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NONDESTRUCTIVE EVALUATION METHODS

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ABSTRACT

Professor Robert M. Koerner (Bob) has successfully and elegantly transitioned his research programs throughout his career. Each successive program has brought new collaborators, contacts and consumers of his developments. Past research efforts may remain unknown to those who only more recently began an association with Bob. It is interesting and insightful to develop and follow the some times convoluted path that has led to the current, well-recognized Geosynthetics Institute. In this paper, I will provide insight into what may be the *missing link* between Bob's research in acoustic emissions and his current program in geosythethics.

INTRODUCTION

While Bob Koerner's accomplishments in the area of geosynthetics currently eclipse some of his past efforts, there still remains a good deal of familiarity of his work in acoustic emissions (AE) in soil and rock, as clearly noted by Dr. McCabe. However, there was a transition period between the heyday of the acoustic emissions work and the zenith of the geosynthetics effort about which far fewer people seem to be cognizant. This area is Bob's work in nondestructive evaluation (NDE) methods. In this paper I will show how the nondestructive evaluation period proved the ideal transition from the acoustic emissions research program to the Geosynthetics Institute. The path is shown schematically in the flowchart in Figure 1.

A SHORT HISTORY LESSON

The 1976 Teton Dam failure and the failure of the Taccoa Falls dam in 1977 created a major push for increased research in dam safety including problem detection and development of early warning systems. This application was perfect for acoustic emissions research and propelled Bob's AE research program into high gear. In addition, what Bob recognized is that most of the failures were attributed or at least related to subsurface water movement and that being able to locate the subsurface seepage was important if not paramount to early detection of potential problems with dams, dikes and impoundments. The excessive cost associated with using drilling and sampling and the limited successes of dye tracing made nondestructive evaluation methods appealing for location of subsurface water. In a paper with Reif and Burlingame, Bob summarized the nondestructive evaluation methods available for water table and seepage identification and commented on their attributes (Koerner, Reif and Burlingame 1978). Efforts were made to use acoustic emissions to locate subsurface seepage but background noise was

