INTEGRITY MOISTURE SOLUTIONS, LLC

ROOF ASSET MANAGEMENT

ROOF CONDITION INDEX PROGRAM (RCI)

For

PENNSYLVANIA STATE UNIVERSITY

SUMMARY

In January of 2018, the Office of Physical Plant advertised a Letter of Interest to a select group of service providers for consulting services to develop an assessment criterion and standard for evaluation of roof and window assets. Integrity Moisture Solutions, LLC (IMS) with O'Donnell Architects, PC, as a sub-contractor, was the selected service provider from the RFP bidding process.

IMS and select Office of Physical Plant roof subject matter experts developed the following manual which provides the framework to support consistent, objective and repeatable assessments of the University's roof assets. The methods and algorithms of this manual will provide the foundation for OPP to build a structured, customizable and unbiased asset management program that fulfills their business needs.

Roof system condition is a measure of a roof's ability to meet all the intended design functions at a given point in time of a roof's service life. As roof's age, their ability to perform the designed functions degrade at a slowly increasing rate over time.

After listing out the applicable defects most common to specific roof system types, an FMEA was conducted and risk priority numbers (RPN) were calculated for each defect. The defect RPN represent the basis for the condition index calculation. Each roof section, depending on what components are installed, will have an RPN which is the sum of all defect RPN'S associated with those components.

The section RPN, which can be derived from design documentation and/or observed at the time of survey, forms the basis for least risk. Observed deficiency RPN's are calculated and summed with the section RPN resulting in a current roof section RPN. The current RPN is divided by the range between the minimum and maximum (all defects are present at 100% occurrence rate) which represents the condition index score for the roof section.

The condition index score is then plotted against the expected deterioration or lifecycle curve to measure performance at the time of the survey and statistically predict future degradation rate. As systems are resurveyed, repairs are made or other changes occur to the roof section, the condition index should be recalculated. With each recalculation of the condition index score, the Weibull distribution used to plot the lifecycle will adjust and provide greater confidence for OPP stakeholders in measuring design, construction quality and maintenance strategy.

1 INTRODUCTION

1-1.1 Objective

The purpose of the manual is to document the intent, methods, algorithms and analysis developed by Integrity Moisture Solutions and O'Donnell Architects in conjunction with the PSU Office of Physical Plant to objectively and consistently evaluate the condition of roof system assets owned by The Pennsylvania State University for project prioritization. Users will be able to perform consistent and unbiased condition evaluations which will serve as the cornerstone for an effective asset management system. Results will provide PSU Office of Physical Plant personnel a road map to maximize funding and reduce asset lifecycle costs.

1-1.2 Scope

Information provided in this manual includes an explanation of the algorithms/equations developed to determine a condition index (CI) score by roof section, a CI based 2 parameter Weibull lifecycle model, and an objective, data driven method for prioritizing repair and replacement projects based on CI, project costs and total cost of ownership (TCO).

The foundation for the roof CI is based upon the existing components of any roof section and a specific set of deficiencies associated to those components. Accuracy of CI for any given roof system will be directly related to the accurate inventory of roof system components, and proper identification and quantification of deficiencies by individuals conducting the assessments.

Application of the methods listed in this manual are to be performed under the direct supervision of qualified PSU Office of Physical Plant personnel. Methods for data collection and database administration were not requested by the Office of Physical Plant and is not included in this manual. All necessary equipment and software will be provided and maintained by the Office of Physical Plant.

1-1.3 Background

The Pennsylvania State University – Office of Physical Plant (OPP) advertised a "Building Envelope Consulting Services" RFP to a number of service providers with a previous work history at the University. The subject of the RFP was to "…. facilitate the development of assessment criteria and standards for evaluation of building envelope systems with specific emphasis on roof and window assets. The intended use of the criteria and standards for evaluation were intended for use in strategic maintenance and capital planning decision making.

Integrity Moisture Solutions, LLC (IMS) with O'Donnell Architects, PC, as a sub-contractor, was the selected service provider from the RFP bidding process. Initial project kickoff included key personnel from OPP departments including Work Control Center, Project Management, Design & Construction and Building & Grounds. Two focus groups, for roof and window assets, were created with personnel from OPP and IMS/O'Donnell. Over the course of Client and Vendor meetings in conjunction with site visits, the assessment criteria and standards for evaluation were developed, tested and refined.

The RAM/WAM development project was formatted into five phases of progression with each building upon the previous phase's work. Deliverables were maintained as additions of various pertinent information and attachment to the meeting minutes. Table 1.1 provides a general description of each phase.

Table 1.1 – RAM/WAM Project Phases

DESCRIPTION	PROJECTED DURATION	PROJECTED DATES
Phase 1 – Pre-Planning Services	Set-up kickoff meeting w/Main PSU Stakeholders within 2 weeks of NTP	04/01/18 - 04/27/18
Penn State Review		
Phase 2 – Inventorying existing assets: Determining specific inspection, testing & field reporting requirements	Conduct meeting w/all various PSU stakeholders to determine database specifics	04/30/18 – 06/01/18
Penn State Review		
Phase 3 – Developing systematic & consistent methods for assessing asset condition rating, lifecycle specifics, rating & ranking procedures	Conduct evaluations of industry standards to be used to determine database specific algorithms	06/18/18 – 07/20/18
Penn State Review		
Phase 4 – RAM & WAM database requirements & guidelines development to create an objective and data driven project prioritization	Compile field and stakeholder information to determine specific database procedures	08/06/18 – 09/04/18
Penn State Review		
Phase 5 – Final written documentation outlining specific processes for creating the RAM & WAM database programs submissions	Submit final procedures for creating a database platform	08/26/19 – 08/30/19
Penn State Review		

2 ROOF FMEA, RPN & CONDITION INDEX

2-1 FMEA Summary

Failure modes and effects analysis (FMEA) is a step-by-step approach for identifying all possible failures in design and operations of a process, system, component, etc. FMEA processes were originally developed by the US military and were further enhanced by the aerospace and automotive industries. FMEA is generally used to eliminate or minimize operational failures and support design improvements.

After the goals, type, purpose and scope of an FMEA are determined, failure modes are then listed as applicable. Severity, detectability and occurrence ratings are developed and applied to each failure mode. A risk priority number (RPN) is calculated by multiplying these rankings together (severity * detectability * occurrence). Failure modes are then prioritized by RPN.

2-2 Roof System Functional FMEA

The diversity of roof system types and possible construction profiles would require an infinite number of FMEA's to be conducted. Therefore, a functional FMEA was conducted for low slope roof systems. Primary functions of typical low slope roof are:

- Exterior atmospheric resistance
- Internal atmospheric resistance
- Thermal resistance

Roof systems are designed to achieve these generic functions through a combination of subsystems that are comprised of various components. Therefore, roof system components were categorized into their respective subsystem. Subsystem groups are:

- Membrane
- Insulation
- Vapor Barrier
- Accessories

The subsystem components and their associated failure modes were listed in table form. The failure modes represent the list of possible defects for a given component that may exist in a low slope roof system assembly. Defects lists for each subsystem category can be found in Appendix A. A snapshot of the membrane subsystem category Functional FMEA is shown in **Figure 3-1**.

