Lifting The Roof: An Analysis of the Moisture Barrier Performance of Large Low-Slope Roofs

Abstract. The roof is a key system for maintaining the durability of a structure, facing the brunt of the elements including windlift and increasing periods of extreme weather. Where the roof system fails, moisture can enter the building and cause structural damage, mold growth, and reduce thermal efficiency. Left unchecked, these damages can lead to very expensive repair/replacement. Automated leak detection systems have been developed as a solution to the problem of long-term roof maintenance, actively monitoring the roof system environment for moisture accumulation / movement as well as membrane integrity.

This paper examines the different types of assembly for large low-slope roofs, with analysis of data from over a decade of roof monitoring as well as case studies, in order to illustrate the challenge of installing roofs defect free as well as the benefits of long-term monitoring for building performance.

1 Introduction

Modern low-slope roofs are not only waterproof coverings for the building, but platforms for building assets such as solar panels, green roofs, water storage in blue roofs and amenity spaces. A leak not only interrupts the business asset below the roof, but often the asset on the roof, above the membrane – and the leak is difficult to locate buried with-in the overburden, insulation, and drainage layers. In response, the integration of advanced sensor technologies has emerged as a transformative solution for commissioning buildings as expected, and as a maintenance planning tool for the building owner long term.

The application of moisture sensors and electronics to roofing surfaces and materials is commonly referred to as a leak detection system. Leak detection systems are generally found in commercial, institutional and multi-unit residential buildings where a flat roof over a larger floor plan is required. Sensors and electronics are configured differently depending on the type of roof assembly; a conventional roof assembly featuring the waterproof membrane as the topmost layer of the roof system, or an inverted roof assembly where the membrane is applied directly to the roof deck of the structure and covered with layers of insulation and overburden.

1.1 Conventional Low Slope Roof Systems

A Roof Assembly is generally considered to be Low Slope when it is of a gradient equal to or less than 3:12 or 14 degrees. The roof system comprises the insulation layer and membrane, installed on the topside of the structural roof deck.

The design of conventional low slope roof assemblies creates the opportunity for a low-profile extensive leak detection system to be installed directly on the structural element of the roof, prior to the completion of the assembly. Crucially this must be installed in dry conditions and covered immediately. Moisture Detection Sensor (MDS) Tape is laid out in discrete individual lines that form a grid covering the roof deck, as well as around key points where the membrane will be most at risk e.g. around vents and drains.

The MDS tape is connected to electronics - generally housed in a junction box on the roof deck - which take sensor readings and upload data to cloud based analytics platforms. When the system is active, sensors will “trigger” from contact with physical water/condensate, and using the x and y grid axis, this moisture can be tracked over time. This information can be used as an early warning system for moisture build up within the roof assembly, which left unchecked could threaten assets below or on the roof. Catching leaks early gives the best chance to preserve the comfort of the occupants and limit the scale of repairs.

