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Predictive Service Life Tests for Roofing Membranes: Phase 1

by
Carl G. Cash
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The Army and roofing industry have extensive field experience with roofing membranes. Roofing manufacturers, however, have been changing the composition of the membranes and introducing new materials at an increasing pace. Despite the initial satisfactory rating of some of the new products, their long-term durability is unknown. Army roofing managers need reliable tests to predict the durability of roofing membranes.

The objective of this study was to characterize roofing membrane material based on in-service performance requirements and criteria, and to identify degradation factors and mechanisms that can be used to propose accelerated aging tests for service life prediction of roofing membranes.

This study determined that existing criteria and measurements for performance testing are inadequate. Predictive service life tests should be developed based on physical and chemical degradation measured after accelerated aging tests in a variety of climates. Degradation modeling and standard test methods should be incorporated into the test process.

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FOREWORD

This research was conducted for the Directorate of Military Programs, Headquarters, U.S. Army Corps of Engineers (HQUSACE) under Project 4A162784AT41, "Military Facility Engineering Technology"; Work Unit MA-CV2, "Evaluation of Roofing Materials Degradation Processes." The technical monitor was Rodger Seeman, CEMP-EA.

This work is being performed by the Engineering and Materials Division (FM), of the Infrastructure Laboratory (FL), U.S. Army Construction Engineering Research Laboratories (USACERL). David M. Bailey is the USACERL principal investigator. Carl G. Cash is a principal engineer and chemist with Simpson, Gumpertz and Heger Inc. of Arlington, MA. Dr. Paul A. Howdyshell is Chief, CECER-FM. Dr. Michael J. O'Connor is Chief, CECER-FL. The USACERL technical editor was Gloria J. Wienke, Information Management Office.

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1 INTRODUCTION

Background

The built-up roof (BUR) membrane is standard for use on low-slope roofs; industry has over 100 years of field experience with BURs. The original BURs that provided the bulk of the experience were reinforced with organic or asbestos felt plies. Glass fiber felts have gradually replaced organic felts and asbestos felts (the latter discontinued for environmental concerns) and are currently the most common. Polyester felts, however, are now starting to be used as reinforcement for some BURs.

Other changes in roofing membranes became apparent in the mid-1960s when other materials such as sheet neoprene (CR), chlorosulfonated polyethylene (CSPE), and polyisobutylene (PIB) sheets began to be marketed. By the mid-1970s, the materials in the roofing market increased as manufacturers began producing ethylene-propylene-diene terpolymer (EPDM), polyvinyl chloride (PVC), chlorinated polyethylene (CPE), and modified bitumens (MB). The Army is now using many of these roofing materials in both new construction and reroofing applications. Corps of Engineers Guide Specifications (CEGS) have been developed for EPDM (CEGS 07530), modified bitumen (CEGS 07535), and PVC (CEGS 07555) membranes.

By 1985, 111 sources of roofing systems were listed in the *Roofing Materials Guide* (National Roofing Contractors Association [NRCA] 1992) as shown in Table 1. Products for the roofing market are added, changed, and deleted at an ever increasing pace. Although some of the new products have initially been satisfactory, their long-term durability is unknown. Often these new materials, and changes in existing materials, are not thoroughly researched before being introduced to the market; currently, no laboratory tests can predict the durability of a roofing system and manufacturers are unable or unwilling to wait the time required for outdoor weathering tests.

The American Society for Testing and Materials (ASTM) has developed manufacturing standards for many of the roofing membranes, but these standards are often consensus standards designed to include the lowest quality product. The standards seldom address the durability of the material in use because data on degradation mechanisms and data on physical tests before, during, and after weathering are lacking. When evaluating inherent stability, most roofing membranes require prolonged exposure before even minor changes in physical properties are evident.

The lack of reliable tests to predict durability may result in systems being introduced that may not be suitable for roofing. The inability to measure rapidly the changes in durability due to changes in the formulation of roofing membrane products often results in "cost improving" the materials until they do not perform adequately. Building owners, designers, and roofing contractors may be attracted by price, warranties, or products with "new" as the primary characterization.

Because the Army and other agencies of the Federal Government may not specify roofing systems by name in acquisitions, insufficiently tested membranes may be substituted for membranes that have demonstrated satisfactory performance. To help Army roofing managers make well-informed decisions about new roofing membranes, the U.S. Army Construction Engineering Laboratories (USACERL) is developing methods to predict long-term performance and expected service life of roofing membranes using accelerated aging tests.

Table 1

Number of Organizations Listed Marketing Each Type of Roofing Membrane*

Year	BUR	MB	PVC	EPDM	CR	CSPE	PIB	CPE	OTHER	TOTAL
1984	13	34	11	23	4	3	4	3	5	100
1985	15	40	10	19	4	11	1	3	8	111
1986	15	42	7	18	3	9	2	2	8	106
1987	15	40	6	19	3	8	1	2	9	103
1988	16	41	6	19	2	10	4	3	9	110
1989	16	40	5	18	2	9	3	3	9	105
1990	18	41	5	19	3	8	2	3	10	109
1991	16	38	5	16	2	10		12**		99
1992	20	39	5	17	1	11		9		102

* Source: *Roofing Materials Guide*, NRCA, 1984 - 1992 editions.
** The numbers for PIB, CPE, and Other are added.

This research approximates the process described in "Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials" (American Society of Testing and Materials [ASTM] E 632-82). This phase of the study centers on characterizing roofing membranes in terms of structure and composition, critical performance characteristics, and degradation factors and mechanisms. The following phases will center on developing and conducting in-service and predictive service testing, and will result in recommendations for conducting predictive service life tests.

Objectives

The objectives of this phase of the research were to (1) characterize roofing membrane material based on in-service performance requirements and criteria, (2) identify critical performance characteristics and properties, and (3) identify degradation factors and mechanisms that can be used to propose accelerated aging predictive service life tests for roofing membranes.

Approach

Researchers conducted an extensive literature search pertaining to membrane types and performance. The study focused on EPDM, PVC, and modified bitumen roofing because these types are the best defined, are the majority of the market, and are documented in Corps of Engineers guide specifications. BUR membranes, for which some performance history exists, were included as a control.

Mode of Technology Transfer

This research will provide the basis for establishing standard tests and criteria for determining a roofing material's ability to perform at the time of application as well as several years after exposure. It is recommended that these tests and criteria be incorporated into Corps of Engineers guide specifications for roofing. The final recommendations of this study should be used to develop or update ASTM standards on roofing materials.

2 PERFORMANCE REQUIREMENTS FOR ROOFING MEMBRANE SYSTEMS

The primary function of the roofing system is to protect the contents and interior of the building from the weather. Any in-service performance requirements should define the minimum acceptable levels in fulfilling the primary function.

Definition of Terms

The following definitions are fundamental to understanding the concepts in this study; they are adopted from various industry and trade publications (ASTM 1979).

accelerated aging test - an aging test in which the degradation of building components or materials is intentionally accelerated over that expected in service.

building component - an identifiable part of a building that may include a combination of building materials, such as a roof or wall.

building material - an identifiable material that may be used in a building component, such as brick, concrete, metal, or lumber.

critical performance characteristic(s) - a property, or group of properties, of a building component or material that must be maintained above a certain minimum level if the component or material is to continue to perform its intended functions.

degradation factor - any of the group of external factors that adversely affect the performance of building components and materials, including weathering, biological, stress, incompatibility, and use factors.

degradation mechanism - the sequence of chemical or physical changes, or both, that leads to detrimental changes in one or more properties of a building component or material when exposed to one or more degradation factors.

durability - the capability of maintaining the serviceability of a product, component, assembly or construction over a specified time.

multiplication factor - the outdoor weathering time divided by the accelerated life testing time, to achieve the same degree of deterioration.

predictive service life test - a test, consisting of both a property measurement test and an aging test, used to predict the service life (or compare the relative durabilities) of building components or materials in a time period much less than the expected service life.

reliability - mathematically, 1 minus the failure rate.

roofing system - an assembly of interacting components designed to weatherproof and insulate a building's top surface.

serviceability - the capability of a building component, assembly, or construction to perform the function(s) for which it was designed and constructed.

use factor - any of the group of degradation factors that result from the design of the system, installation and maintenance procedures, normal wear and tear, and user abuse.

Performance Requirements

Rossiter (Rossiter et al., July 1991, p 12) lists the following functions of a roofing system. The requirements are defined for this study as:

- Watertightness - preventing water from entering into the top of the building and channeling storm water around the protected space.

- Heat Transfer Control - preventing significant heat exchange between the interior and the exterior environments.

- Condensation Control - preventing water vapor condensation within the roof system either by controlling water vapor diffusion or by air convection.

- Load Accommodation - ability of the system to sustain dead and live loads experienced during the expected service life.

- Maintainability - capability of economic repair, by techniques available to maintenance personnel, throughout its service life.

- Noise Control - minimization of the transfer of noise through the system.

Of these functions, accommodation of vertical loads, heat transfer, condensation, and noise control rely on the design of the roofing system and the thermal insulation selected, but are independent of the roofing membrane selected. Watertightness and some important aspects of maintainability are the principal functions of the roofing membrane component of the roofing system.

Although important, other functions such as the appearance, and the safety and environmental impact during installation and removal of the roofing membrane are less important than the membrane's waterproofing function.

Rossiter (Rossiter et al., July 1991, p 15) lists membrane attributes and performance requirement statements associated with the loss of watertightness. These attributes, slightly rearranged, plus some additional attributes, are listed in Table 2.

The attributes not associated with the watertightness of the membrane include:

- the membrane shall not constitute a hazard for the installer, maintainer, or remover of the system, and

- the membrane shall not provide undue hazards to the environment during its entire life.

Table 2

Membrane Attributes and Performance Requirement Statements Associated With a Loss in Watertightness

Attribute	Performance Requirement Statement
• Abrasion Resistance	Withstand wear from foot traffic and scouring from wind blown dirt.
• Biological Resistance	Withstand weakening or penetration by plant roots, microorganisms, and macroorganisms such as insects, birds, or vandals.
• Chemical Resistance	Withstand weakening or increased water permeability due to exposure to chemicals (including solvents and animal greases) during its service life.
• Dimensional Stability	Shall not exhibit a dimensional change in response to changes in temperature or relative humidity in excess of its ability to absorb those changes, at any time in its service life.
• Fire Resistance	Shall not pose an unusual safety hazard when exposed to fire.
• Flow Resistance	Withstand sliding due to roofing system mass, slope, or climate.
• Lap Adhesion	Shall not exhibit any lap or ply separation during its service life.
• Pliability	Survive flexing during installation and service without damage.
• Puncture Resistance	Withstand dynamic and static puncture (including hail).
• Resistance to Water	Prevent the passage of liquid water.
• Split Resistance	Shall not split in response to all internal and external stresses.
• Tear Resistance	Shall not tear (split propagate) during installation or service.
• Weather Resistance	Show no significant changes in properties (changes that reduce serviceability) during service.

