SHRINKAGE OF EPDM ROOF MEMBRANES: PHENOMENON, CAUSES, PREVENTION AND REMEDIATION

RALPH M. PAROLI, ANA H. DELGADO and OM DUTT
National Research Council of Canada
Institute for Research in Construction
Ottawa, Ontario

THOMAS L. SMITH and TERRANCE SIMMONS
National Roofing Contractors Association
Rosemont, Ill.

This paper reports on the problem of EPDM membrane shrinkage. Evaluations included NRCA's Project Pinpoint, shrinkage survey data and field research. Also, to further understand the phenomenon, which typically is not catastrophic, three sets of membrane samples were obtained and analyzed: control samples of new EPDM sheets, samples from roofs that exhibited moderate to severe shrinkage problems, and samples from roofs that had no noticeable problems. Evaluation included measuring the glass-transition temperature (as measured by dynamic mechanical analysis), changes in chemical composition (using thermogravimetry), tensile strength and elongation tests, as well as thermally-induced load tests. Generally, the membrane composition and properties were found to not change sufficiently to cause excessive shrinkage. Only six samples exhibited more than three percent weight loss which was attributed to oil loss and three samples had a change in glass-transition temperature greater than 5°F (3°C). Most of the aged samples met ASTM D 4637-87 specifications for elongation for new materials (300 percent). One sample did not meet this standard. The paper presents conclusions and recommendations for existing roofs, reroofing and new construction.

KEYWORDS

Base securement, bridging, contraction, dynamic mechanical analysis, EPDM, glass-transition temperature, shrinkage, tenting, thermal analysis, thermally-induced loads and thermogravimetry.

INTRODUCTION

Ethylene-propylene-diene monomer (EPDM) single-ply roof membranes have been used in North America for more than 20 years. In the past 10-15 years, their use has been widespread. In part, the acceptance of EPDM membranes has been due to their good low-temperature flexibility and good weatherability.[1] In 1994, EPDM membranes captured 22 percent of the United States commercial roofing market.[2] (Only one other type of membrane [built-up] had a larger market share.) EPDM sheets are composed of EPDM polymer and other ingredients as shown in Table 1.

Ingredient	Percent Composition
Polymer	25% - 35%
Carbon Black (for black EPDM) or Titanium Dioxide (for white EPDM)	25% - 40%
Extender Oil, Accelerator, Sulfur and Anti-oxidant	20% - 25%

Table 1. *Typical composition of a non-reinforced EPDM roofing sheet.*

The performance of EPDM roofs, typically, has been quite good. However, instances of flashing problems attributed to membrane shrinkage have occurred. Shrinkage, also referred to as contraction, tenting, bridging, normalization or volume change is described as the irreversible dimensional shortening of the roof membrane.[3] *Note: In this paper, contraction refers to membrane tightening which may be caused by shrinkage and/or other induced loads.* This dimensional change induces extra forces on lap joints (seams) and flashing/base-securement details. Rupture of the flashing/base-securement (i.e., perimeter/curb) detail may occur as the tensile forces within the membrane increase. When this happens, the waterproofing ability of such a membrane can be greatly affected, as shown in Photos 1, 2, 5 and 7.

Photo 1. *After the field sheet was torn at the metal batten, the originally uncured flashing over the batten stretched and tore. (Georgia)*

Problems resulting from the shrinkage phenomenon (or what is attributed to it) may be associated with material, design, workmanship or a combination of these factors.[3] They can also be related to substrate deterioration. For example:

- Material: The EPDM membrane contains oils added during the manufacturing of the sheet. The oil facilitates mixing and processing of the ingredients and is used in conjunction with the EPDM polymer and carbon black to achieve the desired physical properties for the membrane. Consequently, loss of oil may lead to lower flexibility and shrinkage (i.e., dimensional change).[4] In addition, crosslinking (i.e., a chemical bond joining two polymer chains together) or other molecular changes could play a role.
- Design: The design of the base securement details at perimeters and equipment curbs is important. If the detail's design lacks sufficient strength to resist shrinkage forces and other induced loads, leakage can occur as the flashing detail is pulled apart.
- Workmanship: If the execution of good base securement details is poor (e.g., the actual fastener spacing is far in excess of the specified spacing), the resulting details can be pulled apart.

During the application process, stress may also be inadvertently built into the membrane via the two mechanisms described below:

- Insufficient sheet relaxation prior to attachment: Following the manufacturing process, the sheet is rolled up for shipment. This temporarily locks in stresses, as the sheet is somewhat stretched during the rolling. To avoid building in these stresses, manufacturers recommend allowing the sheet to relax (typically for at least 30 minutes) prior to seaming or attachment. During cold weather application, the membrane may stiffen to some extent. Therefore, a greater time for relaxation is required.
- Sheet expansion prior to attachment: During warm weather application, the sheet expands as the sheet temperature increases (coefficient of thermal expansion, CTE, is 7.2×10^{-5} °F^{-1} [1.3×10^{-4} °C^{-1}]). (On clear sunny days, infrared radiation can cause the black sheets to become quite hot even in moderate ambient temperature conditions.) If the sheets are attached during application in hot conditions before they cool (which is typical), they will develop thermally-induced loads within the sheet, as the sheet temperature drops.

  Although unrelated to shrinkage, the effect of these application-induced loads may be mistaken as shrinkage, since they can cause the membrane to become taut. Fortunately, these induced loads are quite low. However, particularly when combined with high-shrinkage loads, the loading can over-stress weak base securement details and cause problems. These application-induced loads should be taken into account by the manufacturers when designing various termination details.

- Substrate deterioration: If the base securement fasteners were initially installed into a sound substrate, but that substrate subsequently deteriorates (e.g., plywood dry rot due to condensation within the parapet), the base securement fasteners can pull out and cause problems.

In 1994, the Institute for Research in Construction (IRC), of the National Research Council of Canada, and the National Roofing Contractors Association (NRCA) began a cooperative research program on EPDM shrinkage. The purpose of this research is to further understand the shrinkage phenomenon and provide recommendations for problem avoidance. To achieve these goals, 25 samples from nineteen existing roofs ranging in age from 1.5 to 18 years were collected from across the U.S.

Some of the samples came from roofs that exhibited severe shrinkage problems while others came from roofs that had no noticeable problems. In addition to the roof samples, four control samples of new EPDM sheets (produced by two different manufacturers) were obtained from contractors' stock.

Various properties of the field and control samples were investigated, namely: the glass-transition temperature (as measured by dynamic mechanical analysis), changes in chemical composition (using thermogravimetry), tensile strength tests, elongation tests and thermally-induced load tests.[4-6]

This paper presents the industry's recognition of, and response to, the shrinkage problem, field research conducted by NRCA, sample descriptions, laboratory evaluation and discussion of results. Furthermore, a general discussion, as well as conclusions and recommendations for existing roofs, reroofing and new construction, are presented.