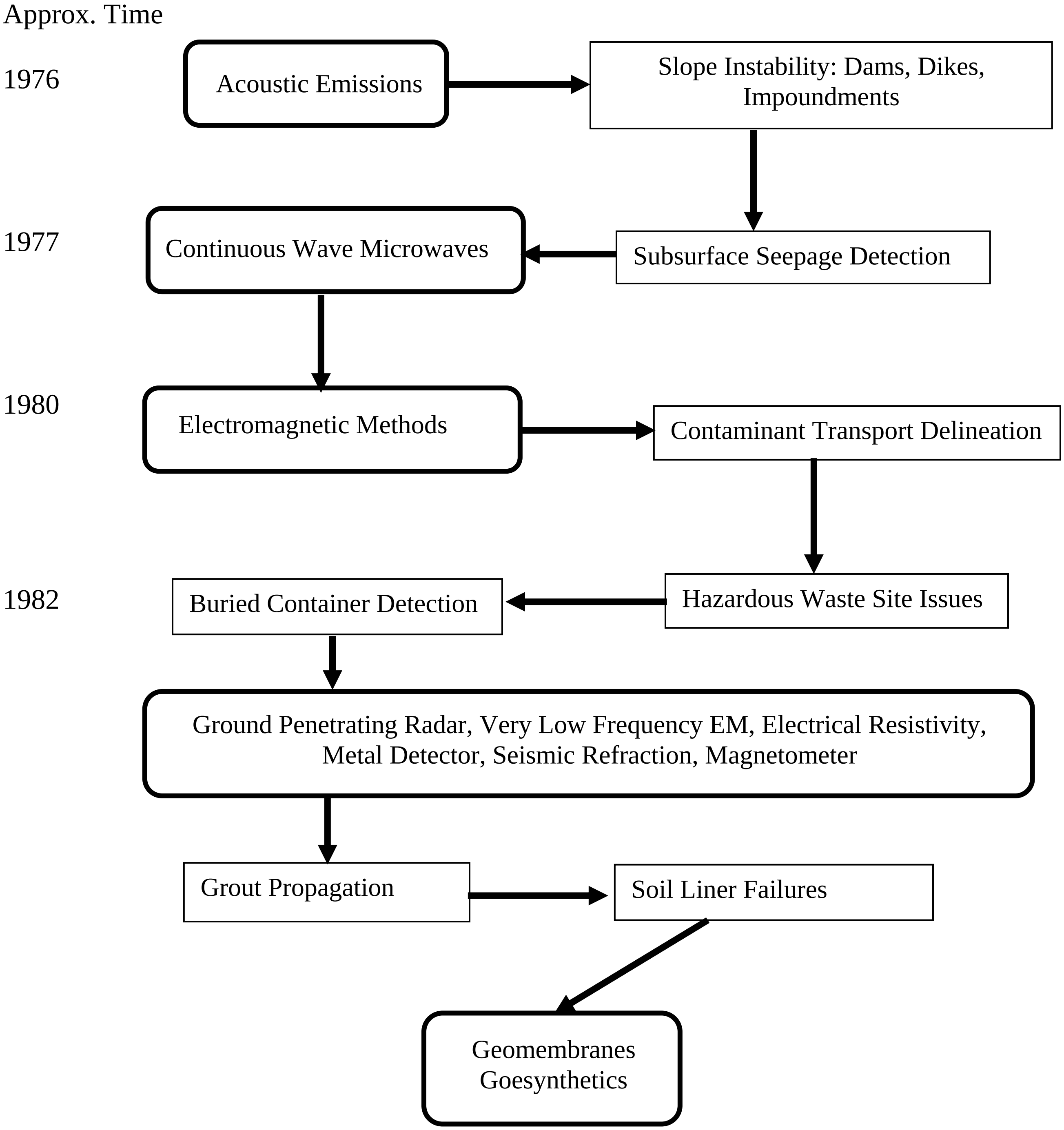


Figure 1 – Flow chart of nondestructive evaluation technologies research and development by RMK at Drexel University.

problematic so Bob along with Professor Arthur Lord realized other technologies might prove better suited to the task. Having already been investigating the electrical properties of soils with Professor Lord (Okrasinski 1977, Reif 1979), they decided to have a look into other (non AE) nondestructive methods for detecting subsurface flow.

MICROWAVE INTERFERENCE METHODS

The first, non-acoustic emission, NDE method to be considered was the microwave interference method. Microwaves occupy that portion of the electromagnetic spectrum between short wave radio and infrared radiation, roughly between frequencies of 10^9 to 10^{12} hz. These frequencies yield wavelengths on the order of 10 cm to 0.01 cm. The typical microwave oven operates at 2.4×10^9 Hz with a wavelength of about 10 centimeters. Microwaves readily propagate through dry materials like plastics, ceramics, and wood, but are attenuated to varying degrees when passing through wet materials. The attenuation results from microwave-induced rotation of water molecules known as a "lossy" process which when given sufficient power is the basis of cooking using microwave ovens.

By the later half of the 1970s, several researchers were working with pulsed microwave systems to nondestructively evaluate subsurface geotechnical anomalies including rock faults, cavities, utilities and karst features. Several commercial systems were available but none of them had been used to identify the water table or subsurface seepage.

Together with trusted colleague Art Lord, students Thomas Okrasinski and Jonathan Reif, Bob constructed a continuous wave (CW) microwave measurement unit (Figure 2) to determine the validity and accuracy of using the microwave interference method to detect subsurface water. Their results were promising as they found an accuracy within about 10 percent between measured and predicted depths to water levels in laboratory and field tests using the CW microwave method (Koerner et al 1978).

The applicability of the CW microwave system to characterize voids beneath paved areas was subsequently evaluated. The method proved applicable for unreinforced pavements and was adept at characterizing the spatial extent of voids; however, determination of the thickness of the voids was not possible at that time (Koerner et al 1982).

The main drawback of the continuous wave microwave method was that the system was not commercially available. The system operated over a limited frequency band (about 2.1 to 4.2 GHz) with wavelengths between 7 and 14 cm. These relatively short wavelengths were easily attenuated in wet soil so penetration depths were not great. During the same time frame, 1975-1980, manufacturers of pulsed systems were rapidly developing their equipment making it readily available and somewhat user friendly.

