet coined the term geosynthetics from which the rest of the geo-terms were created. Standard specifications and test methods were being written, technical publications were being born, industrial organizations being formed.

This phase was the most active of any stage, with the fastest growth in not only market size, but in new product development, testing technology, raw material technology and education. It was a fast paced fun time that slowly ended as the industry matured.

PHASE IV, MATURE PHASE.

This phase sort of sneaks up on the industry. It does not happen in a single year but is the slow maturing of the industry. Little business becomes big business. Small business, wild, shoot from the hip entrepreneurs that thrive in fast growing markets are replaced by more formal big business professionals (not always a different person, but certainly a major change in demeanor and focus). Broad scope, intensive research and learning is replaced by more limited focused areas of research and refinement of information. Innovation and high margins are replaced by commodity pricing and cost cutting. Custom job specifications are replaced with standard specifications (well, maybe someday). The excitement and enthusiasm of double-digit growth is replaced with running a day-to-day business with low single digit growth at best.

This does not mean that working in geomembranes is boring or that there is nothing left to learn or no new innovations to be made. Geomembranes are a very important product and the market place has enough stimulus to maintain interest. New products are being developed, but things are happening at a slower pace than before. The market place is not driving rapid change. For those who have been in the industry for 20 years, 30 years or more, some look back, sigh, and reflect on just how much fun they had back then and, by comparison, how life is now a little less exciting. Of course, I'm sure the changes in accepted business entertainment practices had nothing to do with that.

THE LIFE HISTORY OF SYNTHETIC GEOMEMBRANES

Trying to decide on how to organize the body of this paper caused me considerable consternation. There is an individual history to each of the materials as well as many other segments of industry history. There is enough information to write a long paper on each of the lining materials themselves. Rather than address each of their histories individually from start to end, I cover them in segments using the above four phases.

My apologies to the many people that have made extensive contributions to the geomembrane industry that I have neglected to mention in this paper. Since this is a paper and not a book, I have intentionally limited the details in order to provide an overview of the history of geomembranes.

PHASE I. EXPERIMENTING AND LEARNING.

The early history of geomembranes no doubt has many starts in different places, but the best known is the early work of Mike Hickey at the Bureau of Reclamation and Dr. C. W. Lauritzen at Utah State University. Motivated by preserving valuable water resources in the western United States, they experimented with natural materials, concrete, flexible PVC, polyethylene, rubber sheeting, asphaltic products and other waterproofing sealants. Without the addition of a synthetic hydraulic barrier, many canals, ponds and reservoirs lost up to 50% of their water through seepage to the groundwater. This water was not necessarily lost from use, but was not available where needed and additional expense was needed to drill wells and recover the water.

Their experimentation resulted in a number of publications in the 1950's and 1960's that started the education process and began to make potential users aware of an alternative to natural materials and concrete. Some of the early titles of papers by Lauritzen et. al. are "Butyl Fabrics as Canal Lining Materials" (1953), "Ways to Control Losses from Seepage" (1955), "Plastic Film for Controlling Seepage Losses in Farm Reservoirs" (1956) and "Linings for Irrigation Canals" (1963). Some early papers by Hickey include "Evaluation of Plastic Films as Canal Lining Materials" (1957), "Report on Installation of Experimental Plastic Membrane Canal Lining Material" (1957) and "Plastic Film Cut

Off and Canal Lining" (1959). The focus is clearly on water preservation and a basic understanding of how polymeric films and sheets could be used.

As this period progressed, on the business side of the equation, far away from the research, early manufacturing of plastic geomembranes was done or encouraged by large chemical companies that saw an opportunity to sell pounds. They were creating products and looking for a market for them. A chemical company or a manufacturer converting the raw materials into a liner sold to local distributors who they trained in solvent welding or taping who in turn trained the contractors. The distributors sold a variety of products and would sell whatever they could to whoever was willing to buy.

There was probably less concern than there should have been about whether the products were appropriate for some of the applications where they were used. Installers in the field typically were unaware of technical aspects of the products they were installing and just went out and "winged it" (in the words of an early installer). Installations were done on rocky subgrades and other horrible situations without giving it much thought. Stone backfill was frequently placed on the liners without cushion fabrics to prevent puncture. Many failures paved the way for the CQA companies that sprung up later. Engineering firms were involved, specifying materials, but much of the information they had to work with is what was supplied to them by the distributor representatives.

PVC

I do not know which material was used first for hydraulic containment so I will start with flexible PVC film and sheet since it grew to represent a large portion of the early geomembrane market. PVC is normally a rigid material, but when plasticizers are compounded into it, it becomes flexible and has improved low temperature properties. Flexible PVC's use in the United States started in the 1930's and its first hydraulic containment application was swimming pools. In 1952, Union Carbide Corporation looked at the hydraulic containment market as a place with the potential to move some serious pounds of plastic.

The early PVC geomembranes had several attributes that made them very desirable and is what helped their use grow over other materials. They were very flexible which let them conform to irregular surfaces easily. They had a fairly low modulus, which let them stretch to conform to point stresses such as gravel. They had good puncture resistance and relatively good tear resistance for an unreinforced material. PVC sheet was easily fabricated into large sheets using chemical or heat welding. Also, important as its physical properties, PVC films and sheets were easily joined in the field with chemical methods such as solvent bonding or bodied solvent bonding.

As with all the materials, there were many failures that made learning possible. Animal activity, human activity and mother-nature in acts as violence such as debris carrying gulley washers down PVC lined canals challenged the liners. The early PVC films used by the Bureau of Reclamation were 0.2 mm (8 mils) thick. As the need for durability during installation and use became apparent, the thickness of the PVC liners continued to increase until 0.5 mm (20 mil) PVC was standard for more demanding applications and 0.75 mm (30 mil) was available for those wanting to be sure they were using a liner that would stand up to abuse.

