Lessons Learned from 30 Years of Construction Quality Assurance in Geosynthetic Lined Containment Systems

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ABSTRACT
Construction Quality Assurance (CQA) is a critical component in meeting and maintaining project quality objects and offers perhaps the single greatest Return-on-Investment (ROI) of a construction project. Properly trained CQA personnel working on a construction project will make the difference between a zero-leak success story and a multi-million-dollar future nightmare for the owner. CQA begins well before the fieldwork ever starts and continues through field construction – each step ultimately determines the long-term quality of the project.

The author has compiled lessons learned from containment projects in all sectors of construction including coal-ash. The lessons shared within this paper will be particularly useful to coal-ash geosynthetics projects including some recent findings in the coal-ash industry. Specifically, the paper will highlight examples of suspect/inferior materials and how to identify such materials through MQC/CQA data so that the materials do not arrive on your project. Lessons will also be shared from each of the common components of a geosynthetic installation: subgrade, material delivery and inventory, material deployment, trial seams, production seams, non-destructive seam testing, destructive seam testing, repairs, and final walk-through, as well as materials such as GCL's and drainage composites.

INTRODUCTION
Since 1990, there have been huge advancements in geosynthetics technologies. Material quality has significantly improved with offerings of more specialty products to meet changing needs. Installation and welding processes have continued to improve and can now be aided by data acquisition welding equipment and electric leak location surveys. However, CQA remains a keystone to project success despite all the technological advances. Like the aforementioned advancements, CQA cannot solve all the potential problems but is a resource that when used properly, can significantly increase the quality of the installation and is an important part of the quality equation.

The bar of excellence for containment system standards has also significantly been raised. The industry has gone from accepting that a vast number of leaks will occur post-installation to achieving zero-leak installations. For example, in 2005, it was observed that leakage rates averaging only 4 leaks per hectare (2.47 acres) with rigorous CQA to averaging 22 leaks per hectare (2.47 acres) without CQA.[1] By 2012, Abigail Beck showed the use of electrical leak location surveys in conjunction with rigorous CQA resulted in a 0.00001% probability of exceeding the Action Leakage Rate in the state of New York.[2] These are huge strides!

The author was privileged to lead the CQA effort for 493 acres (199.5 hectares) of a double-lined evaporation pond system at the Palo Verde Nuclear Generation Station (PVNGS) constructed between 2009 and 2013 which resulted in zero-leaks (and was still leak free seven years out when the author had last correspondence with contacts at the site). Participation in this project was crucial to identifying issues and challenges that are often overlooked within the industry – had these issues been overlooked at PVNGS, the project would not have been the zero-leak success story that is highly publicized and serves as a bar of excellence standard today.

With the somewhat sudden push of Subtitle D regulation requirements into the coal-ash containment community, it is important that lessons learned from containment system construction in other industries be shared with this community to help ensure project success.

RETURN ON INVESTMENT

One of the keys to the success of the PVNGS project listed above, is that the owner looked at the project as an asset and managed the project for obtaining a Return-On-Investment (ROI). It is important to understand that ROI is not always a tangible number. News headlines are an example of ROI that can be either positive or negative, and if negative have huge unforeseen costs associated with them.

An example of ROI at PVNGS is the value of zero-leaks to a 117-acre (47.3 hectare) pond. After completion of construction, the pond was filled incrementally to isolate zones if a leak should appear. When the entire floor was filled with process water, 60 million gallons of water would need to be removed to repair a leak. At full capacity, 780 million gallons of water would need to be removed just to repair one leak. Obviously, removing the process water would be an operational hurdle that would need to be overcome, as well as the potential compromise to electrical generation for a good portion of the Southwest United States.

ZERO-LEAKS NOW, ZERO-LEAKS LATER

It is important to understand that a containment system having zero-leaks at inception of operations and zero-leaks later are two entirely different objectives. The goal is to have zero-leaks for the life of the containment system, which requires proper installation and construction practices (as well as post-construction operational practices). The focus herein is only on the construction practices.

