EMERGING ISSUES IN HEAP LEACHING TECHNOLOGY

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Abstract: This paper explores recent trends and emerging issues and technology in heap leaching by summarizing the topics discussed at a recent short course by the same topic. The major use of heap leaching is for the extraction of gold, silver and copper, with secondary applications in salts (e.g., nitrates and iodine) and significant investigative work to apply the process to nickel laterite ores. The paper will look at liner system design for heaps to 200 meters of ore depth, the use of interlift liners for oxide ore leaching, raincoat liners for tropical applications, geopipes for heap drainage (including projects with burial depths of up to 165 m and soon to exceed 200 m) and the emerging use of pipes for heap ventilation, alternative drainage media (geocomposites) to augment solution recovery, closure caps and especially the application of geomembranes to limit oxygen entry to wastes and thus limit acid generation. The application of geoelectric leak location technology will also be addressed. Design approaches, limited case histories and technologies-in-development will be summarized from projects world-wide.

Keywords: leach, nickel, geomembrane, laterite, failure, containment, history, mining, mineral processing

INTRODUCTION

Modern heap leaching might be defined as a controlled process whereby ore is stacked in thin lifts (under 10m in most cases), usually crushed and often agglomerated, on a carefully prepared containment system (the leach pad) and irrigated in a controlled manner with a solvent to extract the optimum amount of the target mineral (usually copper, gold or silver). This contrasts with the parallel and older technology of dump leaching where ore is generally leached in its “run-of-mine” state, placed in very large tonnage and thick lifts often in an unlined area. Dump leaching dates back much of a century but modern heap leaching emerged in about 1980 with the first large scale copper projects in Northern Chile and, at almost the same time, the large number of gold projects in the Western United States. The first heap leach operation may have been the Bluebird copper oxide mine in 1968 (Bartlet 1998) followed in the 1970s by a few other small operations in the Western United States. Modern, large scale heap leaching can be said to have begun in 1980 when three major copper projects were commissioned in Chile and at almost the same time the large number of gold projects being commissioned in the Western United States. By 1983 most new leaching operations used modern technology with fully geomembrane lined leach pods. The gold industry was experiencing all-time high prices and fully embraced heap leach technology as a means to bring projects from conceptualization to production in as little as 18 months (Smith & Belingheri 1986). By 1990, there were at least 10 major copper heap leach projects on line in Chile and copper cathode production, the final product of copper heap leaching, was first tracked in international statistics. From 1990 to 1995, cathode copper production doubled and it has more than doubled each five years since. As the price of copper climbed to a peak of US $1.40 per pound on the London Metals Exchange in 1995, the mining industry continued to embrace heap leaching as a method to both develop lower grade resources and thereby expand production capacity, and as a way to bring projects on line in a fraction of the historic time (Breitenbach and Smith 2006).

Due to changing global economics as well as the success of heap leaching itself, both copper and gold (and, to a great extent, all mining commodities) began a downward slide in price after 1995 with copper reaching the bottom of under $0.60 per pound in 1999, where it hovered for several years. And while heap leach production contributed to the oversupply that brought such low pricing, it also kept many companies solvent during these lean times by allowing very low cost production, with copper cathodes being produced for under $0.40 and gold for as low a $40 per ounce (on a cash-cost basis). Despite the low and downward trend in pricing, 1997 to 1999 saw some of the largest-ever heap leach projects commissioned: Zaldivar, Escondida, Cerro Colorado and Quebrada Blanca in copper and Pierina in Gold. Operations were shifting production away from traditional and expensive milling to low cost heap leaching.

KEY DEVELOPMENTS

From the first lined heap leach project in 1968 until 1987, there were fewer than 50 “modern” heap leach projects commissioned with an average size of about 100,000 square meters (m^2) and total lined area of under 3 million m^2. These first pads used liners as thin as 0.4 mm (and in at least two cases only used “overlapped” seams). From 1987 until the present, there have been *at least* 120 more full-scale projects with the largest exceeding 4 million m^2, or a total of 60 million m^2 or an equivalent of 60 square kilometres of liners installed. Essentially all of these leach pads used geomembrane liners with an average thickness about 1.5 mm; many use composites and some use double geomembranes (Smith 2008). The number of important geosynthetics developments that arisen out of this expanding production is perhaps too large to count, and by necessity this paper will focus on only a few. Without suggesting that these are the only important ones, the author has chosen to summarize these as: liner system selection, electrical leak location surveys, nickel laterite heap leaching, shear strength and stability, and failures.