Even though the market was growing, it was not growing fast enough to hold Union Carbide's interest and in 1962 they got out of the fabrication business. Charlie Staff, who had been working at Union Carbide on the PVC market, left the company and founded a company with his brother Ed that would eventually become Staff Industries. The Staff brothers were successful in their endeavor and helped shape the early PVC geomembrane manufacturing market.

Toward the end of the "experimenting and learning" phase, attention began shifting from pond, canal and reservoir linings to pollution concerns. Preventing pollution of ground water from brine ponds and other chemical storage ponds were becoming more of a concern. PVC was used to line new ponds, retrofitted into existing but cracked concrete storage facilities and being used in floating cover applications to protect potable water from bird droppings and other airborne contamination.

POLYETHYLENE

In the 50's and 60's, polyethylene found limited use in hydraulic applications in the United States, primarily pond and canal linings. The polymer used in that period was conventional, high pressure, low density polyethylene (LDPE), suitable because of its flexibility. LDPE, not to be confused with linear low density polyethylene (LLDPE), has poor tear strength and did not fare well.

High density polyethylene (HDPE) geomembrane production and use originated in Germany in the late 1960's with Schlegel. Early high density polyethylene geomembranes consisted of narrow sheets of polyethylene laid down end to end on a hot roll, the roll indexing and then another layer being laid down on the hot roll, slightly overlapping the first sheet. In this way, a long, wide sheet with cross direction fused overlaps was created. This type of geomembrane was successfully used, and continued to be used into this century. Since the sheet had irregular thickness due to the overlaps, an in between the sheets extrusion welding process was developed to join sheets of material on site.

CHLOROSULFONATED POLYETHYLENE

Chlorosulfonated polyethylene (CSPE) was manufactured by DuPont and sold under the trade name of Hypalon. CSPE began being used in the mid-1960s in both unreinforced and reinforced forms. Reinforcement was typically a polyester scrim.

Black CSPE liners had an advantage over PVC in that CSPE had good UV resistance and was suitable for exposed applications. The reinforcement aided the material in holding up in high stress applications such as steep slopes and floating covers. CSPE saw limited use in this period but became a dominant lining material later.

ASPHALTIC MATERIALS

Asphaltic or bituminous liners fall under the geosynthetic classification since they contain a synthetic reinforcement layer and many contain a polymeric film. Modern bituminous geomembranes look much more like geomembranes than did the first products in the market.

One of the very first synthetic liquid containment lining systems was an asphaltic product made by Gulf State Asphalt. They took the cutout tabs from making asphalt shingles, ran them through an extruder, reinforced them with fiber and made 4’ by 12’ planks. They were welded on site with hot asphalt. The finished liner was then frequently painted with a silver paint. The City of Phoenix used the product to line the inside of concrete water tanks.

W. R. Meadows, started in the 1950’s. Meadow Mat was an 1/8” thick asphalt core board with a plastic 8 mil PVC film suspended between two layers of felt that had a weather coating on top of it. It was a seven element construction for pond linings and canals which sold until mid 70s. It was sold as 4’ wide pieces 8’ to 50’ long. Joining was also with hot asphalt on overlapped pieces or they were butted against each other and gusset strips 6 to 8” wide covered the joints and were then hot moped in place.

These liners found use in military applications, potable water storage and brine storage ponds in the Houston chemicals industry. Because of the weight, it was expensive to ship, handle and install. But it was the only game in town until the more traditional geomembranes came along.

PHASE II, RECOGNITION AND GROWTH

Recognition and appreciation for the performance of flexible membrane liners is what spurred the growth during this period. Growth means business opportunities and more people and companies jumping on the wagon. Proliferation also means more choices as companies attempted to differentiate themselves based on product properties and / or cost. Those attempting to use these materials felt the need for some organization and set about to write the first consensus standards for the products and their installation.

The American Society of Agricultural Engineers, after a number of years of work, wrote a specification on installation (AP340.1). In 1972 the American Society for Testing and Materials (ASTM) generated ASTM Standard D3083 for Flexible PVC Plastic Sheeting for Pond, Canal and Reservoir Lining; Standard D3020 for polyethylene and ethylene copolymer sheeting; and Standard D3254 for butyl rubber sheeting. These specifications provided an easy reference for the novice being introduced to these materials and helped add legitimacy to lining material use for water containment applications.

The Bureau of Reclamation was key in the development and acceptance of geomembranes. People like Bill Morrison and Ron Frobel continued the work of Lloyd Timblin at the Bureau and expanded the use in the western US for water containment.

But it was the United States Environmental Protections Agency (US EPA) that forced the technical growth of geomembranes that paved the way for the tremendous growth in the use of geomembranes in the third period of this history of geomembranes. Robert (Bob) Landreth was a significant force in the United States in this period and the next in providing not only Office of Research and Development (ORD) funding for a broad range of research projects, but also providing his leadership, ethics and insights across the many disciplines and interests that made up the industry.

Much of the increase in geomembrane use in the next phase came from environmental applications, fueled by the US EPA, which began supporting the use of geomembranes in the bottom of hazardous waste storage facilities. On July 6, 1982, the US EPA promulgated regulations that contained the following statement.

> Prevention (via geomembranes), rather than minimization (via compacted clay liners), of leachate migration produces better environmental results in the case of landfills used to dispose of hazardous wastes. A liner that prevents rather than minimizes leachate migration provides added assurance that environmental contamination will not occur.

That statement highlights the recognition of value that geomembranes brought to environmental protection technology.

This activity was not limited to the United States nor was the United States working by itself. Klaus Stief was leading Germany along a similar direction that required the use of thick geomembranes in hazardous waste landfills. In fact, HDPE lining technology was developed in Germany and brought to the US.