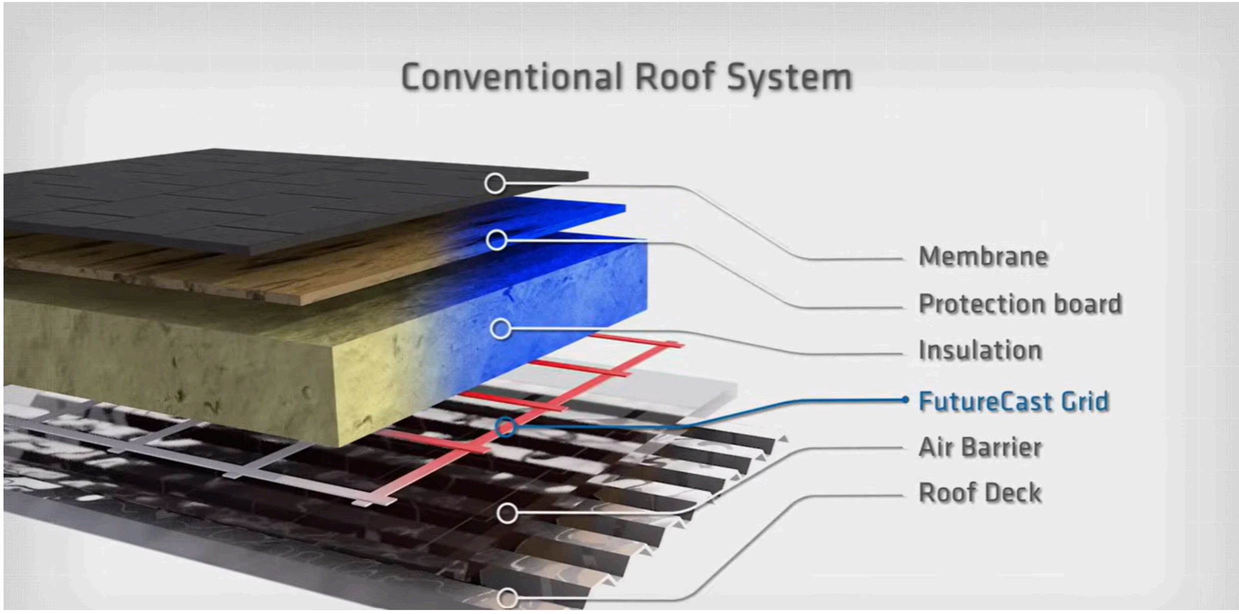

Fig 1: Moisture Detection Sensor (MDS) Tape installed typically on the air barrier, or the lowest point within the assembly to create a sensor grid. Each discrete sensor is placed around the perimeter, penetrations and the field of the roof as a 10' x 10'grid. The MDS measures the presence of liquid water accumulating inside the roof.

1.2 Moisture Accumulation Within Conventional Low Slope Roof Systems

Moisture accumulations within the conventional roof assembly can come from trapped moisture during the construction period, caused by a membrane breach and bulk water intrusion, or from an air barrier leak where the interior warm moist air condenses within the assembly. Construction sequencing can also lead to moisture entering the roof assembly, in this case there is no direct damage to the membrane, however parapets and edge details left unsealed while the horizontal plane of the roof system is completed can allow driving rain to track beneath the membrane.

In some instances, a third party trade may introduce moisture to the conventional roof by membrane damage that goes un-repaired during the construction period, allowing rain to penetrate into the roofing system. Water can accumulate in various layers of the roof including; on the protection board, between insulation boards, under the air/vapour barrier located on the roof deck, and under the roof insulation. Each of the materials chosen for the roof assembly can have an impact on the long term moisture resilience.

Moisture distribution through the conventional roof assembly will change based on seasonal effects of the temperature of the membrane and the related interior temperatures. To understand the basics of seasonal moisture transfer through the assembly, the following figure illustrates the dew point that occurs in the assembly.

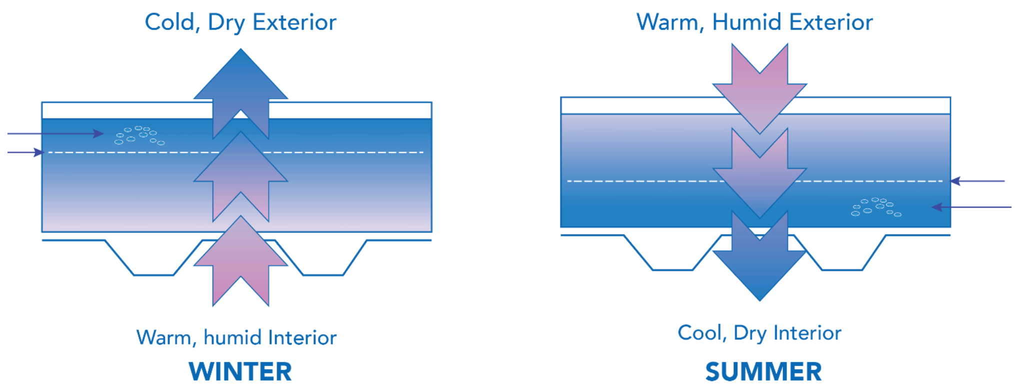

Fig 2: Condensation forms from latent moisture in roofing assembly at various layers based on season, assembly dew point, and materials used for the roofing assembly.