PROBLEM RECOGNITION/RESPONSE

Early formulations of EPDM sheets in the mid-1960s had excessive shrinkage due to the use of a process oil that was too volatile. However, manufacturers soon recognized the problem and began using very low volatility oil.[7]

The issue of EPDM shrinkage did not emerge again in the public venue until the October 1992 Midwest Roofing Contractors Association (MRCA) Convention, at which time an oral presentation was made concerning 11 jobs that had experienced shrinkage. The presentation, which included some limited laboratory testing results, is summarized in References 3 and 8.

After MRCA brought this issue to the industry's attention, NRCA staff performed some initial Project Pinpoint analysis in December 1992 and January 1993. (Project Pinpoint is a database of problem and non-problem jobs, as described in Reference 9.) From this initial analysis, it did not appear that shrinkage was related to climate, as shrinkage jobs were reported throughout the U.S. At that time, there were 1,871 EPDM problem job reports in the database. The leading causes of problems were: laps (seams)—45 percent of the jobs reported this problem, flashings—25 percent, puncture/tearing—17 percent, wind—10 percent and shrinkage—10 percent. (The total exceeds 100 percent because several jobs reported multiple problems.) A more detailed analysis was performed in August 1993. From that additional analysis, it appeared that the type of insulation substrate was not a significant contributing factor, and it appeared that products from several different manufacturers had experienced shrinkage problems. A summary of the Project Pinpoint data on EPDM shrinkage is presented in Appendix 1.

Also in August 1993, NRCA began to solicit samples from members who were aware of jobs that had apparently experienced shrinkage. At the October 1993 MRCA Convention, EPDM shrinkage was again on the program. In the brief presentation, data from Project Pinpoint were presented and information on base securement details was solicited.

In November 1993, NRCA discussed the shrinkage issue with SPRI and requested their input. Also in November, NRCA surveyed the contractor members of its technical committees on the shrinkage issue. A summary of the survey responses is presented in Appendix 2.

In August 1994, NRCA met with technical representatives of two manufacturers to seek their input. At the October 1994 MRCA Convention, a document on repairing EPDM membranes that had experienced shrinkage was presented.[3] Also in October, NRCA staff investigated 13 EPDM roofs, as discussed in the next section.

In August 1994 and March 1995, two articles in *Professional Roofing* discussed shrinkage.[10,11] In November 1994, IRC received verbal reports of EPDM shrinkage in Ontario, Canada, and in February 1995, NRCA received other reports of EPDM shrinkage problems in Ontario, Canada.

Problem job and non-problem job samples submitted by NRCA members, as well as samples taken by NRCA staff, were sent to IRC in 1994 and 1995.

NRCA FIELD RESEARCH

NRCA staff investigated 13 EPDM membrane roofs in an area of Iowa that was known to have several roofs with problems attributed to shrinkage. The purpose of the investigation was to obtain additional information in order to assist NRCA's evaluation of this phenomenon. The investigators were specifically interested in documenting base securement details and collecting samples for laboratory analysis.

Prior to the investigation, some of the roofs were known to have problems attributed to shrinkage. Ten of the roofs were ballasted, one was mechanically attached and two were fully adhered. The fully adhered roofs did not exhibit visible signs of shrinkage. (Further information on these two roofs [e.g., age, manufacturer, etc.] was not obtained.) One of the ballasted roofs, which had a reinforced membrane, exhibited very minor contraction. All of the other roofs exhibited moderate or severe contraction, and six were vulnerable to water infiltration (see Photos 2-7). A summary of the investigation findings is presented in Appendix 3.

In addition to the samples taken by NRCA staff, three NRCA contractor members submitted samples from four problem jobs (Appendix 3) and three additional members submitted samples from four jobs that were not exhibiting problems (Appendix 4).

Photo 2. *Roof S5: The field sheet was attached to a CMU wall with wood battens that were fastened with plastic sleeves/drive pins, spaced at 12 in., 11½ and 9½ in. (305, 290 and 240 mm). The field sheet tore and pulled out from under the batten at the fastener locations. The originally uncured flashing over the batten was then stretched and torn. At other locations, the fasteners pulled out of the wall and the batten moved inward approximately 6 in. (150 mm).*

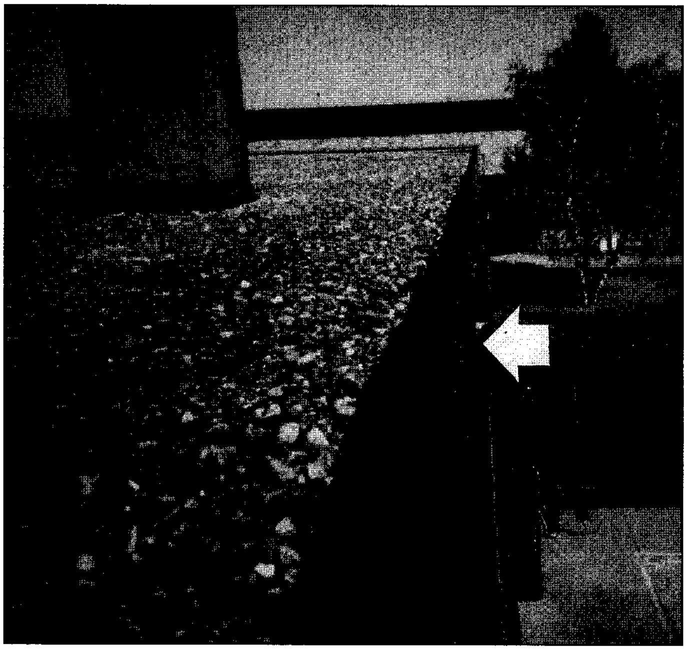

Photo 3. *Roof S7: Membrane contraction caused the top of this weak metal parapet to move to the left. The parapet rested on the field sheet and the sheet was attached with roofing nails spaced at 18 and 18 in. (455 and 455 mm). It may have also had other securement. Water can now enter the top of the parapet (see arrow).*

Photo 4. Roof S9: Along most of this parapet, the wood batten fasteners pulled out of the brick. In some locations, patches had been placed where the ends of the battens had punctured the flashing.

LABORATORY EVALUATION

To further understand the shrinkage phenomenon, various laboratory evaluations were performed on new EPDM sheets, and field samples from problem and non-problem jobs. The purpose of these evaluations was to try to determine if the contraction problems were primarily related to changes in the material properties of the membrane or if the problems were related to other factors such as inadequate base securement details or other induced loads. To accomplish this task, it was necessary to compare the laboratory data to the field data. Each data set gives an incomplete view of the phenomenon, but together, they provide insight on the contraction problem.

