Can the Holy Grail of the Geosynthetics Industry "Zero Leakage" be Achieved by Arc Testing?

Vladimir Nosko, RNDr., PhD., Sensor, Slovakia, nosko@sensorgroup.com
Jon Crowther, MRICS, BSc (Hons), Sensor, UK, jon@sensorgroup.com

ABSTRACT
Arc testing is a method for testing the integrity of exposed nonconductive geomembranes that has now been in use in Europe for more than 15 years. In the last 5 years almost 5-million square meters of arc testing has been undertaken globally, revealing more than 4400 leaks. In this paper, the principle of the arc testing method is described and the results from various surveys totaling almost five million square meters are presented and discussed. The most common argument against adopting the exposed geomembrane leak location methods is that this kind of control should be the responsibility of geomembrane installers. Typical Construction Quality Control (CQC) performed by the installer includes vacuum tests, air channel tests, and visual inspection of the installed area. With the only control of the mid-sheet areas being visual inspection, it is impossible to effectively control large-scale projects. Large, visible leaks can be obvious, but small leaks, cuts and pin holes are invisible faults that regularly remain undetected. The concept that these types of leaks have no significant contribution to contamination and are therefore negligible is an excuse that is in fact untrue. The large scale introduction of arc testing has now provided evidence of how seriously wrong this concept is. Various types of leaks have been detected and located by arc testing, which previously could not be discovered and would therefore have stayed hidden, unrepaired and leaking indefinitely. The significance and unrivaled performance of the arc testing method for leak location on exposed geomembranes is illustrated in this paper. The conclusion being that the arc testing method can once and for all dispel the myth that "zero leakage" is an unachievable aim.

1. INTRODUCTION

1.1 Why, how and where leaks appear? The present situation with ELL for exposed geomembranes.

According to published theoretical information and also the resultant information gathered during the time frame of a geomembrane installation, a tradition of reliance to best practices such as installers CQA and the existence of third party control, as well as the use of recommendations based on valid norms (ASTM or EN), internal procedures, ISO standards, etc has developed. Such procedures are applied either directly by the manufacturer during material processing, or during a subsequent stage (storage, shipping, handling on site and the installation process). These procedures generally follow a commonsense approach and have been proved valid through experience of how damage, or failure can occur during each stage of a geomembrane's life.

Within this paper it should be noted that there is subtle distinction drawn between a hole and a leak. The reason for this is because all pre-existing technologies deployed for the detection and location of defects within geomembrane installations require the existence or temporary creation of simulated leaks (howsoever small). Take for example water based exposed geomembrane testing methodologies. These require that a conductive signal carrier (moisture / water) pass through a hole in order to declare that a 'leak' exists. The only available technology in existence today that can pre-determine the potential for a leak is the process of Arc Testing. This requires only electrons to pass through a hole and can therefore predict a leak thereby finding a hole which will be the cause of leak in the future, if not repaired at the point of detection before covering.

During the lifecycle of a geomembrane there are some periods when such quality control activities are limited **by objective factors** (e.g. weather, region of application, scope and purpose of application, site conditions, understanding of following trades and unfortunately often economic / commercial conditions as well). During these periods of limitation where objective factors can have a very significant effect on eventual geomembrane integrity, without any possibility of corrections / rectification. These objective factors limit the effectiveness of control mechanisms and this provides an opportunity for the existence of leaks in the geomembrane. Another area of **subjective factors**, deliberately kept separate from the first set described above are those directly related to the installer's interaction with the geomembrane material (e.g. training, skill, attitude to the work, as well as machinery condition, calibration and maintenance etc). Based upon our findings it is the installer interaction that exerts the greatest influence on the eventual quality of geomembrane installation. The factors highlighted are commonplace in the wider construction industry as well as the geosynthetics installation industry and unfortunately their existence gives rise to the appearance of leaks. This was the background that formed the main objective in our research and development, to find a method with associated procedures to achieve the unambiguous detection and location of all holes left as a result.

Electric methods for the detection and location of leaks to exposed geomembranes during the construction / installation period included: ASTM D7240 (capacitive spark testing) for conductive geomembranes; whereas for non-conductive geomembranes ASTM D7703 (water lance); or ASTM D7002 (water puddle) were employed. These ELL methods certainly had their place in the leak testing of exposed geomembranes. During our research however we arrived at the realization that these methods were significantly limited by their very nature. Unfortunately the genius of their reason for being adversely affected their ability to perform. In both cases there is a need to use a conductive signal transfer medium in addition to the standard geomembrane. In the case of the capacitive spark test it is necessary to use a specially formulated geomembrane with a conductive backing. Whereas in case of water based methods (water lance or water puddle) it is necessary to use water as the signal transfer medium**. The common factor between ASTM D7240, 7703, and 7002 is a key factor the addition of a signal transfer medium, either a conductive backings or water** which can often be a precious resource in areas where water is scarce and even needs to be imported.

What is actually the most important development and most brilliant invention is not the individual methods themselves but the acknowledgement, or understanding that the exposed geomembrane required a reliable and unambiguous method of testing to the entire surface before covering. This is because it is that time period from geomembrane installation until covering when the geomembrane is the most vulnerable. Of course, the period of geomembrane installation itself is a time period when there is frequent handling of it and therefore there is also a high possibility of damage during this period as well. Over all, even the activities which should be obvious with regard to maintaining the quality of installation - the realization of welds (hot wedge weld or extrusion weld); using only approved, recommended and prescribed procedures - unfortunately time and again on many sites irrespective of region this only appears in writing and not in practice! Albeit reluctantly as the statistics within this paper demand it, we must say so. To complete the picture we must add the time period for production, shipping, handling, factory storage, shipping, off loading at site, as well as final handling, distributing and storing on the construction site. Add to this poor subgrade conditions, traffic over and following trades, then we can clearly see how a wide a range of daily geomembrane treatment can inflict repeated damage allowing holes to occur and therefore leaks to appear. Unfortunately, this time frame in the life of a geomembrane represents a period where a considerable number of breaches in the liner **will** occur.