Moisture accumulation within a conventional low slope roof assembly is never static. Tracking moisture with traditional methods is difficult as moisture can move within an assembly and the point of origin can be unclear - often several feet from where the leak becomes apparent on the underside of the roof, and in some cases over 100 feet. Automated leak detection systems allow for moisture tracking over time, across seasons, with adjustments for the building materials used; giving building owners and operators the most comprehensive understanding possible of the location of moisture within their roof system, allowing the scheduling of repairs with confidence.

1.3 Inverted Low Slope Roof Systems

It is common for large structures such as city block podium style redevelopments with mixed commercial units on the lower floors, and a residential tower above , to have a combination of conventional and inverted roof systems.

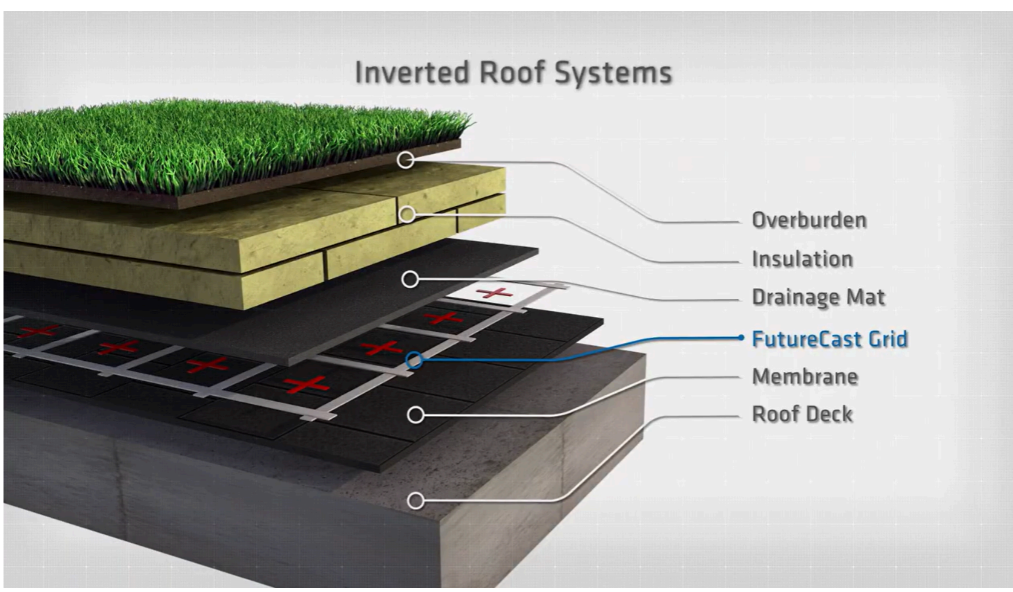

Fig 3: Leak Detection System applied to topside of waterproof membrane in an inverted assembly

Inverted roof assemblies, often referred to as Protected Membrane Roofs (PMR), are defined fundamentally by the placement and performance characteristics of the insulation, rather than the specific material of the structural roof deck. While the deck provides the necessary structural support, the success of an inverted system relies entirely on the insulation's ability to maintain thermal resistance while exposed to moisture. The various component layers (from bottom up) as shown in Figure 3 are;

- Structural Roof Deck: typically concrete
- Waterproof Membrane: Prevents water intrusion, materials include; modified bitumen SBS, sheet goods or liquid applied.
- Leak Detection Sensors
- Insulation: Typically extruded polystyrene (XPS) for its moisture resistance.
- Overburden: Gravel, pavers, Greenroofs, blue roofs, concrete or other materials to weigh down insulation and protect against wind uplift

Inverted roof systems are also known as protected membranes, because the monolithic waterproof element of the roof assembly is covered by other control layers as well as amenity spaces, green roofs, and blue roofs which are commonplace on sustainable institutional buildings. While a great opportunity to take advantage of the roof space, inverted assemblies present a complex maintenance challenge - where large sections of overburden must be removed to test and repair the membrane.

Automated Leak Detection Systems take advantage of the design of inverted roof assemblies, as rainfall and irrigation will create a moisture layer over the membrane. The membrane is divided into zones, and a network of sensors is installed flush to the membrane in a grid-like fashion, connected to power and data relays. Most waterproof membranes are non-conductive, meaning that when the surface moisture is positively charged by the leak detection system there should be an even voltage distribution across the monolithic membrane. Membrane deficiencies and penetrations allow moisture and electricity to pass through into the grounded substrate (i.e. the structural element of the roof). Leak detection sensors measure changes in differential voltage across the electric field, giving a vector of voltage magnitude from the center sensor; these measurements can be used to produce a structural integrity “heat map” of the waterproof membrane.