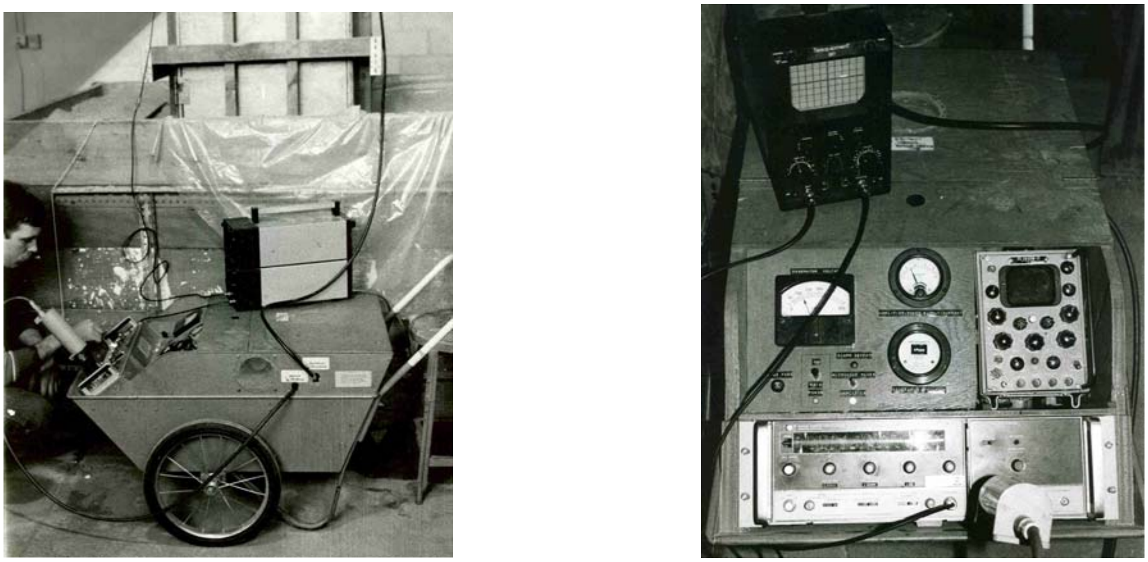


Figure 2 – Continuous wave microwave unit designed and manufactured in the Drexel University nondestructive evaluation techniques research program by Koerner and Lord (c1980).

By 1980, numerous hazardous waste sites were in the news, e.g., Love Canal (Slack 1981), and the US EPA (1980) estimated the cost of clean up of hazardous waste dumps at 50 billion dollars. Bob and Professor Lord proposed an evaluation of a broad range of nondestructive evaluation techniques applied to environmental problems involving hazardous waste spills including the detection of contaminant plumes, a direct outcome of the effort to detect subsurface water seepage. The objective was to develop a matrix ranking the various NDE methods with respect to different environmental applications (Lord, Tyagi and Koerner 1980). The matrix along with their preliminary assessment is shown in Table 1. This effort along with the results from the CW microwave research coupled with the commercial developments in the pulsed systems led to acquisition and evaluation of many of the techniques listed in Table 1.

PULSED RADIO FREQUENCY (RF) METHOD

The electromagnetic spectrum is infinite (Figure 3); however, pulsed radio frequency (RF) systems typically operate from about 1 Mhz ($1x10^6$ Hz) to 200 Mhz ($200x10^6$ Hz). Systems operating at higher frequencies up to about 1 GHz ($1x10^9$ Hz) are routinely referred to as radar systems. The systems are often referred to as ground penetrating radar units. The upper frequency is just below the commonly accepted microwave frequencies. In the radar range, wavelengths are about 3 m to 0.5 m, much longer than that used in the continuous wave microwave device. While the longer wavelengths afford greater penetration depths, they result in reduced resolution since the smallest detectable objects are roughly proportional to the wavelength. The pulsed system operates by sending short bursts of electromagnetic energy into the ground. When the waves infringe on a material with dissimilar dielectric characteristics part of the energy is

Table 1 – EPA potential problem areas rated against possible nondestructive evalaution method of solution (1 – Highest potential of success; 5 – Lowest potential of success, no entry – not applicable) (Lord et al 1980).