The above only confirms the conclusions of authors Forget, Rollin and Jacquelin (2005) who presented within their paper the statistics obtained from surveys of exposed geomembranes applied at 57 sites with different levels of CQA application. According to these authors approximately 30% of leaks are found at seam edges and 70% are found on the panels / mid-sheets. Our own findings concur with those of Forget, et al (2005) even though ours are over a much bigger sample of statistical data totaling 6,820,020m^2 (73410084ft^2). If we take into consideration the existence of valid norms, procedures, regular training and recertification of welders, involvement of third party controllers, strong CQA, etc then **such presented findings represent an alarming situation of which the responsible persons and companies must take serious note.** Unfortunately, even the best designs cannot resolve such a negative situation as this is purely about how the human factor and subjective circumstances will affect the geomembrane installation.

An element of the integrity control process on which no real reliance should be placed is the visual check of the whole surface of the installed geomembrane. Particularly when the area of installed geomembrane is very large a visual check by its very nature cannot be 100% effective and in any event often such a visual installation checks are not carried out at all. The welds have recommended procedures and testing (visual inspection, destructive testing of seams, non-destructive testing of seams, etc.) however in contrast when it comes to the testing of “every square millimeter” of geomembrane surface after its installation there has been no definitive solution. The only ELL methods that have come close are the water based systems for non-conductive geomembranes. The limits and boundary conditions of such solutions are recognized and so far accepted because no others were known to be available.

1.2 Arc testing method and other ELL for testing exposed geomembrane.

The situation described in section 1.1 was the main reason that the development of the Arc Testing method was commenced. The basis of this method is different from the ones described earlier in this paper. In the case of the spark testing method for use with conductive geomembranes, Arc Testing has often been confused due to its similarities, however the difference is an electric spark versus a constant electric arc.

Initially, a dielectric testing method usually called "spark testing" or “Holiday Testing” is traditionally used to detect pin holes / gaps in tank linings, or pipe coatings. Holes are found by a point source of voltage applied across the coating. Sparking occurs when a gap in the coating allows the passage of current to the ground (conductive substrate) or between probes and conductive micro layer in case of so called conductive geomembrane. The spark test or discharge method of checking for holes in linings is found to be reliable and nondestructive. In the case of the spark test method this can be simply explained as a metal brush (comb) being moved in contact with the geomembrane over its surface and in the event of a hole a spark “jumps” to the place of the hole. In the case of the Arc test method a continual arc of electric charges is employed. The arc appears between the edge of hole at either side – one to the probe and one to a conductive subgrade. The signal flows inside the tested material through holes without any apparent limit of length passing inside hole / leak path. The arc is more intensive and bright when the subgrade is more conductive. Such conductivity could be created by certain degree of natural humidity behind the holes / inside a potential leak path and its connection with subgrade or it is created based on material properties. **It works similarly whether a totally dry hole or with a subgrade of conductive material** (this being obligatory within the interstitial space between liners for double lined geomembrane applications for all ELL methods). In this case we would like to pinpoint the situation when for detecting and locating fault in geomembrane using Arc testers the humidity as the pass for signal is not the necessary condition. This is the reason why inside this article we use term “hole” instead of “leak” in regards to Arc Testing Method just to demonstrate the difference between water based method and Arc testing method.

The Arc Testing method is totally different from water based method, simply put Arc Testing finds holes (a precursor to leaks) where only electrons can pass, whereas water based methods can find only ‘leaks’ (a consequence of holes). Also because of the nature of low depth water and water’s surface tension, it is possible to entirely miss holes particularly on slopes and tank walls using water based methods. As their name suggests they use water as medium to allow the transfer of electric charge through a hole in the geomembrane. The electric charge it uses is low voltage; the presence of water itself makes visual and precise determination of leak position (in the case of very small hole or cuts) very difficult due to ambiguity. Very often in the case of a very small hole its precise location is almost impossible when the whole place is “flooded”. The boundary conditions (physical, mechanical and mainly electrical) are limiting its application. Detection of multiple holes is difficult and the detection & location of a hole near to the edges of a geomembrane, or near to electrically conductive mechanical fixations is not so possible creating problems on site. What about the weather? In wetter climates like the UK and Canada it is often cited that the water methods are better because they are not affected by the weather, whereas for Arc Testing it must be quite dry. But in reality water methods are no better in the very high humidity environment because then the environment provides a worsening of boundary condition as the signal dissipates everywhere but through a leak, as a direct result.

1.3 Arc testing method – development and obtained results.

Arc testing as method to control integrity of exposed non-conductive geomembrane was tried for the first time in Slovakia in 1999. Previously known methods like spark and vacuum tests were used only to control the quality of seams, or places containing repairs. The idea of the development was to build and test a method that was able to detect holes in non-conductive geomembranes using only volume or surface conductivity of the environment upon which the geomembrane is placed and mainly to achieve the ability to test large surface areas of standard geomembrane quickly – this means areas between seams / mid-panel. In the past we dealt with the possibilities of using non-electric based methods known as NDT methods to check integrity of different types of materials. In the table below the comparative sensitivity ranges of various leak detection approaches provides an enlightening analysis. Figure 1 produced by Pregelj et al (1997) highlights methods and their limits of leak detection. Based on the criteria stated inside Figure 1 we can assign the sensitivity of leak detection of the spark test method, to the Arc Test* method.

Bubble test (soap painting)	- -	- -	- -	- - →								
Bubble test (air, water)	- -	- →										
Bubble test (He, alcohol)	- -	- -	- →									
He sniffer	- -	- -	- -	- -	- -	- -	- →					
Halogen sniffer	- -	- -	- -	- -	- -	- →						
Pressure decay	- -	- - →										
Acoustical	- -	- -	→									
Vacuum decay	- -	- -	- →									
Spark tester*	- -	- - →										
Thermal conductivity	- -	- -	- -	- -	- - →							
Radioisotope	- -	- -	- -	- -	- -	- -	- -	- -	- -	- - →		
Halogen detector	- -	- -	- -	- -	- -	- →						
Mass spectrometer	- -	- -	- -	- -	- -	- -	- -	- -	- -	- -	- - →	
Dye penetrant	- -	- -	- -	- -	- - →							
mbarr l/s	10^{-1}	10^{-2}	10^{-3}	10^{-4}	10^{-5}	10^{-6}	10^{-7}	10^{-8}	10^{-9}	10^{-10}	10^{-11}	10^{-12}

Figure 1. Sensitivity ranges of various leak detection methods (from Pregelj et al. 1997).

In the very early stages we undertook several theoretical and practical analyses along with computing modelling of the related electric fields. The main realization that we came to during our testing of the commercially available spark testers (and similar equipment to them) at the time was that these only partly satisfied our requirements. This was because our basic requirements were already beyond the maximum limits of the available technology.