A quick example of the difference between zero-leaks now and zero-leaks later is an extrusion bead repair of a pinhole in the geomembrane (when this is allowed). If the material is polyethylene, abrasion is typically required prior to the extrusion bead application in order to remove oxidation (and the bead must be placed in a timely fashion to prevent oxidation of the abraided area), thus providing a long-lasting bond. In most cases, an extrusion bead applied to the polyethylene geomembrane without the abrasion performed will have a temporary bond which will vary based on texturing, the cleanliness of the liner, etc. This temporary bond often will pass both vacuum testing and electrical leak location testing; however, ultimately the bond will fail and the bead will lose its adhesion to the geomembrane. Thus, what appears sound in the short-term may really be problematic in the long-term and this is even more true when stress is introduced in the system during operations.

WARRANTIES

Warranties provided by the manufacturer and installer are often misunderstood. Neither warranty will cover the owner's operational costs associated with the repair.

For instance, assume the extrusion bead placed without grinding the surface of the High Density Polyethylene (HDPE) floor liner in the 117-acre (47.3 hectare) pond at PVNGS failed when the impoundment was in full operational capacity. The installation warranty only covers the cost of the crew coming out to perform the actual repair to the geomembrane. The owner would be responsible for the cost of removing the 780 million gallons in preparation for the repair, and any associated operational costs. The same is true if the bead failed in a municipal solid waste landfill covered by trash – the owner would be responsible for all the costs associated with the trash removal and safe access to the area of repair.

The best practice regarding warranties is to avoid the need by having a comprehensive plan that ensures quality at each stage of the project.

QUALITY IS THE RESULT OF STRUCTURE

The following diagram illustrates the layers required to obtain quality objectives on any project. Each layer builds upon the other layer. The entire project and vision start with the owner who is responsible for holding everyone else accountable to their vision. The project is designed to meet the owners' vision (in accordance with regulations) and project specifications are determined to meet the design objective. The design should also account for proper materials and equipment to be used and purchased followed by the selection of vendors to provide the materials and/or services. Finally, the tip of the pyramid is the fieldwork – the portion of the project where tangible progress can be visually observed.

Figure 1. Structure of Quality

All too often, the success or failure of a project is thought to occur during the fieldwork phase. Whether that thought is accurate or not really depends on all the stages preceding the fieldwork. Is the design constructible? Are the specifications too loose or too strict or even applicable at all? What is the experience of each vendor? What is the experience of each crew member on the team?

Corporate certifications don't always translate to each member of the team. For instance, the International Association of Geosynthetic Installers (IAGI) has an Approved Installation Contractor (AIC) list. While a specific firm may meet these requirements, there is nothing that guarantees knowledge on an individual level by crew member. It is up to the owner to properly vet not only the specific firm, but also the crew members comprising the team – particularly if there are certain minimum standards required (i.e. 1,000,000 square feet or 93,000 m^2 installed per welding operator). Complicating the matter is the shortage of experienced personnel at the time of this writing, and the ability of installers to quickly move personnel from project to project.

A firsthand example of such discrepancy within an installation company is a project on which one installation crew was falling behind. The installation firm supplemented the project with an additional crew to help out (which came from a nearby project which was rained out). The workmanship of the second crew was drastically inferior to that of the initial crew yet both met project requirements and came from a company that met AIC standards.

Such discrepancies exist everywhere – not just on installation crews. The Geosynthetics Institute (GSI) has many member firms and offers inspector certifications in compacted clay liners and geosynthetics (as well as additional certifications). The author has been on several projects in a consulting capacity where a GSI member firm is performing the CQA certification and oversight but none of the CQA field technicians are certified through the Geosynthetic Certification Institute (GCI), a division of the GSI.

The aforementioned examples deal primarily with the top of the pyramid in the fieldwork category. But what about other portions of the pyramid leading up to the fieldwork?

DESIGN

The first question that should be asked of a geosynthetic lined containment system designer is: "How much field experience do you have?" And a good follow-up question to that is: "How much time do you spend in the field?" There is book knowledge, and there is field knowledge, with an area of limited overlap between the two. Unfortunately, the resources available at the time of writing for finding collegiate courses dealing with geosynthetics design are very sparse in the United States – which makes field exposure and experience that much more critical.

In the thirty-plus years of working in the geosynthetics containment industry, the author has consistently observed the best designs in terms of constructability come from engineers who have spent time working in the field. And the best advancements in design typically come from those who spend additional time in the field evaluating their designs to see how they can improve them and make them better, which usually equates to better long-term quality. Without the field experience, it is easy to end up with "the blind leading the blind".