Problems Area / NDT Method	(a) Dike Stability	(b) Deep Depth Tracing	(c) Shallow Depth Tracing	(d) Surface Container Corrosion	(e) Buried Container Location	(f) Buried Container Stability	(g) Buried Pipeline Leads	(h) “Sinker” Chemical
1. Pulsed Microwave	3	2	2		1			
2. CW Microwave	4	2	2		1			
3. Eddy Current				2	2	2		
4. Magnometer				5	3	4		
5. Seismic Reflection	4	4	4		5			
6. Seismic Refraction	4	4	4		5			
7. Electrical Resistivity	4	3	3		5			
8. Penetrating Radiation		4	4	5		5		
9. Acoustic Emission	1			4			1	
10. Liquid Penetrant						4		
11. Infrared Radiation	5	4	4		4	4	3	
12. Ultrasoncis		5	5	1		2	2	
13. Sonar					5		5	3
14. VLF Electromagnetic					5			
15. Induced Polarization					5			
16. Self Potential	5	5	4				4	
17. Optical (Laser)								1

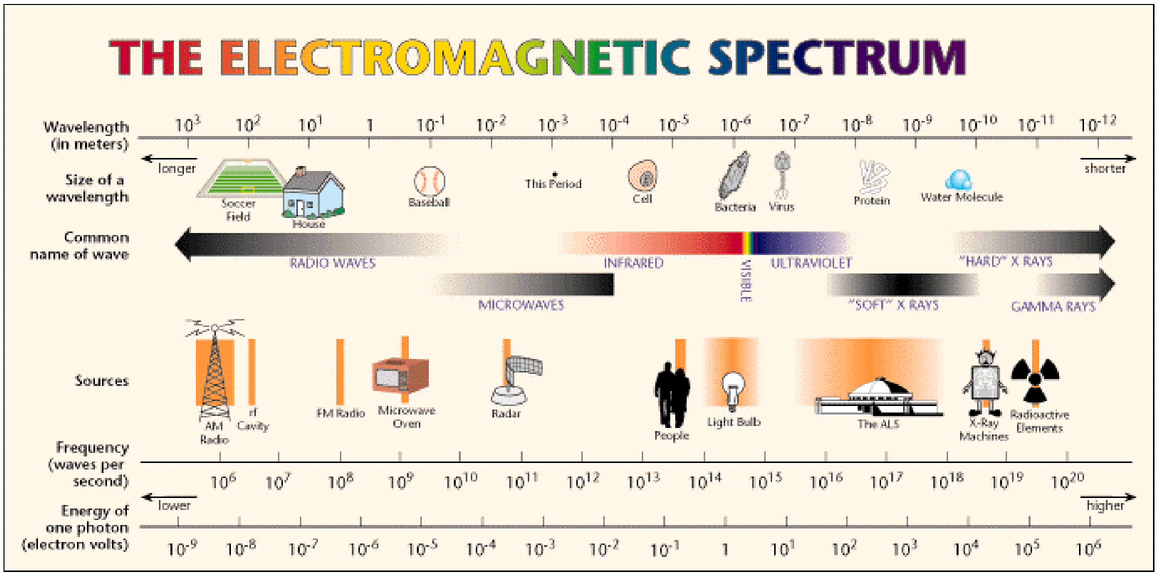


Figure 3 – The electromagnetic spectrum.

reflected back to the ground surface where it is received and the time of travel is recorded. The depth, d to the interface is then calculated from d = (v*t)/2 where v is the wave velocity (which is equal to the $c/\sqrt{\varepsilon_r}$, where c is the velocity of light and ε_r is the relative dielectric constant of the material in which the wave is propagating) and t is the pulse travel time. Commercial manufacturers provided systems capable of real-time display of output with simultaneous storage of data on tape (Figure 4).

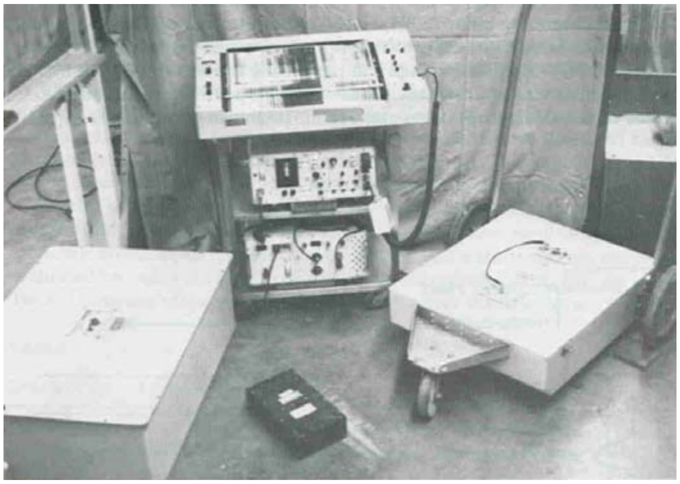


Figure 4 – Pulsed radio frequency (ground penetrating radar) equipment.