3 CHARACTERIZATION OF ROOFING MEMBRANE MATERIALS

Characterization of the different types of roofing membrane materials is a key step in evaluating their long term performance. A lack of knowledge of the membranes' important properties before service would make it difficult to measure the changes in the properties due to weathering and aging. The materials are characterized variously by physical type and composition.

Roofing membranes classified as BUR, PVC, styrene-butadiene-styrene (SBS) modified bitumens, atactic polypropylene (APP) modified bitumens, and EPDM are within the scope of this report. Selected attributes for the characterization of each type of membrane are discussed in the following paragraphs.

BUR

The BUR membrane is constructed on the building by adhering three or more felt plies to each other with hot bitumen. For felt plies 36 in. wide, the side lap width for a base sheet (a bottom ply) is frequently 4 in. The side lap width for the upper felt plies is 19 in. if the system has two felt plies, and 11½ in. if the system has three felt plies.

Current literature lacks life testing data, but estimates of durability, based on widespread experience, is an acceptable substitute. The durability data show (Cash 1980):

- The durability of a built-up roofing membrane depends on the number of plies of the reinforcing felts.
- To a lesser extent, the membrane durability relies on the strength of the individual felts.
- The durability is not a single number, but rather a spectrum, a distribution of values, that are statistically normally distributed.

Figure 1 shows the estimated durability distribution curve for a typical four-ply organic felt asphalt BUR membrane. The dashed lines in the figure illustrate the following readings of the curves:

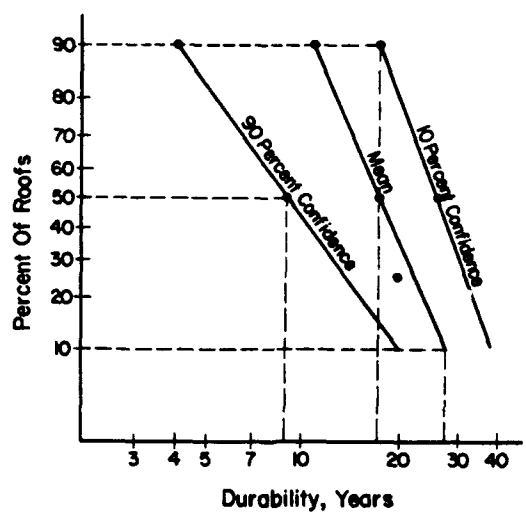


Figure 1. Estimated Durability of an Asphalt Membrane Reinforced With Four Organic Felt Plies.

- with 10 percent confidence, 90 percent of the roofs will exceed 18 years service life,
- with 90 percent confidence, 50 percent of the roofs will last longer than 9 years, and
- the mean life of the best 10 percent of the roofs is 28 years.

Since performance relies on membrane composition, membrane characterization should include an analysis to define the quantity and type of the components present. Tensile properties are the most frequently used physical test to characterize attributes for BUR membranes; these include:

- tensile properties at -20 °C (-4 °F), 20 °C (68 °F), and 60 °C (140 °F),
- load at break (defined for this report as maximum load),
- elongation at break (elongation at maximum load), and
- energy-to-break area under the load-strain curve (to maximum load).

The load, strain, and energy-to-break for a typical roofing membrane are depicted in Figure 2. Other frequently cited properties are tensile-tear, fatigue resistance, static impact resistance, and dynamic impact resistance. They all bear some relationship to the tensile properties, and may be redundant. For example, Nelson (1981) showed that for built-up membranes, the area under the fatigue curve to failure was identical to the area under the creep-to-failure curve. Frequently ignored fundamental properties are thermal and hygroscopic expansion and contraction, density, and water absorption.

Bitumens, defined as "materials soluble in carbon disulfide," are one of the earliest thermoplastics used by man. They provide the waterproofing agents and adhesive properties for the BUR roofing system. Petroleum asphalts, coal tars, and coal tar pitches provide most of the bitumens used in roofing. Small quantities of natural asphalts and stearin pitches are used in some specialty and waterproofing products, but these materials are outside the scope of this study.

Petroleum asphalt is the residue of the distillation of crude oil, oxidized (air blown) at elevated temperatures to provide roofing asphalts of different viscosities and softening points. ASTM Standard D 312 (ASTM 1989) ists four types of asphalt intended for different roof slopes.

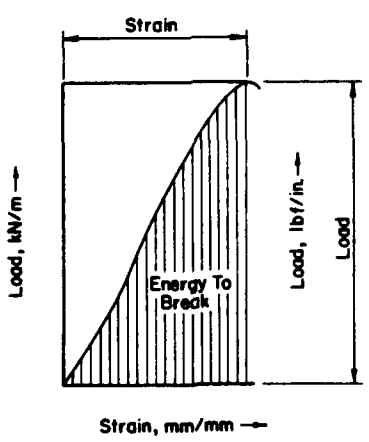


Figure 2. Load, Strain, and Energy-to-Break of a Typical Roofing Membrane.

Asphalts are complex mixtures of hydrocarbons; they obtain their physical properties more from their morphology (arrangement of atoms) than from the distribution of the elements that make up their molecules. Solvent chromatography (Brooks 1991) fractionates asphalts into:

- saturated hydrocarbons (straight chain hydrocarbons without double or triple bonds),
- aromatic hydrocarbons (hydrocarbons that include a ring nucleus in their structure),
- polar aromatic hydrocarbons (sometimes called polar resins), and
- asphaltenes (high molecular weight - hard materials).

The mass of each fraction for typical Type III asphalts is 7 to 13 percent saturates, 14 to 32 percent aromatics, 25 to 42 percent polar resins, and 22 to 42 percent asphaltenes. Both the aromatic fractions serve to bind the relatively low molecular weight saturates with the asphaltenes. The (aromatic + polar aromatic)/(saturates + asphaltenes) ratio is believed to be an important indicator of durability.

Infrared spectroscopy may be used to differentiate between bitumens and to measure the rate of deterioration. The ratio of the absorbance at 1460 cm^{-1} to the absorbance at 745 cm^{-1} wavelengths has been used by Cash in an unpublished study to identify bitumens. For example, a Type I asphalt has a ratio (A_{1460}/A_{745}) of 7.0. A more aromatic Type III asphalt has a ratio of 6.2, and coal-tar pitch has a ratio of 0.2 to 0.6, depending on the pitch supplier. Greenfield and Weeks (October 1963) showed with infrared spectra that the concentration of carbonyl radicals increased with the accelerated exposure of asphalt.

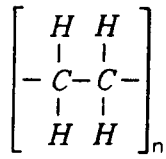
PVC

PVC membranes are made up of thermoplastic sheets seamed together in the field with sidelaps approximately 2 in. wide. Normally, only about 1 in. of the outer part of the sidelaps are adhered by either solvent welding with tetrahydrofuran (THF), or heat welding with a hot air machine. All of the currently marketed PVC membranes are reinforced, usually with a polyester or glass mat. The membranes are characterized by the same tensile properties used for BUR membranes, but using different test methods. In addition, PVC membranes are frequently characterized by:

- percent plasticizer,
- thickness,
- glass transition point, and
- low temperature impact.

In its basic form, PVC resin is relatively hard, requiring plasticizers and other additives to give it the flexibility necessary for a roofing membrane. The nature of the plasticizer (high or low molecular weight, straight or branched chain) and the quantity and type of UV shielding and fungus resisting additives are important, but are usually only tested by or for PVC membrane manufacturers.

The idealized chemical structure of PVC is shown in Structure 1. The more common structure is less orderly; it may contain branches, unsaturations (double bonds that are likely chemical reaction sites), and sensitizers such as entrapped solvents.

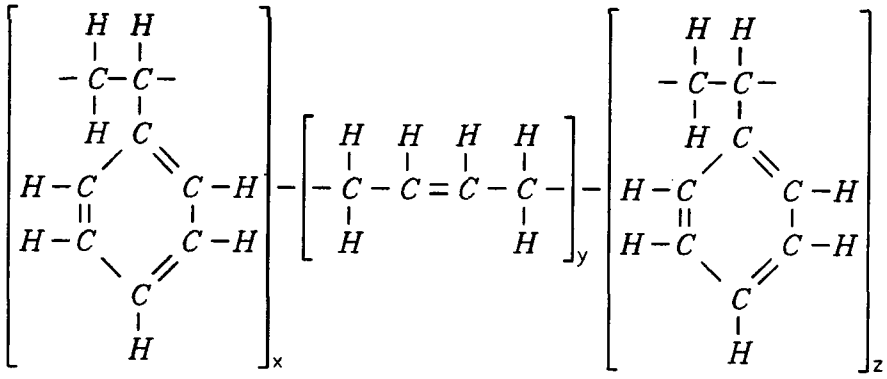


[Structure 1]

Modified Bitumens

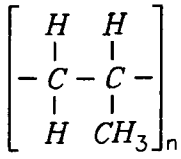
Modified bitumen products are characterized by the type and quantity of the modifier and the type and quantity of the reinforcing mats or felts. Usually these membranes are composed of two or more plies, installed one ply at a time with approximately 4 in. wide sidelaps adhered by torching the membrane roll, hot bitumen, or self-adhering bitumen. Some manufacturers provide single-ply specifications, but most of the 1992 specifications consist of two or more plies. Asphalt polymer modifiers usually have to be more than 4 percent of the asphalt-modifier mixture to demonstrate any significant change in the asphalt's properties. The goal of modification is increased durability through increasing the viscosity, extensibility, and flexibility, while lowering the glass transition point of the bitumen.

Manufacturers use SBS block copolymers (Structure 2), blends of APP and isotactic polypropylene (IPP), and other modifiers that they often choose not to reveal. In one case, the unadvertised "modifier" was air; the manufacturer decided air blowing was modifying the asphalt.



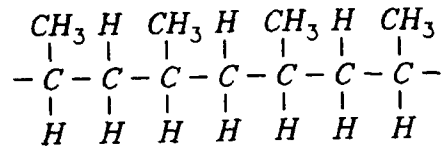
[Structure 2]

The general structure of polypropylene (Structure 3) is closely related to polyethylene and polyvinyl chloride.