Liner System Selection

As typical heap heights exceed 100 m and approach 200 m, engineers are continually pressed to advance the state of design practice to ensure reliable performance. The primary or key engineering/design and construction concerns can be summarized in Table 1.

Table 1. Key engineering, design and construction concerns

Engineering & Design Concerns	Construction Concerns
• Liquid containment: liner integrity • Operational & closure stability: interface friction strength, flexibility, non-planar anchorage • Chemical & temperature compatibility • Subgrade & overliner: gradation, permeability, lift placement, compaction , surface preparation • Long-term exposure: UV, oxidation/aging, animals and other biological attack • Puncture resistance: subgrade & overliner fill type • Flexibility: differential foundation settlement, installation, puncturing • Tensile, tear & seam strength: liner uniformity, thickness • Contact between composite geomembrane liner & low permeability clayey soil subgrade	• Shipping to site: container rolls versus boxes • Installation, deployment & seaming • Ease of repair: local liner expertise, equipment • Site access: storage area, perimeter access, slopes • Dynamic and static loading conditions: cover fill, roads, traffic, ultimate load • Weather & climate: UV, wind, rain, ice, temperature changes, tress cracking, expansion/contraction • Cold weather installation & cover: frozen subgrade, safety • Grade change adaptability: steep grade gravitational forces, corners, benches, pipe boots • Tie-ins for expansion facilities • Overall cost to construct: materials, labor, schedule

Raincoats are becoming much more common in the industry as mineral development moves increasingly into wetter climates. Raincoats service the dual purpose of reducing water entry into the process circuit and related issues of dilution of reagents and surplus water balance, and protection of the surface of the heap from erosion and damage to the agglomerates (Breitenbach and Smith 2007). Interlift liners are becoming universal for oxide copper ores and will probably be adopted by the emerging nickel leaching area. These thin geomembranes are used to separate lifts of fresh ore from underlying leached ore to reduce acid consumption, and have the additional benefit of allowing drainage above leached ore with declining permeability. Both raincoats and interlift liners represent a new view of geomembranes: neither needs to be “near defect free” as we strive to achieve for containment liners, as both are flow restrictors rather than environmental barriers. Both represent demand for vast quantities of product, with a tropical, oxide copper or nickel leach pad of 1 million m^2 base area needing an equal area of raincoats initially, another 200,000 m^2 for annual raincoat maintenance, and up to 10 million m^2 in interlift liners.

Electrical Leak Location Surveys

Electrical leak location (ELL) survey technology emerged as a commercial technology in about 1985 and become broadly used in the 1990s. Since then, the capabilities of the method and relative low cost have brought it to the forefront of geomembrane quality assurance. Required by an increasing number of agencies for new landfill expansions in the Europe and North America, ELLs are now being applied to heap leach facilities in the mining industry and jurisdictions as diverse as California and Argentina are considering making these obligatory. With proper field conditions, an ELL survey can locate defects too small to perceive with an unaided eye. But the methodology is both a science and an art, and only a few groups provide this service reliably. One reason for this limited service is that the method requires specialty equipment and software, which is largely not available commercially. This leads most practitioners to fabricate their own equipment, none of which is standardized, and whose exact specifications are carefully guarded.

One ongoing debate concerns the desiccation of encapsulated geosynthetic clay liners (GCL), purported by some to preclude ELL surveys while others suggest limited suitability (Darilek & Laine 2007). The author’s experience and a recently published article (Peggs 2007) concur that desiccation can and does occur, with conductivity often dropping below the critical level. GCLs are generally considered to be relatively dry at less than 35% moisture content and therefore, control of moisture content in an encapsulated GCL is a necessary step to ensure the performance of an ELL survey. On the other hand, increased moisture content may reduce shear strength of GCL, but generally not until moisture contents exceed 40 to 50% (Erickson & Thiel 2002). Thus, when ELL is specified or desired then the construction specifications should address this issue by both limiting maximum moisture content for stability concerns and minimum for conductivity (Beck *et al*. 2008).