The pulsed RF system was evaluated for use in locating the groundwater table in different soil types and over the complete seasonal change of one year. Water level measurements were also taken in order to provide ground truth of the pulsed RF predictions. A 120 MHz antenna which yielded wavelengths on the order of 2.5 m was used throughout this investigation. Results of the study indicated that locating the water table in sand or gravels was possible and relatively accurate (within about 15%) provided there was no moisture present on the surface. In fine grained soils (silts and clays), the capillary fringe tended to mask the water table reflection and stratigraphic changes in soil layers, especially with different moisture contents, tended to dominate the reflections (Koerner et al 1981).

The pulsed RF system was also evaluated and found to be technically feasible for use to locate buried containers (Lord et al 1980). More extensive work continued resulting in a better understanding of the capabilities and limitations of pulsed RF. The investigators found that in a relatively uniform sand site with the water table approximately 7 m below the surface and a low moisture content (about 2 % dry mass basis) in the sand above the water table, steel drums were easily detected to depths of 3 m to 4 m using an 80 MHz antenna. Near surface drums were more easily detected with a 120 MHz antenna. Empty plastic drums were transparent to the RF; however, when filled with water or a saltwater solution they were detectable. The return signal from the saltwater-filled plastic drum was somewhat weaker than that from the fresh water-filled drum due to the highly conductive nature of the saltwater which attenuates the RF signal. Closely spaced drums could not be resolved to determine the exact number of containers but depth predictions were accurate to all of the drums located using the pulsed RF (Bowders at al 1982a). A limitation of the pulsed RF is the necessity of scanning the antenna immediately above the containers. Drums adjacent to the penetrating signal can easily be missed. In addition, the RF is highly sensitive to soil conditions and sand sites present an ideal situation. Sites in clays and silts met with less success.

OTHER NDE METHODS

Given the limitations of the continuous microwave and pulsed radio frequency methods, other nondestructive evaluation methods must be considered. Bob and his collaborators undertook an extensive study to compare seven nondestructive evaluation technologies for detection of buried containers (Lord et al 1982). The technologies included seismic refraction (SR), electrical resistivity (ER), ground probing radar (GPR), continuous wave microwave (CWM), metal detector (MD), very low frequency electromagnetic (VLF-EM), and magnetometer (MA).

The site, described above, was ideal and consisted of relatively uniform sand, groundwater table at about 7 m and very low moisture content above the water table (about 2% dry mass basis). Metallic and plastic containers ranging in size from 7 L (2 gallons) to 200 L (55 gallons) were buried at depths from 0.3 m to 4 m below the ground surface. Plastic containers were empty, filled with fresh water or filled with a saltwater solution. One area was set up as a random burial site containing a collection of 6 steel drums, 2 plastic drums and several steel plates of various sizes.

Each NDE technique was applied to the various scenarios. The results were analyzed for detection, delineation and prediction of depth of the containers. The results are presented in Table 2.

Only ground penetrating radar, metal detector, very low frequency electromagnetic and magnetometer methods were effective in delineating the buried containers. The continuous wave microwave method was of marginal use and the seismic and resistivity methods were of no use in detection of the buried containers.

The metal detector was very inexpensive, easy to use and quite sensitive to the metallic drums. The magnetometer and VLF-EM both showed excellent sensitivity for the metallic drums. The VLF-EM works for any metallic containers while the magnetometer works only for magnetic materials. The GPR was the only technique to detect both metal and plastic drums and also gave the depth to the objects. In some instances, the GPR was found to be too sensitive and signal returns from small contrasts in dielectric properties were found to mask or cloud the more important data (Bowders et al 1982b). Signal enhancement routines were needed and have since been developed and implemented with good success (Kurtz 1995).