Photo 5. Roof S10: Looking down at a vertical transition between a new and old roof. The field sheet on the left was attached with a 1 in. (25 mm) wide aluminum batten that was fastened with screws at 12 in. (305 mm) on center. The field sheet tore at the fasteners and the originally uncured flashing over the batten was stretched until it tore.

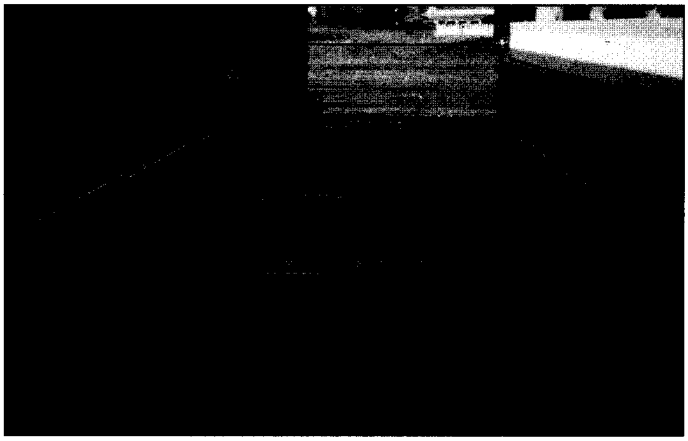

Photo 6. Roof S11: This mechanically attached roof is taut near the metal termination bars. The membrane is susceptible to puncture and tearing at the sharp ends of some of the bars.

The laboratory analysis included thermoanalytical techniques, tensile strength tests, elongation tests and thermally-induced load tests. Thermoanalytical techniques such as thermogravimetry (TG) and dynamic mechanical analysis (DMA) can be of use in monitoring chemical changes in the membrane. TG can be used to monitor weight loss which could occur if oils or plasticizers were volatilized. DMA can be used to study changes in the glass-transition temperature (Tg). The glass-transition temperature is the temperature at which a polymer loses its elasticity and behaves like a glassy material. Below the Tg, the material is stiff and brittle. Above the Tg, the membrane is flexible and exhibits rubbery characteristics.[5] The Tg of the membrane is affected by a number of factors including crosslinking and the amount of oil/plasticizers present in the matrix.

Photo 7. Roof S13: The field sheet is fastened with roofing nails that were also used to attach the metal edge flashing. The nails were spaced at 5 in., 5 in. and 4 in. (125, 125 and 100 mm). The field sheet turned down at the wall and was fastened by the continuous cleat fasteners. As the field sheet moved inward, the originally uncured flashing was stretched and torn.

Experimental

Sample Description

The specifics of the various EPDM roof membrane samples (e.g., location, age, problem severity, etc.), are summarized in Tables 2 and 3. Each sample included a seam. This allowed specimens to be taken from an exposed portion of

Sample	Manufacturer	Roof age	Attachment	Substrate	Vapor Retarder	Location	Problem Severity*
S1	A	11	Ballasted	EPS	Yes	North Dakota	Severe
S2	B	6	Ballasted	EPS	Yes	North Dakota	Moderate
S3-A and B	C	12	Ballasted	EPS	No	Wisconsin	Severe
S4-A and B	D	11	Ballasted	EPS	Yes	Missouri	Severe
S5-A and B	D	9	Ballasted	EPS	No	Iowa	Severe
S6	A	10	Ballasted	EPS	Yes	Iowa	Moderate
S7	A	14	Ballasted	EPS	Yes	Iowa	Moderate
S8	A	18	Ballasted	Rigid fiberglass over BUR	Yes (BUR)	Iowa	Severe
S9	A	15	Ballasted	Wood fibreboard over BUR	Yes (BUR)	Iowa	Severe
S10	E	1.5	Ballasted	Unreinforced PVC over BUR	Yes	Iowa	Severe
S11	E	6	Mechanically attached	Coated plywood	Coating on plywood	Iowa	Moderate
S12	E	12	Ballasted	EPS	No	Iowa	Severe
S13-A and B	E	12	Ballasted	EPS	Yes	Iowa	Moderate/ severe
S14	F	12	Ballasted	EPS	Yes	Iowa	Very Minor

* As reported by the person who took the sample.
Note: 1. Samples S1 to S4 were taken by NRCA contractor members. Samples S5 to S14 were taken by NRCA staff.
2. All roofs, except for S14, used non-reinforced membranes.

***Table 2.** Details of sampled EPDM roofs.*

Sample	Manufacturer	Roof age	Attachment	Substrate	Vapor Retarder	Location
SG1	D	11	Ballasted	Perlite	Yes	Iowa
SG2	D	10	Ballasted	EPS	Yes (BUR)	Iowa
SG3	A	—	—	—	—	Pennsylvania
SG4	B	—	—	—	—	Pennsylvania
SG5-A, B and C	A	11	Ballasted	Polyurethane	No	Colorado

***Table 3.** Details of EPDM roofs without problems.*

the membrane (the "top layer") and an unexposed portion (the "bottom layer" of the seam). In addition to the samples listed in Tables 2 and 3, new control samples were obtained from two manufacturers: Manufacturer A (STC1, STC2) and Manufacturer B (STC3 and STC4).

Since the field samples originated from naturally-weathered roofs, it was difficult to find the same unexposed membrane to be used as a control sample. Without a control it is difficult to evaluate the changes in properties for the exposed membrane. Therefore, it was necessary to use the bottom sheet at the seam which is shielded from some environmental factors (e.g., UV-radiation) as a control. Some have reservations regarding this approach because of the methods used to prepare seams (e.g., solvents, etc.). There is, however, no mention of the potential problems of using this approach in the literature. Another concern is that the temperature of the "bottom" sheet is not very different from the temperature of the "top" sheet and therefore both sheets are being affected by heat at the same rate which some feel preclude the "bottom" from being used as a control. It was found, however, that generally the control samples labelled "STC" gave similar results for the thermal analysis techniques as the "bottom" control samples.

Thermogravimetry (TG)

The weight loss of each EPDM sample was monitored using a TG/DTA 320 manufactured by Seiko Instruments USA, Inc. A platinum pan with 20-22 mg alumina was used as a reference. Each EPDM sample was cut into small pieces, within ± 0.1 mg of the reference and was placed in the sample platinum pan. Each top and bottom sheet specimen was heated from 77°F to 1,110°F (25°C to 600°C) using a heating rate of 20°F/min (10°C/min) with a nitrogen gas flow of 150 mL/min.

Dynamic Mechanical Analysis (DMA)

A Rheometrics dynamic mechanical analyzer RSAII was used to measure the Tg of the EPDM samples. Specimens were cut from the top and bottom sheets of the samples and placed on the fixture. (Note that two samples had three layers of material where an additional strip of membrane was installed.) Due to instrument constraints, the membrane thickness was considered as the width of the specimens. Prior to starting the experiment, specimens were cooled to the initial temperature and allowed to equilibrate for about one minute.