For a heap leach pad, where the solution is both an environmental risk and the source of a mine’s income, the economics of leak prevention become very interesting. Probabilistic risk analyses of the likelihood of leakage versus the level of quality assurance suggest that the benefits of reduced leakage, in terms of only the metal value and not the value of avoiding the consequential damages, exceed the costs by a wide margin and with very quick payback (Beck *et al*. 2007).

Nickel Laterite Heap Leaching

A laterite is a surface formation in tropical or formerly tropical areas, which is enriched in iron and aluminum. Laterites develop by intensive and long-lasting weathering of the underlying parent rock to form a residual soil or a saprolite (weathered rock). Percolating rain water causes dissolution and leaching of primary minerals (e.g., sodium, potassium, calcium, and magnesium), resulting in a residual concentration of more insoluble elements such as iron, aluminum, and occasionally nickel & cobalt. These deposits become interesting to the mining industry when the nickel and/or cobalt content is high enough to be commercially developed (generally above about 1.0% equivalent nickel content). Approximately 65% of global nickel consumption comes from non-laterite or sulfide nickel ores; however, 75% of the known nickel "in the ground" is contained in laterites, and laterite production is expected to exceed non-laterite in the coming decade. Nickel laterites are distributed around the world in locations ranging from the USA's Pacific North West to Turkey, and from Colombia to the Philippines.

On one hand, nickel laterite heap leaching is an extension of the technology that has been developed over the past 30 years in the copper and gold industries. On the other hand, the subtle differences make the application complex. Copper sulfide leaching produces temperatures up to about 45°C due to both the exothermic actions of the acid and the biological reactions. Nickel leaching temperatures can be much higher, reaching 75°C in a recent pilot test, which has affects on geomembrane and pipe performance as suggested in Figure 1 and Table 2. Laterites also vary from copper or gold heap leaching in other following important ways:

- Acid requirements are 10 to 50 times that used in copper;
- Permeabilities are very low and the resulting leach cycles can be as long as 600 days, whereas 200 to 300 days are common in copper sulfide leaching and 30 to 60 days in gold;
- Interlift liners are required, both to reduce acid consumption and to manage the low permeability;
- Most nickel laterite deposits are in high rainfall climates, and therefore, requiring aggressive use of raincoats;
- Leached ore is very weak and wet, requiring considerable investment in stabilization and closure;
- Nickel is the only heap leach process that produces tailings (in volumes similar to the heap volume);
- Due to the siting climates and nature of the wastes, aggressive closure requirements will generally apply.

Table 2. Comparison of pipe deflection for nominal 150mm diameter dual-wall corrugated PE pipe

Heap Height (m)	Vertical Pipe Deflection (as % of original diameter)	
	23°C	50°C
20	5.0	8.0
40	11.6	17.6
100	16.8	24.9
140	21.4	31.0

Figure 1. Puncture test specimen of 1.5mm LLDPE tested at 120m simulated heap height and temperatures of ambient (left) and 60°C (right). White circles (right) show points of significant thinning and eminent penetration.

While not yet commercialized, when compared to the alternate nickel extraction technologies, heap leaching offers a potentially much lower capital cost for approximately the same operating costs (on a basis of kilograms of nickel produced). Traditional nickel smelting ranges from US $45 to $89 per kilogram of annual nickel production capacity. The more established hydrometallurgical process, high pressure acid leaching (HPAL) and the related derivations (PAL, EPAL, etc), comes on line for US $42 to $81 per kilo. Heap leaching promises to bring production capacity to market for US $22 to $33 and in about half the project development time. With nickel demand growing faster than any other metal, and a ten-year average annual demand growth of 5.8%, the need for major new production capacity, such as heap leaching, is hard to over estimate. Moreover, laterites are not the only nickel ore being considered for heap leaching; the Talvivaara mine in Finland plans to commission the first full scale nickel sulfide heap leach project in 2009 to produce 34,000 tonnes per year of nickel.