Figure 2-1 Membrane Functional FMEA Table Sample

DEFECT PRIMARY GROUP	DEFECT CODE	DEFECT DESCRIPTION	DETECTABILITY	SEVERITY	BASE RPN
MEMBRANE	DEBRIS_General	Debris on the roof surface. Remove	1	3	3
MEMBRANE	DEBRIS_ActVeg	supporting active	1	3	3
MEMBRANE	DEBRIS_Decid	Seasonal tree debris	1	3	3
MEMBRANE	DEBRIS_ConstrMaint	Construction or maintenance debris	1	3	3
MEMBRANE	PONDING	Residual water on the membrane surface 48	1	2	2

2-3 Roof Defect Severity, Detectability, Criticality & Occurrence

2-3.1 Severity

Roof defects can vary in degree of severity depending upon their failure effect. For instance, a three-ply modified bitumen roof membrane can have two different severities of punctures: through the membrane & not through the membrane. Punctures through the cap and intermediate plies present one severity affecting the membrane only. However, a puncture through the cap, intermediate and base plies can affect the insulation system, the vapor barrier (if installed) and damage other building components and systems.

Therefore, many defects have more than one variant due to the potential cascading effects that can occur dependent upon the severity of the defect. The severity scale supports a categorization of variants as shown in **Figure 2.1**.

Figure 2-2 Severity Categories

SEVERITY	SEVERITY NAME	SEVERITY DEFINITION
1	NO POTENTIAL FAILURE	ANY DEFECT THAT IS COSMETIC ONLY, AND HAS A LOW PROBABILITY OF AFFECTING THE FUNCTION OF THE SYSTEM
2	POTENTIAL FAILURE	ANY DEFECT WITH AN INCREASED PROBABILITY OF BECOMING A FAILURE TO THE FUNCTION OF THE SYSTEM
3	COMPONENT LIMITED FAILURE	ANY DEFECT TO A COMPONENT THAT COMPROMISES THE FUNCTION OF THE COMPONENT WITH NO CASCADING FAILURE TO ADJACENT COMPONENTS
4	CASCADING COMPONENT FAILURE	COMPONENT DEFECT WHICH HAS CAUSED DAMAGE OR DEGRADATION TO OTHER COMPONENTS IN THE SYSTEM.

2-3.2 Detectability

Detecting and properly identifying defects can present a challenge to any inspector. Certain defects can be visually detected or observed by a layman to the roof industry, while others can only be detected through destructive testing conducted by a competent professional. The scale of detectability for roof defects was based upon the level of difficulty to identify and quantify each defect variation. **Figure 2.2** presents the scale of detectability.

Figure 2-3 Detectability Categories

DETECTABILITY	DETECTABILITY NAME	DETECTABILITY DESCRIPTION
1	VISUAL INSPECTION	OBVIOUS LEVEL OF DETECTABILITY WITH ENTRY LEVEL SKILL REQUIRED BY THE INSPECTOR TO IDENTIFY DEFECTS
2	SKILLED VISUAL INSPECTION	DEFECT REQUIRES FUNDAMENTAL TO EXPERT KNOWLEDGE OF COMPONENT AND SYSTEM FUNCTIONS TO DETECT, QUALIFY AND QUANTIFY
3	NON-DESTRUCTIVE TESTING	DEFECT IS UNDETECTABLE OR NOT QUANTIFIABLE DURING VISUAL INSPECTION WITHOUT USE OF SPECIALIZED TRAINING OR EQUIPMENT
4	DESTRUCTIVE TESTING	DEFECT IS ONLY QUANTIFIABLE THROUGH REMOVAL OF SYSTEM COMPONENTS

2-3.3 Defect Criticality

Defect criticality was developed using a four by four matrix based on the Figures 2-2 & 2-3. By multiplying Defect severity by detectability, a criticality is produced. The matrix below allows for the all defects to be further categorized by their respective criticalities. See the figure below.

Figure 2-4 Criticality Matrix

CRITICALITY MATRIX

D \ S	1	2	3	4
4	4	8	12	16
3	3	6	9	12
2	2	4	6	8
1	1	2	3	4

Criticality categories are indicated by the color coding. The category which a defect falls into will determine the occurrence rate used to calculate the observed defect RPN. The varying degree of risk a defect presents requires different acceptable rates of occurrence. The occurrence rates are further explained in the next section.

2-3.4 Defect Occurrence

Occurrence of any defect is relative to the size or amount of the components to which a defect occurs. Therefore, the occurrence scale is relative to the rate of the defect per the size or amount of the component. Membrane defects are measured in square feet which is divided by the total area in square feet of the roof section. The occurrence scales for each criticality group is presented in **Figure 3-4**.

Figure 2-5 Occurrence Categories

Criticality A	CATEGORY	OCCURRENCE PERCENTAGE
	1	< 5
	2	< 10
	3	< 20
	4	< 100

Criticality B	CATEGORY	OCCURRENCE PERCENTAGE
	1	< 2.5
	2	< 5
	3	< 10
	4	<100

Criticality C	CATEGORY	OCCURRENCE PERCENTAGE
	1	< 1.25
	2	< 2.5
	3	< 5
	4	<100

Criticality D	CATEGORY	OCCURRENCE PERCENTAGE
	1	< .5
	2	< 1
	3	< 2
	4	<100

Occurrence rates are calculated by each defect variation present at a roof section. The quantities for each specific defect are divided by the square footage of the roof section or calculated component length, and then multiplied by 100 to determine a percentage. The occurrence category is then selected from **Figure 2.3** based on the calculated percentage.

Equation 2-1

$$\boldsymbol{Occurrence = \frac{(DEF_{Q1} + DEF_{Q2} + DEF_{Q3} + \cdots DEF_{n})}{AREA \mid LENGTH} * 100}$$

where:

DEF_n = Quantity of defect at each location
AREA = the square foot area of the roof
LENGTH = the calculated component length

2-4 Risk Priority Number

2-4.1 Defect RPN

The defect Risk Priority Number (RPN) is the product of the severity, detectability and occurrence categories. Severity and detectability are static values which were determined for each defect and corresponding variation. The occurrence rate will vary depending upon the size or number of the specific defect variation.

Equation 2-2

$$\boldsymbol{RPN = S * D * O}$$

where:

S = Severity Category
D = Detectability Category
O = Occurrence Category

An example of a 2,500sf modified bitumen roof section with severe surface wear that has exposed the cap sheet reinforcement at one or more locations totaling 65 square feet.