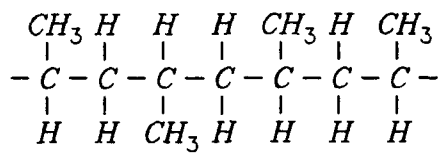


[Structure 3]

The importance of morphology (the structure) is demonstrated by comparing the relatively regular distribution of the methyl (CH_3) groups in the isotactic polypropylene (Structure 4) with the random distribution of the methyl groups in the atactic polypropylene (Structure 5).



[Structure 4]



[Structure 5]

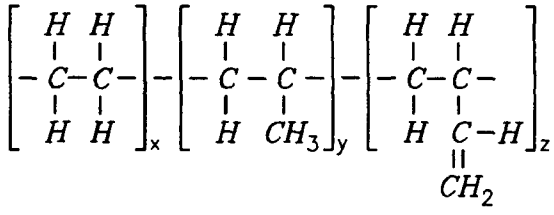
The isotactic form is almost crystalline, and enhances the tensile strength, while the atactic form is weaker, amorphous, and increases the elongation. Usually a blend is used to modify APP modified bitumens.

The products are physically tested for tensile properties using different test methods than are used for BUR or PVC products. Thermal stability and compatibility between the modifier and the asphalt coating are very important attributes that can be revealed through tensile testing before and after heat aging.

EPDM

EPDM is a strong, flexible, weather resistant manufactured rubber sheet. EPDM is usually installed as a single ply membrane with seaming of the sidelaps accomplished with a tape or liquid adhesive. The rubber is characterized by its thickness, hardness, presence or absence of reinforcement, and tensile properties. The tensile test method is again different from the tensile method used for BUR or PVC or modified bitumen, and data obtained from these various methods are not comparable.

The EPDM polymer is typically mixed with reinforcing carbon black, extending oils, zinc oxide, and curatives during the manufacturing process. EPDM's stability comes from the saturated nature of the ethylene and propylene "backbone" of its structure (Structure 6); the diene (butadiene shown) double bonds in the side chains cross link the chains.



[Structure 6]

4 EXISTING MEMBRANE PERFORMANCE CHARACTERISTICS AND CRITERIA

Critical performance characteristics are the properties that must be maintained above a certain minimum level for the membrane to perform satisfactorily. Various authors have proposed lists of requirements for the durability of roofing membranes, (Hoiberg, February 1972; Sneck, September 1987; Mathey and Cullen, November 1974; MRCA 1981; MRCA 1982; MRCA 1983; Rossiter and Seiler, February 1989) and several have suggested criteria for some of the attributes.

The performance criteria suggested are frequently either related specifically to the topical materials (i.e., "Recommended Performance Criteria for PVC Single-Ply Roof Membrane Systems" [MRCA, 1981]), or the criteria are stated in such general terms that they are difficult to quantify, implement, evaluate, or measure. The following paragraphs discuss the currently proposed performance criteria for BUR, PVC, modified bitumens, and EPDM membranes and roofing membranes in general.

BUR

Building Science Series #55 (Mathey and Cullen, November 1974) lists criteria for tensile strength, thermal expansion and contraction coefficient, "thermal shock resistance factor," flexural strength, tensile fatigue strength, flexural fatigue strength, punching shear strength, impact resistance, wind resistance, and fire resistance. All of the tests used to measure the proposed criteria were performed on unweathered laboratory prepared four-ply built-up membranes, and only the tensile strength test method has been issued as a standard by ASTM.

These criteria have not been validated by periodic tests on roofs in service, despite the lengthy history of durable service of many of these membranes. The tests that have been performed on specimens cut from roofs in service (Mathey and Rossiter, June 1977; Boone and Skoda, February 1969) show that the proposed performance criteria are too stringent, because roof membranes in service that do not meet the proposed criteria are performing effectively.

Also of concern, and perhaps a reason for the failure to adopt these criteria, are concepts such as "thermal shock resistance factor," tensile fatigue strength, and flexural fatigue strength. The roofing technologist may find these terms too dependent on untested concepts that rely on measurements with low reproducibility. The concept of "thermal shock resistance factor" is frequently misused as an explanation for the poor performance of a membrane improperly installed or installed with materials unsuitable for the purpose.

PVC

The Midwest Roofing Contractors Association (MRCA) recommends performance criteria for PVC membranes (MRCA 1981) that include performance attributes for the materials, application, and field performance (Table 3).

The performance criteria, given by MRCA for these attributes are for unreinforced PVC membranes that have shown satisfactory performance for 4 to 8 years, but poor durability thereafter. Thus the MRCA criteria, despite their number and extent, are not stringent enough, and cannot be used to predict performance.

Table 3

Summary of PVC Performance Attributes*

Manufacture	Application	Field Performance
1. Tensile Strength	1. Lap Joint Construction	1. Water Resistance
2. Ultimate Elongation	2. Impact and Abrasion	2. Vapor Transmission
3. Low Temperature Flexibility	3. Flashing Attachment	3. Weather Resistance
4. Heat Aging	4. Ballast Mechanism	4. Puncture Resistance A. Static B. Dynamic
5. Temperature Induced Load	5. Attachment Mechanism A. Mechanical B. Adhesive	5. Crack Bridging Ability
6. Dimensional Stability	6. Contaminant Profile A. Compatibility	6. Wind Uplift
	7. Installation Environment	7. Fire

*Source: *Recommended Performance Criteria for Single-Ply Roof Membrane Systems*, Technical Document MP-10 (MRCA, 1981), p 4. Used with permission.

While many of these attributes are valid, the attributes such as weather or water resistance are too general or too difficult to measure to be useful for predicting the service life of a membrane. Some attributes, such as heat aging (resistance), are an attempt to eliminate obviously unsuitable materials, and perhaps a start on an accelerated weathering program. Where limits are specified, the numbers reflect the values that are reported to be suitable for a PVC membrane, thus they are prescriptive rather than performance criterion. The criterion also address only "PVC" membranes and not roofing membranes in general.

Modified Bitumens

Table 4 lists the modified bitumen performance attributes published by MRCA (MRCA 1983). This document has all the excellence and the problems of the earlier MRCA "performance criteria" documents. Test methods, such as load-elongation behavior, low temperature flexibility, and dimensional stability, are intermixed with some of the membrane construction conditions and characteristics (lap joint construction, flashing attachment, ballast, installation environment) and some general terms that may be synonymous (weather resistance, water resistance, and durability).

National Institute of Standards and Technology (NIST) Building Science Series 167 (Rossiter and Seiler, February 1989) lists a set of preliminary performance criteria for modified bitumen membranes. These criteria (shown in Table 5), are some of the best offered, but they are specific to modified bitumen membranes and have not been validated by outdoor weathering studies. Other than heat aging, the NIST criteria did not address exposure of the materials to other degradation factors or agents.

Table 4

Summary of Modified Bitumen Performance Attributes*

Manufacture	Application	Field Performance
1. Low Temperature Load - Elongation Behavior	1. Lap Joint Construction	1. Water Transmission
2. Low-Temperature Flexibility	2. Impact and Abrasion	2. Weather Resistance
3. Heat Aging	3. Flashing Attachment	3. Puncture Resistance
4. Temperature Induced Load	4. Ballast	4. Crack Bridging Ability
5. Dimensional Stability	5. Attachment Methods	5. Wind Uplift
6. Water Resistance	6. Chemical Contamination	6. Fire
7. Granule Embedment	7. Installation Environment	7. Durability
8. Metal Foil		

*Source: *Recommended Performance Criteria for Modified Bitumen Roof Membrane Systems*, Technical Document MB-30 (MRCA, 1983). Used with permission.

Table 5

Summary of Suggested Performance Criteria for Modified Bitumens

Requirement	Test Method	Criterion
Fire Resistance	ASTM, UL, or FM tests	Code conformance
Flow Resistance	Sliding at maximum slope	No slippage
Hail Impact	NBS BSS 55	1-1/2 in. hail stone at 112 ft/s without penetration
	or ASTM D3746	22 lbf x ft without water penetration
Strain Energy	ASTM D5147	Not less than 3 lbf x in./in.^{2}
Uplift	ASTM, UL, or FM	Code Conformance
Dimensional Stability	ASTM D 5147, 24 h @ 80 ° C	Maximum change +/- 1percent
Moisture Absorption	ASTM D 5147 , 100 h @ 50 °C water soak	Maximum 100 g/m^2
Moisture Content	ASTM D5147 (D 95)	Maximum 0.5 dry mass percent
Pliability	(a) ASTM D 5147 (b) UEAtc No. 27 Sec. 5.4.3	No cracking at application temps No cracking when unrolled at 0 °C
Thermal Resistance	ASTM D 5147, 90 days @ °C	Maximum 15 percent change in load elongation, pliability not to exceed 0 °C; Strain energy not less than 3 lbf x in./in.^{2}

EPDM

The MRCA published performance criteria for elastomeric systems in 1982 (MRCA 1982); Table 6 lists the EPDM performance attributes. The attributes include ozone and tear resistance, and "factory seam," which are all "prescriptive" of EPDM. The criterion for the "durability" attribute is that the membrane shall retain the performance characteristics called for in this document throughout the unspecified service life of the roof.

The criteria suggested for the attributes are well intentioned, but fail to provide the basis for predicting the service life of the membrane. While a 10-year minimum service life is required, no information is given on the mean service life, nor the estimated standard deviation for the service life. Reports of real-time weathering tests confirming these criteria and accelerated tests (such as heat aging or carbonyl group formation) are not in the available literature, and may not exist.

General

Additional material and performance standards have been published by the French Centre Scientifique et Technique du Batiment, CIB/RILEM Committee on Performance Testing of Roofing Membrane Materials, Norwegian Building Research Institute, Swedish Council for Building Research (Tornkvist 1990) and other organizations.

The FIT Classification

The FIT system classifies roofing systems by increasing levels of fatigue (F) resistance, indentation (I) resistance, and temperature (flow) resistance (T). The FIT classification for roofing membranes was introduced in France in 1989. Since it was adopted, roofing failure claims dropped from 18 percent in the 1970s to 5 percent in 1990 (Chaize and Fabvier 1991).