Shear Strength & Heap Stability

To summarize the current issues in shear strength including testing, data interpretation and application, and stability analysis are major undertaking and the approaches involve thesis-level works. This area of practice is both critical to the success of large-scale facilities such as leach heaps and landfills, and is the subject of much debate in the professional community. Some of the current discussions are summarized here, with the understanding that these are not a complete list; rather a small window into the larger conversation:

- Types of geosynthetics and their interaction with the surrounding materials;
- Shear strength: interface and internal, peak and post-peak/residual, flat versus dimpled interface;
- Heap slope stability: short- and long-term issues;
- Seismicity, application of seismic risk data in slope stability & liquefaction analyses;
- Construction & operational issues including stacking direction and its affect on stability;
- Normal stress range and the affect of non-linear or bi-linear failure envelopes;
- Apparent and real cohesion, especially on interfaces;
- Compressive stress perpendicular to direction of shearing;
- Texturing and asperity height issues;
- First lift stability and global stability (first lift is often critical);
- Limiting equilibrium and deterministic stability analyses;
- Probabilistic stability analyses;

In terms of the important issue of peak versus residual (or post-peak) shear strengths, the conversation has been on-going for at least 15 years and is anything but over. Various authors have suggested different approaches, with some are summarized in Table 3.

Table 3. Summary of recommendations for use of peak vs. residual shear strength parameters

Author	Date	Recommendation
Stark & Poeppel	1994	Performed both peak and residual analyses
Liu *et al.*	1997	Use large displacement (post-peak) shear strengths
Gilbert	2001	Use residual or post-peak parameters for all cases
Thiel	2001	a) residual for all components, or b) residual for interface with lowest peak strength, or c) peak and with high FS-value, or d) residual on side slopes and peak on base areas
7th IGS Workshop Nice, France	2002	At conclusion of the workshop: 74% of participants recommended using values between peak and residual, 12% recommended peak and 4% recommended residual
Jones *et al.*	2000	Use post-peak for large equipment or steep slope field conditions (i.e., where large displacements are likely); Otherwise use peak shear strength
Koerner	2003	Use peak shear strength when the factor of safety greater than 1.5 except for seismic loading conditions or for unusual construction practices, where residual may be appropriate
Christie	2008	1) residual for all components and moderate FS-value, or 2) use interface with lowest peak strength and high FS-value, and 3) check lowest residual strength and FS>1.1

Problems and Failures

The industry is still daunted by many of the same problems that were encountered in the earliest operations, and many new problems arising out of the evolution of the technology. Generally, the sources of failure and some of the core issues faced by most heap leach operations can be summarized as follows:

- Design
- Testing: Design and conformance
- Specification development and application
- Construction defects: Geosynthetics, pipes, earthworks
- Closure and post-closure maintenance
- Permeability: Ore, overliner (operations layer), and subgrade or clay-component of the liner system
- Slope stability and erosion control
- Liner & piping issues: Materials, design, chemical and temperature resistance
- Operational issues: Pipe and liner damage, overliner (quality, availability, clogging), acid and temperature

- Solution management (e.g., PLS or pregnant leach solution) collection system: Permeability, drain piping, clogging
- Increasing size of facilities: Pad areas in the square kilometres, heap depths approaching 200m (and ability to simulate these conditions in the laboratory)
- Total project costs and the influence of investigation and engineering costs

One area predicted to pose the potential for serious problems, liquefaction, has in fact not manifested. Though a map of intense seismic hazards corresponds closely to a map of heap leaching, there are only two liquefaction failures known to the author and only one of these has been (briefly) published. Both of these cases were in Peru and both mobilized only very shallow zones in the heaps. Neither failure was deep enough to engage the liner system and neither caused any significant damage outside of the containment area (only one left containment). Whether this is a result of good engineering practice or a fundamental quality of heap leaching is an area of ongoing debate.