Automated Leak Detection Systems are intended to be used as part of an overall moisture management plan. The more complex the system of overburden, the more likely it is that there will be deficiencies from the construction period or else degradation over time. An automated leak detection system will continuously track the health of the membrane using electronic field sampling, pushing notifications to key stakeholders including building owners and managers. The data from leak detection sensors can be displayed on a cloud-based analytics dashboard for periodic review, allowing stakeholders to commission repairs with confidence and extend the useful life of the roof.

2 How Roof Membranes are Damaged

The most common period in which roof membranes become damaged is during construction. While roofing contractors generally do excellent work, the waterproof membrane on both conventional and inverted assemblies is often left exposed and used as a staging area for other third party contractors. [1] Figure 4 represents findings from membrane integrity scanning on hundreds of roofs over decades, the most common damage by far (29.5%) was found to be from nails used to fix in place concrete form-work, construction debris compressed into the membrane, and on one occasion even punctures from the underside of the roof as trades on the interior of the structure fixed gantries to the ceiling.

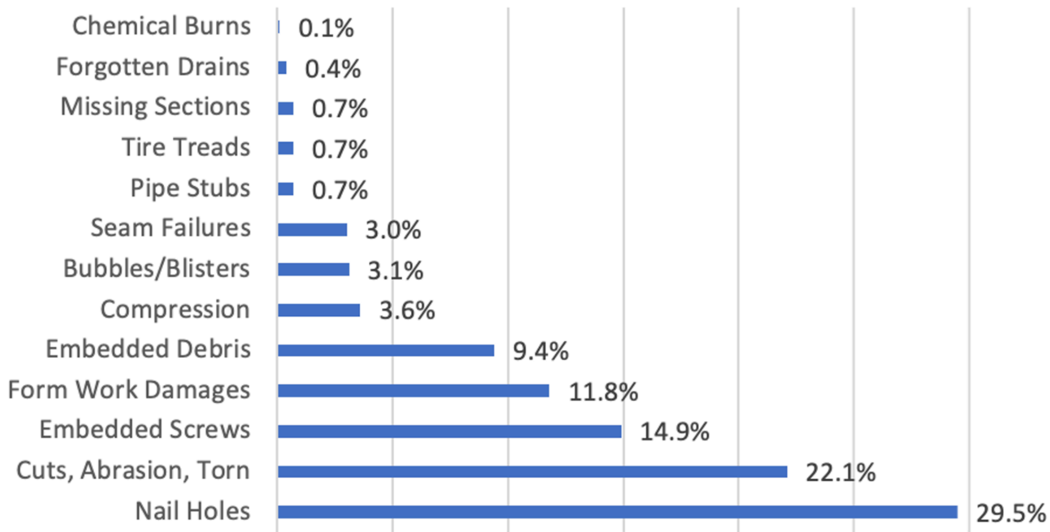

Fig 4: Types of damage found on waterproof membranes during leak detection scan

It is also possible for roof membranes to become damaged after construction. As buildings settle and shift, cracks can appear in parapet walls, allowing water to enter the roof assembly. Furthermore, the membrane can stretch over time, or else be damaged by UV and weather events, creating penetrations or gaps. In the first two to five years post construction, it is not uncommon to see rusted pipes or corroded flashing which introduce water into the roof environment, increasing the potential for a leak.

3 The Cost of Damaged Membranes

3.1 Impact of moisture intrusion: mold, structure decay, thermal bridging

While visible water inside the building is a simple sign that repairs are needed, moisture ingress can sometimes be difficult to detect - however the impact on building efficiency can be seen in the performance data. Per Lopez-Carreon et al, “The intrusion of moisture into building envelopes can lead to a range of problems, including mold growth, deterioration in the performance of thermal insulation, and ultimately structural degradation that may compromise the overall integrity of a building” [2]