Table 6

Summary of EPDM Performance Attributes*

Manufacture	Application	Field Performance
1. Tensile Strength	1. Lap Joint Construction	1. Water Transmission
2. Ultimate Elongation	2. Impact and Abrasion	2. Weather Resistance
3. Low Temperature Flexibility	3. Flashing Attachment	3. Puncture Resistance
4. Heat Aging	4. Ballast Mechanism	4. Crack-Bridging Ability
5. Temperature Induced Load	5. Attachment Methods	5. Wind Uplift
	A. Mechanical	
	B. Adhesive	
6. Dimensional Stability	6. Contaminant Profile	6. Fire
7. Ozone Resistance	7. Installation Environment	7. Durability
8. Tear Resistance		
9. Factory Seam		
10. Water Resistance		

*Source: *Recommended Performance Criteria for Elastomeric Single Ply Roof Membrane Systems*, Technical Document ME-20 (MRCA, 1982). Used with permission.

The fatigue resistance is intended to measure the ability of the membrane to survive movement of the substrate. The fatigue resistance is rated $F_{1 \text{ to } 5}$ by increasing initial joint width 1 to 2 mm (0.04 to 0.08 in.) and amplitude of movement 1 to 2 mm (0.04 to 0.08 in.), and decreasing temperature from -20 to +20 °C (-4 to 68 °F), as shown in Table 7.

The indentation resistance, rated I_{1-5}, is defined by the static puncture (L_{1-4}) from <7 to >25 kg (<15 to > 55 lb) and dynamic puncture (D_{1-3}) from <1000 to >2000 N (< 225 to > 450 lbf) subclasses as shown in Table 8.

The temperature resistance (T_{1-4}) is rated by the slippage from >2 at 60 °C (140 °F) to <2 at 90 °C (194 °F), in accord with Table 9. (The slippage units are not defined).

The recommended classes in the FIT system for different substrates, roof use, and type of protection, are shown in Table 10.

This classification technique has apparently been useful in promptly lowering litigation resulting from roofing claims, but there is little information on the long term use of this technique, nor is this technique useful in predicting changes the material may undergo upon weathering.. Accelerated or natural weathering data that would support these criteria have not been found, although membrane toughness is surely required for durability.

CIB/RILEM Standard

The standards proposed by the CIB/RILEM committee (NRCA 1990b) involve static puncture resistance (L_{1-4}) from <5 to >25 N (<1 to >5.6 lbf), dynamic puncture resistance, and cyclic fatigue resistance (identical to the requirements of the FIT classification).

The accelerated heat aging conditions suggested by the committee vary depending on the percent of sunshine hours, the approximate maximum daily summer temperature, and adjustments for the type of surfacing. For samples exposed in the temperate climatic zone, the heat aging should be for 56 days at 80 °C (176 °F). For other climates, Table 11 may be used as a guide (AMC, March 1975).

No specific criteria exist for pass or fail after heat aging, but the committee suggests: less than 10°C (18 °F) change in the flexibility, no visible cracking or crazing, and less than 10 percent change in the tensile strength and elongation. CIB/RILEM also suggests ultraviolet (UV) aging for the equivalent of 4000 hours at 80 °C (176 °F), with no change in appearance, and no significant change in low temperature flexibility. Also suggested are water soak for 56 days at 50 °C (122 °F) [less than 2 percent weight loss, and less than 50 percent reduction in tensile strength], ozone exposure of elastomers for 56 days at 200 parts of ozone per hundred million (pphm) at 40 °C (104 °F) under "stress" [no cracks when viewed under 10X magnification], and contact compatibility for 28 days at 70 °C (158 °F) [with no observable problems].

Norwegian Building Research Institute

The Norwegian Building Research Institute (Paulsen 1990) has been evaluating low slope roofing materials since the 1970s. Their program for modified bitumen membranes includes 24 weeks of aging in special roof weathering test equipment where the temperature varies from -10 °C (14 °F) to 60 °C (140 °F) under constant UV, and with three sprays of water per day. Other tests include heat aging for 24 weeks at 70 °C (158 °F), 8 weeks of exposure in the roof weathering equipment with a wet base (the samples are exposed on wet blotting paper), and outdoor exposure.

Table 7

Fatigue Classification Indexes (F)

Class, F	Initial Joint Width, mm (in.)	Amplitude of Joint Movement, mm (in.)	Test Temperature, °C (°F)
F_1	1 (0.04)	-0.5 to 0.5 (-0.02 to 0.02)	20 (68)
F_2	1 (0.04)	-0.5 to 0.5 (-0.02 to 0.02)	0 (32)
F_3	2 (0.08)	-1 to 1 (-0.04 to 0.04)	0 (32)
F_4	2 (0.08)	-1 to 1 (-0.04 to 0.04)	-10 (14)
F_5	2 (0.08)	-1 to 1 (-0.04 to 0.04)	-20 (-4)

Table 8

Indentation Classification Indexes (I)

Class, I	Static Puncture Load Subclass, kg (lb)	Dynamic Puncture Load Subclass, N (lbf)
I_1	L_1 = < 7 (< 15.4)	D_2 = 1000 to 2000 (225 to 450)
I_2	L_2 = 7 to 15 (15.4 to 33)	D_2 = 1000 to 2000 (225 to 450)
I_3	L_3 = 15 to 20 (33 to 44)	D_2 = 1000 to 2000
I_{3S}*	L_{3S} = > 20 (> 44)	D_2 = 1000 to 2000 (225 to 450)
I_4	L_4 = > 25 (> 55)	D_2 = 1000 to 2000 (225 to 450)
I_5	L_4 = > 25 (< 55)	D_3 = > 2000 (> 450)

* for single ply membranes.

Table 9

Thermal Slippage Indexes

Thermal Classification T	Slippage Amplitude	Test Temperature, °C (°F)
T_1	> 2	60 (140)
T_2	< 2	60 (140)
T_3	< 2	80 (176)
T_4	< 2	90 (194)

Table 10
Roof Use and Type of Protection

	Use:	Maintenance	Maintenance	Pedestrian	Vehicles	Pedestrian	Gardens	Walkways	Walkways
Substrate	**Slope**	**Factory Surfacing**[1]	**Ballast**[2]	**Pavers**	**Pavers**	**Pavers + Pedestals**	**Direct Drainage**	**Factory Surfacing**	**Slabs + Gravel**[2]
Thermal Insulation	0 low pitched	$F_4I_2T_2$[3,4] $F_4I_2T_2$[3,4] $F_4I_2T_2$[6]	$F_3I_3T_1$[5] $F_3I_3T_2$[5]	$F_4I_4T_2$	$F_4I_4T_2$	$F_5I_4T_3$ $F_5I_4T_3$	$F_3I_5T_1$ $F_3I_5T_2$	$F_4I_4T_2$ $F_4I_4T_2$ $F_4I_4T_2$[6]	$F_3I_3T_2$[5] $F_3I_3T_2$[5]
Concrete	0 low pitched	$F_4I_2T_2$ $F_4I_2T_2$ $F_4I_2T_2$	$F_3I_3T_1$ $F_3I_3T_2$	$F_4I_4T_2$	$F_4I_4T_2$	$F_5I_4T_3$ $F_5I_4T_3$	$F_3I_5T_1$ $F_3I_5T_2$	$F_4I_4T_2$ $F_4I_4T_2$ $F_4I_4T_2$	$F_3I_3T_2$ $F_3I_3T_2$
Concrete + Prot. Memb.	0 low		$F_3I_3T_1$ $F_3I_3T_2$	$F_4I_4T_2$		$F_3I_3T_2$[2] $F_3I_3T_2$[2]	$F_3I_5T_1$ $F_3I_5T_2$		$F_3I_3T_1$ $F_3I_3T_2$
Cellular Concrete	low pitched	$F_4I_2T_2$ $F_4I_2T_2$	$F_3I_3T_2$					$F_4I_4T_2$ $F_4I_4T_2$	$F_3I_3T_2$
Wood or Plywood	low pitched	$F_4I_2T_2$ $F_4I_2T_2$[6]	$F_3I_3T_2$					$F_4I_4T_2$ $F_4I_4T_2$[6]	$F_3I_3T_2$
Existing Membranes	0 low pitched	$F_4I_2T_2$ $F_4I_2T_2$ $F_4I_2T_2$[6]	$F_3I_3T_2$ $F_3I_3T_2$	$F_4I_4T_2$	$F_4I_4T_2$	$F_5I_4T_3$ $F_5I_4T_3$	$F_3I_5T_1$ $F_3I_5T_2$	$F_4I_4T_2$ $F_4I_4T_2$ $F_4I_4T_2$[6]	$F_3I_3T_2$ $F_3I_3T_2$

(1) Index I becomes I_{3s} for single ply membranes.
(2) Index I becomes I_4 for single ply membranes.
(3) Index I becomes I_3 for mineral wool on concretes.
(4) Index I becomes I_3 for R = >2 ((m^2 x K)/W mineral wool.
(5) Index I becomes I_4 for EPS and for mineral wool on concretes.
(6) Index T becomes T_3 for R = >2 (m^2 x K)/W (See notes).

Notes: "Pitched" is slopes greater than 3 to 5 percent (0.36 to 0.6 in./ft). "R > 2 (m^2 x K)/W" means unusually thick insulation.

Table 11

Guidelines for Heat Aging Roofing Materials

Average Daily Maximum Temperature, Summer	Group	% Sunshine Hours <40	40-80	>80
Approx. 25 °C (77 °F)	A	56 days @ 80 °C	112 days @80 °C	224 days @ 80 °C
Approx. 35 °C (95 °F)	B	56 days @ 90 °C	112 days @90 °C	224 days @ 90 °C

The attributes evaluated are tensile strength and elongation at -20 °C and 23 °C (-4 ° and 73 °F), flexibility (0.2, 0.4, 1.2, 2, 4 in. diameter) at 5 °C (9 °F) intervals from 25 ° to -20 °C (77 ° to -4 °F), change in dimensions, change in weight, and change in the appearance of the surface.

Swedish Council for Building Research

The Swedish Council for Building Research suggests (Tornkvist 1990) heat aging tests [12 weeks at 70 °C (158 °F) for nonexposed materials {not directly exposed to the weather} and 24 weeks at 70 °C (158 °F) for exposed materials], and ozone tests [with 50 pphm ozone at 30 °C (86 °F) at 80 percent strain, for 96 hours]. Roofing systems are rated depending on the exposure and the following criteria.

