CURRENT QUALITY ISSUES IN POLYETHYLENE GEOMEMBRANE INSTALLATION:

"THE DEVIL IS IN THE DETAILS"

INTRODUCTION

What kinds of concerns should owners, engineers, and regulators have during the installation of polyethylene geomembranes, both smooth and textured sheet? With much progress and technical input over the last 15 years, what concerns should we still have for today's practice? And with mechanisms for MQC/MQA and CQC/CQA, where should today's responsible party focus his/her attention?

MANUFACTURING/CONSTRUCTION QUALITY CONTROL AND ASSURANCE

Today's typical specifications for geomembrane installation call for construction quality assurance (CQA) and often for manufacturing quality assurance (MQA) (EPA, 1991 and EPA, 1993). This is in addition to the quality control which manufacturers and installers apply to their work using process control of production variables on equipment (temperature, pressure, speeds, etc.) and testing of materials (both raw and finished product). Typical quality assurance specifications are listed in Tables 1 and 2.

Manufacturing quality assurance is essentially third party inspection of production and material testing at the factory. This can also include assurance of continuous spark testing during geomembrane roll production to identify pinholes, if any. Spark testing applies an electrical voltage differential through a conductive brush contacting the surface of non-conductive geomembrane across its entire width as it is in the roll wind-up process. Should any holes, even pinholes, be present, current will pass through, demonstrating a spark and triggering an alarm.

TABLE 1
Manufacturing Quality Control and/or Assurance Specifications

Typical MCQ and/or MQA	Typical Frequency
1. Spark Testing For Pinholes	1. Continuous, over 100% of liner produced
2. Polymer Resin Testing	2. One per Batch of Resin
3. Liner Physical Property Testing	3. Every Roll to Every 20 Rolls, depending on test
4. Visual Inspection	4. Continuous during manufacture and field deployment

TABLE 2
Construction Quality Control and/or Assurance Specifications

Typical CQC and/or CQA	Typical Frequency
1. Prequalifications of all Welding Machines and Technicians	1. Once, prior to installation.
2. Qualifying Test Welds	2. At least once per day, up to two times per day
3. Non-Destructive Seam Testing	3. Continuous, over 100% of seams
4. Destructive Seam Testing	4. Once per 500 feet of seam
5. Supplemental Material Conformance Testing on Field Samples	5. One per acre to One per 10 acres depending on test
6. Visual Inspection	6. Continuous, 100% of seamed and completed liner
7. CQA Inspection Personnel	7. Full Time, responsible to project owner

Construction quality assurance involves third party attention to on-site storage of materials, subgrade preparation and maintenance, roll and panel handling and placement, field seams, anchor trench connections, ballast loading, pipe penetrations, connections to concrete structures, geomembrane repairs, and geomembrane protection from potentially damaging activities. These activities are by their nature less prone to control and consistent quality, being subject to the vagaries of weather, field inconsistencies, and human error.

Can things go wrong in spite of official MQA and CQA? Sure can, because details often go unprescribed or uncircumvented by built-in mechanisms of quality. As the saying goes, "the devil is in the details". Consider the following example.

EXAMPLE OF INSTALLATION "MALPRACTICE"

Introduction and Background. An HDPE geomembrane in a raffinate pond at a copper mine experienced holes and slits along the edge of hot wedge seams causing severe leakage. The site was visited and observed, and various personnel were interviewed. Samples from the pond were selected for testing to help answer the important questions. They were keyed to a panel layout of the raffinate pond, as well as correlated to manufacturer QC certificates.

Assessing the complete picture regarding project location, exposure, chemical contact, seaming considerations, and history involved in the development of the leaks, there were several dynamics to consider.

Chemical Exposure, U.V. Exposure and Tension Accelerating Stress Fracture. The action of strong oxidizing acids such as is present for the heap leaching of copper can cause chain scission and/or cross-linking of HDPE polymer. While sulfuric acid does not normally oxidize high quality well-stabilized HDPE, its effect can be exacerbated by combination with other stresses. Oxidation can be catalyzed by U.V. light. The combination of desert conditions at high elevation constituted a rigorous U.V. light exposure situation. In concert with the oxidizing tendency of the sulfuric acid leaching solution, there could have been a promotion of oxidative degradation.