The Tg values for the samples reported in Appendix 5 were taken at the maximum of the loss modulus, E". Samples were analyzed under the following experimental conditions:

Geometry:	Film fixture
Length of specimen:	0.83 in. to 0.91 in. (21.0 mm to 23.0 mm)
Width:	0.04 in. to 0.06 in. (0.89 mm to 1.51 mm)
Thickness:	0.01 in. to 0.02 in. (0.27 mm to 0.57 mm)
Sweep type:	Temperature sweep
Temperature range:	-150°F to 105°F (-100°C to approximately 40°C)
Frequency:	1 Hz
Temperature increments:	4°F (2°C)
Soak time:	1 min.
Strain:	0.01 %
Autotension mode:	On
Initial static force: (pretension):	100 g (tension mode) used for most samples. 30 g was used for some. Plus 25% of the dynamic.
Autostrain mode:	On (to be increased by 25% when dynamic forces dropped below 5 g)

Mechanical Analysis

Specimen preparation—All EPDM tensile and induced load test specimens were prepared using die C (ASTM D 412) and a rectangular die 1 in. x 6 in. (25.4 mm x 150 mm), respectively. Four replicates (machine direction only) for the tensile test and four replicates for the induced load test were cut from each sample. In some cases, four replicates were not available (e.g., induced load test samples S5-A, S8 and S3-A) because of the varying lap joint sizes.

Machine direction of samples were determined by close observation of lap joints. A second set of characteristics used for directional identification was the material matrix of the sheet (e.g., honey comb pattern). These observations were compared to control materials if available. Several specimens required cleaning by vacuum and/or washing with warm water. For extreme cases, photographs of samples were taken under the EMS (electron microscope), to determine exposed and unexposed layers. The amount of dirt and dust present was used as the determining factor for assigning the label of exposed.

Several samples required "hand-peel" separation of exposed and unexposed layers. Samples were allowed to relax for a minimum of 24 hours prior to cutting. A layer of adhesive remained on most of the specimens after cutting. Some exposed layers were rough to touch, while others maintained elastic properties.

Tensile Test—The tests were carried out at room temperature using an Instron tester (model 1122) with pneumatic grips at 50 kPa pressure. The grip spacing was 2.4 in. (60 mm) and the loading speed was 2.4 in./min (60 mm/min). An Instron extensometer with a gauge length of 1 in. (25.4 mm) was used to monitor the elongation of the specimens. The results were displayed and stored in the microcomputer dedicated to the tensile tester. Each specimen was monitored carefully during the testing. Any specimen failing near the grips or extensometer clips was examined and included only if the failure was deemed valid. The final test results for each set of specimens were averaged and the standard deviation determined.

Induced Load Test—The apparatus used for this testing was designed and constructed by IRC.[6] The equipment consists of a notebook computer, a temperature controller, load cells, an analog to digital (A/D) converter and a well-insulated chamber. The dimensions of the chamber are 13 in. x 13 in. x 16 in. (330 mm x 330 mm x 400 mm). To reduce the static load deformation, the entire apparatus sits on a reinforced metal frame. An eight channel A/D converter allows four specimens to be tested simultaneously. The temperature is controlled by thermocouples connected to the A/D converter. The A/D converter is also used to monitor the voltage from each of the load cells. Specially designed miniature grips allow the specimens to be mounted vertically as well as ensure that no slippage occurs during the test. Each load cell has a capacity of 99 lbs. (45 kg). All signals are monitored and recorded by a notebook computer via an RS-232 serial interface and an IEEE-488 interface bus. The testing apparatus is controlled by software program written in Q-Basic.

In a test, four specimens are mounted vertically at room temperature and preloaded to approximately 0.2 lbs. (0.1 kg). They are then immediately cooled to 32°F (0°C) and maintained for one hour. The temperature is then allowed to decrease in 20°F (10°C) decrements, each being maintained for one hour, until -94°F (-70°C) is reached. The total testing time for each set of specimens is approximately eight (8) hours. The results were filtered to include only induced loads achieved when the temperature was constant for at least four (4) time intervals and then the mean for all four specimens calculated.

Results and Discussion

The weathered EPDM roofing membrane samples under study are 1.5 to 18 years old. This, however, includes S10, which will be discussed later, was installed over an unreinforced PVC membrane. Excluding this sample, the age of the EPDM membranes ranged from six (6) to 18 years.

Thermogravimetry

Typical derivative thermogravimetry (DTG) plots for exposed (top) and unexposed (bottom) EPDM membranes are shown in Figure 1. As can be seen, there are two degradation steps. The shoulder observed between 410°F (210°C) and 780°F (415°C) may be attributed to the partial volatilization of oil. While the weight loss region between 780°F (415°C) and 930°F (500°C) corresponds to further volatilization of oil and the decomposition of the polymer. It is evident that the region where the oil is lost overlaps with the region where the polymer degrades. As a result, the weight loss observed is a combination of oil and polymer loss. The total oil content for each EPDM sheet being tested is thus difficult to measure by conventional TG. However, the EPDM rubber polymer is relatively stable and is not expected to decompose when exposed to natural weathering. Hence, it is possible to compare the

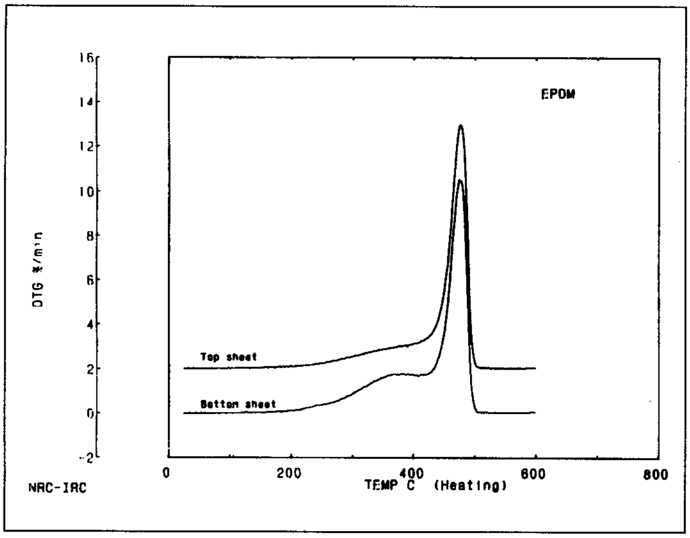

Figure 1. DTG plot for the SG1 EPDM roof membrane.

difference in oil content between the top and bottom layers by subtracting the total weight loss below 930°F (500°C) for the top sheet from that of the bottom sheet.