- After Thermal Aging — no visible cracks,
  >80 and <150 percent of original tensile strength,
  <50 percent change of original elongation,
  <10 °K (18 °R) change in the brittle temperature, and
  <50 percent change in the "elongation with retained watertightness test."
- After UV Degradation — no visible cracks,
  <30 percent change in tensile strength,
  <30 percent change of original elongation,
  <10 °K (18 °R) change in the brittle temperature, and
  <50 percent change in the "elongation with retained watertightness test."
- Ozone resistance — no visible cracks.
- Sliding at High Temperature — <2 mm (0.08 in.) sliding after 24 hours vertically at 80 °C (176 °F).
- Dimensional Stability — <0.5 percent change in length, width, or diagonal after 24 hours at 80 °C (176 °F).
- Resistance to Ignition By Flying Brands - 80,000 mm^3 pine brand, 2 and 4 m/s (4.5 and 9 mph) wind — in triplicate
  in the membrane or substrate, the average damage > 550 mm (22 in.) from the center of the fire,
  in both the membrane and substrate, maximum damage in any test is <800 mm (<31 in.).
- Protection Against Slipping - test method being prepared. Currently (1990), subjective evaluation by three people of a coated inclined plane.
- Adhesion of Surfacing - <150 g/m^2 (0.03 lb/ft^2) loss.
- Ability to Accommodate Movement -
  Class 1 - ≥ 10 percent - slopes < 1:16 (¾ in./ft), risk of ice thicker than 50 mm (2 in.), and/or substrate movements greater than 5 mm (0.2 in.).
  Class 2 - ≥ 5 percent - slopes <1:16 (¾ in./ft), icing risk is < 50 mm (2 in.), and/or the substrate movements are < 5 mm (0.2 in.).
  Class 3 - ≥ 1 percent - slopes >1:16 (¾ in./ft), little ice risk, and substrate movements transmitted to the membrane are small.

- Resistance to Mechanical Action -
  Class 1 - Dynamic puncture - ≤ 10 mm (0.39 in.) diameter at -10 °C (14 °F),
  Static puncture - ≥ 250 N (56 lbf).
  Class 2 - Dynamic puncture - ≤ 20 mm (0.78 in.) diameter at -10 °C (14 °F),
  Static puncture - ≥ 150 N (34 lbf).
  Class 3 - Dynamic puncture - ≤ 30 mm (1.18 in.) diameter at -10 °C (14 °F),
  Static puncture - ≥ 70 N (16 lbf).
- Resistance to Fatigue - under preparation, no test or criteria listed.
- Water Vapor Transmission - no requirement.
- System Safety (reliability) -
  Application Method A - Application is in two separate watertight applications.
  Application Method B - Application is in one watertight application.

Summary

Many of the proposed performance criteria rely on the properties of the material under test, and the change in the values with accelerated exposure, rather than any critical performance characteristic. Even deceptively simple performance criteria, such as for fire resistance, are arbitrary. They have not been verified by experience in the field. Indeed, few of the proposed criteria have been verified by outdoor weathering or life study tests. In addition, these "performance values" are not helpful in estimating how long a roofing system will last.

The changes in the physical properties of a material are frequently used as a measure of the rate of deterioration due to weathering or accelerated aging tests. Indeed, most existing performance criteria are based on the retention of physical properties. Although these physical property tests are useful in evaluating a single generic type of membrane (i.e., comparing two PVC membranes, or two EPDM membranes) they can only be of secondary interest when comparing different types of membranes, because of divergent degradation mechanisms, and because different membranes are tested by differing test methods that are not comparable.

Some advocates of a "performance property" erroneously believe that below a minimum value for each physical property (such as tensile strength, elongation, etc.) any membrane will fail, and above that value, any membrane will endure; researchers only have to determine these minimum values. These overly simplistic concepts do not fit the very complex nature of the weathering process. In any one material there is no single or group of physical tests that will accurately predict the durability of a membrane. There is also the inability of a single battery of tests to determine the more weatherable from a heterogenous group of membranes. The validity of the "critical performance characteristics" is thus in question.

Researchers frequently avoid some of the problems of comparing alternate membrane materials and systems by means of physical testing by following the assumption that any change in the physical properties of a membrane demonstrates weather instability. They will use some empirical or arbitrary limit such as "the elongation shall not change more than 10 percent" or "the sample shall retain 95 percent of its mass."

Despite the problems associated with measuring the effect of weathering using physical tests, the physical properties of materials are too important to be ignored. Studies to date show that tensile strength and elongation are not useful in tracing the comparative rates of deterioration of the different roofing membrane materials.

5 DEGRADATION FACTORS

Degradation factors are defined as external factors that adversely affect the performance of building materials and components. These include weathering, biological, stress, incompatibility, and use factors. The U.S. Army Materiel Command has identified and discussed 21 environmental factors to which materials are exposed during their life cycle (AMC, March 1975). The natural environmental factors are:

- Terrain
- Humidity
- Solar Radiation
- Solid Precipitation
- Wind
- Macrobiologic Organisms
- Microbiologic Organisms
- Temperature
- Pressure
- Rain
- Fog and Whiteout
- Salt, Salt Fog, and Salt Water
- Ozone

The induced environmental factors are:

- Atmospheric Pollutants
- Vibration
- Acceleration
- Electromagnetic Radiation
- Sand and Dust
- Mechanical Shock
- Acoustics
- Nuclear Radiation

The "roof environment" covers all possible combinations of factors — it is an indivisible whole. For this study, however, it is practical to consider the factors of the broad spectrum of climates where military facilities are required, to consider those environmental factors that influence the performance life of roofing membranes, and to consider those roofing system design variables that tend to magnify the effect of the environmental factors such as:

- the presence or absence of thermal insulation,
- the type and degree of roofing-to-structure attachment,
- the stability of the substrate,
- the slope of the membrane surface toward drains,
- the quantity and type of roofing system penetrations, and
- the presence or absence of a vapor retarder or air barrier.

Most U.S. military facilities are in moderate climates; few permanent installations are in the arctic, antarctic, or tropic zones. The roofing system design requires care at any time, but unusual care is needed for the few facilities located in the arctic and on top of mountains, because the magnitude of the extremes of temperature, solar radiation, and wind in these remote regions is great and requires individual study, outside the scope of this report. Table 12 shows the relationship of the important environmental factors to the local climate. The factors previously listed that are unimportant for roofing systems are not included.

The environmental factors can have different effects if present when the membrane is applied, during the middle of its service life, or as it reaches the end of its service life.

Due to experimental constraints, it is not feasible to include the effects of all degradation factors within this study. For roofing membrane materials, the following factors should be considered at a minimum — temperature (heat), solar radiation, water, ozone, and hail. When possible, the range of degradation factors are quantified by means of weathering and climatological data. None of the climatological contaminants such as "acid rain" are reported to affect any of the materials included in this

Table 12

Relationship of Environmental Factors for Roofing to Climate

Factors, in Decreasing Order of Influence	Cold	Desert	Temperate	Tropical
Temperature	xxx	xxx	xx	xxx
Solar Radiation	x	xxx	xx	xx
Rain	xx	x	xx	xx
Humidity	o	o	xx	xxx
Wind	xx	xx	xx	x
Salt, Salt Fog, Salt Water	x	x	x	xx
Sand and Dust	o	xxx	x	x
Snow and Ice	xxx	o	xx	o
Microbiological Organisms	o	o	x	xxx
Macrobiological Organisms	x	o	x	xx
Atmospheric Pollutants and Ozone	o	o	xx	o

Legend: xxx = key factor; xx = important factor; x = factor; o = unimportant factor.

report. The specific local contaminants that can damage individual materials are considered in the next section on the reported degradation mechanisms.

Temperature (Heat)

Temperature is the relative measure that indicates the capacity of a body to transfer heat according to one of several arbitrary scales (Celsius, Fahrenheit, Kelvin, or Rankine). The temperature scales are usually defined by three points: absolute zero (the lowest possible temperature), the ice point (where pure water freezes), and the steam point (where pure water boils at sea level). Table 13 list the temperature at each of these points for each arbitrary scale.

The natural air temperature of the earth ranges from -88 to 58 °C (-127 to 136 °F). The full range does not occur at any one point, but temperature changes of 100 °C (180 °F) have been recorded at some locations.

Table 13

Comparison of Temperature Scales at Standard Fixed Points*

Standard Point @ Sea Level	Celsius	Fahrenheit	Kelvin	Rankine
Absolute zero	-273,15	-459.67	0	0
Ice point	0	32	273.15	491.67
Steam point	100	212	373.15	671.67

*AMC, *Engineering Design Handbook, Environmental Series, Part Two, Natural Environmental Factors*, Headquarters, U.S. Army Materiel Command, AMC Pamphlet 706-116, April 1975, p 3-2.

For roof surfaces, the temperature depends on the quantity of solar radiation, the degree of cloud cover, the absorbance of solar radiation (the color of the roof) and, to a much lesser extent, the wind speed and the quantity of insulation in the roofing system. Table 14 lists the maximum probable temperatures in Washington, DC, for black, gray, and white roof surfaces, with a surface wind of 8 to 16 kph (5 to 10 mph), and an indoor temperature of 22 °C (72 °F), both with an infinite quantity of insulation, and with no insulation.

These values are important, because they demonstrate that the color or a roof membrane has a greater influence on the surface temperature of the membrane than the quantity of insulation. Membrane color typically changes with age; it tends toward the color of the ambient dirt. In addition, 70 °C (158 °F) loosely forms the upper bound for the temperature for life testing roofing membranes, because membranes tested above that value may display reactions that do not accurately portray the reactions during normal weathering. A 10 °C (18 °F) rise doubles the rates of many reactions, and incorrect conclusions may be drawn from these test data. While 70 °C (158 °F) is a practical upper limit, temperatures sometimes are higher; roof surface temperatures of 74 °C (166 °F) have been measure on wind sheltered, black surfaces, in full sun, in Newtown, CT, and air temperatures as high as 100 °C (212 °F) have been measured inside a steel boxcar in Savannah, GA (unpublished data).

The thermal history of a roofing membrane is the single greatest factor in the durability of the roofing system, because, while some of the results of thermal cycling are reversible, some are cumulative. Leikina et al. (1971) showed that temperature was a greater influence on polymer tensile strength and elongation than radiation, time of wetness, and total test time. Of the normal ranges of the climatic factors of heat, water, and solar radiation, temperature is likely the most pervasive and powerful. Heat aging is an accelerant in almost all accelerated weathering tests, (Farhi 1980, Burstrom 1980, Beech 1991) and is frequently used in quality control tests of bitumens and rubbers.

Solar Radiation

Solar radiation includes everything that radiates from the sun. Virtually all of the radiation power that impinges on the earth comes from the 100 nm to 100 µm region of the solar spectrum. Solar radiation intensities are 0 to 111 Btu/sq ft/h. The region of the solar spectrum of interest when considering degradation of roofing membrane materials includes ultraviolet radiation, visible radiation, and part of the infrared band. X-rays have not been shown to influence the performance of roofing materials.