Severity = 3
Detectability = 1
Criticality = 3 ***(Criticality Group C)***
Occurrence = $\frac{65}{2500}$ = .026 * 100 = 2.6% **(category 3 from Figure 3-4)**
RPN = S * D * O = 2 * 1 * 3 = **6**

The defect initially had an RPN of two but has now increased to 6 due to the increase in occurrence of the defect versus the total area of the roof section and its corresponding criticality group. The RPN for this defect has increased by a factor of three.

Considering the relatively small physical size of the defect compared to the area of membrane, the increase may seem excessive. However, roof defects tend to grow with time and/or affect other components if left unmitigated over time. Since the current state of the defect is unrepaired, the increased risk is present and therefore is represented by an increased RPN.

2-4.2 Roof Section Base RPN

A base RPN for each roof section is determined by the type of roof system and components that exist in that system. Each roof system will have certain components and the existence of those components must be known to accurately calculate a base RPN for each roof section. Necessary component inventory information for the calculation is listed in Appendix B.

Once existing components of a roof section are identified, all applicable defects can be selected for that roof section. As stated in the previous section, the occurrence category for each defect is set to 1. The defect RPN's are then calculated and summed together which represents the base RPN for that roof section.

Consider the modified bitumen roof system installed at roof section 4 on Academic Activities Building. This roof section has a vapor barrier, insulation system, and modified bitumen roof system. Additionally, it has internal roof drains, edge metal flashings, and counter flashings at curbs and walls. Each of these components represent a specific set of possible deficiencies and, therefore, a specific risk to the roof system.

Table 2-1 Academic Activities ROF04 Original RPN

Component / Subsystem	RPN
Modified Bitumen Membrane	146
Vapor Barrier	64
Insulation System	88
Internal Drains	16
Counter Flashings	11
Edge Metal	11
Total	**336**

Generally, the base RPN will not change unless additional components are added to the roof system that were not previously included in the base RPN. If changes are made to the roof system, the base RPN will need to be recalculated and used for any future inspections. The new base RPN should not be used to recalculate any previous inspections as the additions were not present at the time of those inspections.

2-4.3 RPN Range

After a base RPN has been calculated, an RPN range can be established. The RPN range is represented by the lowest possible RPN (the base RPN) and the highest possible RPN (the maximum RPN). Because the occurrence categories are 1 to 4, the maximum RPN is 4 times the base RPN.

The example roof from Academic Activities has a base RPN of 336 as shown in ***Table 5-1***.

$$RPN_{base} * 4 = RPN_{max}$$

$$336 * 4 = 1{,}340$$

So, the RPN range is equal max RPN minus the base RPN.

$$RPN_{max} - RPN_{base} = RPN_{range}$$

$$1{,}340 - 336 = 1{,}008$$

The RPN range can be interpreted as a perfect roof system at the base and a complete failure at the maximum. Every roof section RPN will calculate to some number within the calculated range based on the base RPN.

2-4.4 Roof Section Current RPN

Once a roof inspection is conducted and data collected, the totals of each defect variation are summed, then occurrence rates are calculated and categorized per the appropriate occurrence scale (see Figure 2.3). Each defect variation RPN is then calculated per Equation 2-1. The roof section current RPN is the sum of the defect RPN's.

The defects identified for the example roof at Academic Activities can be observed in Figure 2-5 below. The occurrence rates were calculated using the square footage of the roof section or the linear foot total calculated from the perimeters, curbs, etc. as applicable.

Figure 2-4 Acad. Activities Defect RPN's, Grouped by Variation

Defects	Total by Defect*	DETECTABILITY	SEVERITY	CRITICALITY	CRITICALITY GROUP	OCCURRENCE RATE:	OCCURRENCE CATEGORY	RPN
DEBRIS_Decid	25	1	3	3	C	0.182%	1	3
FUNCPATCH_Rep	327	1	1	1	A	2.378%	1	1
OPENLAPS_Full	1	2	4	8	D	0.007%	1	8
OPENLAPS_Part	44	2	2	4	C	0.320%	1	4
POND_Field	200	1	2	2	B	1.455%	1	2
PUNC_NotThru	1	2	3	6	C	0.007%	1	6
SPLIT_NotThru	45	2	3	6	C	0.327%	1	6
SSURF_ReinfExp	22	1	3	3	C	0.160%	1	3

*SF OR LF UNITS

SUM OF RPN's FROM DEFECTS 33

ROOF SF = 13,750

ROOF LF = 710

2-5 Roof Condition Index

2-5.1 Condition Index Calculation

Once the base RPN and maximum RPN are established and the roof section current RPN is calculated from data collected during an inspection, the condition index can be calculated for a roof section. The condition index is calculated as shown in *Equation 3-4*.

Forty percent of the RPN range represents the point at which repairs of a given roof system are not likely viable and/or economically prudent. and the system requires replacement.

Equation 2-3

$$\boldsymbol{CI = \left(1 - \frac{RPN_{curr}}{.4 * RPN_{range}}\right) * 100}$$

where:

CI = condition index
RPN_{curr} = sum of the defect RPN's identified during an inspection
RPN_{range} = 40% of the RPN range

Continuing the example of Academic Activities ROF04, the RPN range calculated in **Section 1-5.3** was 1,004. The inspection conducted using the FMEA established by the project calculated the current RPN to be 33 based upon the observed deficiencies. Using the Equation 2-4, the condition index for ROF04 is:

$$\boldsymbol{CI_{ROF04}} = \left(1 - \frac{RPN_{curr}}{.4 * RPN_{range}}\right) * 100$$

$$= \left(1 - \frac{33}{.4 * 1{,}008}\right) * 100$$

$$= (1 - .0818) * 100$$

$$= .918 * 100$$

$$CI_{ROF04} = 91.8$$

2-5.2 Condition Index After Repairs

Most defects can be repaired, while some such as ponding cannot be repaired without replacement. Membrane defects will usually result in a patch repair and are considered a minor defect in the model because they typically fail, especially smaller patches, prior to the membrane system more broadly. As repairs are completed and marked as such in the collection application, the defect will need removed and a patch defect added. It is recommended this be an automated process to limit errors.

The repairs that could be completed and would be removed from the condition index calculation or replaced with a functioning patch deficiency should trigger a recalculation of the condition index. For the example roof section, after repairs, the resulting condition index would rise to a score of 99.3. The model will not allow for a repaired roof section to return to a perfect condition of 100.

Additionally, roof leaks will typically be associated with a defect within the roof system that is included in this model. However, leaks can have a substantial cascading effect on the insulation system components and vapor barriers. Therefore, it is recommended that defects associated with leaks should also be collected in the roof data similar to any other defect found during an inspection.

It is also advised that at least a placeholder defect for wet insulation also be collected. The wet insulation defect should trigger a moisture survey of the roof system adjacent to the area of the roof leak to verify the presence of moisture within the roof system and quantify the total area of the roof system that may be affected. The quantity of the wet insulation defect can be adjusted to that amount and occurrence, and a recalculation of the condition index should be completed.