Such an example is illustrated by Figure 2 below.

Figure 2. Weir with excessive damages and subsequent repairs.

This photo was taken of looking down inside a weir which was constructed with a stud liner backed geomembrane used to attached the liner to the concrete. The general contractor had never worked with the geomembrane before and asked the design engineer how to secure the geomembrane to the forms. The design engineer stated "nail the shit out of it", which the contractor complied with, using finishing nails. Everyone was surprised when the weir was put into service and leaked! The extrusion beads shown represent the repairs of the finishing nails, which were found by vacuum testing the entire surface given the finishing nail holes were extremely hard to visually locate.

Another flaw in the design were the weir corners. The contractor tried to extrusion weld the corners in the actual corner whereas a prefabricated corner joint readily available on the market could be used to provide better accessibility and assurance that a higher-quality weld would be obtained on all corners.

SPECIFICATIONS

Simply put, if it is not in the specifications, do not expect it to be done! The author has worked with certifying engineers throughout the United States and the common stance regarding construction questions is, "I can only certify to what is in the specifications". Best practices that are known, and shared throughout the industry are neglected simply because the engineer feels they could be liable for increased costs of the installation.

At the 2016 Geo-Americas conference, the author led a panel discussion on geosynthetics specifications and a large part of the discussion was devoted to the trend of design engineers using cut and paste specifications. During discussions, one engineer from the back of the room raised his hand and stated "we use cut and paste specifications because the owner won't pay us to develop our own". That is an unfortunate condition. Even more unfortunate is that the trend continues where cut and paste specifications continue to be used, resulting in avoidable issues and delays to the project.

The specifications (and CQA Plan) should empower the CQA personnel to ensure the products and installation are performed to the best quality standards available at the time of construction.

MATERIALS

All materials are not created equally and some cannot be readily substituted for others. As with most of the content within this paper, full elaboration would require separate papers, so the author is focusing on a few highlights to illustrate items commonly missed or misunderstood. There are things that should be done during manufacturing and post-manufacturing that can help ensure an owner is getting the quality material they are paying for.

First, plant inspections may be warranted for certain materials – in particular, specialty products such as coal-ash resistant GCL's. Figure 3 below illustrates how on this batch of material, the coating separated from the cover geotextile during unrolling because of adhesion to the coating on the carrier geotextile layer. As the roll was unrolled, delamination of the coating occurred as illustrated in the blue areas. The result was a permeability that did not meet the project specification.