Increased Thermal Conductivity. The roof is a key component of the building envelope, a series of control layers designed to prevent moisture intrusion and to keep the building at an appropriate temperature. There exist many different products on the market that can be included in the building envelope, with various approaches used to prevent heat loss through the walls and roof via the use of insulation. A 2019 study on the thermal conductivity of insulation used for heating pipes tested thermal conductivity of fiberglass, mineral wool and rock wool at different densities with varied moisture content. Invariably the thermal conductivity increased with moisture content, in the most extreme case a moisture content of 15% led to a 446% increase in thermal conductivity. This is significant because the greater the thermal conductivity, the more heat will be lost as it bridges the insulation - releasing waste heat energy and increasing the cost of heating overall. [3]

Structural Degradation. In a recent risk assessment study on moisture-related envelope degradation, Bristow et al noted “ Examples of moisture-induced wall degradations include the growth of mold, rusting of fasteners, swelling and disintegration of cladding, and rotting of stud cavities and other wood-based products. Moreover, an envelope that is overly damp may affect the occupants’ health through development of hazardous organisms.” [4] These examples are at best a detriment to the aesthetics of a building, however it is not difficult to imagine structural degradation of fasteners and cladding might lead to expensive repairs if not a risk to the health and safety of occupants.

Mold Growth. Fungal growth is an important concern when considering the impact of moisture ingress on a structure. Simply, an increase in moisture content - coupled with the right temperature - can allow the growth of black mold and other fungi within the building envelope and on the interior of the structure. Mold is unsightly, a telltale sign of poor building performance that is the first thing prospective tenants often look out for. Furthermore, mold growth can reduce the service life of building components, with one paper noting "mold is responsible for early biodeterioration of building materials", which leads to negative economic consequences, a 2001 study finding that Germany suffered economic losses of more than $200 million due to mouldy interiors, which the authors believe may be a common phenomenon elsewhere. [5]

Mold has also been linked to several health issues. "A damp environment usually implies a higher risk of mold growth, which has significant negative implications for human health. Indoor mold has been related to adverse health symptoms such as severe allergic asthma, hypersensitivity pneumonitis and allergic alveolitis, allergic rhinitis and sinusitis". Damp indoor spaces is not only an issue in older buildings, with multiple studies finding increased occurrences of adverse health symptoms in newly built energy-efficient buildings - citing mold as one of the primary causes. [6]

3.2 The cost of reroofing

Damaged roof membranes, or roof assemblies that contain moisture, do not last as long as products without those defects. This can lead to early renewal, which is a significant cost burden on building owners as well as a disruption for occupants. While specific cost data can be difficult to ascertain as prices and materials vary so much between projects, re-roofing costs cover a range from $3 to $90 per square foot - depending on the type of roof and scale of repairs needed. What follows is a range of roofing materials by estimated cost of installation per square foot. [7]

- Built-Up Roofing (BUR) $3 - $6 sq.ft
- Modified Bitumen roofing $4 - $8 sq.ft
- EPDM (Ethylene Propylene Diene Monomer) $5- $9 sq.ft
- TPO (Thermoplastic Polyolefin) $5 - $10 sq.ft
- PVC (Polyvinyl Chloride) roofing $6 -$12 sq.ft
- Green / vegetative roof $40 - $90 sq.ft

It should be noted that the cheaper roofing materials generally are less durable or require more maintenance, while the more expensive materials may offset their cost through energy efficiency, long term durability, ability to serve as an amenity space, or else environmental impact. What must be accepted is that renewal of roofing is a disruption and cost - a professional once remarked that "down-time in a data centre is measured in ferraris per second" - illustrating the benefit of extending the life of a roof assembly.

4 Roof Performance Data

Seventy (70) projects selected, majority lower-mainland British Columbia, which have been constructed with a leak detection system permanently installed within the roof system. This data set was compiled from projects completed in the past 15 years, 16 are conventional assemblies, 46 are inverted assemblies, and 8 are hybrid assemblies. Not all the monitored roofing assemblies were included in this study due to data use agreements.

Initial data comes from quality assurance scanning during construction, where deficiencies such as nail holes and thin application are identified for repair prior to completion.

Table 1: Deficiencies found on membranes during in-construction quality assurance scanning.