Finally, I would be remiss if I failed to mention the mining industry in this paper. While mining does not hold the same interest for the public as pollution and the need for potable water, the use of geomembranes in mining applications certainly got the attention of mines, geomembrane manufacturers and engineers. Rising metal prices in the 1970's along with the abundance of low grade ores, prompted the use of geomembranes in heap leach pads, solution ponds and evaporation ponds. And with the large size of many mining applications, mines came to represent a significant percentage of geomembrane use.

PVC

PVC's growth continued steadily during this period, being supported more and more by environmental needs. An example of PVC recognition by regulatory agencies is in 1977, prompted by an increase in drilling for oil in northern Michigan, the state of Michigan passed a requirement that reserve pits for the drilling mud be lined with 0.5 mm (20 mil) PVC. This and other regulatory activities brought new companies into the market. PVC found itself as the solution to many other environmental problems such as capping landfills, closing unlined facilities and in ponds at wastewater treatment plants.

As the market grew and there became more competition, quality improvements were made. Companies like Watersaver, Palco, EPI and Staff fabricated and installed PVC liners along with Hypalon and other lining materials. They were responsible for promoting the materials, improving factory seaming processes and improving overall product quality.

Even though PVC was not viewed as UV resistant or very chemical resistant, in most applications PVC performed very well and was relatively inexpensive. Toward the end of this period, PVC was king and life was good for those in the PVC liner business. By 1983, PVC had almost 50% of the geomembrane market (percent of area installed).

POLYETHYLENE

As mentioned earlier, thick polyethylene geomembrane technology started in Germany with Schlegel. Heiner Hammer was a driving force responsible for many of the developments at Schlegel. With their new technology they tackled lining the Garling industrial waste site. From the experience at Garling, other landfills and ponds, Dr. Knipschild published the first product and installation specifications.

In South Africa around 1978, Clifford Gundle became aware of Schlegel, and was intrigued by the potential for large projects with polyethylene liners. Gundle was in the blown film and recycling business and was making construction and agricultural film up to 0.25 mm in thickness. Some of these were being used in what we would consider geomembrane applications, liners for irrigation ponds. They had been working with polyethylene since the 1960's, but not in geomembranes and they were interested in getting into the thicker liner market.

Gundle offered to supply Heiner Hammer (who was no longer with Schlegel) and his South African partner, to make a 1.5 mm HDPE liner for a large oil storage facility in South Africa. Gundle had an 1800 mm diameter die but had no idea how to make a 1.5 mm thick material. The HDPE they used at the time was a real HDPE with a density in the 0.960 range. To make it usable in geomembrane applications, they alloyed the HDPE with ethylene vinyl acetate (EVA). While they had a raw material with workable physical properties, they were not having any luck making the heavy gauge material because the molten polymer was too weak to hold itself up during the extrusion process. Fred Struve came up with the idea of using an internal mandrel (cooling can) to hold the bubble up and stabilize the sheet. It worked and they were into the beginning of what I would consider to be main-stream polyethylene production.

Having made the sheet, the challenge of consistently making good welds was in front of them. Gundle was familiar with a variety of welding technologies but none worked as well as they would have liked. That is when Fred Struve invented his extrusion welder with the mixing tip that agitated the extrudate and surface of the sheet to make reliable welds. With that, they were in the business and ready to expand to the United States.

As a side note, today’s standard width polyethylene geomembrane originated with that mandrel. They wanted to ship product by rail and two rolls 6.86 meter wide (22.5’) would fit in a standard open top rail car. Once the mandrel was made, they had no options to make other sizes without making new mandrels. So they stuck with that size and brought it to the United States when they opened a plant in Houston.

Schlegel was first to enter the US HDPE geomembrane market. They started selling their liners out of a Houston facility in 1977 and started production there about 1979. Schlegel was the dominant player in the world thick (2.0 and 2.5 mm) HDPE liner market at the time.

Gundle started operations in the US in 1982, in part, because of the impending US regulations requiring the use of lining materials. They initially took the position of being a manufacturer only and relied on installation companies like Serrot to do the installations.

Schlegel and Gundle started the polyethylene geomembrane market in the United States and had the immense task of not only making and selling the materials, but educating the end users, installers and engineers on the material’s properties and proper use. By comparison to even just a few years later, they were dealing with a very unsophisticated customer base, and were learning fast themselves

While Gundle and Schlegel started the HDPE geomembrane market, there were many other players that had a significant roll in shaping the market. Large chemical companies, the manufacturers of the resins used to make the liner, had a large economical and liability interest. They provided state of the art research facilities and technical assistance. Engineering firms provided innovative designs. Entrepreneurial installers developed installation techniques and made the roll goods into functioning facilities.

CHLOROSULFONATED POLYETHYLENE

Hypalon, along with PVC dominated the geomembrane market during most of this period. When someone said liner, many people thought Hypalon. Manufactured in relatively narrow sheets, it was easy to fabricate into wide panels for easy field installation. Like PVC, it was flexible and easy to solvent weld. With the added benefit of long term UV stability, it took over the exposed geomembrane markets such as ponds, emergency containment liners and floating covers.

Hypalon was not without its weaknesses. It was not chemically resistant as some other so called specialty geomembranes of the time. It was more expensive than most other materials. It tended to cross-link or cure with time, making repairs increasingly difficult. There we occasional blistering problems, particularly in floating covers. Solvent welding became more difficult as the temperature dropped. With PVC's better pricing and HDPE's better chemical resistance, Hypalon began losing market share in 1981.

BITUMINOUS

During the last period, bituminous (asphalt) geomembranes were thick, heavy chunks of material whose installation was very labor intensive. As the other polymeric geomembranes became proven, these slabs were replaced by lighter weight geotextile impregnated, modified asphalts. They continued to be a built up technology containing several functional layers. This product was more popular in Europe than the United States.