3 Analysis

3-1 Lifecycle

3-1.1 Weibull Distribution (Two Parameter)

Per the LOI issued by the Office of Physical Plant, the Army Core of Engineers ROOFER program was reviewed for methodology of assessments and algorithms used to calculate a roof section condition index score. The ROOFER program is a division of a larger building assessment program named BUILDER. The primary method used to establish condition indexes for building systems and components is a statistical analysis known as a two parameter Weibull distribution.

Figure 4-1 was taken directly from the ***Facility Degradation and Prediction Models for Sustainment, Restoration, and Modernization (SRM) Facility Planning*** written by Michael Grussing who an engineer with the ACE CERL Research and Development Center.

Figure 4-1

2.4 Weibull probability distribution

The Weibull cumulative probability distribution function is used to model the condition life-cycle curve. The Weibull statistical distribution represents the probability of time to failure of a component-section in service. It has natural boundary conditions that abide by the assumptions discussed above, and takes the shape of a classical condition-deterioration curve. The resulting mathematical condition-prediction model is:

$$C(t) = a \times e^{-(t/\beta)^{\alpha}} \quad (1)$$

where

C(t) = component-section condition index as a function of time
t = time, in years, since component-section was installed or constructed
e = exponential
a = parameter, initial steady state component-section condition index
β = parameter, service life adjustment factor
α = parameter, accelerated deterioration factor.

The Weibull distribution is very well known and used in reliability engineering. However, the studies and ROOFER program developed by the CERL are the only known attempts to determine reliability of roof systems using this distribution.

3-2 Roof Program Weibull Model

The field surveys of roof sections completed for the program included 41 sections of modified bitumen roof systems. Those were chosen because the large percentage of recent replacements on campus have been modified bitumen roof systems. The 41 roof sections surveyed represents approximately 3% of the modified bitumen roof system inventory.

A linear regression of system age and condition index derived from the model was used to estimate the slope parameter of Weibull distribution for this program. The scale of the life cycle curve was manually adjusted to such that the curve intersects the 30-year time horizon at the estimated condition index of failed. Failed in this instance means beyond repair in terms of condition and cost.

The following equation represents the model for this program with the parameters being shown.

Equation 4-1

$$CI(t) = 100 * e^{-\left(\frac{t}{95}\right)^{2.5}}$$

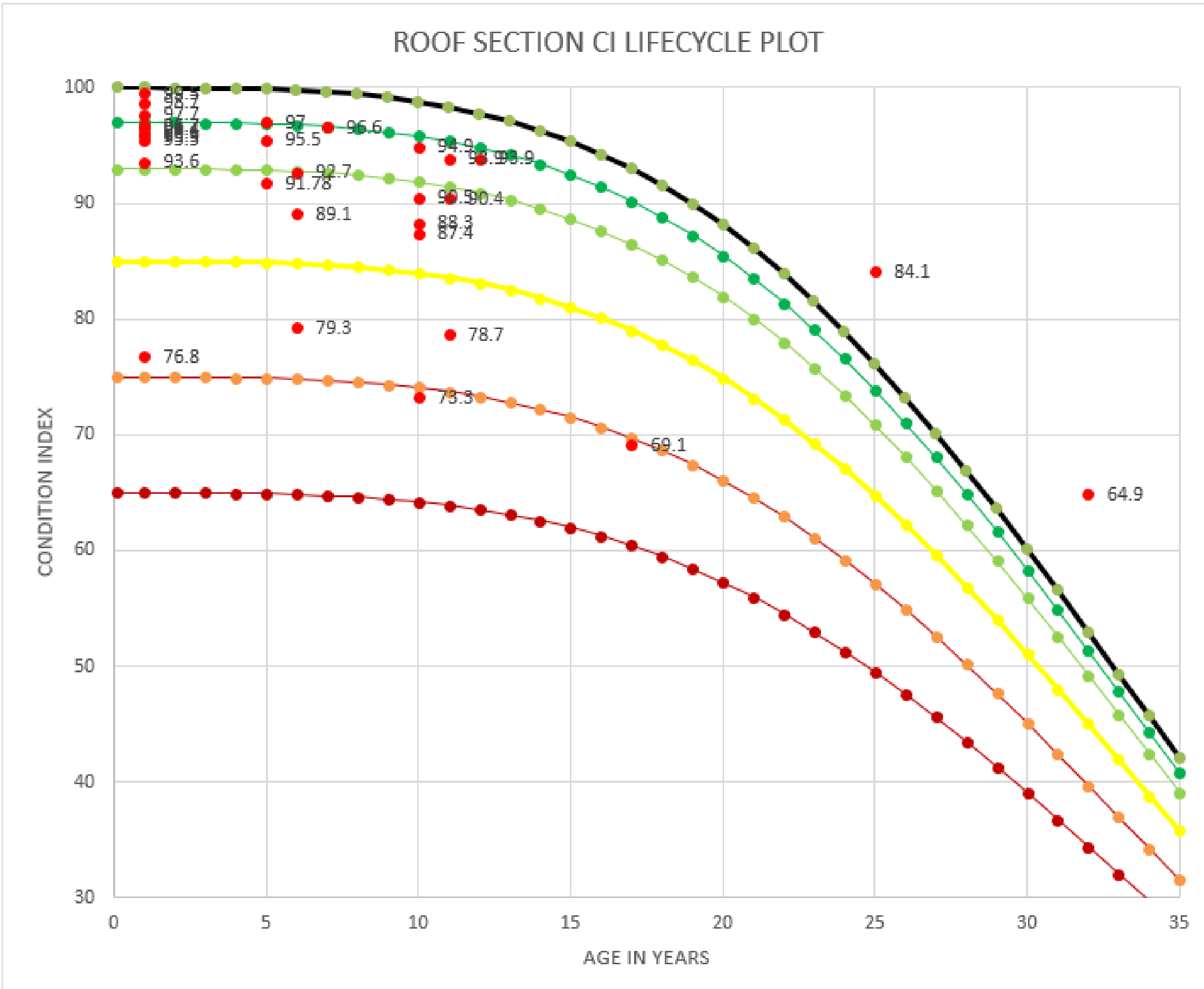
Where:

CI(t) = Condition index at a given time
100 = initial condition index of a roof (perfect condition)
e = exponential
t = time in years
95 = scale parameter (point that curve will reach a CI of 0)
2.5 = deterioration factor (linear regression of the sample roofs that were surveyed)

Due to the limited data sample size, the parameters are the "best educated guesses" for the model. As previously state, the max CI is 100, otherwise a perfect roof system. Based upon the data collected, it appears the condition and economical failure score is at or near a CI of 60. However, as additional roofs are assessed and as the inventory ages, the data will need to be reanalyzed and the parameters adjusted accordingly.