A decision was made to develop a completely new device which would satisfy all our main requirements among which the key one was to reliably detect holes in non-conductive geomembranes. Of course the boundary conditions of the Arc method need to be respected by fulfilling the conditions of minimum electrical subgrade conductivity and providing a conductive connection to the whole surface. The principle was to create so called "dark current" (a cloud of negative pole) with the ability for migration under the surface of the tested material. The next condition was to achieve a large enough potential difference between the abovementioned negative electric potential and artificially excited positive charge at the probe of the device. To achieve this the output voltage created was in the adjustable range of 2.5 kV to 35.0 kV with minimal electric current.

We achieved the creation of visible electric arc in the location of any hole even that of very small size. Interestingly the color of electrical arc varies according to the degree of conductive connection through the hole from a very bright white/blue to almost invisible red/brown. Presently valid ASTM D6747 defines the smallest possible detectable leak by spark tester and arc tester as a size of less than 1mm in diameter.

After our successful tests we carried out several small and large scale tests at our own expense to show Clients the legitimacy and also necessity of using the Arc test method for testing the integrity of exposed geomembranes. We received a great deal of positive feedback from sites and Clients offered us excellent testimony with regards to the Arc tester´s sensitivity and effectivity. **On other side, when we tried to obtain budget from them for next project we always received arguments that these activities of geomembrane integrity testing of exposed geomembrane should be the responsibility of the geomembrane installers because it came under the geomembrane installation phase of the project.**

Step by step we were gradually detecting faults and holes which by their nature and character would not be detected and located by conventional methods valid under normal CQA procedures and therefore they would remain hidden and stay unrepaired forever. When we started to demonstrate this situation the attitude of Clients started to change. **As the weight of evidence grew from sites highlighting such findings, finally some Clients started create budgets for independent Arc test surveys.** They understood the root of the problems and received excellent results. On the other side, many of the holes we discovered were faults and mistakes that originated from the installation and should have been revealed by the normal CQA procedures already in place. Unfortunately, the quality of the geomembrane installation process (placing of geomembrane panels, handling on site, welding of panels, related testing of seams, etc.) varies country by country and depends on: the degree of CQA application; training and experience of the installers; and undoubtedly the quality of geomembrane welding equipment used (including the age of equipment, quality of maintenance and most importantly whether it is correctly set up).

Setting aside these subjective and influencing factors there were still other cases which prior to the Arc tester were unknown, ignored, not attended to, assumed non-existent or simply not anticipated. This has opened up a new horizon and level of knowledge, which has remained hidden and overlooked. In 2009, based on several years of testing activities we deployed the Arc tester to test the integrity of leaking process ponds following an emergency call from a Client. With incredible ease the Arc tester detected all leaks even ones in areas not anticipated by the Client. The need for the survey was generated because the geomembrane installers on the site could no longer continue. They had already installed three layers of geomembrane in attempts to abate leaking. Despite this the ponds were still leaking and the contaminants always appeared under the newly placed geomembrane layer after use of the ponds. The lining installers work was excellent quality, the degree of CQA was usual and good enough to even convince the authorities to allow the ponds to be put into service. The result of the ponds being completely out of service would have been enforced stoppage of the client's production processes which would have caused massive losses. Thanks to excellent results using the Arc tester it was discovered that the problem was not because of improper or poor quality work by the geomembrane installers, but in fact careless work of other construction companies doing maintenance of related facilities, such as pipes and other construction work (dropping of hand tools, almost invisible holes due to sparks from mig welding of metal pipes, etc.).

At the same time and based on results from previously successful surveys we used Arc testing on an exposed textured geomembrane. During the survey of this facility we found surprising results - many small almost invisible holes. Analysis of the cause of the holes revealed a production fault within the material itself. Such leaks are unable to be seen by visual inspection or revealed by any other known conventional ELL system for exposed membrane testing. In addition any inspection by the dipole method when geomembrane is covered by material could also not have revealed such tiny and high density (by area) of holes. Furthermore we also detected and located large amount of other holes of more classically known origin: faulty extrusion seams; faulty hot wedge seams; holes next by hot wedge seam created by high pressure between machine pinch wheels; overheated and burned out areas; punctures by sharp objects; and stones coming from poor subgrade conditions when geomembrane is placed over the top during its installation; etc, etc. We also discovered damage due to wrongly stored rolls of geomembrane and holes as a result of their shipping and handling.

The next interesting findings were leaks under drainage pipes created during pipe installations. Debris and small sharp stones and objects creates small punctures. Based on expert opinion on site even such small holes can create significant leakage of productive material contaminating the subgrade. This is because of their position directly under drainage pipes where there is also usually a depression in the subgrade. Based on these findings such places were more carefully treated, cleaned and tested twice, once before placing a pipes and second time after their installation to ensure that no damage was left in these areas.

Other discoveries were the existence of many holes were created due to the frequent passage of people over already placed panels of geomembrane, moving small machineries during installation process or other additional construction works. Whilst other holes were as a result of accidents caused by strong wing and moving objects over the geomembrane surface. Thanks to the Arc testing process all holes were detected, located successfully repaired allowing the site to reach the status of zero leakage.

In another example, when we presented arguments to other Clients in relation to the necessity of using the Arc Testing method we faced preference for the use of water based methods. In one particular instance we persuaded a client to provide a test field of 2,000m^2 of previously installed geomembrane on a live project that had been approved as intact by a water based method. In preparation for the test the Client also created 20+ test holes of different shapes, sizes and in various positions. All of them were successfully detected and in addition we found many others holes that had not been created by the client, or previously detected by the water method. As a result of that test the Client adopted Arc Testing on his sites. After analysing the reasons that holes remained despite the previous survey done using a water method it was stated that the survey was carried out by unskilled technicians. According to our findings we noted a significantly the lower sensitivity and along with a wider and more difficult boundary condition for water based methods in comparison to dry testing with Arc Testers. As a result it can be stated with confidence that the efficiency of water based methods is far behind that of the Arc Test. Control of the edges of geomembranes and places with mechanical fixation also favours the Arc testing method.

Following on from the abovementioned site the same Client requested our services on another of his sites. In total almost 1,000,000m^2 of PVC geomembrane was to be tested. Again many holes were located and unfortunately many of them appeared as faulty material.