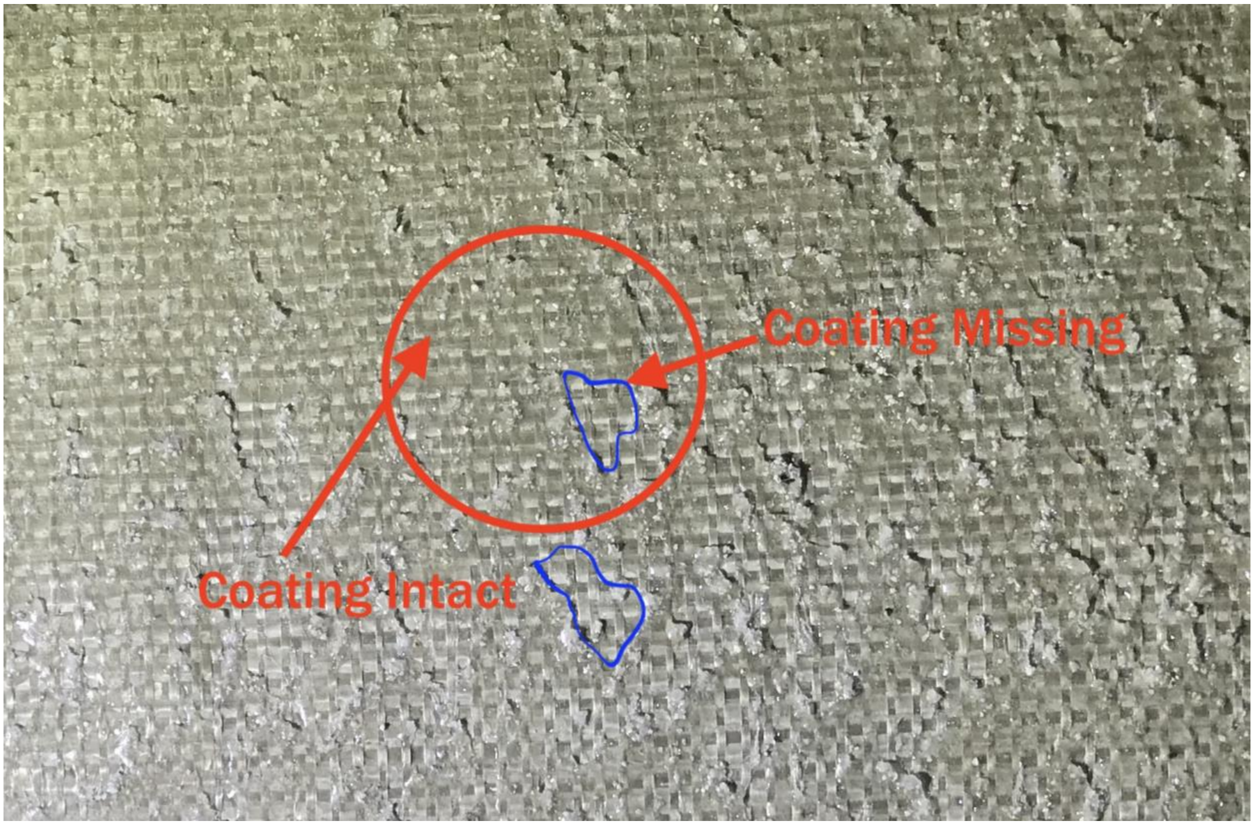

Figure 3. Coating missing from specialty GCL.

Second, the CQA firm should be looking for any trends in the data from Manufacturer's Quality Assurance (MQA) data as well as third party CQA conformance testing data when applicable and available. There are many tests that still use "average value" requirements as a pass/fail criteria for the material. ASTM D6693/D6693M-20, which deals with tensile properties of nonreinforced polyethylene and flexible polypropylene geomembranes, is one example. The reporting requires the individual values, average value, and standard deviation of the five coupons tested (as well as additional data)[3]. However, when results are interpreted, there really is no existing guidance on acceptable standard deviations nor even minimum values. Experience shows that if the material has significant variability (which remains undefined), there can be problems with not only with the material itself in the form of blemishes or other property flaws, but also in the welding of the seams. Figure 4 below is an example of how the minimum average can be achieved with values on the high side of the average overshadowing the lower values, which can be significantly lower and still achieve the average requirement. If such trends are observed in the data, the rolls should be visually inspected, preferably before leaving the manufacturing plant, to determine the underlying issue for the variability. Many projects are set up where the material will not ship until approved by the certifying engineer, and the certifying engineer should use all the tools necessary to ensure the material is acceptable before leaving the plant. As a worst-case scenario, at a minimum, rolls having variable characteristics should be inspected in the field by both the CQA personnel and installer before the panels are seamed.

60 mil HDPE Smooth

						Min Average	Required Value
Break Strength							
	135	255	200	285	300	235	228
% of Required	59%	112%	88%	125%	132%		
Break Elongation							
	800	309	825	900	780	722.8	700
% of Required	114%	44%	118%	129%	111%		
Thickness							
	54	59	56	67	66	60.4	60 avg /54 min
% of Required	90%	98%	93%	112%	110%		

Figure 4. Examples of Minimum Averages Carrying Low Values

Another trend to look is whether or not the rolls remain sequential for the project. If there are rolls missing from the sequential roll list, odds are the manufacturer caught something in their MQA/MQC process and removed rolls that may have failed. Thus, it is often a good practice to inspect and/or test any rolls bounding such a gap.

SUBGRADE

It should go without saying that the subgrade should not damage the geosynthetics. However, stones continue to be, and for the foreseeable future, always will be a potential issue when using a soil subgrade. The deployment method can result in loosening of stones or hardened clay clods that were not problematic before – even foot traffic can do this on certain subgrades. Therefore, it remains important that the subgrade and deployment process be thoroughly examined at the onset of the project, and throughout the duration of the project. Skid steers turning on the subgrade are especially a source to keep an eye on.