The amount of oil loss for the top sheets for S3A, S5-A, S7, S5-B, S13-B and SG1 is at least 3 percent (Appendix 5). For instance, the total weight loss below 930°F (500°C) for the top sheet of sample SG1 was 52.9 percent while for the bottom sheet, the weight loss was 60.9 percent. This indicates that the top sheet has lost some oil (~8 percent) during exposure to natural weather conditions. Results obtained for sample S13-B could indicate that the two bottom layers that have been naturally aged, but protected by the top layer, are losing oil at a slower rate. As can be seen from the results, the total weight loss for the oil and polymer region of the middle sheet is 2.6 percent higher than the top sheet, but 2 percent lower than the bottom sheet (i.e., the retained oil content is greatest for the bottom sheet).

Samples S1, S4-B, S12, S13-A and S14 show a difference of less than 3 percent between the top and bottom layer oil content. The oil loss of the top layer of all the other samples is between 2 and 3 percent when compared to the bottom sheet.

The weight loss below 930°F (500°C) for the top and bottom samples originating from S2, S3-B, S4-A, S6, S8, S9, S10, S11, SG2, SG3 and SG4 show less than 2 percent weight difference between top and bottom layers. In fact, samples S6, S8, S10 and SG2 show more oil for the top layer than for the bottom layer. This could mean that natural weathering did not have any effect on those samples. For example, SG2 exposed and unexposed layers are exhibiting 58.7 percent and 58.2 percent weight loss below 930°F (500°C). It is also possible that after having been exposed for a long number of years (6-15 years, except for S10), the top layer degrades and loses its maximum amount of oil. The bottom layer continues to lose oil slowly until no more oil loss occurs. As a result, the weight loss detected for both top and bottom layers of a sample are almost identical.

In some cases (e.g., S3), the top and bottom layers of a sample taken from the same roof show different weight losses (S3A had 3.7 percent while S3-B had a loss of 1.1 percent). This could imply that although both samples are from the same roof, the natural exposure of S3-B was more severe than S3-A and led to greater oil loss. Alternatively, a different batch of material could have been installed. As mentioned earlier, shrinkage can also be related to crosslinking or may be related to stress induced by insufficient relaxation time prior to installation or application on a warm sunny day. Thus, if no oil loss is detected, then one of the alternative causes should be considered.

One sheet from SG5-C exhibits a weight loss between 480°F (250°C) and 700°F (370°C) which is not observed in a typical EPDM membrane (Figure 2). This sample, which was taken near a flashing, is an originally uncured sheet. It is interesting to note how the TG and DMA techniques can easily be used to differentiate between the various membranes on this roof. Using other chemical techniques such as Fourier-transform infrared (FTIR) spectroscopy, one can determine if the originally uncured flashing is either butyl- or neoprene-based. In this case, it is neoprene-based.

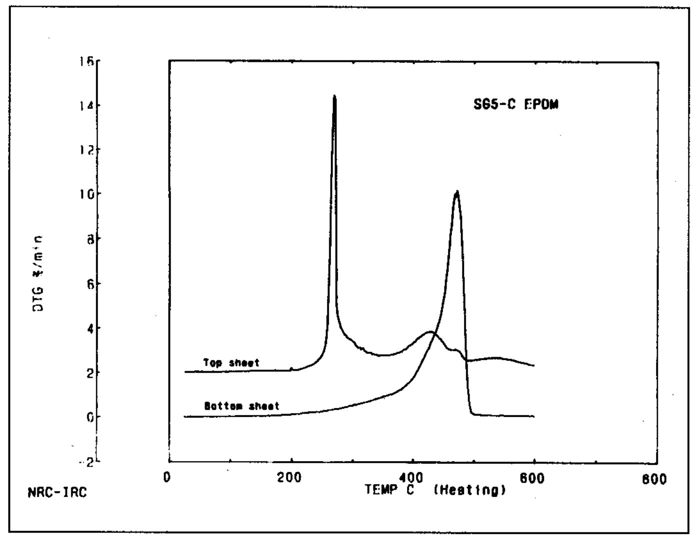

Figure 2. DTG plot for the SG5-C flashing.

Results obtained solely from thermogravimetry cannot explain the shrinkage phenomenon in all the membranes. Correlation with results obtained from mechanical testing and other thermoanalytical techniques (such as DMA) give a better overview.

DMA

A typical DMA plot showing the storage modulus (E"), loss modulus (E') and damping factor (tanδ) is shown in Figure 3. The data are summarized in Appendix 5. In general, the Tg values did not change substantially. The ΔTg (Tg [top sheet or "exposed"] - Tg [bottom sheet or "unexposed"]) was as low as 0°F (0°C) to a high of 16°F (+9°C). A change in Tg to warmer temperatures can be attributed to various factors such as crosslinking, loss of oils (or plasticizers) or other molecular rearrangements. The only EPDM samples to show a change in Tg greater than 5°F (3°C) were S5-A, S13-B and SG1. This implies that although oil loss was detected in other samples, the amount was not sufficient to affect the Tg.[4] On average, the Tg values ranged from -54°F (-48°C) to -72°F (-58°C). Only one sample, the originally uncured neprene-based flashing in SG5-C, had a Tg value as high as -36°F (-33°C).

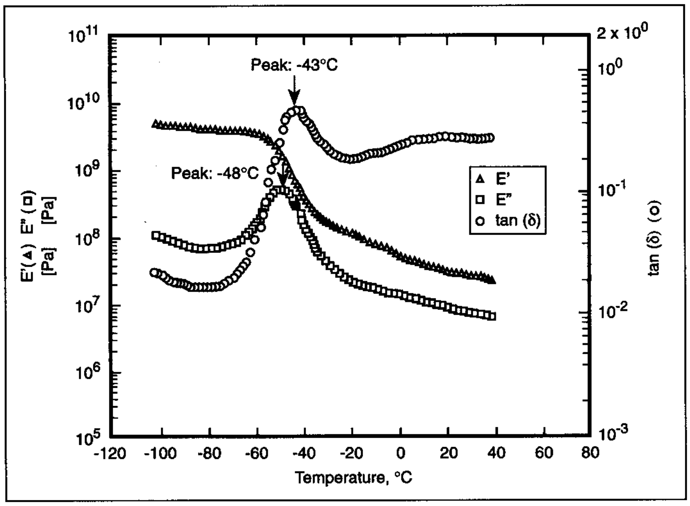

Figure 3. DMA plot for the S3-B EPDM roof membrane. (Note: E' is the storage modulus, E" is the loss modulus and tanδ is the damping factor.

DMA does provide insight into the shrinkage/contraction of some of the membranes. Once again, however, correlation with results obtained from other techniques is required to get a better understanding.

Tensile Strength and Elongation

The tensile strength and elongation results from the control samples, STC1, STC2, STC3 and STC4 (see Appendix 6) represent the mechanical properties of a new membrane. It is important to realize that EPDM sheets are not fully cured at the time of installation. Part of the membrane continues to cure as the membrane gets hot and part will undergo oxidative crosslinking which will reduce elongation and increase the tensile strength. It is also accepted that a decrease in elongation associated with an increase in tensile strength can occur due to weathering. Solar radiation, rain, temperature change or air pollution may all affect a membrane.