Extensive testing for oxidative induction time (OIT), molecular chain scission, and microscopic examination of the holes and slits indicated that while oxidative degradation was proceeding under the rigorous environment, it had not proceeded to the point of brittle fracture to cause the leakage (Fig 1).

Complication of Material Degradation Due to Off-Grade Product. Failures in the raffinate pond could certainly indicate poor quality material; material that was not properly stabilized, of adequate stress crack resistance, or adequately resistant to oxidation. Certain residual catalysts remaining in polyethylene resins have been traced to the promotion of premature oxidation, and a check for material conformance to manufacturer's specifications was important in combination with an inspection of the degree to which oxidative degradation had occurred to date. It was expected that some surficial oxidation had occurred, but the degree of surface oxidation relative to the bulk material oxidation would be of interest and important for an estimation of expected material lifetime.

Conformance testing for the several samples collected indicated that the HDPE geomembrane met the specifications and complied with the manufacturer's QC testing. The material was within standard industry quality parameters, and was comparable to competitive materials.

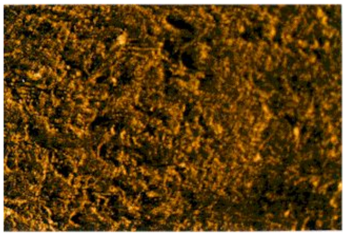

Figure 1 - Microscopic View of Surface Oxidation
Due to High U.V. and Strong Oxidizing

Hot Wedge Pressure Rollers Scoring the Sheet. It is known that stress crack and stress rupture can occur along seam edges (effective "notches" between top and overlapped sheets along the edge mark of the pressure roller track in a hot wedge weld). When stress cracks develop, they typically develop along seam edges, whether they be hot wedge or extrusion welds, because of stress concentration at the "notch". Welding equipment can impact the development of stress cracks through imperfection in the knurles pressure rollers and/or nicks in the wedge itself along the rollers. Such imperfections can score the liner along the welded tracks and promote and accelerate cracking along the edge of the pressure roller marks in hot wedge welding. Stress cracking usually reveals itself under microscopic examination as a "brittle" fracture as opposed to a more "ductile" (stretching and necking down of polymer) rupture.

Ductility in the tears at the sheet edge pointed away from this possibility of failure. Neither did it appear that tension due to contraction in cold weather was a problem, since wrinkles were evident even on cold mornings.

Physical/Mechanical Damage. The known holes occurred where the upper flap of the overlapped sheet had been cut back to view seam continuity. Microscopic examination of the holes revealed that the holes were indeed ductile in nature indicating that they were created rapidly and definitely not the result of slow crack growth leading to brittle failure as in the case of stress crack development and oxidative degradation. Discussions with personnel eventually revealed the damaging manner in which weld flaps were pulled after a razor knife initiated the tearing off of the flaps along sections of the hot wedge welded seams. The weld flaps apparently were "yanked" and "jerked" at times during removal of the weld flaps. Kicking flaps in an effort to bend them up may also have popped open holes.

There seems to have been a certain increased susceptibility to the ravages of tearing back the flap along the seam (probably from the surface oxidation). Magnified photos of cross sections of the torn edges revealed the inducement of several crack locations into the sheet. The cracks also provide evidence that the holes themselves were apparently related to catastrophic stress of the tearing action (Fig 2).

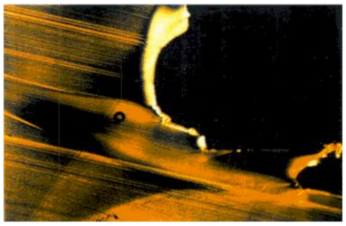

Figure 2 - Microscopic View of Torn Hot Wedge Flap Showing
Ductile Tear and Several Points of Cracking Caused
by the Tearing Action

Magnified photos also revealed that these microscopic fractures were "healed" (closed up, filled in, melted back) under the application of the repairing extrusion weld bead (Fig 3). This is important because if unattended, such cracks at the seam edge would provide risk of future leakage.