DEPLOYMENT

In addition to not damaging the subgrade, deployment methods must not damage the geosynthetics. Dragging of the geomembrane or any material should be avoided as stones can get trapped and the underside of the material typically cannot be inspected. Using proper tools during deployment is also extremely important in minimizing the risk of damage.

Another consideration is electrical leak location surveys (ELLS). In all cases, intimate contact between the geomembrane and the soil subgrade are desired but it is not uncommon to have specifications that allow for a minimum wrinkle size to be accepted. However, if an ELLS is going to be used, it is important to have intimate contact because air acts as an insulator and could therefore provide false confidence that no holes exist (depending on the ELLS method). One way to offset this is the use of conductive backed sheet.

TEXTURED MATERIAL

As mentioned earlier, all material is not created equally. Nor is each side of a textured geomembrane! Calendared products typically are manufactured with one side that is better suited to interface with soil and the other side better suited to interface with geosynthetics. It is important to understand not only is there a difference, but that the interface friction testing should be done with the proper orientation of the interfaces! Likewise, installers often take the liberty of reversing the material, so that different sides are facing up throughout the project – this is something that field CQA needs to keep an eye on as having the wrong side up could be detrimental to the long-term function of the project.

Other products such as spray-on texturing or gas impingement can result in an uneven coating and uneven asperity height. Field CQA needs to also be on the lookout for these issues, as again they can be detrimental to the long-term function of the project.

TRIAL SEAMS AND SEAMING

Trial seams are important because they determine if the welding methods will work under the current conditions with the particular material. One of the biggest areas of concern is that trial welds are rarely thoroughly inspected. Inspection of trial seams offers the installation and CQA personnel an opportunity to prevent issues with seams, even if the peel and shear tests are passing.

For any seam to achieve maximum quality, there are three parameters that must be obtained – proper contact time, heat, and pressure during welding. In addition, the seam area must be clean and dry. Today’s trend in this regard appears to be towards potential overheating of the geomembrane during seaming as this will help prevent peel failure and still pass shear testing. There is quite a bit of research elsewhere on this topic given by Dr. Kerry Rowe, Dr. Ian Peggs, and others. It is quite possible that geosynthetics installations are reaching the point where testing beyond simple peel and shear tests could be possible to evaluate the impact of such welding. Figure 5 shows excessive heat on a fusion seam and Figure 6 shows excessive heat on an extrusion seam.