The criteria used to separate the elongation and load/width results into different categories are as follows:

Elongation Change	Category	Tensile Strength
0% - 5%	No difference	0% - 5%
>5% - 15%	Slight difference	5% - 10%
>15% - 25%	Moderate difference	10% - 15%
Greater than 25%	Significant difference	Greater than 15%

The standard deviation for each test was also examined. A range of possible values was established using the standard deviation values. If the value ranges from the top and bottom layers overlapped, no conclusion could be drawn from the results. The samples affected by this were S3-A, S3-B, S4-A, S4-B, S9, S10, S13-A, SG3, SG5-B and SG5-C.

Based on the elongation test results (Appendix 6) and the criteria previously established, it can be seen that S5A, S7 and S13B showed significant differences. Samples S1, S2, S5B, S8, S11, S12, SG1, SG2 and SG5A all showed moderate differences in elongation values. Samples S6 and SG4 had very little change in elongation.

Only samples S1, S5-A, S13-B, S14 and SG4 had changes in tensile strength greater than 15 percent. The other samples had changes less than 10 percent or no noticeable change.

The tensile strength and elongation results for S14 seem to be opposite from what would be expected for a sample that has been exposed to the elements. This may have resulted from an incorrect assumption of the exposed and unexposed surfaces on this sample or the top and bottom layers may be different materials.

Although each specimen fails in a different way depending on its weak areas and chemical composition, some general observations can be made. Specimens from the top, exposed layers, seemed to fail suddenly while the bottom, unexposed layers, exhibited more elastic behavior at failure.

Induced Loads

Roofing membranes typically need to be able to respond to low and high temperature environments. Essentially, the membrane needs to be able to respond continuously to daily temperature changes throughout its service life. An increase in the maximum induced load may be an indication that a material has degraded and lost some of its original flexibility from natural weathering. However, depending upon the type of degradation, the maximum induced load could decrease. The criteria used to separate the induced load data into different categories is as follows:

Induced Load Change	Category
0% - 5%	No change
>5% - 25%	Slight change
Greater than 25%	Significant change

As shown in Appendix 7, the induced load results for S3-B and SG2 reveal that the exposed layer exhibited noticeably higher induced stress levels, showing signs that degradation has occurred in these samples. The top layers from S2, S3-A, S8, S9, SG3, SG4, SG5-A, SG5-B and SG5-C exhibited slight changes in induced stress levels, but still showed signs of material degradation. The induced load results from S4-B, S5-A, S5-B, S6 and S7 showed little change between the bottom layer and the top layer. It is interesting to note that although the induced test results from S5-A did not show any changes from the top to the bottom layer, they are extremely high. These results are higher than any of the control samples tested. Also, note that the induced load results for STC2 and STC3 control samples are quite low when compared to the other control samples, even though STC2 and STC3 are from different manufacturers.

A sudden increase in the induced load values for the weathered materials at temperatures between -49°F (-45°C) and -76°F (-60°C) indicates that the materials have attained the glass transition. Again, the problem with lap joint adhesive on one side of the specimens was present. For one particular sample, SG3, three of the four specimens had no adhesive present but one specimen had a layer on one side. The induced load on this specimen (with adhesive) averaged 31 percent higher than the other three over the entire eight-hour test.

GENERAL DISCUSSION

Base Securement Details

Base securement details at the roof perimeter and at equipment curbs need to have sufficient strength to resist design contraction forces that are induced by shrinkage and temperature change (as discussed in the next section), as well as loads contributed by wind uplift. Ultimate design load information on shrinkage and temperature-induced forces has not been made readily available by the sheet manufacturers. Accordingly, designers have had to rely primarily on manufacturers to provide base securement requirements. Reference 3 does provide recommendations on ultimate pull-out values for fasteners, but it does not give the design load on the base securement, nor does it give the applied safety factor.

Since the introduction of EPDM roofing sheets, the various manufacturers/suppliers have recommended a variety of base securement details, and individual manufacturers have typically changed their requirements over the years. Some manufacturers did not recommend mechanical attachment near the base of parapets or curbs (Figure 4), but rather relied upon the bonding adhesive to resist the contraction load. However, because of the adhesive's low peel-strength, the membrane could be pulled off the parapet or curb with very little force.

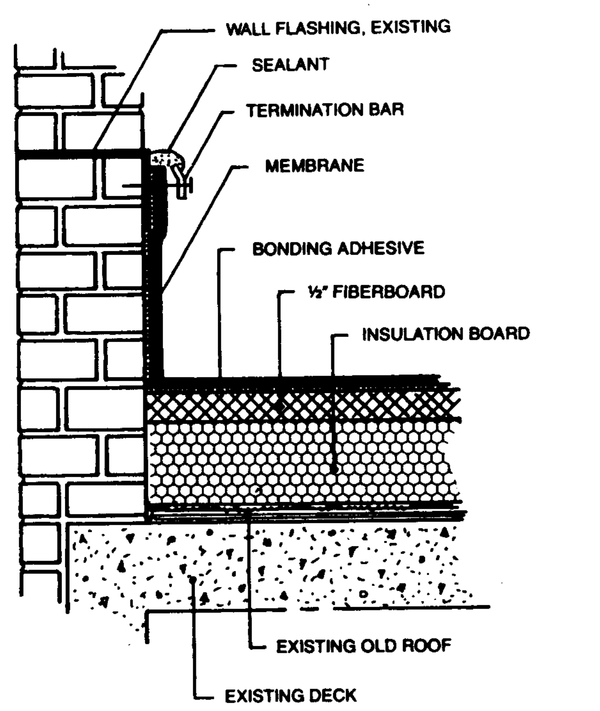

Figure 4. A 1980 detail from a manufacturer that did not recommend mechanical attachment near the base of the parapet. (This manufacturer no longer supplies EPDM sheets in North America.)

Early base securement details relied on roofing nails, which typically proved to be ineffective. A variety of base securement devices followed, including wood, metal and polymer battens (see Figure 5). Metal and polymer edge flashings of various designs have also been used. The latest base securement detail uses a strip of reinforced EPDM, which is fastened with screws and plates (see Figure 5-E). The Second and Third Editions (1985 and 1989) of *The NRCA Roofing and Waterproofing Manual* show batten strips near the base of parapets and curbs, and most of the details indicate a fastener spacing of 12 in. (300 mm), but the type of fastener is not indicated. The *Manual* also has a metal edge flashing detail that is similar to that shown in Photo 7.