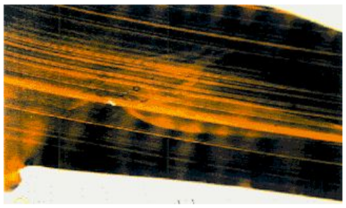

Figure 3 - Microscopic View of Extrusion Bead Repair of
Torn Seam Showing How Repair Eliminates,
or Heals, Crack Points Caused by Tearing Off Flaps

or Heals, Crack Points Caused by Tearing Off Flaps

A subtle detail of methodology and technique ("jerking" back the overlapped flaps during removal) was shown in this case to be the final culprit which dramatically cut the useful life of the acid raffinate pond. The problem occurred in spite of official CQA specifications and inspection personnel from a reputable CQA firm on site, and illustrates that things can go wrong with installation procedure in spite of mechanisms for safeguarding quality.

The CQA document, or plan, is a "mechanism" (standard/method/system) to secure quality by making it less dependent on the excellence of individuals or companies, and more dependent on the protocol of the CQA document. Though the systems are not perfect, they reflect a quality strategy which is wide ranging in concept.

MATERIAL/EQUIPMENT INNOVATIONS LIFTING BURDEN OF INSTALLATION OFF PERSONNEL

Quality systems like ISO 9000 focus on creating mechanisms and procedures which circumvent error. If we create "idiot proof" systems and devices, we can bypass problems created by human input and poor training. This has been the goal behind the effort to develop completely automatic, fully "process controlled" welders which try to disconnect operator judgment and skill from the seaming operation. But the vagaries of field conditions are difficult to overcome through mechanical devices and robotics. In our efforts to build a perfect containment facility we are forced to depend at some point on imperfect people in an imperfect environment.

Besides CQA documents, geomembrane installation has adopted certain "mechanisms" for materials and equipment to automatically circumvent error. One development of note is the perfection of stress crack resistance in polyethylene geomembrane resins. With high quality stress crack resistant resins there is less dependence on stress free installation to ensure long-term performance.

Other mechanisms to promote quality installations involve product innovations and improvements, for example, smooth-edges textured sheet for smooth-edged seaming.

Example of Welding Smooth Edge versus Rough Edge. (Jett and Cadwallader, 1997) Installation personnel know that textured geomembranes, for all their benefit to slope stability and slope safety, are simply more difficult and slower to weld than their smooth cousins. Fusing textured sheet together requires melting through the asperities of texture and contending with difficult-to-remove dust settling between textured peaks in the weld-path.

Comparison of data for sequentially constructed landfill cell closures have recently been reported and are reproduced here (Hsuan and Koerner, 1997), revealing some of the quality improvements associated with this particular product development. The data should not be taken as statistically conclusive, but simply to represent the experience of this particular case.

TABLE 3
Seaming Parameters and Destructive Testing Results for
Landfill Cell Closed With "Rough-Edged" Co-Extruded Texture

Time Frame for Heat Seaming	Oct 18 - Dec 9, 1995
Ambient Temp	High 82° F, Low 25° F, Avg 57° F
Welding Temp*	750° F
Welding Speed*	5 to 7 ft per minute
Destructive Test Requirements	Peel 78 lbs., Shear 120 lbs.
No. of Samples Tested	116
Destructive Sample Failures	5 or 4.3%
Avg Dual Track Fusion Weld Peel Values	Inside 134.8 lbs., Outside 134.8 lbs.
Standard Deviation	Inside 19.3 lbs., Outside 17.0 lbs.
Minimum	Inside 100 lbs., Outside 105 lbs.
Maximum	Inside 165 lbs., Outside 165 lbs.

Table 4
Seaming Parameters and Destructive Testing Results for Landfill Cell
Closed With "Smooth-Edged" Co-Extruded Texture

Time Frame for Heat Seaming	May 29 - July 25, 1997
Ambient Temp	High 102° F, Low 77° , Avg 87° F
Welding Temp*	Varied from 700 - 750° F
Welding Speed*	5 to 10 ft per minute
Destructive Test Requirements	Peel 78 lbs., Shear 120 lbs.
No. of Samples Tested	91
Destructive Sample Failures	2 or 2.2%
Avg Dual Track Fusion Weld Peel Values	Inside 107.5 lbs., Outside 112.7 lbs.
Standard Deviation	Inside 9.1 lbs., Outside 12.6 lbs.
	Inside 89.0 lbs

Minimum	Inside [illegible] lbs., Outside 81.0 lbs.
Maximum	Inside 136.0 lbs., Outside 144.0 lbs.