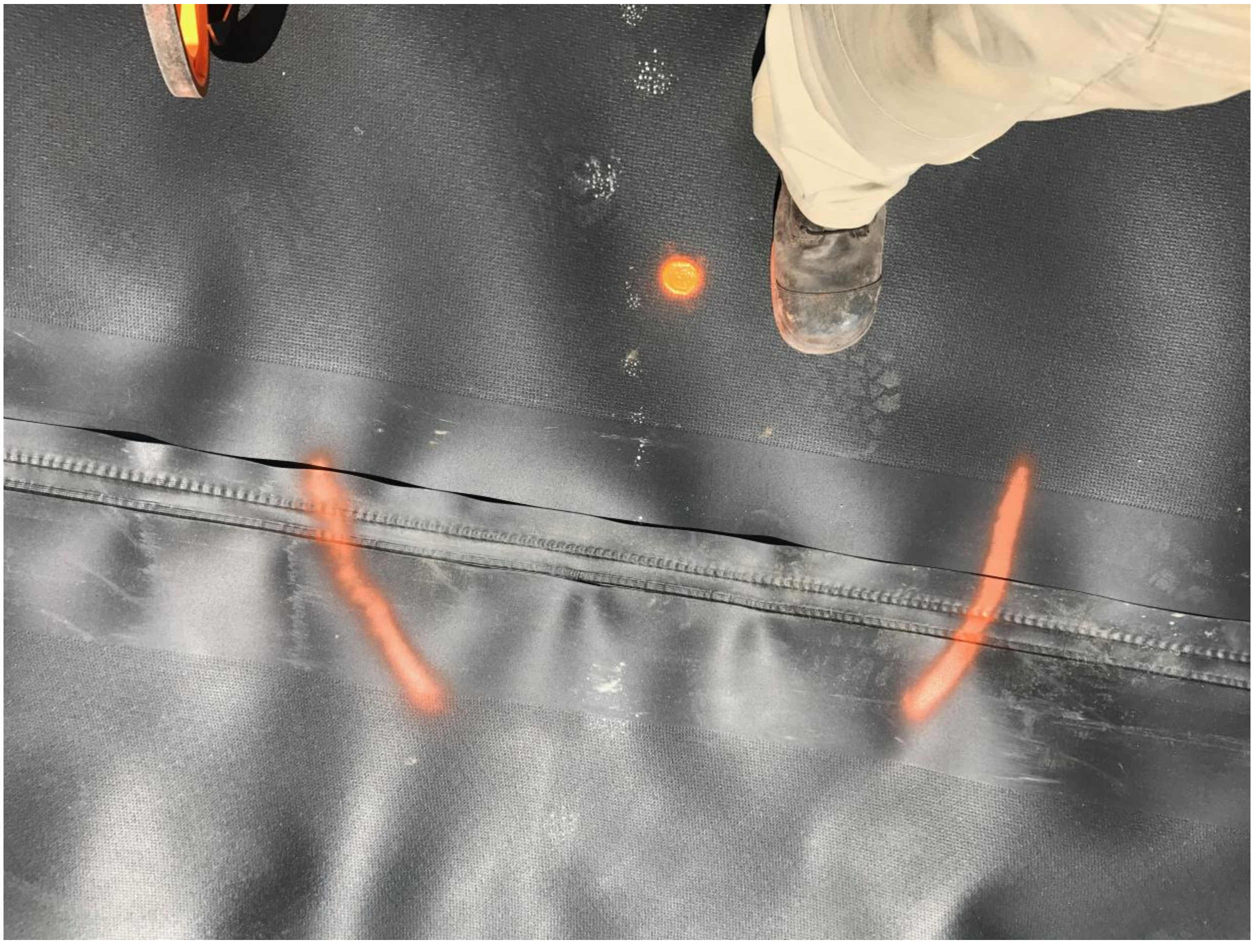

Figure 5. Excessive heat during fusion welding (entire seam, not just marked area).

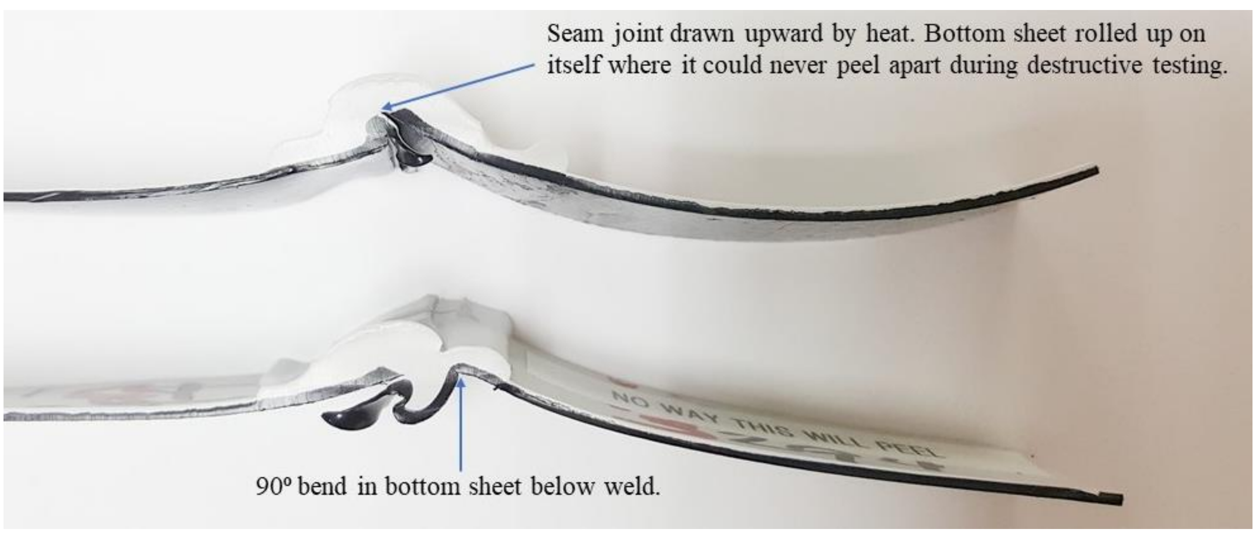

Figure 6. Excessive heat during extrusion seaming.