CHLORINATED POLYETHYLENE (CPE)

Chlorinated polyethylene (CPE) and CPE alloy liners were popular for a few years particularly in exposed applications. It was used in both reinforced and unreinforced forms. It tended to have good UV and chemical resistance along with reasonable flexibility. In 1980, approximately 12,000 square meters of CPE was used in the Mt. Elbert Forebay impoundment. That installation alone was about 10% of the entire North American geomembrane market that year. Being chemically in-between PVC and Hypalon, it found use as a transition strip between the two materials.

ETHYLENE INTERPOLYMER ALLOY (EIA)

The first ethylene interpolymer alloy geomembrane was developed in 1975 as a coated fabric by a company making plastic coated fabrics for a variety of non-civil engineering applications. The first installation of an EIA geomembrane took place in 1976. EIA was developed in response to the need for more a more petroleum resistant liner than the CPE products being used. This product, in several variations, has been successful in substantial niche markets from its introduction through today.

OTHER POLYMERIC GEOMEMBRANES

This period saw considerable experimentation with polymer types, thermoplastic and rubber compounds. Several were of significance for a period of time, but never became main stream. For that reason, they will not be discussed here.

PHASE III, GEO-ERA, TECHNOLOGY AND PROSPERITY

I picked 1983 for the start of the third period because of all the notable activity that year. 1983 saw a number of engineers who were becoming the leaders of the industry organizing technical information and industry interactions. This period is marked by the coming of age of geomembranes and related products. NSF published Standard 54 on Flexible Membrane Liners. The International Geosynthetics Society (IGS) was formed in 1983. The Geotechnical Fabrics Report (GFR), the first industry publication, started to be printed. Joe Fluet coined the term Geosynthetics from which the rest of the geo-terms were formed. Sponsored by the US EPA, J.P. Giroud started giving courses on geosynthetics in the United States. The first conference on geomembranes was being organized for 1984. 1984 saw the birth of the Journal of Geotextiles and Geomembranes. Manufacturers of geomembranes were pushing education of users, regulators and engineers on how to specify and use their products. Geomembrane use was just starting a rapid growth in environmental applications. Construction quality assurance (CQA) also became an area of rapid growth as everyone grappled with quality problems, failures and how to prevent them.

Wow, what a year! Still, geomembrane use in North America was just a small fraction of what it would be just a few years later. Figure 1 shows the value in millions of dollars of geomembrane sales in North America. 1983 sales were only half of what they would be in 1984 and growth continued at a brisk pace for many years.

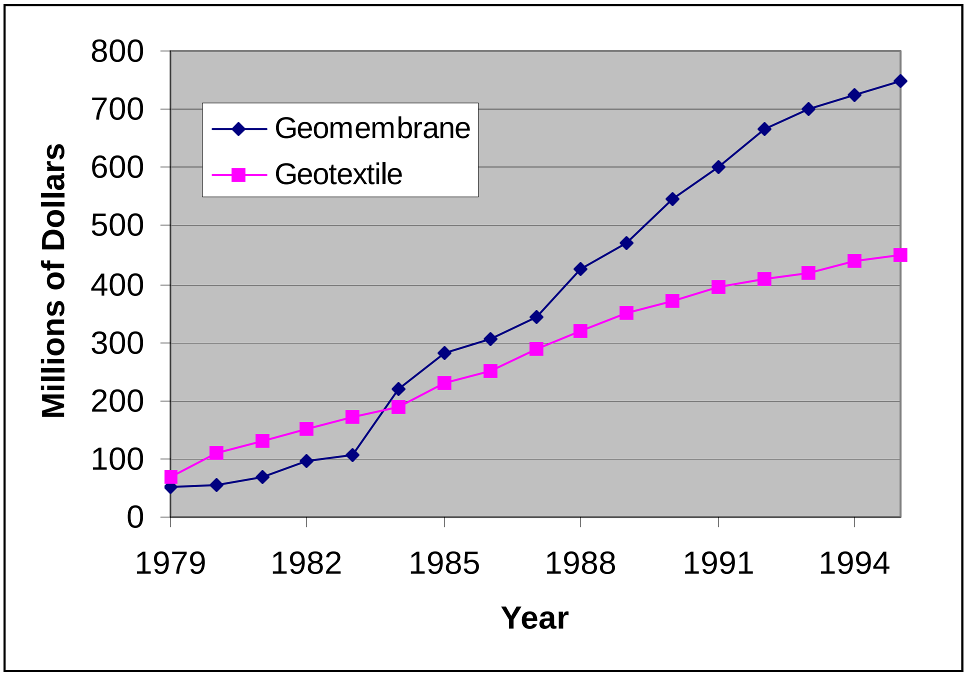

FIGURE 1. ESTIMATED GEOSYNTHETIC MARKET IN NORTH AMERICA

During 1983 and the following years, the engineering and construction world as a whole learned about and started using geomembranes in more applications than ever. The products, the specifications and many of the designs were still fundamental in nature and were changing as people learned more about geomembranes, how to use them and what their shortcomings were. In 1985, Dr. Robert Koerner formed the Geosynthetics Research Institute (GRI) and a geomembrane manufacturer was the first company to step up to the plate, cut a check and become a member. In 1986, Dr. Koerner published the first edition of "Designing with Geosynthetics", "the" textbook on geosynthetics design worldwide for almost 20 years.

As this period continued into the late 1980's and early 1990's, in the area of polyethylene geomembranes, friction sheet and a variety of coextruded products came to market. The significance of stress crack resistance forced resins for HDPE geomembranes to change. VLDPE appeared in the market place. Performance tests came to the forefront of test development.

Information and direction came from many organizations. ASTM committee D35 tackled the enormous needs of the industry for standard test methods. Technical Guidance came fast and furious through the EPA. Of the many very informative and useful EPA technical guidance documents, one in particular needs to be mentioned. Some of us refer to it as the bible of early geomembrane research and chemical compatibility. It is the Lining of Waste Containment and Other Impoundment Facilities by Matrecon written by Henry Haxo. It houses much of the early research that led to the US EPA specifying geomembranes for containing pollutants.