*For hot wedge only. No data for extrusion welding.

With the smooth-edged material, destructive seam failures by the same FTB (Film Tear Bond)/Peel (delamination) requirements decreased by a factor of two compared with the rough-edged material used on the earlier cell closure. This finding supports the logical contention that it is easier to achieve good results welding with smooth-edged sheet.

Average peel strengths were understandably higher for rough-edged sheet due to the added thickness provided by a co-extruded coating of texture. However, variability of strength (standard deviation and range) increased significantly with rough-edged material versus smooth-edged sheet, suggesting improved control (and its implications on quality) with smooth-edged texture.

Microscopic views of cross sections of textured edge welding and smooth edge welding reveal the tendency for textured edges to include voids at the edge and base of squeeze-out. This brings up the question of initiation possibilities for stress cracking, although the rounded character of these voids should preclude the formation and propagation of crazing/cracking. Smooth edge welding, by contrast, does not raise the question with the smooth fusion and transition evident in cross sectional microscopic views (Fig 4a and Fib 4b)

INCREASED SOPHISTICATION REGARDING STRESS CRACKING

Concerning the question of stress cracking, we can point to increased consideration of it in design specifications and/or CQA practice. And we can point to the new quality "mechanism" of improved stress crack performance via notched constant load testing (ASTM D5397) in standardized specifications (Hsuan and Koerner, 1997). The survivability-rate-determining process for polyethylene geomembranes in many cases is the development of stress cracking. And improved performance in this test can arguably excuse many other design and installation quality flaws. Nevertheless, long-term tension or compression stresses focused on points of concentration are threats to the lifetime of any material.

Stress cracking is accelerated by high temperatures and by contact with certain surface-active substances. Yet if stress is not present, then by definition one should not have stress cracking! For this reason, knowledgeable engineers and installers have learned to construct geomembrane facilities minimizing the amount of stress carried by the liner.

Stress cracks appear at points of stress concentration in the sheet, called "stress risers". Stress risers are typically any abrupt change in material thickness, any notch or score mark of significant depth, or any material non-uniformity, etc. From an installation perspective, the avoidance of scoring of the sheet and excessive abrasion during welding is therefore important.

What Constitutes a Significant Defect or Score Mark in HDPE? Modern fracture mechanics technology in polyethylene gas transmission pipe has produced an impirical method for estimating lifetimes in polyethylene for stresses sustained across a notch defect at various temperatures. The technique has certain uncertainties associated with it, but it does provide an approximation of the significant of defect depth.

According to the impirical model presented by Kanninen, et al (1993), the difference between a 0.08mm (3mil) notch depth and a 0.03 mm (12 mil) notch depth is 20% in lifetime for a "no slack" initial condition and a temperature drop of 2 degrees. The difference in lifetime between a 3 mil notch depth and a 12 mil notch depth becomes 50% for a "no slack" initial condition and a temperature drop of 15 degrees C.

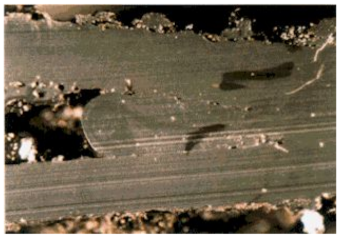

Figure 4a - Microscopic View of Textured Edge Welding Revealing Voids at Edge and Base of Squeeze-out

Figure 4b - Microscopic View of Smooth Edge Welding Revealing Void-free Fusion and Transition

Two conclusions stand out: (1) It is important to add slack (compensation) and to reduce liner temperature swings so that contraction stresses are eliminated or minimized, and (2) Notch depth (score or scratch depth) is significant.