Progressively from 2009 within next 4 years and in different countries (several within the EU plus, Turkey, Chile, Bolivia) and in different geomembrane applications (water ponds, municipal landfills, process ponds, mining sites, roofing, etc) we carried out many surveys covering nearly 5,000,000m^2 on a variety of geomembranes types (HDPE, LLDPE, PVC, PP, fiberglass, PU liquid coatings, etc.) and over many different thickness from 0.6 – 5.0mm. The results far exceeded our expectation. More than 4,700 holes were detected. From these real life findings we created some statistics which are hereby presented within this paper.

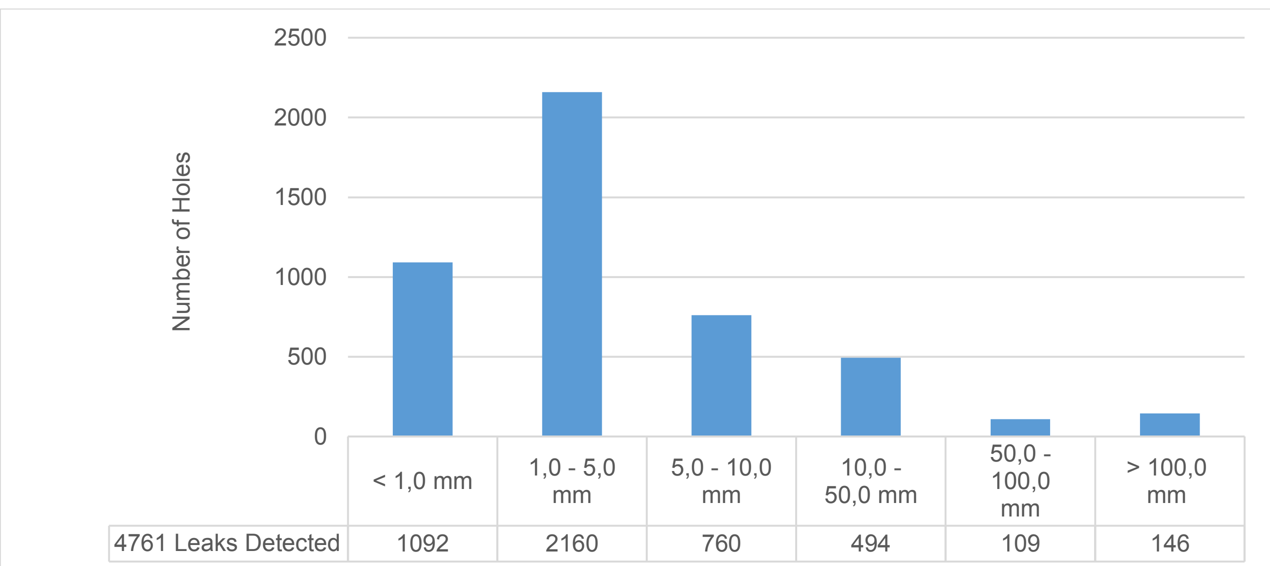


Figure 2: Analysis of detected and located holes/leaks based on size. Total sample size 6,820,020m^2 surveyed area.

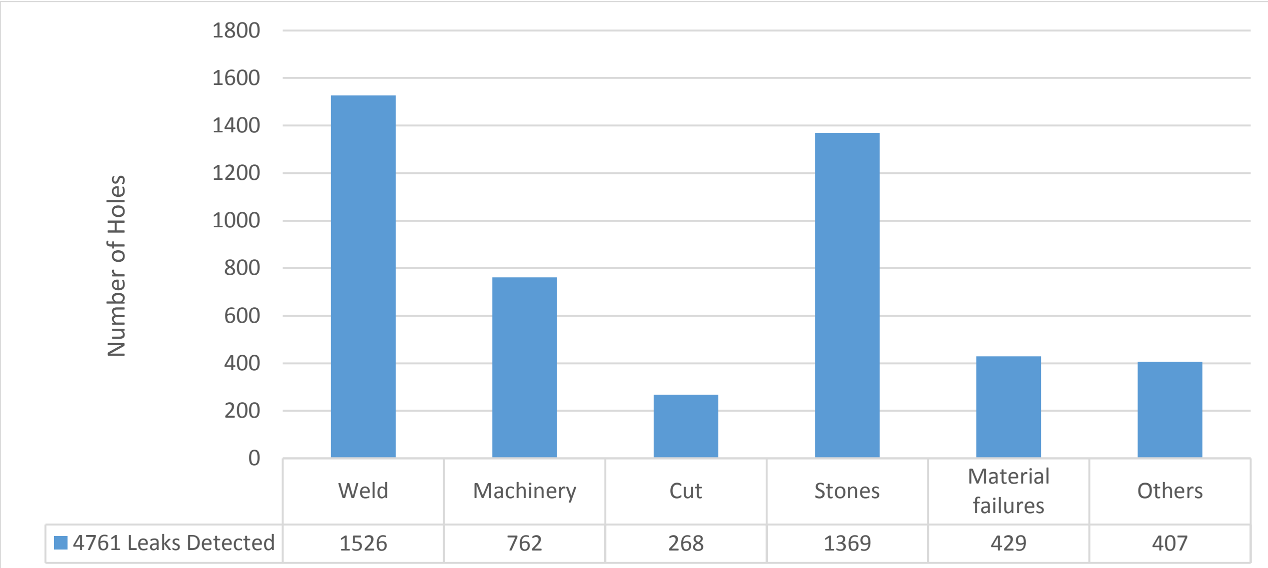


Figure 3: Analysis of detected and located holes/leaks categorized by cause. Total sample size, 6,820,020m^2 surveyed area.

Figure 2 shows the general analysis of all detected holes in relation to their size. Within figure 3 is an analysis of all detected holes in relation to their causes. What is incredible looking at the data is the realization that without Arc Testing how many holes must stay undiscovered, creating potential places for leaks and contamination, or loss of production material.

In order to highlight the contribution of each ELL method in relation to amount of holes / leaks detected Figure 4 was created. Inside Figure 4 the both the Arc Test and Dipol method are compared. This comparison is linked through the sizes of detected leaks / holes so to be able to pinpoint their productive mutual complementarity. It should be noted that the overlapping area of size of leaks / holes (5.0 – 50.0 mm) is represented by diametrical opposing hole / leak types. In the case of Arc Testing it is mainly faulty seams and cuts in geomembrane. Whereas in case of Dipole method these are mainly tears and damage caused by heavy plant.