Another important thought about polyethylene extrusion seams is the different stages that are required. If a patch is required, it will require being cut to the proper size and shape per the specifications as well as beveled when appropriate (usually based on thickness). As mentioned earlier, the area to be welded then requires abrasion and finally application of the extrusion bead/seam. Each of these stages may be performed by different personnel depending on the specific liner crew and their capabilities. Often overlooked is the idea that trial seams should be performed with each person performing the function/role they will play in the actual production seaming/repairs. The grinder operator is crucial to a good weld but is never specifically evaluated. Often, as a CQA inspector, one will see multiple personnel performing all the different roles except for that of the extrusion welding which the author believes can lead to long-term problems.

DATA RECORDING AND SMART WEDGES

Data recording or data acquisition fusion welding devices are becoming more predominant in the United States. Smart wedges (fusion welding device) are less predominant. It is important to understand that these terms should not be interchanged. The data acquisition (or data recording) device simply records the heat, speed, and pressure during seaming operations whereas a smart wedge has special circuitry that allows the machine to self-regulate these parameters so they remain consistent while welding.

Are data recording and/or smart wedges the answer to our welding problems? The short answer is "no". Either machine is only as good as the input the operator initially sets. If the welding temperature required for a 60-mil (1.5 mm) HDPE is 800^{o}F (427^{o}C) and the operator sets the temperature to 650^{o}F (343^{o}C), the seam will not be properly bonded if bonded at all. Assuming no significant change in welding parameters for the duration of the weld, the output from data acquisition would show uniformity in the numbers or a smooth graph but yet not be welded! The same is true for the smart wedge – if the same numbers mentioned above are used, the smart wedge might maintain the welding temperature for the entire length of the seam but still the seam would not be properly welded!

These instruments are another useful tool in the quality tool chest. As with any newer technology, it is important to understand any limitations to ensure proper quality.

NON-DESTRUCTIVE SEAM TESTING

This is perhaps one of the most consistent areas falling short of expectations over the past thirty years.

In most cases, non-destructive testing does not correlate to integrity testing – either of the sheet, or of the seam! A non-destructive test is a continuity test, not an integrity test. Table 1 illustrates the difference. There are a significant number of projects where the non-destructive test is being used to replace the integrity test. This practice should be stopped!

Table 1. Non-Destructive Test vs Integrity Test

Non-Destructive Test (Continuity)	Integrity Test (Tensile Properties)
Air Pressure Test	Destructive Seam Testing for Peel &

Vacuum Test Holiday Spark Test	Shear
Bare Geomembrane ELLS Covered Geomembrane ELLS	Sheet Tensile & Break Properties

There also is a considerable lack of training on installation personnel performing the non-destructive testing. During the course of about 5 years of projects the author was involved on, it is estimated that over 90% of vacuum testing personnel on these projects did not know what a leak was, and over 50% of personnel performing air pressure testing only knew to write "30/30" on the geomembrane and were not recording true measurements. The easy solution to the vacuum test issue is to take a large scrap of liner, make a discrete pinhole, and see if the technician can find it. Trial welds are excellent for this. As for the air test issue, there is no easy solution other than better training and attentive CQA.

Additionally, concerning vacuum box testing, some specifications still require 5 pounds per square inch (psi) of pressure to be obtained on the vacuum box during testing. The current machines that run on a shop-vac type motor are typically incapable of generating this pressure but this largely goes unnoticed because the gauges provided are graduated for inches mercury (inHg) which is approximately two-times the psi reading. In other words, the gauge is reading 5 inHg which is only approximately 2.5 psi. In order to achieve 5 psi, a Venturi vacuum box system is needed, which requires a separate pump.

DESTRUCTIVE SEAM TESTING

It is virtually unanimous that the idea of cutting extra holes in the geomembrane is not a good idea. However, there needs to be some assurance of quality, and the best way to guarantee this quality at the time of this writing is to take physical samples from completed seams. The prevailing specification that has been used since before 1990 is to take one sample per 500 lineal feet (150 m) of welding, typically per welding machine and operator combination. Given the improvements in materials and technology and the knowledge that repairs to these destructive sample penetrations will be made with an inferior weld type, more flexibility should be allowed in the sampling to reduce penetrations while maintaining a comfort level for the owner. The Geosynthetics Research Institute came out with GM-14 in 1998 and GM-20 in 2003 which allow for rewarding good welding with fewer samples and in general, much more flexibility. However, the author has seen these methods implemented on less than a handful of projects over his thirty-plus year career. The standard still remains at 1/150 m.