Installing with Slack. Because stress is meant to be kept out of the liner, installation practice in the United States has sought to incorporate sufficient slack to avoid tension stress placed in the material.* The thinking here has been that bent-strip stress crack testing (like that which results from folding or bending a liner and holding it, e.g., a wrinkle) is more easily accommodated by the material than is "constant load" stress crack situations (like the stress of sustained tension in a liner). But the material difference between hot and cold installation, resulting in wrinkles or bridging, respectively, is another difficult detail to gauge (Fig 5a and Fig 5b).

Of the two approaches to stress crack testing, 1) constant strain (e.g., bent strip testing, by ASTM D1693, and 2) constant load (e.g., ASTM D5397 which sustains tension along a dumb-bell strip), constant load testing is the more rigorous on polyethylene. Both tests apply stress across a razor blade slit (a "notch" acting as a stress riser), to focus the point of stress. Because Notched Constant Load is more rigorous, ASTM D5397 is becoming regarded by engineers as the proper material performance stress crack test to specify.

ASTM D1693 (the traditional bent-strip stress crack standard) simulates the bending and folding stresses that can be left in a liner. In this sense, it is a very relevant performance test. If the molecular structure at the bend or fold is able to relax through "stress relaxation" (i.e. align itself to assume the "U" shape of the bend) the stress is relieved. This happens in polyethylene because polyethylene has viscous flow properties, as well as elastic properties (a "viscoelastic" material). The molecules are able to "flow" into the bent condition, relieving the stress. For this reason ESCR values cited much in excess of 1000 hours for ASTM D1693 do not generally provide additional information about stress crack resistance. By that time stress relaxation has usually occurred at the elevated temperatures of the test and the specimens should continue to perform because the stress has dissipated.

* The American approach of encouraging slack differs from the German approach where liners are installed taught, removing wrinkles and depend on stress-relaxation to get past the initial constant load stress condition. Such strategy may work in Germany where buried liners are required, and where one does not encounter the extreme temperatures that American desert climates provide.

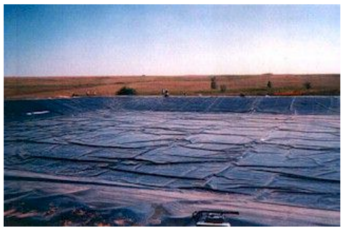

Figure 5a - Retention Pond Liner During Heat of Day
Showing Wrinkle Development

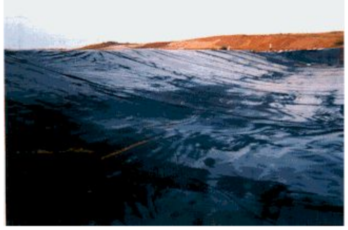

Figure 5b - Same Retention Pond Liner on Cold Morning
With Minor Bridging at Toe of Slope

This knowledge should also be weighed with the fact that removal of covering soil and cutting and capping a wrinkle could risk potential damage of the liner and create new seams possibly perpendicular to slopes. Problems could actually be created by trying to repair wrinkles, when the supposed problem is actually not very critical.

Constant load-type stresses in the liner may occur in cases of extreme and long-term thermal contraction. Field seams can behave similarly to a lab test "notch", focusing the point of stress. Therefore, several thermal contraction which results in tension across seams can produce cracks at seams in exposed liners. This is why the thinking is that proper installation should eliminate those stresses. Installation of exposed liner during hot weather must mean deploying excess material to compensate for thermal contraction which will occur as temperatures decrease. Proper installation also means that seams should as much as possible run parallel to the slope direction (to prevent tension stresses from occurring across seams). In addition, slope angles should be designed to be less than the friction angle of the liner in order for loads on the liner to be transferred through to the subgrade. Compressive loads on the liner should, by design, not be allowed to become stresses in the liner.

The Question of Partial Peel. Stress crack potential across stress risers brings up the question of partial peeling in destructive testing (as opposed to a full delamination or peel). A significant percentage of specifications call for zero "partial peel". Another common specification calls for maximum partial peel of 10% (difficulties of measuring percentage aside). Two principle points are made to argue for partial peel: 1) Partial peeling reveals the abraded portion of liner underneath welds and these portions are more susceptible to stress cracking. (The actual evidence for this point, however, is lacking.) 2) The fact that some welding can meet a zero partial peel tolerance means (to some engineers) that zero partial peel should therefore be the standard. If it can be done, it should be done, so the thinking goes.