For non-reinforced membranes, all of the base securement details that use battens rely upon batten compression. If the batten does not provide sufficient compression and if the non-reinforced membrane contracts, then the membrane begins to tear around the strip's fasteners (Photo 2 and 5). As the field sheet becomes unrestrained, the originally uncured flashing is stretched. If stretched sufficiently, it can tear (Photo 1 and 7). (When stretched, originally uncured flashing can tear more easily than stretched field sheet.)

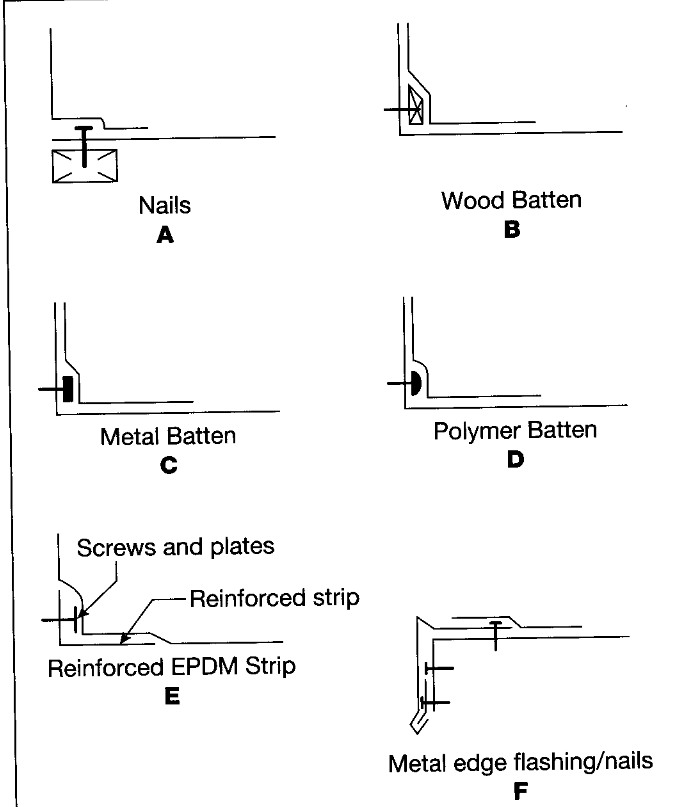

Figure 5. Common base securement details that have been or are still being used. (Typically, fastening strips may be installed on the vertical or horizontal plane.)

To enhance the probability of maintaining sufficient compression during the design service life of the roof, batten fasteners could be specified to be spaced more closely together (e.g., 6 in. [150 mm]), rather than the common 12 in. (300 mm). Also, it is of critical importance to specify a fastener, such as a screw, that is capable of pulling the batten snugly to the substrate and maintaining it there. Attention by the sheet manufacturer to the type of batten fasteners that they recommend for various substrates is also vital. The substrate under the EPDM should be firm and capable of maintaining the compression load. Bending characteristics of the battens are also important, although the batten needs to be flexible enough to conform to common substrate irregularities.

Considering the variabilities of construction, relying on compression securement of non-reinforced sheets is problematic, particularly when the battens are fastened at 12 in. (300 mm) on center or greater. This difficulty is minimized when the batten fasteners are securing a reinforced sheet. In this case, if compression is lost, the sheet's reinforcement can resist tear propagation around the fastener hole. Alternatively, rather than relying upon batten attachment, a reinforced EPDM strip (see Figure 5-E) may be used.

For metal edge flashings, securement of non-reinforced sheets may be successful if the sheet is turned down at the outside face of the wall and fastened with capped-head nails which are closely spaced (e.g., 4 in. [100 mm] on center), and the membrane is additionally secured with a continuous metal cleat. The 90° angle change reduces the tearing stresses at the holes around these fasteners. However, some tearing/elongation of holes around the fasteners securing the horizontal flange of the edge flashing may still occur. Periodic observation and repair of the flashing may be required (Photo 7), as is commonly the case with similar details in built-up roofs.

In addition to base securement problems associated with loss of compression, the batten fasteners can be pulled out of the substrate (Roofs S2 and S9), the batten can be pulled over the heads of the batten fasteners (Appendix 2), or weak parapets can be displaced (Photo 3). When battens are displaced, the ends of the battens can puncture the flashing (Photo 4).

Contraction Loads

Information on the contraction load induced by the combination of shrinkage and temperature change has previously been published.[12] However, the amount of the load contributed by shrinkage and the amount contributed by temperature change was not determined. These loads were derived from sheets that had been artificially aged. More recently, in 1994, NRCA was advised by two manufacturers that 24 lbs/ft (0.35 kN/m) would be a reasonable ultimate design load (i.e., this would be the expected load if the membrane shrank 2 percent, as permitted in the ASTM D 4637 material standard).

In addition to the 24 lbs/ft shrinkage load, an allowance should be made for thermally-induced loads. As can be seen from the induced load tests (Appendix 7), these loads are quite small until the membrane reaches the glass-transition temperature. It is noteworthy that thermally-induced load data reported in Appendix 7 compare well with those for artificially-aged EPDM sheets reported in References 6 and 12. Below the Tg the loads substantially increase. However, assuming that the membrane remains chemically stable, the glass-transition temperature, which appears to occur at approximately -58°F (-50°C) or colder, will not be reached on most roofs in North America.

A combined ultimate design load of 40 lbs/ft (0.58 kN/m) for shrinkage and temperature-induced forces appears to be a reasonable value for most EPDM membrane roofs. In addition to resisting shrinkage and temperature-induced forces, the base securement detail also needs to resist wind-induced forces. SPRI recommends that base securement details provide a "minimum design holding power of 90 lbs/ft (1.31 kN/m)."[13] This load includes an allowance for shrinkage, temperature and wind, however, the amount of load assigned to each load category was not determined.[14] If 40 lbs/ft (0.58 kN/m) is subtracted from SPRI's recommendation of 90 lbs/ft (1.31 kN/m), then 50 lbs/ft (0.73 kN/m) is left to account for wind loads. This appears very conservative for fully adhered and ballasted systems (assuming the membrane does not balloon). For mechanically attached systems, depending upon the wind environment and the location of the first row of membrane fasteners from the perimeter, this load allowance appears inadequate.

SPRI's recommended load should have a safety factor applied to the base securement fasteners.[14] Incorporating a safety factor of 4 (which is suitable for masonry) for the base securement fasteners gives an ultimate design load of 360 lbs/ft (5.2 kN/m).

Note: Fastening into masonry substrates (brick or concrete masonry units [CMU]) is challenging. Some types of fasteners are very applicator-sensitive (e.g., slightly enlarged or elongated holes can greatly minimize their withdrawal strength). The EPDM manufacturer should consider the load capacity of the fasteners as well as their application sensitivity prior to fastener approval for these types of substrates.