Even with these efforts, there was still a need for more research, more standard test methods and more professional guidance. GRI provided methods and specifications that ASTM could not develop or develop fast enough. The forceful, focused technical leadership from Bob, Grace and George at GRI brought the entire geosynthetic industry together and deserves much credit for the growth of the industry.

And that leadership was desperately needed. Manufacturers, while training many engineers and installers in the use of geosynthetics, also spent a fair amount of effort fighting each other. Specification wars were rampant. One up-man-ship, touting one's products while smashing the competition did so much damage that some engineers, regulators and users lost faith in any of the products. Specifications were written by manufactures as marketing tools. Specifications being written by engineers were sometimes performance and design based, but often were only a copy of a manufacture's specification. As this period comes to an end, NSF 54 was loosing credibility due to neglect and opened the door for GRI specifications.

DUEL TRACK HOT WEDGE WELDING

I start this section out with a discussion of welding technology instead of the materials because of the importance of welding in the successful use of geomembranes. In talking about geomembranes I frequently think about the as manufactured sheet or the finished installation. A whole lot of stuff goes on in between the two. Design, site preparation, deployment, welding and finishing off the construction are all key phases of a successful geomembrane installation. Welding is sometimes viewed as material specific, but one welding technique can be applied to most all thermoplastic geomembranes, wedge welding.

The reason for focusing on wedge welding is that it has become the preferred method of welding for many engineers and geomembrane installation owners. Wedge welding joins two sheets of plastic by passing the sheets over a heated wedge that melts the two surfaces and joins them with pressure to make a seal. No outside adhesives or chemicals are introduced. When using duel track welders, an air channel is formed between the two seals, which can be pressurized with air to check seam continuity. The process is mechanically controlled with the operator(s) monitoring the welder functions and making sure the sheet edges going through the welder are clean. This type of welder has shown a high rate of success and is capable of consistently making good welds.

Hot wedge welding did not originate in the geomembrane industry. It was developed by a Mr. Kurylec in Czechoslovakia in 1947 for welding linoleum. In 1978, Sarnafil of

Switzerland developed their version of the welder for polyethylene geomembranes and received a patent for it in 1982.

Clark Gunness, working for Sarnafil, introduced wedge welding to John Hardison of National Seal Company (NSC) in the early 1980's, granting NSC the right to use the welder for geomembranes. Even though NSC supposedly had exclusive rights to use the welder for geomembranes, Sarnafil was not enthusiastic about enforcing their patent and other companies began using the welding technology.

Clark Gunness was very active in spreading the use of wedge welding. He worked with Columbia Lining Systems in Calgary, Alberta one of the first companies to use the duel track welder. They developed a wide channel, high pressure test to really challenge the integrity of the seam, not just its continuity. Clark started developing his own welder, the Resicon R88 in 1981. It was a small welder compared to the Sarna and NSC welders and was designed to fit under the seat in commercial aircraft. In 1985, he started selling the welder commercially and their use became fairly widespread by 1988.

In Germany, the Bundesanstalt fur Materialforschung and Prufing (BAM) required both wedge welding and on-board data acquisition with respect to welding conditions such as welding speed, wedge temperature, pressure, etc.. Jack Donaldson and myself carried the technology a step further and developed the "Smart Mouse" welder. Not only did the welder monitor the welding conditions, it also controlled the speed of the welder to respond to changes in liner temperature during the course of making a weld.

In spite of an EPA conference on the subject in 1993, the smart mouse did not catch on for a couple reasons. First it cost about three time more than a normal welder. It had greater maintenance costs because of the technology. And lastly, it did not eliminate cutting holes in the liner every 500 feet because it could not eliminate weld failures. Contamination such as soil or moisture in the weld was not detected or controlled by the welder. Still, a lot was learned as a result of the research and some of the infrared sensors for sheet temperature and auto speed controls did find their way into production equipment.

PVC

The North American PVC industry grew and was prosperous, peaking out during the late 80s and early 90s. Even though the PVC lining industry was growing and doing well during that time, the rate of growth was only a small fraction of that being experienced on the polyethylene side of the industry.

The marketing, research and training done by the polyethylene manufacturers supported engineers and regulators with what they wanted, information they could hang their hats on, advance the state of practice and write specifications and regulations that they could justify with data. The PVC manufacturers, fabricators and installers did not jump on the technology band wagon and provide the same kinds of data and did not pursue education of engineers and regulators anywhere near the same extent as the polyethylene industry. The PVC group spent more effort complaining. As a result, polyethylene products became the material that was written into more and more specifications and regulations. By the time the PVC industry recognized what was happening, it was too late.

PVC technology was not stagnant during this period. The quality of plasticizers improved. In the early stages, dioctyl phthalate (DOP) was the predominate plasticizer used. During the end of this period, DOP started being replaced by less migratory plasticizers such as diisodecyl phthalate DIDP.

While the technology was available, not much duel track wedge welding was being done with PVC geomembranes, maybe none in the US. It is thought that some Canadian PVC geomembrane installers were using wedge welders in the 80's. EPI was the first US PVC installer to attempt to embrace wedge welding to at least a limited degree in the early 90's. The main driving force for using wedge welding on PVC at the time was to extend the installation season, being able to weld in cool conditions in the early spring and late fall without tents and other such measures.

POLYETHYLENE

While I refer to this period as the Geo-Era, in the geomembrane market, it can easily be referred to as the polyethylene era. Polyethylene geomembrane producers stepped up to the plate and blasted the geomembrane market wide open with aggressive marketing to end users, design engineers and regulators. Not only did their efforts propel polyethylene use over other types of geomembranes, they also accelerated the widespread use of geomembranes as a solution for environmental and water quality problems.