Figure 4-2 represents a number of roof sections (red dots) with their respective CI scores plotted against the Weibull model for this program (black line). The black line is the expected degradation curve for a modified bitumen roof system. The area directly below the black line up to the first green line indicates an excellent condition considering the overall age of the roof system. Each line working further down the chart represents good, fair, bad and failed conditions throughout the roof systems service life.

Figure 4-2 Roof Section CI Lifecycle Plot

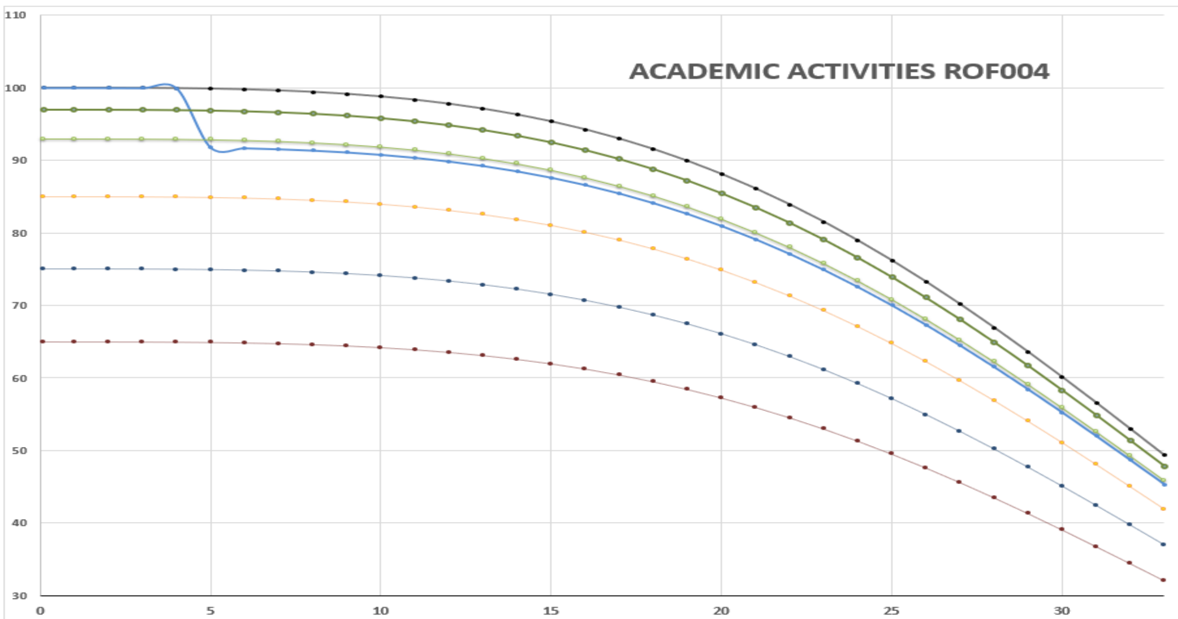


3-3 Roof Section Specific Lifecycle

Plotting the CI on the same graph for each survey for a given roof section will allow for trending of the condition over the lifecycle. As more surveys, especially early in the lifecycle, will improve the accuracy of the model in the later time of the lifecycle.

The example roof section previously used in this manual is plotted below in blue dots and a blue line. The roof section is currently at the high end of fair condition near good condition.

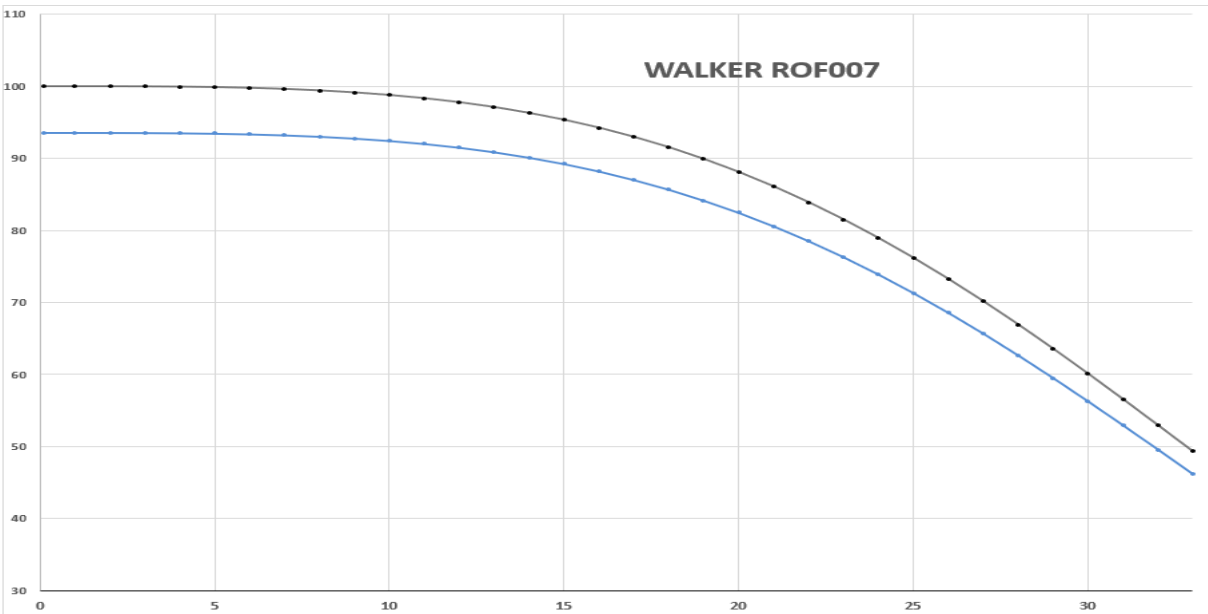
Figure 4-3



The blue line represents that anticipated condition index of this roof section over time. Note the reduction at year 30 is approximately 1.6 years. Future surveys that trend lower as more defects occur will cause the reduction in useful life. Repairs that are completed to the defects will cause the line of deterioration to improve towards the expected or desired line of deterioration.

The above model assumes the roof started with a perfect CI of 100, however, newly installed roof systems are rarely are without defects (repair and required patches are considered defects because of their inherent weakness). The figure below shows the lifecycle curve of ROF007 at Walker building that was installed in 2018. The survey was completed at the time of final inspection for the reroof project with the manufacturer's representatives, University personnel and the contractors. The condition index calculated for this small roof was 93.6. Note the impact in time at year 30, the roof design life, is approximately a little over a year.

Figure 4-4 Walker Roof ROF007



3-4 Project Prioritization based on Lifecycle

Roof condition index and lifecycle modeling an be an effective tool for project prioritization and planning purposes. They will support maintaining a near to midterm list of roofs to prioritize repairs and replacements. However, a cost analysis including ROI for repairs and anticipated extension to a roof system's useful life must also be completed and taken into consideration before finalizing any decisions.