Table 2(a)– Summary of results from nondestructive evaluation methods to detect and locate buried containers (Lord et al 1982)

Method / Pattern	Seismic	Resistivity	GPR	CW µ Wave	Metal Detector	VLF-EM	Magnetometer
STEEL DRUMS (EMPTY)							
Various Depths (30 gal.)	X	X	detected all	X	detected all but 10’ deep	detected all but 10’ deep	detected all
Various Sizes (55, 30, 5, 2 gal. – 3.5 cover)	X	X	detected all	X	detected all	detected all	detected all
Various Orientations (in 3’ cover)	X	X	only good to axis of drum	X	detected all	detected all	detected all
PLASTIC DRUMS							
Various Depths (40 gal. empty)	X	X	only at 1’	X	X	Only at 1’	X
Various Contents (2’ cover) Salt Water	X	X	much better than empty	X	X	X	X
(2’ cover) Fresh Water	X	X	much better than empty	X	X	X	X
TRASH DUMP	X	X	locates excavation boundaries	X	detected well	detected well	detected well

NOTE: “X” suggests that the method used is of little or no value in this particular situation

Table 2(b) – Summary of attributes of best nondestructive evaluation methods for detection and delineation of buried containers (Lord et al 1982).

METHOD / CAPABILITY	GPR		Metal Detector	VLF-EM		Magnetometer
	St	Pl	St	St	Pl	St
Depth Detection	to 10’	to 3’	to 10’	to 6’	to 1’	to 10’
Axial Resolution	-10’	-10’	-4’	-10’		-10’
Lateral Scan Sensitivity	Poor	Poor	Good	Excellent		Excellent
Soil Condition Sensitivity	Very	Very	Good	Good		Insensitive
Sensitivity to Orientation of Drum	Very	Very	Good	Good		Good
Size of Drum Sensitivity	Moderate	Moderate	Fair	Fair		Good
Sensitivity to Contents of Drum	None	Liquid filled best	None	Very little		Very little
Ease of Deployment	Moderate		Very East	Easy		Very easy
Data Interpretation	Ease		Very East	Easy		Easy
Expense of Equipment	-$40,000		$300-500	-$8,000		$3,000-5,000
Major Drawbacks	Cost		Does not work on plastic	High cost very limited on plastic		only works on magnetic materials
Major Advantages	Need not be metal- Determines depth		Sensitive and very low cost	Very sensitive		Very sensitive

1. Steel drum
2. Plastic drum

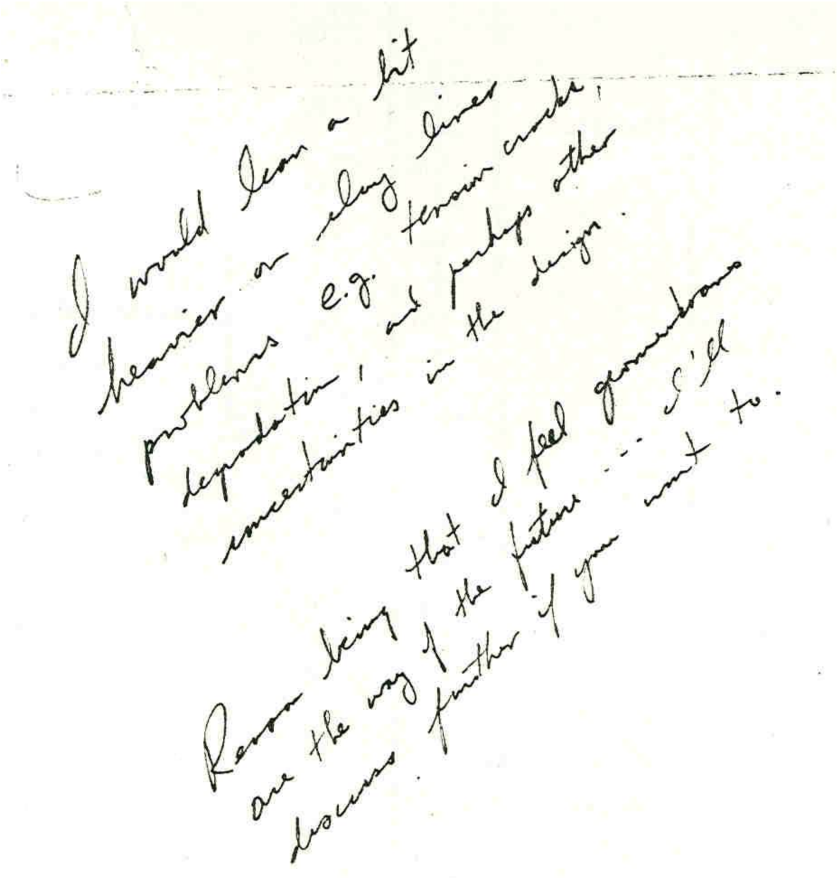
HISTORY LESSON CONTINUED…

Working with Joe Welsh of Hayward Baker, the pulsed RF was applied to verify geotechnical grouting beginning in 1981 (Hayward Baker 1981, Byle and Borden 1995). Pre- and post-grouting surveys for sections of the Pittsburgh Pennsylvania light rail tunnel were performed using the change in travel times to assess grout location (Parish et al 1983).