The industry also had the help of some researchers and regulators that saw the inertness or chemical resistance of high density polyethylene as a distinct advantage in the lining of hazardous waste landfills. Work published by Dr. Hans August and others in Germany showed HDPE to be the only material to stand up to the wide variety of chemicals being placed in hazardous industrial landfills at the time. Similar work funded by the USEPA had Henry Haxo developing chemical compatibility procedures and comparing the available lining materials. When that testing started in the early 80's there were many types of liners being used and evaluated and not much PE. By the late 80's polyethylene was the material of choice, not just because of good performance in the chemical compatibility tests such as EPA method 9090, but also because the polyethylene suppliers participated more in the testing.

But life was not a walk in the park for the polyethylene industry. There were many problems to be solved. In that group was friction, or the lack of it. As many people learned the hard way, walking on a wet, three to one, polyethylene lined slope frequently resulted in an unexpected quick trip to the bottom of the slope. If personal embarrassment and an occasional broken leg was the only issue with smooth PE geomembranes, textured geomembranes may never have been developed. As it turns out, heavily loaded wet soil and waste does not like to stay put on a steep polyethylene lined slope either. Neither does a heavily loaded polyethylene liner like to stay put on a wet slope. Failures occurred at both interfaces and the industry needed to provide a solution.

One of the most studied failures and one that forced friction sheet into production was the 1988 slope failure at the Kettleman Hills Waste Landfill in California. 490,000 m^3 of waste was involved. The landfill design was state of the art, incorporating multiple geomembranes, drainage layers, cushion layers and a compacted clay liner. Failure occurred at more than one interface. The primary failure was at the clay-geomembrane interface. Byrne, et. al, published one of several papers analyzing the failure.

One of the first structured geomembranes (referred to as friction or textured in the US) was developed in Germany by Agru in the late 80's. It had 5 mm tall spikes embossed on the surface. Subsequently, several variations were developed with ribs and other protrusions by Agru and others.

Not everyone thought the first alternative to smooth polyethylene sheet was good enough. Besides being dangerous to fall on, the large dramatic structures significantly reduced the materials tensile strength and elongation at break. Even though HDPE is not designed to be used past its yield point of about 13%, some engineers did not like the dramatic change in properties.

One of Schlegel Lining Technology's customers, BFI, encouraged them to develop an alternative. In the US in the late 1980's, SLT developed a friction sheet by adding a spray on PE coating that was fairly well adhered, but not well enough to seriously reduce the tensile properties at break.

National Seal Company (NSC) developed yet another textured sheet, a smooth sheet coated with a thin foamed layer of polyethylene. The Foam bubbles broke open during the coating operation yielding a rough textured surface. Like the SLT sheet, this textured sheet retained more of the smooth sheet tensile at break properties and was one of the most aggressive textures on the market.

Gundle purchased their second blown sheet line in 1986. This line had coextrusion capabilities and the extruders were designed for injection of nitrogen in the outside two layers. In this way, they made a textured sheet. As the plastic came out of the die, the bubbles being stretched broke open and cooled to make a rough surface. There we many problems with this product early on (holes in the sheet, globs of foamed material sticking to the die then sloughing off onto the sheet, poor consistency, etc.). It eventually became the industry standard as the process was improved to make a better product and it proved to be the least expensive way to make a textured sheet.

With all the choices available in textured sheet and geosynthetic clay liners (use instead of compacted clay in some instances), the USEPA with the cooperation of Waste Management and the manufacturers, set up a long-term slope stability evaluation in Cincinnati. There were 14 instrumented, full scale tests performed on 2:1 and 3:1 slopes. Three of the 2:1 slopes failed. The failures along with the non-failures provided valuable information for future designs.

Another major problem was stress crack resistance. The resins used for many of the early HDPE geomembranes were hand-me-downs from the gas pipe industry. These were real HDPE resins with densities of 0.940 to 0.945. While they may have worked well for pipe, they did not stand up to the abuse taken as part of a PE lining system. Most of the failures occurred at welds that were overheated, distorted, over ground or some how made with a stress concentrating defect.

The industry responded by making stress crack performance improvements such as lowering the density of the polyethylene resin being used. It was necessary to take the density down below 0.940 g/cm^3, the lower boundary set by ASTM for HDPE (0.940 being a somewhat arbitrary number). Since HDPE was already engraved in the industry as a product, no one wanted to change the product name to medium density polyethylene liners. So the industry definition of HDPE was changed to a finished sheet density of at least 0.940 using a polyethylene with a density of at least 0.932 g/cm^3. (The carbon black, used for UV resistance, brings the density up about 0.008 to 0.012 g/cm^3).

While everyone realized that the stress crack resistance of the products needed to be improved and lowering the density was a good way to go, more factors effect stress crack resistance than density (average molecular weight (MW), MW distribution, distribution of comonomer on the polymer backbone, distribution of the comonomer across the different MW molecules, comonomer type, processing conditions, stabilization and so on). So a quantitative test was needed to measure the stress crack resistance of HDPE geomembranes. The “bent strip” testing being used was useless since all the materials in use had good enough stress crack resistance to stress relax before failing.

Dr. Grace Hsuan of GRI developed the notched constant tensile load (NCTL) test to differentiate materials. The test avoided the stress relaxation interference of the bent strip and had short enough failure times to be used as a quality control test (not as short as the industry would have liked, but short enough to be practically useful). By evaluating the NCTL properties of many liners, some that failed and many that did not, a specification was arrived at that is still the standard today.

Many properties were evaluated and tests developed for geomembranes in this period, often with a focus on polyethylene. Lifetime assurances were addressed with oxidation induction time (OIT), carbon black content, carbon black dispersion, air oven aging and UV aging. Durability and resistance to puncture were evaluated with large-scale hydrostatic tests and multi-axial tensile.