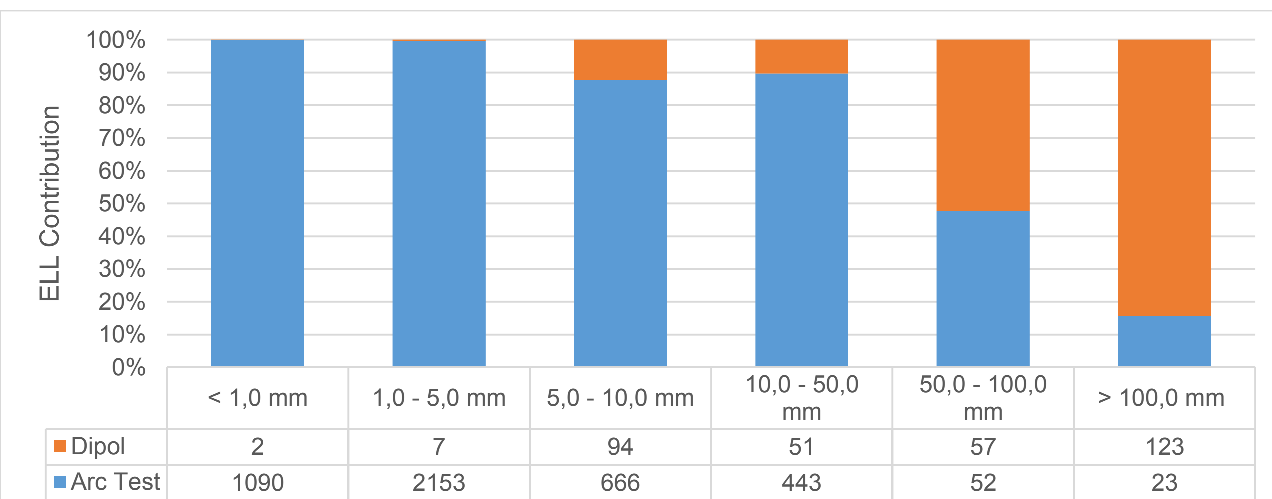


Figure 4: ELL Contribution to the whole quantity of leaks / holes detected. Size of leaks vs type of ELL method. Total sample size 6,820,020m^2 surveyed area.

Figure 4 shows the contribution of both analysis methods to the total amount of 4,761 holes / leaks detected and located. 100% means the detection of all existing holes / leaks located within the surveyed area. The presented data is based on real results from surveys completed over a total area of 6,820,020m^2 which represent **6.98 holes / leaks per Hectare**. Further conclusions can be drawn from Figure 4 as this shows the clear dominance of the Arc Testing method as a proportion of detected leaks which represents **92.98%** of the 4,761 leaks / holes detected and located. The remaining 7.02% were discovered by Dipole statistically filling the overall balance. The next conclusion that can be drawn from Figure 4 is that the holes sized from 1.0mm to 50.0mm are predominantly found by Arc Testing. On the other hand it is necessary to say that within the interval of 10.0 – 50.0mm the dipole method is equally good at detection of leaks. In this case this is represented mainly by serious damage like tears or general damage caused by heavy machinery. Also it should be noted that, **leak size interval of 1.0 – 50.0 mm by its very nature covers the majority of emerging breaches in the liner . The aforementioned interval represents 94.64% of all leaks detected and located within the survey analysis.**

This clearly confirms that the dominant quantity of leaks are created during the geomembrane installation period and within a time period when the geomembrane is not yet covered. So far we could only intuitively think about it, but now we have very clear tangible evidence of this incredible issue. Of course on other side this is confirmation of the necessity of use of ELL methods to control the integrity of geomembranes after covering and in the end to have sites free of leaks. Again we can authoritatively state based on Figure 4 above that **the Arc testing method creates a logical pairing with the Dipole method**.

Furthermore in order to obtain a complete picture with regard to leaks in exposed geomembranes it is very important to include data from the time when uncovered geomembranes that are in use and subjected to some periodical maintenance work.

Table 1. Summary of Holes / Leaks detected by Arc Test and by Dipole method and their contribution to the whole quantity of Holes / Leaks detected within analyzed area of 6,820,020m^2.

Leak size	**Total Leaks Detected**	**Contribution (%)**	**Arc Test Method**	**Contribution (%)**	**Dipole method**	**Contribution (%)**
< 1,0 mm	1092	22,94	1090	99,82	2	0,18
1,0 - 5,0 mm	2160	45,37	2153	99,68	7	0,32
5,0 - 10,0 mm	760	15,96	666	87,63	94	12,37
10,0 - 50,0 mm	494	10,38	443	89,68	51	10,32
50,0 - 100,0 mm	109	2,29	52	47,71	57	52,29
> 100,0 mm	146	3,07	23	15,75	123	84,25
Total	**4761**	**100,00**	**4427**	**92,98**	**334**	**7,02**
< 50,0 mm	4506	94,64	4352	91,41	154	3,23