More generally, seismic stability continues to be the subject of ongoing study, with investigators considering testing and modelling methods as well as actual field performance. The most common method of analysis, at least as a first step, is the pseudo-static analysis using limiting equilibrium techniques. In this method, the ground acceleration is applied as an equivalent static force and the factor of safety is then calculated using the same methods as for true static (i.e., self weight) loading. The sensitivity of pseudo-static factor of safety to the assumed horizontal ground acceleration is shown in Figure 2, where a typical slope is subjected to a range of accelerations from zero (no ground movement) to strong ground motion. The resulting factors of safety range from 2.5 (static) to 0.95 (strong ground motion).

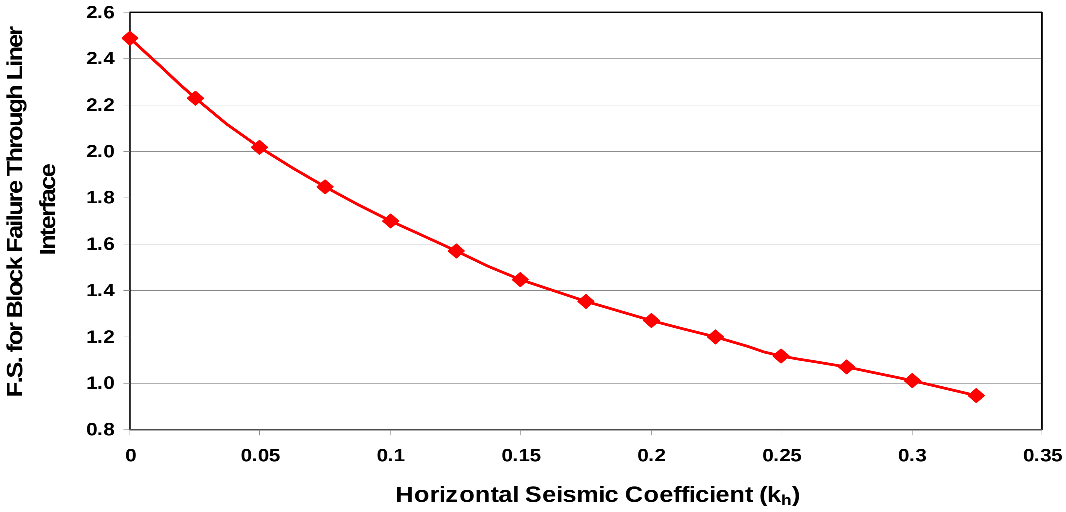

Figure 2. Change in pseudo-static factor of safety as a function of horizontal ground acceleration

An interesting tendency in mining, and perhaps in other industries, is to assume that “no known failures” equates to “no failures.” However, in many cases this only means that if a problem exists, it is below the detection threshold (or that a detection method simply doesn’t exist). This is certainly the case with some heap leach pads, which are usually single lined, have no or very limited vadose zone monitoring, and with very deep groundwater. In such a scenario, the absence of detected leakage should not be confused with the absence of leakage. This neglect could have serious consequences and calls for a cooperative effort of operators, consultants, manufacturers & construction professionals in analyzing, understanding and preventing failures.

Karl Terzaghi, the father of soil mechanics, once said "*On account of the fact that there is no glory attached to the foundations and that the source of success or failure are hidden deep in the ground, building foundations have always been treated as stepchildren and their acts of revenge for lack of attention can be very embarrassing."* What Terzaghi said in reference to building foundations could very well be applied to leach heaps and landfills.

CONCLUSIONS

Heap leaching has been a major contributor to geosynthetics technology since it first emerged as a large scale application in the 1980s. This trend will almost certainly continue, both in terms of quantity of material used and intensity of use. Some of the current challenges include depth of burial (approaching 200m at a density of twice municipal waste), high temperatures combined with concentrated sulphuric acid, critical slope stability factors, increasingly challenging siting factors such as terrain, climate and seismicity. There is also an increasing demand for higher levels of containment – both for increased environmental stewardship and for economics - resulting in more attention to construction quality and broader application of electrical leak location surveys. Despite all the advancements of the past decades, we are still haunted by some of the same mundane but yet critical problems of the early days of the technology, which range from inappropriate material selection to inadequate design and poor installation and operational practices.