But some roadblocks were introduced to new innovation. One that appeared that has not gone away is viewing thickness as a performance property. Many industries have gone to better performing and more expensive grades of polyethylene to get better performance and offset the raw material cost increase by down-gauging, making a thinner product. Since thickness was viewed, at least in practice, as a performance property, minimum thickness is almost always the first property listed in a material specification.

There were some exceptions. For instance, even though HDPE was a dominant lining material, linear low density polyethylene (LLDPE) began growing in applications such as caps where its flexibility and ability to conform to moving subgrades was viewed as positive. Being a cap, it was not perceived to need the same chemical resistance as a primary bottom liner. LLDPE was not specifically addressed in the regulations and was, by default, allowed to be thinner than HDPE in some applications such as landfill liners.

Then very low density polyethylene showed up with even better extensional properties. It did not have the UV or chemical resistance of HDPE or even LLDPE but provided some unique properties. NSC patented a coextruded liner with a VLDPE core and HDPE skins so as to get the most flexibility and the best UV and Chemical resistance in one sheet.

FLEXIBLE POLYPROPYLENE

Flexible Polypropylene (fPP) geomembranes appeared on the market in the early 1990's. The resin was made with a "Catalloy" process that allowed a high percentage of ethylene-propylene rubber (EPR) to be co-polymerized with polypropylene in the reactor. This very flexible material did not resemble standard, stiff polypropylene and made an early splash in the market in both reinforced and unreinforced forms despite its high cost. By 1993, several papers had been written on the use of fPP geomembranes.

The fPP took some market away from polyethylene. It was more flexible than even VLDPE (but not as flexible as PVC). It also had better stress crack resistance than HDPE and was thought to be a good alternative for black liquor lagoons at pulp mills.

fPP took a big chunk out of the Hypalon market. It had better cold weather properties than Hypalon. It was easier to install and repair after having aged. It was easily wedge and hot air welded. It was processed on the same extrusion equipment as polyethylene and other reinforced geomembranes. Even though it cost a lot compared to PE, it was less expensive than CSPE.

CHLOROSULFONATED POLYETHYLENE

Hypalon continued to lose market share during this period, being replaced more and more by polyethylene and, toward the end of the period, by fPP. CSPE had its niche markets where it dominated, such as floating covers, but polyethylene made inroads there as well and fPP was coming on strong. Still, Hypalon had a good piece of the market during this period.

PHASE IV, MATURE PHASE.

Of all the dates I have selected for the phases of geomembrane growth, this is the least well defined. The beginning of this phase could be defined by a change in the growth of the market. It could be defined by a change in market profitability. It could be defined by an onset of mergers and acquisitions. It could be defined by a reduction in funds available for research and product development. It might be defined by a reduction in attendance at industry conferences and symposiums.

But it cannot be defined by an end to the need to learn, develop new products, develop new designs, develop new installation procedures, write new standards, conduct more research or find interesting topics to disagree on. After all, we still, still had not succeeded in one of the most fundamental tasks of all. One of the most annoying, counter productive procedures that continues to haunt the industry. Taking a perfectly good geomembrane installation with good dual track wedge welds and cutting a three foot long hole over a foot wide every 500 feet. So there was definitely work yet to be done.

For the sake of attaching a general date, I would say we had progressed well into this phase by the mid-1990's and will use 1994 as year one.

Based on my description of this phase of geomembrane life, you might think that there is nothing to write about. While I claim the industry entered a mature phase, I said nothing about it entering a grave. New product development and research was alive and well. New spray on bituminous and polyurea geomembranes were introduced. Very flexible polypropylene geomembrane applications were growing. New coextruded PE products were coming to market.

The Bureau of Reclamation (Jack Haynes, Jay Swihart, Alice Comer) began monitoring the Deschutes lining project to evaluate geomembranes in rough sub grade irrigation canals (installed in 1991-1993). A workshop was held in Berlin at the BAM to work through the differences in philosophy of landfill design and construction. The

International Association of Geosynthetic Installers (IAGI) was formed in 1995 to provide a voice for the installers.

Also in the period, signs of the mature stage show themselves in the merger of SLT and Gundle to form GSE. Bob Landreth sadly retires long before we wanted him to. Long after it outlived its usefulness, the once hallmark of the industry, but now outdated NSF 54 on FML's is withdrawn.

WELDING

Refinement and continuous improvement is a necessary part of the "mature phase". Wedge welding continues, more than ever, to be the preferred method of making field welds in thermoplastic liners. Since the smart mouse could not stop failures or reduce the number of destructive field seam tests, the effort changed to smart people as the answer. This approach is two fold. The first is taking seam samples wisely, not just at fixed intervals. The other is to better educate and train the people making the seams.

The first effort to reduce the number of destructive seams through a variable sampling rate came from the Geosynthetics Institute GRI GM-14 guide for "Selecting Variable Intervals for Taking Geomembrane Destructive Seam Samples Using the Method of Attributes", adopted in 1998. This guide attempts to reward successful welding efforts on a job site by reducing the test frequency and it penalizes poor welding with more frequent testing.

IAGI approach the people side by setting up a certification program for welding technicians. An experience technician can go through training, take a written exam and take a hands on exam to be certified. This program kicked off in 2002 for polyethylene geomembranes and in 2004 for reinforced geomembranes. IAGI is trying to convince engineers to specify certified technicians as a requirement and has published a White Paper on "Improving Geomembrane Installations."

PVC

The PVC market began shrinking in this phase of geomembrane history and continues to shrink slowly today. PVC is not technically as accepted by much of the engineering and regulatory community today as polyethylene is. PVC is not a bad material and there are not many material failures. There is just a perception issue with many regulators and engineers. Many engineers can't get what they want from the material, such as the consistency of dual track field welds with air channel testing. While some material is being wedge welded today, much of it is still chemically welded. Technically, the manufacturers have not done enough to improve the perception of their product.