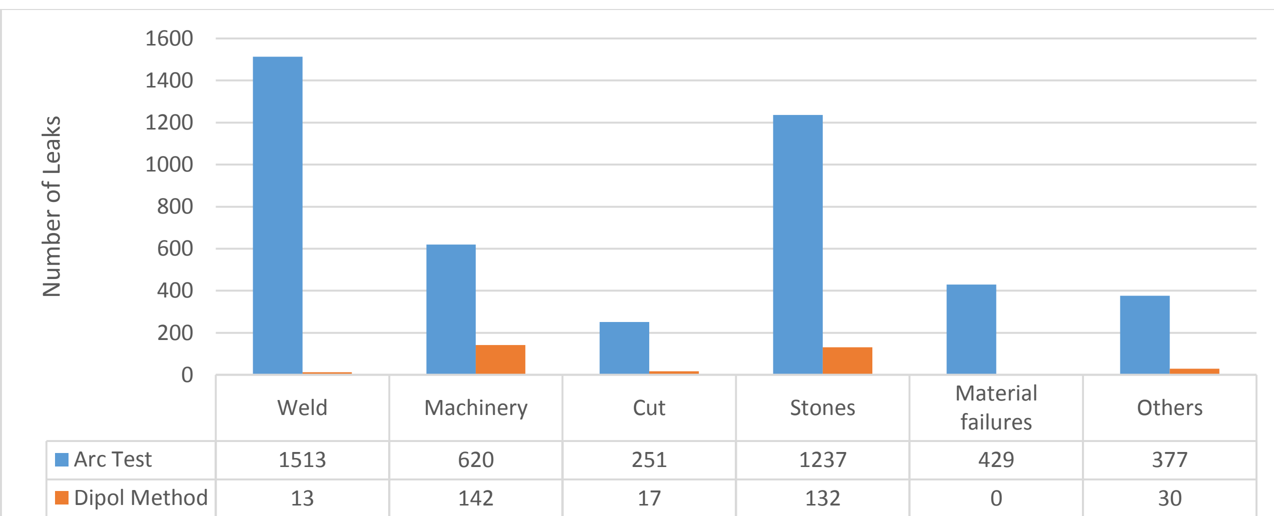


Figure 5: Analysis of detected and located holes / leaks obtained by different ELL methods. Results are related to cause of leaks. Total sample 6,820,020m^2 area surveyed.

This presented article highlights the indispensability and suitability of the Arc Testing method for exposed geomembranes and its application before being covered. The assumption that the Dipole method is enough to detect and reveal every hole / leak including the ones described above detected by Arc Test is wholly incorrect because the principle and character of the Dipole method does not enable it to detect such geomembrane damage. Notwithstanding that the combination of Dipole with Arc Testing significantly moves meaningful ELL work to the pinnacle of a "Zero Leak" geomembrane installation. The Arc Tester under appropriate boundary conditions is able to detect 100% of all existing leaks in exposed geomembranes and the Dipole method contributes through the detection of leaks created during subsequent processes such as placement of drainage and protective layers on top of geomembrane. This is extraordinary and productive combination of ELL methods. In fact similar findings were published by authors Forget, Rollin and Jacquelin (2005), whose analysis reached similar findings but based on water based method applications along with Dipole application. The clarity of need for such a unique combination of testing methods (exposed geomembrane testing and covered geomembrane testing) and creation of one logical set for achieving leak free installation is documented by Beck, A. (2012) whose paper describes the application of a conductive geomembrane tested by spark test and followed by Dipole method after covering, showing that in this combination of ALR 0.00001% can be achieved.

To obtain another very valuable finding we included within the analysis three sites where the pairing of Arc testing with Dipole testing was applied. We named them generically site "A", site "B" and site "C". These three sites were chosen due to the relatively large scale of their surveys in order to ensure statistically better and more relevant data. Standard CQA was applied as a matter of course. With regards to geomembrane installation sites B and C deployed an LLDPE 2.0mm double textured material whereas site A was constructed using LLDPE 1.5mm in a combination smooth and textured materials. In the case of site A the installation was done in portion of 40% of steep and gentle slopes. In case of sites B and C these were mainly flat areas with slight and general site gradient.

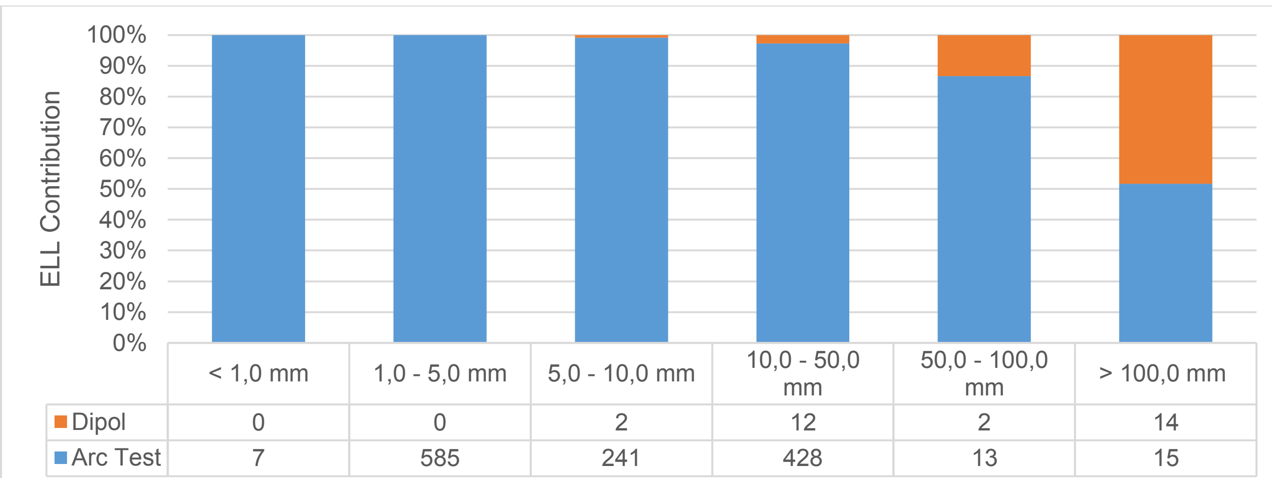


Figure 6: Analyzed site "A" - Analysis of detected and located holes / leaks obtained by Arc tester and Dipole method. Results are related to size of holes / leaks. Total surveyed area by Arc tester was 740,479m^2 and by Dipole method was 441,069m^2.

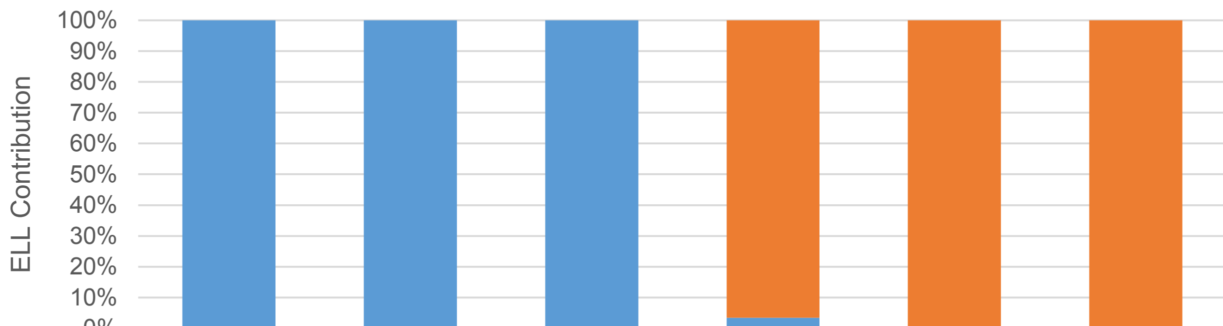
Table 2. Analyzed site "A" - Summary of Holes / Leaks detected by Arc Tester and by Dipole method and their contribution to the total quantity of Holes / Leaks detected. Total surveyed area by Arc tester was 740,479m^2 and by Dipole method was 441,069m^2.