Mining is a major application of geosynthetics both in terms of the quantity used and in developing the technologies. Heap leaching has been the largest consumer of geosynthetics in mining, principally geomembranes and related components. The trend is for increasing mineral production in traditional areas of copper and gold heap leaching as well as expanding applications to non-traditional minerals such as nickel and uranium. There is also a strong trend for increasing use outside the heap leaching area, including liners and caps for tailings and waste rock dumps. Simultaneously, global demand for minerals is likely to continue to outpace either population or total GDP. From this, some conclusions can be put forth as follows:

- Population and GDP growth should increase both mineral and geomembrane demands (see Figure 3);
- Increasing per capita GDP suggests increasing per capita geosynthetics demand as higher income levels both drive demand for technology and affords more advanced environmental standards; this is driven both by the emerging economies of China and India, and the general advancement in Latin America and other developing areas;
- Diversified uses such as waste dump closure, tailings impoundments and ARD control should accelerate demand beyond what historic growth figures suggest;
- Nickel heap leaching will begin affecting geomembrane demand especially of 1.5mm thick by 2010, with annual consumption exceeding the equivalent of 1 million square meters, and uranium heap leaching could match that of nickel heap leaching;
- Total mineral demand is expected to grow fastest in locations such as Brazil, Southeast Asia, Western Australia, and Africa;
- Considering all these, it is likely that mining demand for geomembranes will double over the next 20 years.

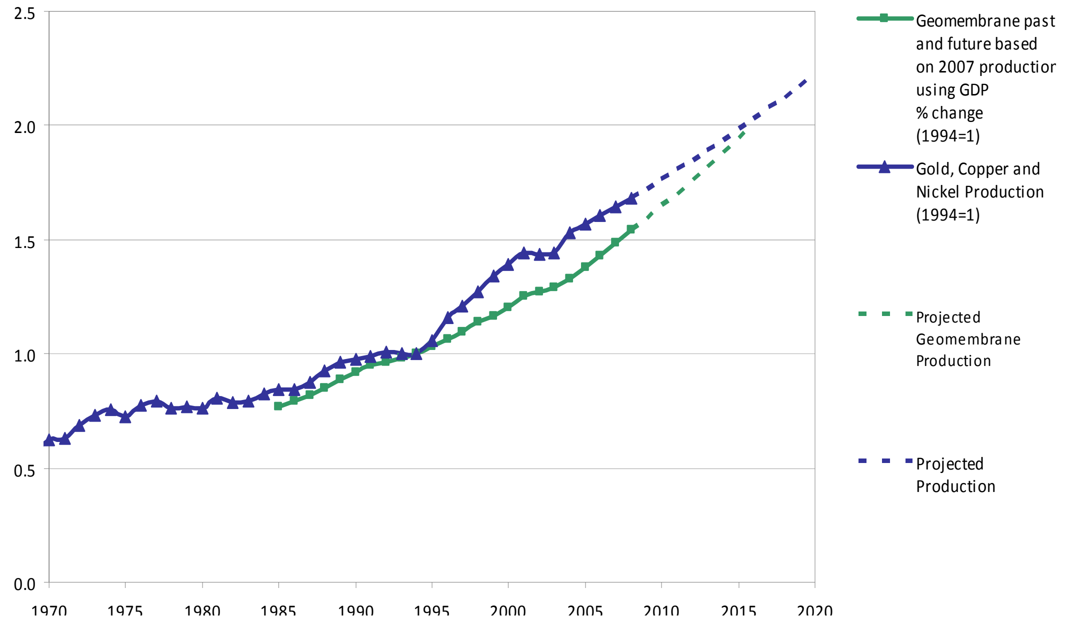

Figure 3. Demands for geomembranes, and copper, gold and nickel - historic and projected (normalized to 1994)

Acknowledgements: The authors would like to acknowledge and thank the presenters of the GeoAmericas 2008 Emerging Issues in Heap Leaching short course (Cancun, Q. Roo., Mexico, March 2, 2008): Allan Breitenbach, Dr. Krishna Sinha, Abigail Beck and Monte Christie, as well as the participates therein whose questions and discussion greatly contributed to the development of this technology and this paper.