The author also has a controversial recommendation concerning extrusion welds and taking destructive samples on extrusion repairs. Based on the author's experience, destructive samples taken on extrusion repairs provide the opportunity for great benefit and a chance to fully evaluate inferior welding. PVNGS would not have been leak free if extrusion destructs were not taken and further research in this regard by the author has shown failure rates on extrusion welds can be substantial – as high as 60% of original samples. Table 2 illustrates findings in additional research by the author[4].

Table 2. Destruct Failure Rates, Peel or Shear, Based On Original Samples

Project Size (Geomembrane Deployed Acres)	Extrusion Weld Total Footage (Lineal feet)	Extrusion Primary Original Samples Obtained	Extrusion Number of Original Sample Failures	Extrusion Repair Original Failure Rate (%)	Sampling Frequency	Sampling Mandated?
3.3 (13355m^2)	1044 (318.2m)	2	0	0.00%	1/522 lf	N
3.8 (15378m^2)	2324 (708.3m)	5	3	60.00%	1/465 lf	N
17.2 (69606m^2)	7427 (2263.7m)	15	0	0.00%	1/495 lf	Y, 1/500 lf
18.0 (72843m^2)	5580 (1700.8m)	11	1	9.09%	1/507 lf	Y, 1/500 lf
81.9 (.33144km^2)	14286 (4354.4m)	20	2	10.00%	1/714 lf	N

The failure rates vary, period. Some projects worked on reflect the implementation of mandated sampling frequencies, as required either by owner or by regulatory agencies. All of the failures reflected above were found on repairs, not primary extrusion seaming.

If samples are going to be taken on an extrusion patch, they should be taken in such a manner whereby the whole patch can be removed and replaced to avoid overlapping extrusion welds which reheats and degrades the area.

And, with all destructive samples, locations should be selected that minimize additional holes in the geomembrane, such as at intersections. Samples should not be taken in high stress or critical areas, such as sumps or flowlines.

REPAIRS

The goal should always be to minimize the number of repairs required. The design phase can help in this regard by anticipating where seams and intersections will be required. Choosing a wider material may help reduce the number of seams and therefore the number of repairs. And, finally, fusion caps should be considered as an alternative to long extrusion caps or long extrusion welds.

One best practice that is often neglected is the rounding or termination of straight-line cuts in the geomembrane. There is plenty of research (see Edward Kavazanjian from Arizona State University) in particular that show straight-line cuts will propagate under stress right through (below) an extrusion repair. Rounding of all cuts like the keyhole termination of a wrinkle repair shown below in Figure 7 is a recommendation the author strongly believes will help long-term quality, particularly on projects were stress is likely to be induced into the liner system.


Figure 7. Keyhole termination of straight-line cut.

FINAL WALK THRU

This practice is mostly neglected on projects and when required, typically the responsibility falls solely on the QA inspector. This is the last chance for inspection to ensure no damage was missed or has occurred. When damage is found, another critical component often overlooked is restricting foot/equipment traffic to and from the area(s) needing repair as well as subsequent inspection of these areas. Incidental damages can and will occur, so it is imperative that traffic be limited and a thorough inspection be performed after all activities are finished in the areas impacted by the repair.

ROUTINE INSPECTION

Particularly areas of exposed geomembrane but also areas of covered geomembrane/geosynthetics should be inspected on a regular basis to ensure damage has not happened post construction completion. There are numerous potential sources of damage such as wildlife, ancillary activities surrounding the area like road grading or fence installation, weather, etc. The key to minimizing the impact of any damage is finding it as soon as possible.

CONCLUSION

The geosynthetics industry has made huge strides forward since 1990 and many lessons have been learned – both success stories and failures. Carrying these lessons learned forward is critical in continuing to move the bar of excellence up the ladder. The coal-ash industry has a huge benefit in that many lessons learned already exist and now are being shared with the industry. Being mindful of the content of this paper should help the coal-ash industry as well as the geosynthetics industry as a whole.

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