Ultraviolet rays have been blamed for accelerating the deterioration of roofing materials. Organic fibers and fabrics are particularly sensitive to UV radiation, losing tensile strength, elongation, and energy

Table 14

Calculated Roof Surface Temperatures as a Function of Color and Insulation Quality*

	Maximum Roof Surface Temperatures, °C (°F)		
Insulation Thickness	Black	Gray	White
None	62(144)	55(131)	48(119)
Infinite	70(158)	62(143)	53(128)

*Source: Rossiter, W.J., R.G. Mathey, *Effect of Insulation on the Surface Temperature of Roof Membranes*, NBSIR 76-987 (National Institute of Standards and Technology, February 1976), p 9.

to break. The extent of solar radiation damage can be determined by examining the exposed surface of the solvent extraction residue of asphalt saturated felts (an increasing darkness of the stain is directly related to an increasing exposure time). As shown in an unpublished study by Cash, this stain is not a UV effect. Felts exposed under thick lead glass, which should filter out all of the UV, shows stains identical to felts exposed without cover glasses. Since depth of stain is consistent with the degree of deterioration, the radiation of wavelength longer than UV may be of importance in some or all roofing deterioration.

Exposure of plastics of all kinds show that UV radiation breaks chemical bonds within the polymers. UV cabinets are used to test PVC membranes, but investigations (Cash 1991) found the UV cabinet does not accurately reproduce the same route to failure as outdoor weathering. The low influence of UV as compared to temperature on roofing materials is probably partly due to the success of the manufacturers in minimizing the UV effect by the use of carbon black (in rubbers) and UV absorbers in PVCs.

Radiation from visible and infrared regions of the spectrum supply most of the heat in our atmosphere (the balance comes from the internal heat of our planet). As such, they are a significant consideration in the performance of the roofing.

Water

Aside from hail, precipitation in all its forms in various climates such as drizzle, fog, rain, salt fog, snow, and whiteout are not principal causes of the deterioration of a properly designed and installed roof. Although, water ponded on the roof surface can cause a 50 percent loss in the projected life of the membrane, the presence of ponded water is the result of either inadequate design or improper workmanship.

Experience shows that prompt, effective drainage of the roofing surface is critical to roofing membrane performance. Water retained by constructions that tend to retard the drying of surface moisture, such as ballasted or inverted membranes, reduces the life of the membrane by leaching plasticizers, attacking adhesives, and weakening reinforcing felts or scrims.

In addition, dew or condensation can provide an important source of destructive moisture by increasing the time the roofing surfaces are wet. The "wet time" is probably a more important index for deterioration than the quantity of precipitation at any given location. The higher the "wet time," the greater the degradation.

A given storm may provide from 0.1 to 40 in. of rain in a single fall. Wide differences in rainfall intensity require drainage systems with a wide capacity range. While outside the scope of this report, other documents (ASPE, September 1990) provide drainage system guidance to designers.

Ozone

Ozone is both a natural and a man-made pollution contaminant in the air. Its chemical formula is O_3, and it has a specific gravity of 1.658 relative to air. Ozone encountered in unpolluted air near the surface of the earth is probably synthesized in the stratosphere by photosynthesis from oxygen (per Equation 1) and conducted to the earth's surface by atmospheric circulation.

$$3\ O_2 + \text{photons} \Rightarrow 2\ O_3\ (\lambda < 240\ \text{mm wavelength}) \qquad \text{[Eq 1]}$$

The quantity of natural ozone is not likely to exceed 6 pphm (parts per 100 million). Ozone is also produced by lightning, electrical discharges, and nuclear radiation.

The quantity of ozone synthesized in polluted air is 10 times greater than the concentration found in clean air, because of the presence of organic pollutants that are quickly oxidized in the presence of solar energy to produce ozone. Ozone is quite toxic (*Toxic and Hazardous Industrial Chemicals Safety Manual* 1975-1976); its threshold limit value (TLV) is 0.1 ppm and its Toxic Dose Level (TDL) is 2 ppm.

Ozone is very reactive and causes deterioration of all polymers with double bonds that are under stress. Rubbers, with the many double bonds they contain, are particularly sensitive to ozone attack.

Hail

Hail is the most destructive type of precipitation for roofing membranes. Until recently, most hail damage was claimed due to crop damage. With urban areas expanding in formerly agricultural areas that are hail prone, claims are increasing for hail damage to residential and industrial roofing. The "hail belt" in the United States includes the high plains states east of the Rocky Mountains and the Mississippi Valley plains states (AMC, April 1975).

The impact of hail on a flat roof depends on mass and terminal velocity. The terminal velocity depends on the density, diameter, and aerodynamic drag of the hailstone. Investigators (Flueler 1990; Mathey and Cullen 1974) have suggested that all plastic materials should be able to resist a 1.6 in. diameter hailstone traveling at its terminal velocity of 56 mph.

ASTM has adopted a hail resistance test (ASTM D 3746) that uses a falling dart to create an impact energy of 22 lbf x ft. The 5 lb missile has a 2 in. diameter spherical head and is dropped 53 in. Test data agree closely with the damage made by ice bullets propelled by compressed air traveling at their terminal velocity. This ASTM test has also been useful in testing the brittleness of exposed PVC specimens, when the specimens are tested at -18 °C (0 °F). Specimens that fail this low temperature test are susceptible to a shattering type of failure in service.

6 DEGRADATION MECHANISMS

A degradation mechanism is the sequence of chemical or physical changes, or both, that leads to detrimental changes in one or more properties of the membrane materials when exposed to one or more degradation factors. The most frequently observed physical changes due to weathering include a loss of strength, reduction in elongation to failure, and increased water content. Membrane materials also experience complex changes that involve chemical reactions and morphological changes comprising:

- chain scission (breaking molecules),
- crosslinking (joining molecules),
- condensation-polymerization (extending molecules),
- crystallization (becoming more structured), and
- volatilization (loss of low molecular weight components).

The remainder of this chapter describes the general changes in the physical and chemical properties roofing membranes undergo due to exposure. The probable ultimate failure modes for an aged membrane are also discussed.

BUR

Physical Changes

Glass fiber and organic felt reinforced asphalt BUR membranes increase in density, tensile strength, and moisture content as they weather. They have a decrease in mass, tear strength, elongation, and flexibility. The ultimate failure mode of the membrane is either splitting (permitted by aged, wet, reinforcing felts) or wearing out (through propagation of surface cracks).

Chemical Changes

Until recently, most evaluations of weathering mechanisms of asphalt relied solely on physical testing. The rapid chromatographic separation of the asphalt fractions, which replaced the tedious solvent elution techniques, is encouraging the study of the chemical changes that take place as asphalt weathers. Both the solvent elution and the chromatographic techniques show that part of the aromatic fraction of the asphalt in built-up roofing membranes is converted by oxidation and condensation to increase the resin fraction, and part of the resin fraction condenses to increase the asphaltene fraction. The loss from the low molecular weight saturates fraction and the increase in the high molecular weight asphaltenes fraction, are confirmed by the increase in tensile strength and decrease in the elongation of exposed membranes.

Infrared spectra (Mathieu and Pagnini 1991) show an increase in the hydroxyl groups (-OH), carbonyl groups (-C=O keytones, anhydrides, carboxylic acids and derivatives), and carbon-to-carbon double bonds (-C=C-). Studies by Greenfield and Weeks (October 1963) demonstrated that the degree of carbonyl formation was proportional to the thin film weathering time of asphalts in carbon arc Weather-o-Meters.

PVC

Physical Changes

Reinforced PVC roofing membranes usually increase in density, hardness, and tensile strength as they weather (investigations [Leikina et al. 1971)] showed that the tensile strength declined with irradiation at low temperatures). The membranes decrease in elongation, energy under the load-strain curve, plasticizer, thickness, and resistance to low temperature impact. Common failure modes are holes in the membrane due to mechanical damage permitted by the low energy under the load-strain curve, decreased low temperature impact resistance, and cracks from surface crazing. Some unreinforced PVC membranes have shown severe shrinkage due to plasticizer loss and the tendency to shatter (catastrophic splitting over the entire area) at low temperatures (Cash, February 1992).

Chemical Changes

The weathering of PVC polymers has received more attention than any other polymer. The degradation mechanisms (Wypych 1990) include the complementary thermal and irradiation effects. "Pure" PVC membranes should be inert to photodegradation because of the absence of double bonds in the chain, but photodegradation can be initiated by thermal dehydrochlorinization, solvent residues, unstable plasticizer fragments, carbonyl groups, and hydroperoxides.

Dehydrochlorination is the primary method of PVC thermal degradation (Equation 2).

$$-(CH_2\text{-}CHCl)_n\text{-} \Rightarrow HCl + -(CH{=}CH)_n\text{-} \qquad \text{[Eq 2]}$$

This leads to unsaturation (the formation of double bonds), which are precursors of hydroperoxides, and carbonyl groups, which ultimately result in an increased molecular weight. In most temperate climates, thermal degradation is more important than photodegradation.

Photolysis (light induced destruction) and photooxidation (light induced oxidation) are responsible for the formation of free radicals that tend to form carbonyl groups, hydroperoxides, hydroxides, unsaturations, crosslinks, and chain scissions. The carbonyl concentration increases with time, dehydrochlorinization, temperature, radiation, and the stress in the membrane. The photodegradation starts at the exposed surface, and gradually penetrates through the membrane.

Bowley, et al. (December 1986) showed that more dehydrochlorination took place in samples exposed at 0 ° incline (horizontal) than in samples exposed at 45 ° facing south. The authors concluded that the samples at 0 ° incline received more ultraviolet radiation in the high energy 292-350 nm range (UV < 292 is filtered out by the atmosphere) than the samples exposed at 45 °, because of the UV scattered by the atmosphere. This work is important, because it demonstrates that the conventional exposure angle of 45 ° facing south (in the northern hemisphere) does not provide the most severe exposure condition.

Modified Bitumens

Physical Changes

The physical properties of modified bitumens before weathering have received more attention than the change in physical or chemical properties during weathering. USACERL Report M-86/21 (Rosenfield

et al., September 1986) provides an excellent background and tabulation of the as-manufactured physical properties of many modified bitumen products.