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REFERENCES

Bartlet, R. W. 1998. Solution Mining: Leaching and Fluid Recovery of Materials, Routledge publishers. 113 pp.

Beck, A., Kramer, E. and Smith, M. E. 2008. Specifications for Moisture Content of GCL to Perform Electrical Leak Location Surveys, to be presented at EuroGeo 4, Scotland, September.

Beck, A., Smith, M. E. and Colmanetti, J. 2007. Métodos Geoelétricos empregados na Minimização de Perdas de Solução em Pilhas de Lixiviação de Minério, Proc. of the VI Congresso Brasileiro de Geotecnia Ambiental e V Simpósio Brasileiro de Geossintéticos, Recife, PE, Brasil, 18-21, June.

Breitenbach, A. J. and Smith M. E. 2007. Geomembrane Raincoat Liners in the Mining Heap Leach Industry. Geosynthetics, IFAI, April, 25 (2), 32-39.

Breitenbach, A. J. and Smith, M. E., 2006. Overview of Geomembrane History in the Mining Industry, Proceedings of the 8th Bi-annual meeting of the International Geosynthetics Society (8IGS), Japan, September.

Christie, M. 2008. Shear Strength of Geosynthetics, presented as part of the short course entitled Emerging Issues in Heap Leaching, Geoamericas, Cancun, Q. Roo., Mexico, March 2.

Darilek, G., and Laine, D. 2007. Experience with Geosynthetic Clay Liners as a Conductive Layer in Geomembrane Leak Location Surveys. Geosynthetics, June-July, pp. 30.

Erickson, R. B. and Thiel, R. 2002. Design and application of the geomembrane supported GCL in one-product and encapsulated composite liner systems. Swets & Zeitlinger, Lisse, ISBN 90 5809 380 8.

Gilbert, R. B. 2001. Peak vs. Residual Strength for Waste Containment Systems. Proc. GRI-15, Hot Topics in Geosynthetics II, GSI Publ., Folsom, Pa., pp. 29–39.

Jones, D. R. V. 2002. Serviceability Concerns of High Deformations Between Geosynthetic Interfaces. Workshop at 7th Intl. Conf. on Geosynthetics, Nice, France.

Jones, D. R. V., Dixon, N. and Connell, A. 2000. Effect of Landfill Construction Activities on Mobilized Interface Shear Strength., Proc. EuroGeo 2000, Bologna, Italy, pp. 581–586.

Liu, C.N., Gilbert, R.B., Thiel, R.S., and Wright, S.G. 1997. What is an Appropriate Factor of Safety for Landfill Cover Slopes?. Conference Proceedings from Geosynthetics ’97. IFAI, Roseville, MN, pp. 481-496

Koerner, R. M. 2003. A Recommendation to Use Peak Shear Strengths for Geosynthetic Interface Design, in Geotechnical Fabrics Report, April.

Peggs, I. D. 2007. Liner integrity/leak-location survey: The Significance of Boundary Conditions. Geosynthetics, February-March, pp. 34.

Smith, M. E. 2008. Mining and Geosynthetics: Emerging Technology, Growing Markets, key note presentation, GeoAmericas, Cancun, Q. Roo., Mexico, March 2.

Smith, M. E. and Belingheri, K. M. 1986 A Low Capital, Fast Track Approach to Plant Start-Up: A Case Study, in Mineral Processing, February.

Stark, T. D. and Peoppel, A. R. 1994. Landfill Liner Interface Strengths from Torsional-Ring – Sress Tests. ASCE, Journal of Geotechnical Engineering, 120(3), 597–617.

Thiel, R. S. 2001. Peak vs. residual shear strength for landfill bottom liner stability analyses. In: Proceedings of 15th Geosynthetic Research Institute Conference on Hot Topics in Geosynthetics-II, Folsom, Pa.: GRI Publishers, pp. 40-70.