Simultaneously, the entire hazardous waste site/leaking landfill issue was coming on strong especially when in 1982 Professor Kirk Brown and graduate assistant David Anderson blew the lid off compacted soil liners by publishing their work on the permeability of compacted soils to organic liquids (Anderson et al 1982).

But Bob had already been on the leading edge as evidenced by his response, written in 1981, in a report on innovative NDE techniques to detect landfill liner failures (Figure 5): "I would lean a bit heavier on clay liner problems, e.g., tension cracks, degradation, and perhaps other uncertainties in the design. *Reason being that I feel geomembranes are the way of the future*."

There you have it, nondestructive evaluation methods proves to be the *missing link* that transitioned Bob from a stellar program in acoustic emissions to the geosynthetics area and subsequently the beginnings of *The Institute* (Figure 6).



I would lean a bit
heavier on clay liner
problems e.g. tension cracks,
degradation, and perhaps other
uncertainties in the design.

Reason being that I feel geomembranes
are the way of the future ... I'll
discuss further if you want to.

Figure 5 – Robert M. Koerner quote as taken from comments on a 1981 report regarding methods to detect landfill liner failings. "…*Reason being that I feel geomembranes are the way of the future*…"

LESSONS LEARNED

What can we learn from this slice of Bob's career?
One never knows where the thread will lead! Keep following it.
Connections, acoustic emissions to geosynthetics – its not as far removed as one might think!

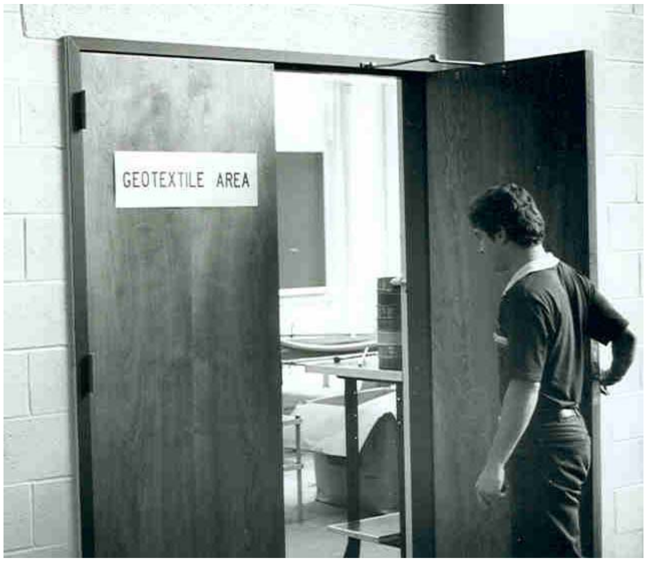


Figure 6 – The beginnings of the *Geosynthetic Institute*.

ACKNOWLEDGEMENTS

Thanks to George Koerner and Joe Wartman for initiating and leading this much deserved symposium. The events described herein are to the best of the author's recollections and the interpretations are entirely his own. Hopefully others will put the correct spin on any events that might be deemed misrepresented. A list of collaborators involved with Bob on the NDE work is given in Table 3. My sincerest apologies to anyone I may have over looked. Finally, my deepest gratitude is reserved for Bob as it was and remains his guidance and example that put me on my career path and has kept me on it. Thanks Doc.

Table 3 – Robert M. Koerner's collaborators on nondestructive evaluation methods.

Jonathan S. Reif	Graduate Research Assistant
Thomas A. Okrasinski	Graduate Research Assistant
Michael J. Burlingame	Graduate Research Assistant
William W. Dougherty	Graduate Research Assistant
John J. Bowders	Graduate Research Assistant
Arthur E. Lord	Professor of Physics
Somdev Tyagi	Professor of Physics

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