My opinion and the opinion of several people from the PVC side of the business that I spoke with as part of gathering information for this paper is that if the PVC industry had pursued a similar, aggressive marketing, education and technology strategy as the polyethylene industry did, the PVC geomembrane share of the market would have been and would still be much larger.

Processing and compounding improvements have been made but the manufacturers do not advertise or promote those changes. In compounding PVC, mixtures of plasticizers and stabilizers can be used to make products for different applications. South American and European manufacturers make different products for buried vs unburied applications.

There are those in the PVC FML industry that are actively working for improvement. The industry did join together to form the PVC Geomembrane Institute (PGI) for conducting research, publishing technical information on PVC geomembranes, writing a standard specification for PVC geomembranes and offering an opportunity to address the technical needs of the engineers and owners. They continue to investigate ways to improve PVC specifications such as adding a requirement for a minimum plasticizer molecular weight.

Dan Rohe and Mark Wolschon are heading up two ASTM PVC task groups. The first is an attempt to write a consensus ASTM standard specification for PVC geomembranes, something even the polyethylene industry has been shy to do. The other is a dual track weld air channel test to evaluate the peel strength of a seam to eliminate the need to cut holes every 500 feet in field seams. Hats off to them for their efforts.

For the foreseeable future, there will continue to be a need for the PVC geomembranes. It has advantages and it has a place. But it will not be on par with PE products. PE is entrenched and is inexpensive. PVC continues to do better in South America than the US.

POLYETHYLENE

The changes that took place in the polyethylene geomembrane industry during the previous period were amazing. At the beginning of the period, it was a small specialty market that was not well known. By the end of the period, incredible advances were made in products and technology. Equally amazing to those who took polyethylene through that period is how by the beginning of this period, polyethylene geomembranes had become a commodity product, sold by the pound as unenthusiastically as PVC pipe is sold at a home improvement store.

Technology advances were still being made at a fairly brisk rate in materials, extrusion technology, welding, installation and design. But the market had become so large that the only way the manufacturers could service it was selling standard product is mass. This has served to limit new product development for smaller niche areas by major manufacturers. Since higher raw material costs cannot be easily passed on, new materials like metallocenes are very slow to enter the market.

FLEXIBLE POLYPROPYLENE

Flexible polypropylene use grew quickly during the early part of the period and had 5% of the geomembrane market by 1995. It's high cost compared to polyethylene and PVC limited its use to places where its combination of flexibility, chemical resistance, UV resistance and ease of wedge welding allowed it to compete on performance.

There were several failures early on as the industry learned how to properly design with and use the product. Some aging concerns still have to be fully addressed at the writing of this paper and continue to be under investigation.

HYPALON

Through the early 90's Hypalon's share of the market rapidly decline and was down to only 5% of the North American market by 1995. Flexible polypropylene was rapidly replacing it. DuPont, eventually walked away from the market, not in that they quit selling the raw materials to the industry, but in that they quit promoting its use. Hypalon geomembranes are still made and installed but represent only a small amount of current geomembrane use.

BITUMINOUS GEOMEMBRANES

A number of companies continue to make bituminous geomembranes. Their use is Europe is still fairly strong and represent over 10% of geomembrane use. Their use in North America is less than 2% of the geomembrane market but may be growing. They have a 30 year history of use and find there way into a variety of applications including waterproofing dam faces, pond liners, canals and transportation.

EPDM

Ethylene propylene diene terpolymer (EPDM) is not a new polymer or new to geomembranes but is seeing some new life in civil engineering applications. EPDM was introduced in 1963 but saw most of its use in single ply roofing products. EPDM was used in geomembrane applications in the US, but like the bituminous geomembranes, it has found more use internationally. The exception is the home and business decorative pond market, where EPDM enjoys over 90% of the market.

EPDM is a very flexible, versatile material with good UV resistance. Because it is a fully cured rubber, it cannot be heat welded and must be glued or taped together in the field if the project is larger than what can be factory supplied. Since installation does not require any specialty equipment, EPDM is well suited to small applications. That said, it has been used in landfill caps larger than 4 hectares (10 acres).

FUTURE PHASE

I don't claim to be able to predict the future but there are a few observations I would like to make. The world population continues to grow. Land, air and water requirements for that population continue to grow. The world continues to get more polluted, not less. The rates may have been reduced dramatically in many parts of the world and the impact of select pollutants may have been reduced, but pollutants as a whole continue to spread. Popular talk about global warming is starting to be replaced by discussions of solar dimming, the reduction of sunlight reaching the earth's surface due to air borne pollutants and increased cloud cover.

Geomembranes are an important tool in conveying water, holding water, covering water, protecting water by containing hazardous materials, being a hydraulic barrier in purification processes and being a gas barrier, preventing air pollutants from escaping. Their need will not diminish during the foreseeable future. As the demand placed on geomembranes get greater, I believe new polymers will find their way into geomembranes. The polymers used today are good polymers and, for the most part are inexpensive. Many other polymers have barrier properties superior to the most common polymers being used in geomembranes today (and they cost more). Want a glimpse of the available technology, just take a look at what is going on in the booming industry of food and medical packaging. I can see five, seven and more layer coextruded geomembranes with polymers like polyamide, ethylene vinyl alcohol, polyester and other barrier materials being used in conjunction with polyethylene. We may even see breathable geomembranes that let moisture through but contain pollutants.

Through these challenges of the future and changes that are certain to come, sound research, active industry interaction and education of new and existing engineers and scientists will be needed to provide direction and high-quality information. The leadership provided by the Geosynthetic Institute, its associated institutes, Robert Koerner, George Koerner, Grace Hsuan, others at Drexel University, and many others in the industry will be invaluable in keeping us on track and focused on the key issues.

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