The change in the physical properties of modified bitumen membranes is influenced by the type of reinforcing and the type of modifier. Both increases and decreases in tensile strength and elongation are reported after weathering or heat aging (Baxter and Kearney 1991), largely dependent on the type of reinforcement. The cold temperature bending properties are controlled principally by the modifier, and decrease (degrade) in every case tested after heat aging, C/UV (condensing ultraviolet), and outdoor weathering. The ultimate failure mode for at least some of the modified bitumen membranes is shrinkage, pulling the seams apart. In more dimensionally stable systems, ultimate failure is likely to be membrane splits, permitted by the decreased load under the load-strain curve, or propagation of surface cracking.

Chemical Changes

The changes in the properties of the membrane are thought to be similar to a blend of the deterioration mechanisms of built-up roofing membranes and the polymer used as a modifier. The SBS modified asphalt membranes are theoretically more sensitive than the APP modified asphalt membranes to both heat and UV radiation, due to the double bonds within the SBS polymer. But, as in PVC, the apparent orderliness of the APP polymer masks the disorder (unsaturations, broken chains, contaminants) found in the manufactured product.

Duchesne (1991) reported that the polymer content, the elasticity and the modified bitumen softening point and penetration decrease with weathering, while the mean molecular weight increases. This is consistent with the deterioration of the modifying polymer (that provides the elongation, elasticity, and softening point increase to the bitumen), and the hardening due to the shift toward the asphaltene fractions, that is typical of asphalt aging. Other investigations (Mathey and Rossiter, September 1974) have shown that certain modified bitumen sheets lost less mass and are more dimensionally stable than some EPDM and PVC sheets after being exposed to 14 days at 75 °C (167 °F).

The polymer changes during weathering are influenced by heat, stress, and UV exposure to form free radicals that result in carbonyl, peroxide, and hydroxide groups, chain scission, crosslinks, and condensations. The concentration of the carbonyl groups grows as the thermal deterioration increases (Wypych 1990). Since carbonyl groups are able to absorb sunlight in the UV region, the carbonyl concentration determines the photo stability of the membrane. These reactions first take place on the exposed surface and later extend into the body of the material. Carbon black is considered an excellent stabilizer for polyethylene; perhaps asphalt serves a somewhat similar function.

EPDM

Physical Changes

EPDM membrane tensile strength decreases after an initial slight increase, the water absorption and hardness increase, and the elongation decreases (Bailey, Foltz, and Rosenfield 1991) as the membranes weather outdoors. The most common failure mode currently observed is leakage through open seams (usually associated with the application of inadequate quantities of adhesive). Aside from seam failure, EPDM rubbers fail by embrittlement and propagation of surface crazing.

Chemical Changes

The degradation mechanisms of the polyethylene and propylene component of EPDM are very similar to the deterioration of polyethylene (Wypych 1990); it oxidizes at elevated temperatures to form hydroperoxides that are converted by UV exposure to carbonyl and hydroxide groups. UV radiation increases the crystallinity and shrinkage within the polymer, tending to decrease the tensile strength and elongation.

The EPDM rubbers are considered "saturated rubbers" because of the few double bonds they contain. The absence of double bonds reduces the EPDM susceptibility to the ozone deterioration experienced by the natural and other synthetic elastomers. Koike (Koike and Tanaka 1973) measured the ozone resistance of sheets made from IIR (butyl), IIR-EPDM blends, CR (neoprene), and PIB (polyisobutylene) rubbers. One CII-EPDM did not fail during the test; the other samples all failed during the testing interval. Increasing ozone resistance of the blends depends on increasing the proportion of EPDM present (Nix and van Eeden 1981).

EPDM material is so stable that little is documented about its failure mode, and the literature reports (Rossiter and Seiler, June 1989) favorably on EPDM durability. The durability of the seams in the EPDM membrane is currently of the greatest concern, the source of most of the problems reported (Rossiter et al., January 1991), and the subject of many studies (Martin et al., May 1990) As with most rubbers, EPDM membranes have a low tear strength, and poor resistance to petroleum solvents and greases.

7 PROPOSALS FOR ACCELERATED AGING TESTS AND SERVICE LIFE PREDICTION

Accelerated Aging Tests

The following lists propose specific procedures for accelerating the identified mechanisms of degradation. All accelerated aging tests imply most of the following concepts:

- The sample under test is suitable for the intended purpose at the start of the test (accelerated aging is obviously superfluous if the unaged sample is unsuitable for the use).
- Either one or more degradation factors are used to apply stress to the sample for the time period necessary to develop a specific level of response (sometimes called the failure point), or the change in the response is measured due to stresses applied for a specific period.
- The aging stress applied is not of such a large magnitude that it causes degradation mechanisms that are absent in aging in the natural environment.
- Each material has a level of stress resistance that is irreversibly diminished by exposure to the imposed stresses.
- While not identical, the degradation factors of heat, radiation, mechanical, and all other stresses are interchangeable, through the use of appropriate conversion factors.
- The reduction of the stress resistance level is proportional to the service life of the sample.
- A direct ratio exists between the outdoor weathering time and the accelerated aging time required to achieve the same level of response from the sample.

Some of the techniques used to accelerate the aging process include heat (aging at 60 to 150 °C [140 to 302 °F]), ultraviolet radiation (aging in a UV light chamber), water (spray or soak), and mechanical load.

Heat

Heat is the most popular aging method. Every accelerated aging method includes heat as one of the applied degradation factors, and heat aging is the method of choice for aging bitumens, modified bitumens, EPDM, and PVC.

The temperatures for heat aging sometimes vary with the product being tested. A review of some of the ASTM test methods shows temperatures ranging from 60 °C (140 °F) for the back panel temperature in carbon or xenon arc Weather-o-Meters and condensing UV equipment, through 70 °C (158 °F) for heat aging sealants (ASTM C 792) and liquid applied roofing membranes (ASTM C 836), through 105 °C (221 °F) for heat aging papers and boards (ASTM D 776), to 100 to 150 °C (212 to 302 °F) for rubber products such as belting (ASTM D 378) and rubber carpet underlay (ASTM D 3676). Most of the heat aging tests for building materials use 70 °C (158 °F).

Ultraviolet Radiation

Ultraviolet radiation exposure is provided by sunlight carbon arcs (ASTM G 23), xenon arcs (ASTM G 26) UV fluorescent, or mercury lamps (ASTM G 53). Some equipment, such as EMMAQUA (equatorial mount with mirrors for acceleration with water), concentrates sunlight (ASTM G 90) on samples by lens or mirrors.

Relative photon energy decreases sharply from 2.75 pm (2.75 a.u.) at a wavelength of 300 nm as the wave length increases. The solar radiation that reaches the surface of the earth is cut off by the atmosphere near 300 nm. This is important, because samples exposed to wavelengths lower than this threshold are likely to exhibit different reactions than observed in natural weathering, and therefore limiting the light sources which can be used for accelerated weathering. Both the sunshine arc and some of the fluorescent lamps provide radiation below 300 nm, and their utility is questionable. Some researchers (Rabinovitch and Butler, March 1991; Cash 1991) concluded that QUV testing (that uses fluorescent lamps) cannot predict the weathering performance of PVC membranes. Studies also show the EMMAQUA equipment focuses a larger proportion of ultraviolet, compared to the total radiation, than the proportion of ultraviolet radiation found in sunlight.

Water

Water exposure is part of many accelerated testing programs. Water spray is used in some programs to provide a "thermal shock" to the samples, and to wash away any water-soluble degradation products. Condensing humidity is the feature of some programs, and intervals of water soak and freezing are provided by some equipment used by investigators in colder climates. One roofing product manufacturer has used heat and steam in an autoclave, and in 1981 and 1984, the MRCA used a water soak at room temperature to accelerate the deterioration of felt plies.

Relatively few studies have been made of the effect of water exposure alone on roofing membranes. It is known that exposure to ponded water decreases the effective life of built-up and PVC membranes, but the long term effect of water on EPDM membranes is currently unknown.

Mechanical Loads

Mechanical loads are frequently used with ozone exposure of elastomers. Indeed, the ozone exposure has little or no effect if the sample is not stretched. Some investigators measure the time needed for an applied load to dissipate, and some regard the relaxation time at various temperatures to be an index of durability. Dead loads, for creep-to-failure, are often used in service life tests.

Service Life Prediction

Service life reliability tests are accelerated tests that use statistical techniques to estimate the mean exposure time to failure, within a specific reliability (Nelson 1990). Both Nelson and Martin (Martin 1982) provide the mathematics for service life reliability tests that are too extensive for the scope of this report, but should be consulted when applying mathematics to life testing.

To perform comparative service life reliability tests, ideally it is necessary to:

- define "failure,"
- have physical test methods to track the rate of degradation,
- have chemical tests that can nondestructively measure the rate of deterioration,

- expose representative samples of each membrane under study, and
- expose the samples to identical stresses (since the materials are exposed to the same stresses in nature).

Definition of Failure

Although failure was defined in Chapter 2 using the most common general definition, a more specific definition must be found for service life prediction. The use of "catastrophic failure" (when the sample falls apart) would likely require either extreme stress or an inordinately long testing time to fail most samples of very stable membranes.

Since the exclusion of water is of primary interest, time to failure might be chosen to mean: "time to water leakage." However, the event of water leakage could be difficult to monitor on a continuing basis. "Time to water leakage after testing the aged membrane" (for example: to the impact of a falling dart at low temperatures) would be more practical.

Time to failure could also be defined as the time for the loss of a specific quantity (or proportion) of a specific chemical or physical property. This can be of great utility when comparing similar materials, but it may be inappropriate when attempting to compare materials with widely different properties.

The major problem with defining failure for the purpose of predicting service life is that too little is known about how the physical and chemical properties compare before and after aging, since each membrane is tested by a different test method.

Physical Tests

Many of the physical tests used to characterize membranes are not suitable to track the rate of degradation. Changes in tensile strength, elongation, mass, dimensions, color, and other similar properties have not proven to be consistent measures of aging. In addition, different test methods are used with different materials, so resulting data cannot be compared. For example, Table 15 shows the differences in the specific test methods use to test the tensile properties of the membranes in this study. The tensile strength for EPDM membranes is reported in pounds per square inch (psi), while the breaking load for the other membranes is reported in pound-feet per inch (lbf/in.). Obviously researchers must combine these test methods so one single test method can be used with all of the membranes.