Additionally, age of a roof system should also be considered. While the membrane system maybe functioning beyond the design life, subsurface insulation components may not be, and any savings realized by extending the waterproofing ability of the membrane could be reduced by weakened insulation system that is not functioning at a high level.

3-5 Additional Analysis & Considerations

The granularity of this methodology will support additional analysis beyond just condition index and lifecycles of roof systems. Specific components and defects can be analyzed and trended to identify such things as improvements in design to remediate high frequency deficiencies. And possibly identify trends in reduced construction and material quality.

As the more data is collected through surveys and assessments, comparisons of different types of similar systems can also be analyzed and assist in procuring the best performing products. There are different variations of modified bitumen and thermoplastic membrane systems produced by a wide range of manufacturers. This methodology should also support comparative analysis between these systems and their variations.

4 Future Program Recommendations

The model was tested and adjusted against a small sample set of roofs that ranged in age from just constructed up to 32 years old. The limited sample size was sufficient to build the foundation for a roof assessment and condition indexing program. However, as assessments are completed using this methodology, adjustments may be necessary to the FMEA, Weibull parameters and indexing calculations.

It is critical that the assessors are sufficiently knowledgeable in the field of commercial roofing, design and forensics to properly apply this methodology during an assessment.

CRITICALITY MATRIX

		S			
		1	2	3	4
D	4	4	8	12	16
	3	3	6	9	12
	2	2	4	6	8
	1	1	2	3	4

Criticality	CATEGORY	OCCURRENCE PERCENTAGE
	1	< 5
	2	< 10
	3	< 20
	4	< 100

Criticality	CATEGORY	OCCURRENCE PERCENTAGE
	1	< 2.5
	2	< 5
	3	< 10
	4	<100

Criticality	CATEGORY	OCCURRENCE PERCENTAGE
	1	< 1.25
	2	< 2.5
	3	< 5
	4	<100

Criticality	CATEGORY	OCCURRENCE PERCENTAGE
	1	< .5
	2	< 1
	3	< 2
	4	<100

DEFECT PRIMARY GROUP	DEFECT SUB GROUP	DEFECT CODE	DEFECT DESCRIPTION	DETECTABILITY	SEVERITY	CRITICALITY DET x SEV	CRITICALITY GROUP
MEMBRANE	DEBRIS	DEBRIS_General	Debris on the roof surface. Remove debris and inspect roof components below for damage.	1	3	3	3
MEMBRANE	DEBRIS	DEBRIS_ActVeg	Debris that is supporting active vegetation, moss or mold growth.	1	3	3	3
MEMBRANE	DEBRIS	DEBRIS_Decid	Seasonal tree debris	1	3	3	3
MEMBRANE	DEBRIS	DEBRIS_ConstrMaint	Construction or maintenance debris	1	3	3	3
MEMBRANE	FAILED_PATCHES	FAILPATCH_Req	Failed required patch (T_football_bow tie)	2	3	6	3
MEMBRANE	FAILED_PATCHES	FAILPATCH_Rep	Failed repair patch of any type	2	3	6	3
MEMBRANE	FASTENERS	BACKOUT_INSU	Fastener backout due to insulation compression.	2	2	4	3
MEMBRANE	FASTENERS	BACKOUT	Fastener has backed out or was insufficiently driven at construction.	2	2	4	3
MEMBRANE	FUNCTIONING_PATCHES	FUNCPATCH_Rep	Required patch (T_football_bow tie) in good condition	1	1	1	1
MEMBRANE	FUNCTIONING_PATCHES	FUNCPATCH_Req	Repair patch in good condition	1	1	1	1
MEMBRANE	INTERPLY_BLISTER	BLISTER_Water	Interply blister with trapped air	2	4	8	3
MEMBRANE	INTERPLY_BLISTER	BLISTER_Air	Interply blister with trapped water	2	3	6	3
MEMBRANE	MINOR_SURFACE_WEAR	MSURF_ManuDef	For roofs with a non-waterproofing (aluminum coating) applied to entire membrane. Any defect or damage to the coating only. Defects to the underlying membrane should be marked up separately.	2	2	4	3
MEMBRANE	MINOR_SURFACE_WEAR	MSURF_MatEquHnd	Minor degranulation from manufacture defect	1	3	3	3
MEMBRANE	MINOR_SURFACE_WEAR	MSURF_FootTraf	Minor degranulation from material and/or equipment handling on the roof top (single occurrence)	1	3	3	3
MEMBRANE	MINOR_SURFACE_WEAR	MSURF_CoatDet	Minor degranulation from focused pattern of foot traffic on the surface	1	3	3	3
MEMBRANE	OPEN_LAPS	OPENLAPS_FullField	Lap is open completely through the width	2	4	8	4
MEMBRANE	OPEN_LAPS	OPENLAPS_FullFlash	Lap is open completely through the width	2	4	8	4
MEMBRANE	OPEN_LAPS	OPENLAPS_PartField	Lap is partially open (less than 30% of the lap width)	2	2	4	3
MEMBRANE	OPEN_LAPS	OPENLAPS_PartFlash	Lap is partially open (less than 30% of the lap width)	2	2	4	3
MEMBRANE	PONDING	PONDING	Residual water on the membrane surface 48 hours after a rain event.	1	2	2	2
MEMBRANE	PUNCTURES	PUNC_Thru	Puncture through all layers of membrane	2	4	8	4
MEMBRANE	PUNCTURES	PUNC_NotThru	Isolated puncture into the membrane_but not through all layers of membrane	2	3	6	3
MEMBRANE	SEVERE_SURFACE_WEAR	SSUFR_Contamination	Bitumen chemical contamination or accelerated UV degradation.	2	3	6	3
MEMBRANE	SEVERE_SURFACE_WEAR	SSUFR_CoatDet	For roofs with a waterproofing (aluminum coating) applied to entire membrane. Any defect or damage to the coating only. Defects to the underlying membrane should be marked up separately.	1	4	4	3
MEMBRANE	SEVERE_SURFACE_WEAR	SSURF_CompExp	Severe degranulation resulting in wear of the cap sheet exposing the underlying base layer	1	3	3	3
MEMBRANE	SEVERE_SURFACE_WEAR	SSUFR_MemExp	Severe degranulation causing the reinforcement of the cap sheet to be exposed	1	3	3	3
MEMBRANE	SEVERE_SURFACE_WEAR	SSURF_ReinfExp	Degranulation resulting in a bald membrane (excessive manufacture defect_bald but no exposure of the reinforcement or base sheet)	1	3	3	3
MEMBRANE	SPLITS_TEARS	SPLIT_Thru	Split or tear through all layers of membrane.	2	4	8	4
MEMBRANE	SPLITS_TEARS	SPLIT_NotThru	Split or tear in the cap sheet_but not through all layers of membrane	2	3	6	3
MEMBRANE	SUBSTRATE_ADHESION_LOSS	SUBS_Ext	Extensive flashing substrate adhesion loss (Consistent frequency)	2	4	8	4
MEMBRANE	SUBSTRATE_ADHESION_LOSS	SUBS_Iso	Isolated substrate flashing adhesion loss (No consistency)	2	2	4	3