Roof assembly type	Number of deficiencies	Average deficiencies / project	Average when outliers excluded
Conventional	36	2.25	12
Hybrid	776	97	19
Inverted	2183	47.45	25.56

As the data in table 1 demonstrates, conventional roof membranes feature significantly fewer deficiencies than hybrid and inverted assemblies. Even removing extreme outliers, inverted assemblies featured the highest occurrence of deficiencies, which is in line with our experience of the conditions on inverted roof assembly construction sites where the exposed membrane is used as a staging area.

Of the 70 projects, 20 received leak investigations post construction. It is important to note that these were not necessarily the only roofs that had failed, rather these were the ones where building ownership/management elected to engage the leak detection system. 14 of these leak investigations occurred on buildings completed since 2020, with 8 of them completed in the last 3 years. These projects featured a relatively even split between granulated SBS modified bitumen roll membranes (8) and non-granulated (10), with 2 being hot fluid applied membranes. In terms of assembly type, 4 were hybrid, 5 were conventional, and 11 were inverted. Again this is consistent with our experience that inverted assemblies tend to require the most attention for maintenance. This however is not necessarily to do with the membrane itself, as in some cases the cause of moisture intrusion was found to be from edge details such as parapet walls.

5 Conventional Roof Leak Investigation

A large 2-tier data centre was constructed in the interior of Canada, where weather extremes are common. The data centre incorporated unique design features: low points and drains over hallways, not over rack space to protect vital assets. The architects specified that an automated leak detection system be included as part of the roof assembly. This system covered 120,000 sq.ft of conventional roof assembly, with linear stainless steel moisture sensors adhered to the vapour barrier in a 10’ x 10’ grid. During construction, the peel and stick night seal failed, allowing moisture into the unfinished roof assembly. The leak detection system was triggered by the moisture intrusion, and tracked its spread. This allowed roofers to understand the extent of the damage and verify efforts to dry the area as repairs were made.

This project was not without difficulties.. Commonly, moisture will collect at parapet edges, indicating liquid water on the leak detection sensors. This moisture must be tracked over several months if not years, correlated with weather data and construction documentation to ascertain whether investigation is needed. This project also changed ownership several times, thus continuity of data has not been easy to establish. See appendix for CAD drawings illustrating moisture tracking on a conventional roof using an automated leak detection system.

6 Inverted Roof Leak Investigation

On a large development in the lower mainland of British Columbia, two buildings stand in stark contrast when considering the application of leak detection systems. Both structures are inverted roof assemblies with leak detection systems installed directly on the waterproof membrane. On structure A, the system was used to verify the condition of the membrane as construction finished and has not been engaged since. On structure B, the system has been used multiple times to detect leaks.

On the top floor of structure B, during construction the leak detection system was engaged to verify the condition of the membrane prior to covering with overburden, locating several damages to the membrane including shovel marks and embedded gravel from landscaping activity, a penetration near a planter that created a leak every time the irrigation system was activated, and a drain which was not on the plans and had been overtightened - breaching the membrane.

Two years after these events, once the roof membrane had been covered with insulation, vapor retarders, and pavers, a leak was found indoors. Water tests using green dye yielded no results. The leak detection system was activated and produced a few areas of concern. The most likely area was uncovered and scanned with a handheld electronic leak detection tool, and while a penetration was not found, a strong grounding signal was coming from a small step up onto a raised section of the roof. Once this small detail was investigated, it was apparent that a downspout was pouring onto this raised section and leaking into the ceiling via a small penetration in the membrane. In the case of structure B, proactive use of the leak detection system post-construction allowed for timely repair and minimal disruption.

7 Conclusions

Large flat roof membranes, both conventional, inverted, and hybrid are installed with modern practice by skilled contractors. However, both during and after construction these membranes are subject to the risk of damages. By far the most common damage type occurs within the construction period, with physical penetrations of the membrane either intentionally or unintentionally. Leak detection systems and scanning tools can be used during construction to identify these membrane breaches and mark them for repair prior to commissioning of the building, which is a huge improvement over past construction practice. However, there remain damages that go unnoticed, accidental damage can occur post-construction, and materials will wear over time (sometimes within a year or two) allowing moisture to ingress into the roof environment. Data shows that both in-construction and post construction, inverted roof assemblies tend to be the most problematic, with analysis of case studies suggesting this is due to their complexity as well as risk factors during construction. Leak detection systems have demonstrated how moisture moves within the assembly, either trapped within the layers of a conventional assembly or freely flowing and finding deficiencies in the moisture barrier of an inverted assembly. In these scenarios, tracking the movement of moisture within the roof assembly will help contractors and consultants understand the roof environment and narrow down areas for investigative and remediation work. Proactive use of leak detection systems can limit the risk exposure by tracking problems as they develop, and before the cost of repairs balloons. All roof membranes feature deficiencies, and without action, all roofs will leak. However, the materials, workmanship, and risk mitigation tools exist to extend the lifespan of these membranes for the financial benefit of owners and tenants, and ultimately reducing the environmental impact of construction.