Leak size	**Total Leak Detected**	**Contribution (%)**	**Arc Test Method**	**Contribution (%)**	**Dipole method**	**Contribution (%)**
< 1,0 mm	7	0,53	7	100,00	0	0,00
1,0 - 5,0 mm	585	44,35	585	100,00	0	0,00
5,0 - 10,0 mm	243	18,42	241	99,18	2	0,82
10,0 - 50,0 mm	440	33,36	428	97,27	12	2,73
50,0 - 100,0 mm	15	1,14	13	86,67	2	13,33
> 100,0 mm	29	2,20	15	51,72	14	48,28
Total	**1319**	**100,00**	**1289**	**97,73**	**30**	**2,27**
< 50,0 mm	1275	96,66	1261	95,60	14	1,06

Total surveyed area of site A was 740,479m^2 by Arc Testing and 441,069m^2 by Dipole testing. The difference is due to steep slopes without any cover which therefore required only Arc Testing. The results are given in Figure 6 and in Table

2. Of special note is the finding that 96.66% of all leaks are within the interval 1.0 – 50.0 mm. Additionally dominance of detection and location of leaks / holes by Arc Testing is because of the larger surveyed area (steep slopes). The dipole testing detected and located only leaks purely caused by heavy plants and were in a majority of sizes within the interval above 50.0mm. Leaks under 5.0mm were not found during this survey by the dipole method.

Total surveyed area of site "B" was 230,400m^2 by both methods Arc testing and by Dipole testing. The results are given in Figure 7 and in Table 3. Of special note is finding that 58.82% of all leaks are within the size interval 1.0 – 50.0mm. It can be seen from Figure 7 that there is a very sharp boundary between intervals of leak sizes to 10.0mm for Arc testing and above 10.0mm for Dipole testing. The explanation of this finding is that leaks detected by Arc testers were mainly caused by faulty seams and cuts and punctures by small stones. On other side the leaks sizes above 10.0mm detected solely by Dipole method were created by heavy machinery / plant (tears and larger punctures by stones) during placing of covering layers. Holes / leaks of sizes under 10.0mm did not appear during dipole testing. According to these results it can be stated that the presented character of leak division between Arc testing and Dipole testing as logical and with justification.



	< 1,0 mm	1,0 - 5,0 mm	5,0 - 10,0 mm	10,0 - 50,0 mm	50,0 - 100,0 mm	> 100,0 mm
Dipol	0	0	0	28	5	23
Arc Test	2	3	6	1	0	0

Figure 7: Analyzed site "B" - Analysis of detected and located holes / leaks obtained by Arc tester and Dipole method. Results are related to size of holes / leaks. Total surveyed area by both ELL methods was 230,400m^2.

Table 3. Analyzed site "B" - Summary of Holes / Leaks detected by Arc Tester and by Dipole method and their contribution to the total quantity of Holes / Leaks detected. Total surveyed area by both ELL methods was 230,400m^2.

Leak size	Total Leak Detected	Contribution (%)	Arc Test Method	Contribution (%)	Dipole method	Contribution (%)
< 1,0 mm	2	2,94	2	100,00	0	0,00
1,0 - 5,0 mm	3	4,41	3	100,00	0	0,00
5,0 - 10,0 mm	6	8,82	6	100,00	0	0,00
10,0 - 50,0 mm	29	42,65	1	3,45	28	96,55
50,0 - 100,0 mm	5	7,35	0	0,00	5	100,00
> 100,0 mm	23	33,82	0	0,00	23	100,00
Total	**68**	**100,00**	**12**	**17,65**	**56**	**82,35**
< 50,0 mm	40	58,82	12	17,65	28	41,18

Total surveyed area of site "C" was 411,102m^2 by both methods Arc testing and by Dipole testing. The results are given in Figure 8 and in Table 4. Of special note is the finding that 89.25% of all leaks are within size interval 1.0 – 50.0mm. Again evident from Figure 8 a very sharp boundary between intervals of leak sizes to 10.0mm for Arc testing and above 10.0mm for Dipole testing. The explanation of this finding is that leaks detected by Arc testers were mainly caused by faulty seams and cuts and punctures by stones. Of special note is detection of production faults inside geomembrane – almost invisible perforation at many places represented by leaks sizes below 1.0mm. The Client decided to exchange several panels of geomembranes based on this finding. After placing material on top of the geomembrane the dipole method was applied. Cause of detected and located leaks were purely from placing layers of stone by heavy machine (tears and wheel tracks). Leaks sizes of below 10.0mm did not appear in this construction period. According to these results it can be stated that the presented character of leak division between Arc testing and Dipole testing as logical and with justification.

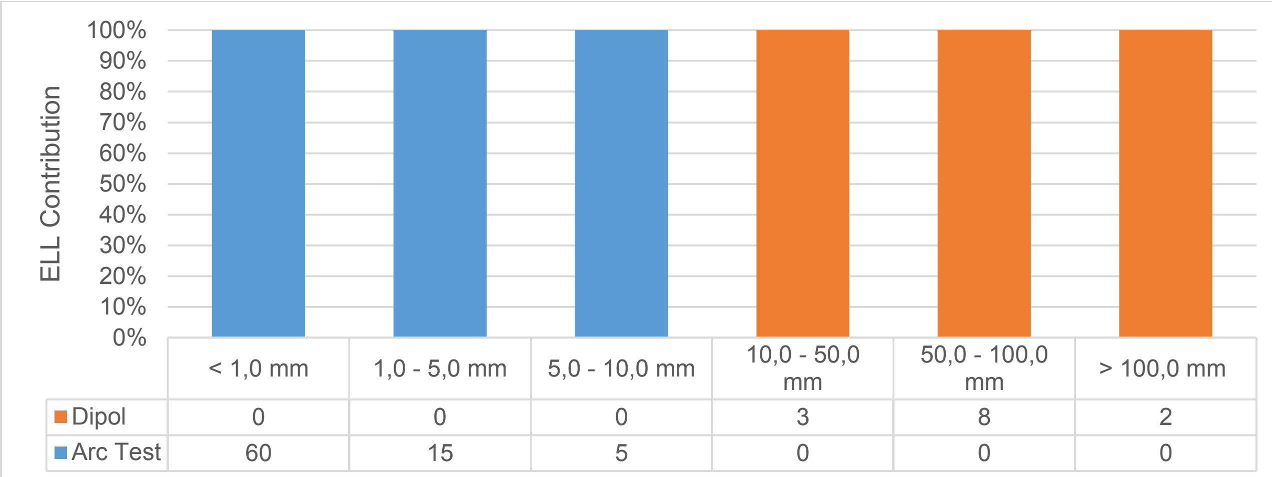


Figure 8: Analyzed site "C" - Analysis of detected and located leaks obtained by Arc tester and Dipole methods. Results are related to size of leaks. Total surveyed area by both ELL methods was 411,102m^2.