Table 15

ASTM Tensile Test Parameters for Roofing Membranes

Membrane Type	ASTM Method	Temp, °F	Gage Length, in.	Width, in.	Test Speed, in./min
• BUR	D 2523	0	3	1	0.05
• PVC	D 751	70	3	1	12
• MB	D 2523	0	4	1	2
• EPDM	D 412	70	1.3	0.25	20

The energy-to-break at low temperatures seems to be the outstanding candidate as a physical property for tracking the weathering process in these membranes. The National Bureau of Standards tested the tensile properties of organic felt reinforced coal-tar pitch membranes both before (Mathey and Cullen 1974) and after (Mathey and Rossiter, June 1977) 21 years of outdoor weathering at three locations. These data do not include the energy-to-break of the samples, but the energy-to-break can be estimated from the load at break and the secant modulus of elongation by:

$$\text{energy-to-break} = \frac{(\text{load-at-break})^2}{\text{modulus}} \qquad \text{[Eq 3]}$$

Table 16 shows the estimated energy-to-break of the new membranes compared with the percent loss of the estimated energy-to-break after 21 years of weathering. While the load-at-break decreased 17 to 27 percent, and the tensile modulus increased approximately 500 percent, the energy-to-break lost a significant 88 to 91 percent, confirming the importance of the energy-to-break concept.

In an unpublished study by Cash, samples from 94 5- to 13-year-old PVC membranes were tested and found to show a linear relationship (linear regression coefficient of 0.946) between the energy-to-break at -18 °C (0 °F) and the logarithm of the exposure time (Figure 3).

A paper by Strong (1983) provides load-strain graphs for tensile tests performed on PVC membranes exposed in New Mexico, and EPDM membranes exposed in Florida at intervals up to 15 years. The log of the area under each load-strain curve is plotted vs. the exposure time in Figure 4. Neither the tensile test methods or test temperatures are reported, but these data confirm the linear relationship between the log of the energy-to-break and the exposure time.

Chemical Tests

The candidate roofing materials are all chemically complex (the most complex is the oldest; asphalt), and each is very different from the other membranes. In developing service life prediction tests, finding a single factor that can be measured to trace the rate of deterioration for all the materials is highly desirable. The carbonyl group of organic compounds shows significant potential as such a factor.

Free radicals are formed in organic materials during the weathering process. Their formation in the presence of oxygen may lead to organic acids (Structure 7), ketones (Structure 8), and esters (Structure 9). Collectively, they contain the carbonyl group (C=O), and are often called carbonyl-containing compounds. The group has an infrared absorbance at about 1710-1720 cm^{-1}, that can be measured.

Table 16

Selected Load-Strain Properties @ 0 °F - lbf/in. of Organic Felt Reinforced Coal-Tar Pitch Membranes

	Machine Direction			Cross Direction		
Sample	**Load**	**Modulus**	**Energy**	**Load**	**Modulus**	**Energy**
Unexposed	468	67,000	3.27	265	74,000	0.949
Exposed	385	422,000	0.40	192	456,000	0.084
% Loss	18	-530	88	27	-516	91

(A negative means an increase.)

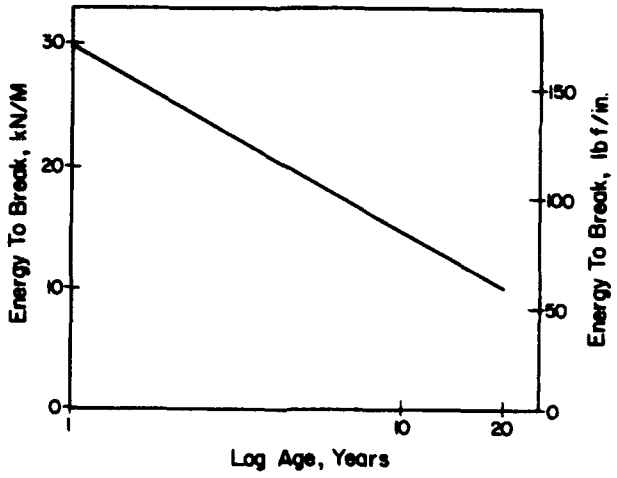


Figure 3. Energy to Break vs. Log Exposure Time for 5- to 13-year-old Reinforced PVC Membranes.

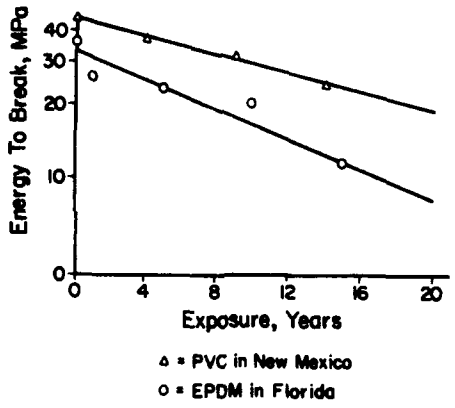
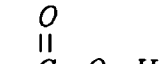
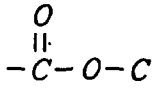


Figure 4. Energy-to-Break vs. Exposure Time.



[Structure 7]

[Structure 8]



[Structure 9]

The carbonyl index is the ratio of the carbonyl absorbance to the carbon-hydrogen absorbance (at ~1460 cm^{-1}). This index is used to correct for the quantity of the sample being tested. For example, when two samples are tested, it would not be known if the difference in the carbonyl reading is due to a change in the carbonyl concentration or the quantity of the sample. By relating the carbonyl reading to the carbon-hydrogen reading (that varies with the quantity of the sample), changes in the carbonyl concentration can be measured.

The change in carbonyl concentration has been used successfully to track the deterioration of asphalt (Greenfield and Weeks, October 1963), PVC (Matsumoto, Ohshima, and Hasuda 1984) and a long list of other polymers (Winslow, Matreyek, and Trozzolo 1972). This concept has been used to measure the difference in weathering rate of liquid-applied neoprene, CSPE (Hypalon), and polyvinylfluoride (Tedlar). In every case, the carbonyl concentration increased directly with the exposure time, and the slope of the individual curves (the rate of deterioration) was consistent with the performance in outdoor exposure. The change in the carbonyl concentration does not work with inorganic materials or silicones.

Because of the availability of modern micro-instrumentation, it may be possible to use a dedicated infrared photospectrometer to nondestructively measure the carbonyl index in the field. If nondestructive testing is successful, a method to trace deterioration in the field can be developed which could compare the deterioration rates of different materials, and perhaps (with calibration curves) estimate the remaining service life in any roof.

Representative Samples

As with any statistical testing program, the samples tested must be representative of the type of membrane being tested. It would therefore be more important to obtain samples from many runs of different manufacturers, than to obtain one large sample for outdoor, accelerated, and aging studies.

Representative samples should be randomly chosen for the various exposures. Outdoor exposures in varying climates are required to validate the measurements made during the accelerated aging tests, and to measure the effect (if any) of the different climates. Accelerated aging tests are required to predict membrane durability by some reasonable testing interval. Aging tests are required to separate effects due to aging alone from those due to accelerated aging, and those due to aging in the weather. The emphasis must be on a larger number of samples in test, rather than fewer larger samples, to maximize the reliability of the conclusions drawn from data. Single-ply membrane samples must also include laps or seams, because they are often the weak point in the membrane.

Exposure Stress

Just as all roofs are exposed to identical stress during outdoor exposure, researchers must expose the accelerated aging samples to the same stress to compare properly the performance of different membranes.

At least part of the stress applied to accelerate the aging of the samples must include heat, because temperature is so important in influencing the durability of materials. But, all of the accelerating stress cannot be provided by heat alone. Prolonged exposure to temperatures above 70 °C (156 °F) may result in reactions not observed due to natural exposure.

Of the remaining sources of stress (mechanical load, moisture, radiation), mechanical load is the most promising test parameter because it is relatively easy to apply and control and does not have the same severe limit of the stresses induced by heat. Radiation stress is probably a very small part of the

stress applied to the roofing; the stress due to radiation can be considered part of the mechanical stress applied to the samples during accelerated aging.

During accelerated aging, the stress can be applied constantly, in incremental steps, in cycles, or gradually increasing (a ramp). Constant stress is preferred because the mathematics for analysis are well developed and understood. The mathematics relating to the analysis of data from incremental step, cyclic, or ramp stress applications would be extremely complex if not incomprehensible.

Constant thermal stress can be applied in a conditioned room, and the constant mechanical load can best be provided by dead loads (hanging weights) because all but the EPDM membrane are thermoplastic.

8 CONCLUSIONS AND RECOMMENDATIONS

The existing criteria and measurements for performance testing generally are inadequate for predicting the performance of roofing membranes, because many of these measurements have not been validated as predictors of performance. Often, they are tests traditionally used for the quality control of the individual materials rather than to determine performance of generic roofing membranes.

The major performance requirements for roofing membranes are watertightness and maintainability. These factors rely principally on membrane composition. Therefore, membrane characterization should be based on the quantity and type of components in the membrane. Infrared spectroscopy and solvent chromatography can be used to determine the the physical properties based on morphology (arrangement of atoms). Because membranes are often defined by their tensile properties, tensile measurements should also be included in membrane characterization if standard test methods are developed.

The major degradation factors that should be considered in membrane characterization include heat, solar radiation, water, ozone, and hail.

The energy-to-break is proposed as the tracer of the physical deterioration of the samples, since this is the sole property that seems to vary consistently with exposure, regardless of the organic material tested. To be effective for this purpose, the load-strain test methods for the different roofing materials should be combined or "blended" to create a standard test.

The carbonyl index is proposed as the tracer of the chemical deterioration of the membrane. To measure the index efficiently, a portable infrared instrument that permits readings to be taken quickly and easily on the roof is desirable.

The following steps should be used in developing predictive service life tests:

- develop the appropriate physical and chemical degradation tracking methods.
- combine the test methods selected such that all membranes will be tested in an identical manner,
- conduct long term in-service tests of random samples in cold, temperate, desert, and tropical climates,
- conduct accelerated aging tests of random samples using several different heat and mechanical loads and possibly different levels of relative humidity.
- provisionally, use catastrophic membrane or lap failure, and failure during a uniform low temperature impact test to define failure,
- develop degradation models for predicting service life and comparing relative durabilities of roofing membrane materials.

The following tasks are recommended before initiating the accelerated aging tests and in-service tests.

- develop a single standardized load-strain test method that can be used to determine the energy-to-break at low temperatures for the different roofing materials. The test should have the necessary attributes required of an ASTM standard test method.

- Conduct laboratory investigations to determine the validity of using energy-to-break and carbonyl concentration to track physical and chemical degradation of the different roofing membrane materials. This should be accomplished by exposing material samples to accelerated aging tests of incremental durations to determine the correlation of both properties with time of exposure.

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