References

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Appendix

1. CAD overlay on as-built drawing of conventional roof assembly demonstrating how axis lines on a leak detection system trigger when the presence of moisture is detected. The time and geographical data of these events are interpreted to track the moisture back to its source.

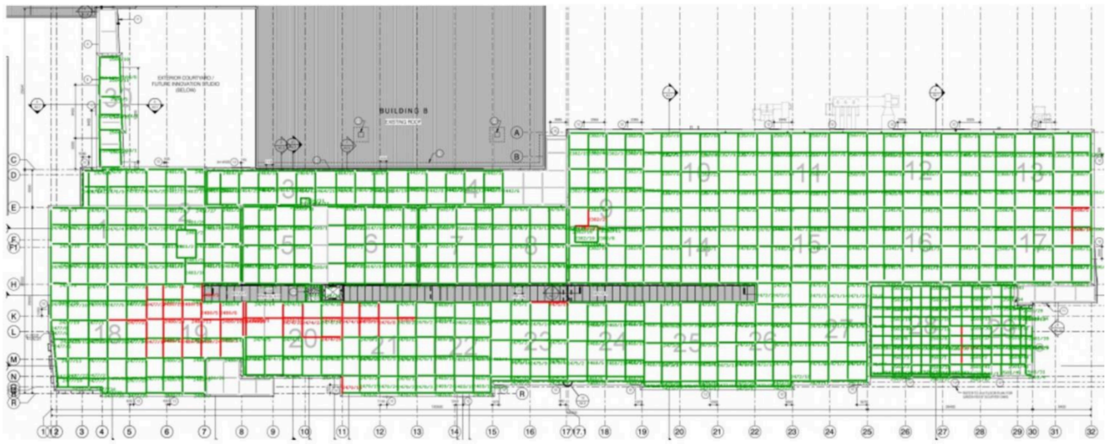

Figure 1. Event Status - May 10th, 2018

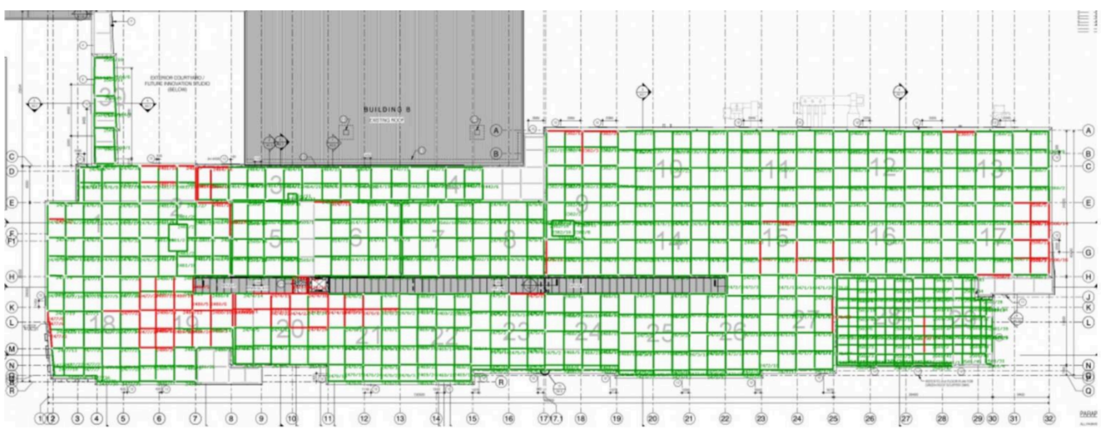

Figure 2. Event Status Sept 9th, 2018