Table 4. Analyzed site "C" - Summary of Leaks detected by Arc Tester and by Dipole method and their contribution to the total quantity of Holes / Leaks detected. Total, surveyed area by both ELL methods was 411,102m^2.

Leak size	Total Leak Detected	Contribution (%)	Arc Test Method	Contribution (%)	Dipole method	Contribution (%)
< 1,0 mm	60	64,52	60	100,00	0	0,00
1,0 - 5,0 mm	15	16,13	15	100,00	0	0,00
5,0 - 10,0 mm	5	5,38	5	100,00	0	0,00
10,0 - 50,0 mm	3	3,23	0	0,00	3	100,00
50,0 - 100,0 mm	8	8,60	0	0,00	8	100,00
> 100,0 mm	2	2,15	0	0,00	2	100,00
Total	**93**	**100,00**	**80**	**86,02**	**13**	**13,98**
< 50,0 mm	83	89,25	80	86,02	3	3,23

2. CONCLUSIONS

This article sets out the requirement and proves the necessity of the joint application of ELL methods required for testing: exposed geomembranes; and for testing covered geomembranes. It was clearly demonstrated the combination of Arc and Dipole testing methods can create a logical set of ELL methods necessary to achieve "Zero Leaks" site status.

In the same manner that spark testing of conductive co-extrusion geomembranes can achieve the 100% leaks detected and located, Arc testing can be used for all other geomembranes (PEHD, LDPE, LLDPE, PVC, PP, etc.) including bitumen, fiberglass and polyurethane / polyuria liquid applied membranes and coatings.

The tandem pairing of Arc testing with the Dipole method (and with permanent monitoring systems) as set out within this paper can achieve leak free geomembrane installations. Through such joint applications we can protect the environment against pollution caused by leaks, or stop the loss through leaking of valuable production materials like gold.

Like it or loath it, the detection of precursor holes by Arc testing must be the cornerstone of any intelligent persons approach to achieving a "zero leakage" environment. The combination of MIT, MOBLE and FIXED system provides a robust and undeniable route to a zero leak installation. On any site we can see the antagonism present when clients buy waterproofing geomembranes and at the end has to accept a situation when he has no proof whether this geomembrane is free of leaks or not. The Professionals in ELL are trying to convince clients on a daily basis to spend a little more money on clearing their sites of leaks, using the most modern ELL methods and processes. Unfortunately, we still do not see a lot of interest in so doing by owners and clients.

We would ask such owner / clients “why do you not hesitate to buy a leaking geomembrane without wanting to spend a little more money to ensure your brand new geomembrane is leak-free?”

Is it not a waste of money to install geomembranes without ELL checking?

Thanks to the results presented in this article more clients and environmental authorities (government agencies) are requesting geomembrane integrity testing. The only way is for us to work with clients and responsible agencies and to analyse the results together, so that they can make an informed decision based on reality.

Many leaks that are created by unskilled geomembrane installers using the newest and the most modern welding tools in the same way that many leaks stay undetected due to ELL being carried out by untrained, uneducated people using powerful modern devices.

The existence of ASTM is only guideline a but **ELL when carried out in practice needs strong requirements – regarding technical and human resources – e.g. calibration of devices and regular education of practitioners. Including acceptance that exposed geomembrane testing especially Arc Testing is the keystone of the ELL process necessary to achieve a “Zero Leak” site.**

As a final conclusion we present the following summary of findings:

1. Inside Figure 4 followed by Table 2 we can clearly see the predominance of **Arc testing in detection and location leaks** which **represents 92.98%** from whole amount of 4,761 successfully detected and located leaks. In addition it can be seen from this Figure 4 the leak sizes within interval 1.0mm to 50.0mm are mainly obtained by Arc testing. It is necessary to say the interval of leak sizes 10.0 – 50.0 mm covers leaks detected and located by Dipole method as well but that in this case the cause of leaks are mainly serious damage caused by heavy machinery.
2. **Interval of leak size 1.0 – 50.0 mm by its nature covers the majority of existing leaks. This leak size interval represents 94.64% of all detected and located leaks.**
3. Presented results are derived from real data obtained from surveys amounting to 6,820,020m^2 and reveals a **leak density of 6,98 per hectare**.
4. Along with usual types of leaks that have been detected and located **surprisingly many are small and almost invisible holes.** By analysis on site followed by analysis in the lab has classified these **as a geomembrane production mistake**. **Only Arc testers can detect such a specific type of hole.** It is absolutely clear that if these holes remained after covering of geomembrane, the dipole method would be unable to detect them and they would therefore remain undetected and unrepaired forever.
5. Based on the presented results of the **joint application of Arc testing and Dipole testing (or a permanent monitoring system) is unambiguous and creates logical and unique pairing set** to achieve leak free geomembrane installations. **Such a unique set of ELL methods should be recommended under ASTM.**
6. **In the case when an exposed geomembrane is not leak tested prior to being tested post covering, this should be classified as non-conformity with all related consequences.**
7. **The sum of Arc Testing together with Dipole Testing (or Permanent Monitoring) is greater than its individual parts. This seemingly incredible statement is backed by analysis of results from a sample size 6,820,020m^2 and also by the analysis of the Arc testing method contribution to overall leak testing methodologies. Simplicity, effectivity and most importantly the sensitivity of the Arc tester gives us the keystone to what is in biblical literature is known as the "Holy Grail" and in our microscopic world of Geosynthetics applications known is as "Zero Leak".**

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