Criticality Sum	Max RPN	RPN RANGE
146	584	438

Single Ply

DEFECT PRIMARY GROUP	DEFECT SUB GROUP	DEFECT CODE	DEFECT DESCRIPTION	DETECTABILITY	SEVERITY	CRITICALITY DET x SEV	CRITICALITY GROUP
MEMBRANE	BALLAST	DISPLACED_Ballast	Ballast displacement or scour	1	3	3	3
MEMBRANE	DEBRIS	DEBRIS_ActVegNonPen	Active vegetation that is not penetrating the roof system (moss, mold, algea)	1	2	2	2
MEMBRANE	DEBRIS	DEBRIS_Decid	Decidious tree debris (leaves_whirlybirds_pollen)	1	2	2	2
MEMBRANE	DEBRIS	DEBRIS_ConstrMaint	Construction or Maintenance debris (piping_wood_abandoned equipment)	1	3	3	3
MEMBRANE	DEBRIS	DEBRIS_ActVegPen	Active vegetation that is penetrating the roof system (tree growing out of the roof)	1	4	4	3
MEMBRANE	FAILED_PATCHES	FAILPATCH_Req	Failed required patch (T_football_bow tie)	2	4	8	4
MEMBRANE	FAILED_PATCHES	FAILPATCH_Rep	Failed repair patch of any type	2	4	8	4
MEMBRANE	FASTENERS	BACKOUT_INSU		2	3	6	3
MEMBRANE	FASTENERS	BACKOUT		2	3	6	3
MEMBRANE	FUNCTIONING_PATCHES	FUNCPATCH_Req	Required patch (T_football_bow tie) in good condition	1	1	1	1
MEMBRANE	FUNCTIONING_PATCHES	FUNCPATCH_Rep	Repair patch in good condition	1	2	2	2
MEMBRANE	MINOR_SURFACE_WEAR	MSURF_MatEquHnd	Minor non-damaging from material and/or equipment handling on the roof top (single occurrence)	2	2	4	3
MEMBRANE	MINOR_SURFACE_WEAR	MSURF_FootTraf	Minor degranulation from focused pattern of foot traffic on the surface	2	3	6	3
MEMBRANE	OPEN_LAPS	OPENLAPS_Part	Lap is partially open (less than 30% of the lap width)	2	2	4	3
MEMBRANE	OPEN_LAPS	OPENLAPS_Full	Lap is open completely through the width	2	4	8	4
MEMBRANE	PONDING	PONDING	Ponding of water on the roof surface for longer than 48 hours	1	3	3	3
MEMBRANE	PUNCTURES	PUNC_Thru	Puncture through membrane	2	3	6	3
MEMBRANE	SEVERE_SURFACE_WEAR	SSURF_ReinfExp	Exposed reinforcement	1	4	4	3
MEMBRANE	SEVERE_SURFACE_WEAR	SSURF_Deterioration	Chemical or UV or Chalking of membrane	1	4	4	3
MEMBRANE	SPLITS_TEARS	SPLIT_Thru	Split or tear through membrane.	1	4	4	3
MEMBRANE	SUBSTRATE_ADHESION_LOSS	SUBS_Iso	Isolated substrate adhesion loss including shrinkage less than 3 square feet	2	3	6	3
MEMBRANE	SUBSTRATE_ADHESION_LOSS	SUBS_Ext	Substrate adhesion loss including shrinkage over 3 square feet	2	4	8	4

Criticality Sum	Max RPN	RPN RANGE
102	408	306

Built-up

DEFECT PRIMARY GROUP	DEFECT SUB GROUP	DEFECT CODE	DEFECT DESCRIPTION	DETECTABILITY	SEVERITY	CRITICALITY DET x SEV	CRITICALITY GROUP
MEMBRANE	DEBRIS	DEBRIS_ActVegNo	Active vegetation that is not penetrating the roof system (moss_mold_algea)	1	2	2	2
MEMBRANE	DEBRIS	DEBRIS_Decid	Decidious tree debris (leaves_whirlybirds_pollen)	1	2	2	2
MEMBRANE	DEBRIS	DEBRIS_ConstrMa	Construction or Maintenance debris (piping_wood_abandoned equipment)	1	3	3	3
MEMBRANE	DEBRIS	DEBRIS_ActVegPe	Active vegetation that is penetrating the roof system (tree growing out of the roof)	1	4	4	3
MEMBRANE	FAILED_PATCHES	FAILPATCH_Req	Failed required patch (T_football_bow tie)	2	3	6	3
MEMBRANE	FAILED_PATCHES	FAILPATCH_Rep	Failed repair patch of any type	2	3	6	3
MEMBRANE	FUNCTIONING_PATCHES	FUNCPATCH_Req	Required patch (T_football_bow tie) in good condition	1	1	1	1
MEMBRANE	FUNCTIONING_PATCHES	FUNCPATCH_Rep	Repair patch in good condition	1	2	2	2
MEMBRANE	INTERPLY_BLISTER	BLISTER_Air	Interply blister with trapped air	1	3	3	3
MEMBRANE	INTERPLY_BLISTER	BLISTER_Water	Interply blister with trapped water	1	3	3	3
MEMBRANE	MINOR_SURFACE_WEAR	MSURF_MatEquH	Minor gravel surfacing loss or displacement from material and/or equipment handling on the roof top (single occurrence)	2	2	4	3
MEMBRANE	MINOR_SURFACE_WEAR	MSURF_FootTraf	Minor gravel loss or displacement from focused pattern of foot traffic on the surface	2	3	6	3
MEMBRANE	MOLE_RUN_FISHMOUTH	MOLE_Run	Mole run or wrinkle through plies that extends greater than 3 feet in length	1	2	2	2
MEMBRANE	MOLE_RUN_FISHMOUTH	FISHMOUTH	Fishmouths at leading edge of top plies for any reason. Include separately from mole runs.	1	3	3	3
MEMBRANE	OPEN_LAPS	OPENLAPS_Part	Lap is partially open- Flashings (less than 30% of the lap width)	2	2	4	3
MEMBRANE	OPEN_LAPS	OPENLAPS_Full	Lap is open completely through the width - Flashings	2	3	6	3
MEMBRANE	PONDING	POND_Field	Ponding of water on the roof surface for longer than 48 hours	1	3	3	3
MEMBRANE	PUNCTURES	PUNC_NotThru	Isolated puncture into the membrane_but not through all layers of membrane	2	3	6	3
MEMBRANE	PUNCTURES	PUNC_Thru	Puncture through all layers of membrane	2	4	8	4
MEMBRANE	SEVERE_SURFACE_WEAR	SSURF_ReinfExp	Severe gravel surfacing and flood coat deterioration or loss causing the reinforcement of the felts to be exposed	1	3	3	3
MEMBRANE	SEVERE_SURFACE_WEAR	SSURF_Scour	Gravel surfacing scour	1	3	3	3
MEMBRANE	SPLITS_TEARS	SPLIT_NotThru	Split or tear in the cap sheet_but not through all layers of membrane	1	2	2	2
MEMBRANE	SPLITS_TEARS	SPLIT_Thru	Split or tear through all layers of membrane.	1	3	3	3
MEMBRANE	SUBSTRATE_ADHESION_L	SUBS_Iso	Isolated substrate adhesion loss less than 3 square feet	2	3	6	3
MEMBRANE	SUBSTRATE_ADHESION_L	SUBS_Ext	Substrate adhesion loss over 3 square feet	2	4	8	4