The second point follows the philosophy of quality control which says that if higher standards can be met, allowing those other variables which may not be measured in a quality assessment. And, or course, we want to be sure that all quality variables are maintained at the highest level. "Raising the bar", so to speak, to zero partial peel, for all the trouble is may cause and however pointless it may be in certain cases, provides another opportunity for a differentiation of quality.

DESTRUCTIVE AND NON-DESTRUCTIVE TESTING

Destructive seam testing has emerged as the principle means of assessing weld quality in spite of the inherent irony of cutting holes in liners to verify that an installation does not or will not have holes. Engineers often criticize the peel test as not reproducing actual field stresses and therefore having little merit as a quality measure, making the test appear even more ironic. But is must be remembered that simulation of field stresses and performance is not the reason for peel testing. The reason for peel testing is to gauge degree of bonding (true welding as opposed to tack welding) which has occurred, precluding future relaxation and delamination due to chemical absorption, etc.

Nevertheless, the procedure is much less than ideal, inviting human error and increased stress crack opportunities through increased scoring, seaming, and notching. The knife work, the heavy reliance on proper skill and technique associated with extrusion welding patches invite many problems, with knife slits and detailed work having high frequencies of leaks in leakage studies (Laine and Darilek, 1993, Thiel and Cadwallader, 1993). Destructive testing involves many details of technique and skill. And once again, "the devil is in the details". Alternative mechanisms to reduce the use of destructive testing could quite arguably decrease the number of defects left in liner systems.

Non-destructive testing for leaks is now normally limited to seams. Yet there are viable ways to test entire liners for leakage, even after the application of solid backfill. Why focus so much on peel testing and ignore a final leak test of the entire system before putting it to use? Here is a case where the mechanism of quality control and assurance (destructive testing) has become overly entrenched, providing (perhaps) a false sense of security to responsible parties.

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CONCLUSION

When we are able to create mechanisms or procedures circumventing dependence on variability of installation personnel and environment, we take strong steps toward increased quality. This is the strategy of quality systems like ISO 9000. It is also the strategy behind statistical quality control (SQC) based on probability science.

Probabilistic risk assessment making use of Probability Density Functions (PDF's) is a tool engineers in the nuclear power industry apply to estimate life-times based on the safety, redundancy, and number of details in running a nuclear power plant (Flavin, 1993). The probability techniques are founded upon the famous Boltzmann equation, $S = k \log w$, which relates entropy to the number of possible arrangements of a system (the number of details, for example) and therefore to probability. In effect, the fundamental equation of probability says that the degree of disorder is proportional to the number of details (variables) to be controlled.

The details of any project tend toward disorder under the probabilities governed by increasing entropy. Therefore, it is the details which we must work to incorporate into well thought out mechanisms of quality, whether they be material improvements or work-procedure improvements.

Through mechanisms of QC/QA, will we ever be able to rule out the probability of error? The frustration is no, so long as we are governed by the principles of increasing entropy (the Second Law of Thermodynamics) and as long as we are confined to working in an imperfect environment with imperfect people.

DEDICATION

The above concluding comment is not just opinion, nor even just scientific theory, but also an important principle of Judeo-Christian tradition, which clarifies further and relates the two: a world in bondage to decay (entropy) and a world in bondage to sin (moral imperfection). The saying, "The devil is in the details", is more true than many people realize. "For the creation was subjected to frustration, not by it's own choice, but by the will of the one who subjected it, in hope that the creation itself will be liberated from its bondage to decay and brought into the glorious freedom of the children of God." Rom 8:20,21.

ACKNOWLEDGEMENT

Microtome photos by Rick Thomas, TRI/Environmental, Austin, TX.

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Figure 6 - As it starts to rain, should we wipe the liner dry ahead of the welding to finish a corner panel and ensure the subgrade does not wash? Or should we stop immediately?

Figure 7 - With so much patching, there's more opportunity for dust to interfere and go untested.

Figure 8 - Consider the patching frequency required when air pressure testing panel widths at the toes of slopes. Can this really be the best practice?

Figure 9 - Somebody procured an undersized tool. The devil is in the details.

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