Criticality Sum	Max RPN	RPN RANGE
99	396	297

DEFECT PRIMARY GROUP	DEFECT SUB GROUP	DEFECT CODE	DEFECT DESCRIPTION	DETECTABILITY	SEVERITY	CRITICALITY DET x SEV	CRITICALITY GROUP
ACCESSORIES	BOX GUTTERS	BOX_Corr	Corrosion	1	3	3	3
ACCESSORIES	BOX GUTTERS	BOX_OpenJnts	Open Joints	1	4	4	3
ACCESSORIES	COPING	COP_Corr	Corrosion	1	1	1	1
ACCESSORIES	COPING	COP_LseMissFast	Loose or missing fasteners	1	2	2	2
ACCESSORIES	COPING	COP_OpenJnts	Open Joints	1	3	3	3
ACCESSORIES	COPING	COP_LseMiss	Loose or missing coping	1	4	4	3
ACCESSORIES	COUNTERFLASHING	CF_Corr	Corrosion	1	1	1	1
ACCESSORIES	COUNTERFLASHING	CF_DetSeal	Deteriorated sealant	1	1	1	1
ACCESSORIES	COUNTERFLASHING	CF_LseMiss	Loose or missing counterflashing	1	2	2	2
ACCESSORIES	COUNTERFLASHING	CF_LseMissFast	Loose or missing fasteners	1	2	2	2
ACCESSORIES	COUNTERFLASHING	CF_OpenJnts	Open Joints	1	2	2	2
ACCESSORIES	COUNTERFLASHING	CF_SurfMount	Surface mounted counterflashing	1	3	3	3
ACCESSORIES	DOWNSPOUTS	DS_Corr	Corrosion	1	2	2	2
ACCESSORIES	DOWNSPOUTS	DS_OpenJnts	Open Joints	1	3	3	3
ACCESSORIES	DOWNSPOUTS	DS_MissLse	Loose or missing	1	4	4	3
ACCESSORIES	EDGE_METAL	EM_Corr	Corrosion	1	1	1	1
ACCESSORIES	EDGE_METAL	EM_LseMissFast	Loose or missing fasteners	1	3	3	3
ACCESSORIES	EDGE_METAL	EM_OpenJnts	Open Joints	1	3	3	3
ACCESSORIES	EDGE_METAL	EM_LseMiss	Loose or missing edge metal	1	4	4	3
ACCESSORIES	GUTTERS	GUT_Corr	Corrosion	1	2	2	2
ACCESSORIES	GUTTERS	GUT_LseMiss	Loose or missing	1	4	4	3
ACCESSORIES	GUTTERS	GUT_OpenJnts	Open Joints	1	4	4	3
ACCESSORIES	INTERNAL_DRAINS	ID_MissBrkStrn	Missing or broken strainer	1	2	2	2
ACCESSORIES	INTERNAL_DRAINS	ID_MissBrkBolt	Missing or broken bolts	2	3	6	3
ACCESSORIES	INTERNAL_DRAINS	ID_BrkClampRing	Broken clamping ring	2	4	8	4
ACCESSORIES	PITCH_POCKETS	PPOCK_GoodCond	Good condition pitch pockets	1	2	2	2
ACCESSORIES	PITCH_POCKETS	PPOCK_PoorCond	Poor condition pitch pockets	1	4	4	3
ACCESSORIES	SCUPPERS	SCUP_Deteriorated	Deteriorated or corroded scupper	1	2	2	2
ACCESSORIES	SCUPPERS	SCUP_Loose	Loose scupper	1	2	2	2
ACCESSORIES	SCUPPERS	SCUP_Miss	Missing scupper	1	4	4	3
ACCESSORIES	SCUPPERS	SCUP_OpenJnts	Open Joints	1	4	4	3

DEFECT PRIMARY GROUP	DEFECT SUB GROUP	DEFECT CODE
INSULATION	WET_INSULATION	WETISO_VBDefect
INSULATION	WET_INSULATION	WETISO_Mdefect
INSULATION	THERMAL_BRIDGING	THERMBR_Stagg
INSULATION	THERMAL_BRIDGING	THERMBR_ExcJoints
INSULATION	INSULATION_DETACHMENT	DETACHISO_Const
INSULATION	INSULATION_DETACHMENT	DETACHISO_FastFailure
INSULATION	THERMAL_BRIDGING	THERMBR_WetIso
INSULATION	INSULATION_DETACHMENT	DETACHISO_WetIso
INSULATION	WET_INSULATION	WETISO_Design

DEFECT DESCRIPTION	DETECTABILITY	SEVERITY	CRITICALITY DET x SEV
Vapor Barrier Failure	4	2	8
Membrane Failure	4	2	8
Stagger	4	2	8
Excessive Joints	4	2	8
Contruction or installation failure	4	2	8
Fastening failure	4	2	8
Wet Insulation	4	3	12
Wet Insulation	4	3	12
Design flaw	4	4	16

CRITICALITY GROUP
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Criticality Su	Max RPN	RPN RANGE
88	352	264

DEFECT PRIMARY GROUP	DEFECT SUB GROUP	DEFECT CODE
VAPOR_BARRIER	VB_PUNCTURES	VB_Punc
VAPOR_BARRIER	VB_SPLITS_TEARS	VB_Split
VAPOR_BARRIER	VB_OPEN_LAPS	VB_OPENLAPS_Full
VAPOR_BARRIER	VB_DETACHMENT	VB_SUBS_Ext
VAPOR_BARRIER	VB_OPEN_LAPS	VB_OPENLAPS_Part
VAPOR_BARRIER	VB_DETACHMENT	VB_SUBS_Iso

DEFECT DESCRIPTION	DETECTABILITY	SEVERITY	CRITICALITY DET x SEV
Puncture	4	3	12
Split or tear	4	3	12
Full open lap	4	3	12
Extensive detachment from substrate (greater than 3 sf)	4	3	12
Partial open lap (less than 30%)	4	2	8
Isolated detachment from substrate (less than 3 sf)	4	2	8

CRITICALITY GROUP
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Criticality Su	Max RPN	RPN RANGE
64	256	192