Lap Problems

Based on strength values determined from lap-shear tests,[15] well-constructed laps should have sufficient strength to resist ultimate design shrinkage forces coupled with expected temperature-induced loads (as discussed previously), provided that the lap is loaded in shear. (Data in Reference 15 are for neoprene-based adhesives. Laps made with butyl-based liquid adhesives and tapes have greater lap-shear strengths than laps fabricated using unprimed neoprene adhesives.)[16,17] Also, Martin reported that EPDM shrinkage loads are too small to cause lap-shear failures.[18] More important, Martin also reported that the neoprene-based specimens loaded in shear at about 20 percent of their ultimate strength did not fail over seven months. Similarly, Rossiter showed that well-prepared laps with butyl-based adhesives did not fail when loaded at about 10 percent of their sheer strengths during three years of creep-rupture testing.[19]

Laps loaded in shear are significantly stronger than laps loaded in T-peel.[20] Therefore, based on strength values from T-peel tests,[21] if a lap becomes loaded in peel, shrinkage-induced loads may become high enough to cause a creep-rupture failure of the lap.

In this study, only two roofs were observed to have a lap problem (S8 and S12). They both had an open base flashing lap.

Differential Shrinkage

It has been reported that shrinkage on some roofs seems to be confined to a few individual sheets.[11] This was not documented on any of the roofs sampled in this research. However, on some roofs with different base securement details on the roof perimeters, it was observed that while one perimeter might exhibit problems, another perimeter did not. These variations were attributed to strength variations of the different base securement details.

Correlation With Other Problems

As shown in Appendix 1, 61 percent of the shrinkage problem reports also indicated lap problems. Although this may suggest that shrinkage caused many of these lap problems, it is believed that typically this was not the case. Since lap problems are the leading cause of EPDM problems in the Project Pinpoint database, it is probably because of their relatively large number that so many of the shrinkage problem jobs also reported lap problems.

Appendix 1 also shows that flashing problems were recorded in 46 percent of the shrinkage reports. Since only 25 percent of all problem jobs reported flashing problems, many of the reported flashing problems may have been related to membrane shrinkage.

System Influences

Based upon Project Pinpoint (Appendix 1), the limited NRCA survey (Appendix 2), field observations, analysis and literature review, it appears that the following factors do not influence EPDM shrinkage: deck type, insulation type or presence (or absence) of a vapor retarder. However, it does appear that the type of system attachment can influence shrinkage problems.[11] Only 17 percent of shrinkage problems in the Project Pinpoint database occurred with fully adhered membranes. During NRCA's field investigation, shrinkage problems were not observed on the two fully adhered roofs. It is believed that with fully adhered systems, the shrinkage forces are essentially uniformly distributed through the bonding adhesive to the insulation substrate. This greatly minimizes the pulling force on the field sheets at their base securement.

Climatic Influences

Project Pinpoint provides shrinkage reports from 41 states (5 percent of the reports do not indicate the state). Of the reports indicating the state, 46 percent were received from eight states (as noted in Appendix 1), with each state representing from 5 percent to 6 percent of the reports.

Baseline data (i.e., the database of non-problem jobs under construction at a given time) was analyzed to determine if the incidence of problem reports was related to market share. However, there are insufficient data to explain why a large number of shrinkage problems were reported from the eight states. Perhaps the large number is related to market share, but this is uncertain. From the problem job and baseline data, it is not possible to correlate shrinkage problems with climatic influences. Shrinkage problem jobs have occurred in areas with substantially different climates, but the significance (if any) of climatic influence is unknown. (A minor amount of temperature-induced stress can result when application occurs during very cold or warm sunny weather, as previously discussed.)

ASTM Standard D 4637

ASTM Standard D 4637 is the material specification for EPDM. The 1987 edition of the standard allows a maximum lineal dimension change of 2 percent, around the time of manufacture, when tested in the prescribed manner. This allowable percentage appears to be well in excess of the maximum shrinkage that quality EPDM sheets experience in the test.[22] Accordingly, at the request of NRCA staff and a contractor member, it appears that the next edition of the standard will have a substantially lower allowable shrinkage value. (Incidentally, if the allowable shrinkage value is made too low, other important characteristics of the sheet will be compromised.)

ASTM D 4637-87 specifies a minimum of 300 percent elongation for new non-reinforced EPDM and 200 percent after heat-aging. *Most samples had elongation values exceeding this requirement.* Only samples S3-A, S11, S13-B and SG4 had elongation values below 300 percent with S13-B actually having values below 200 percent. Samples S3-B, S6, S13-A, SG1 and SG2 fall below, or are very close to, 300 percent when the standard deviation is taken into account.

	Manufacturer	Age	Greater than 3% change in weight	ΔTg> 3°C	Mechanical Test, Significant Change	Induced Load, greatest change
S1	A	11			Yes	Slight
S2	B	6				Slight
S3-A	C	12	Yes			Slight
S3-B	C	12				Yes
S4-B	D	11				None
S5-A	D	9	Yes	Yes	Yes	None
S5-B	D	9	Yes			None
S6	A	10			Slight	None
S7	A	14	Yes		Yes	None
S11	E	6				Slight
S13-A	E	12				Slight
S13-B	E	12	Yes	Yes	Below ASTM standard.	Slight
SG1	D	11	Yes	Yes	Slight	Slight
SG2	D	10				Yes
SG4					Yes	
SG5-A	A	11			Slight	Slight

Table 4. *Summary of laboratory evaluation.*

Flashing Degradation

Many of the roofs that were investigated in Iowa had severely deteriorated originally uncured flashings, including roofs S5, S7, S9, S13 and S14. These roofs, which ranged in age from nine to 14 years, were from four different manufacturers. All of the flashings were probably made of neoprene. In some areas, the tautness of the flashing appeared to exacerbate the deterioration. However, the poor performance of the flashing did not appear to be related to shrinkage of the field sheets.

CONCLUSIONS

- Laboratory evaluation is summarized in Table 4. As can be seen, in most cases, it is difficult to attribute the cause of flashing/base securement problems (i.e., shrinkage) to changes in material property. It is noteworthy that SG1 had oil loss in the amount of 8 percent and a $\Delta Tg > 5°F$ (3°C), but the roof did not exhibit problems. (This roof was secured with wood battens, which were attached to CMU with metal or plastic sleeve inserts/drive pins spaced at 12 in. [300 mm] on center.) Nearly all the samples passed the ASTM criterion for elongation. Six samples had a difference in weight loss (between top and bottom layer) exceeding 3 percent. Only three samples had a change in Tg greater than 5°F (3°C). The induced load experiments revealed that S3-B and SG2 had undergone the greatest property change. It is interesting to note, however, that S5-A did have the highest initial induced load. Thus, factors other than change in material property need to be assessed as possible causes for the flashing/base securement problems.

  Overall, it was shown that all of the techniques indicated property changes for samples SG1 and S13-B, and most of the techniques also indicated changes for S5-A.
- Based on the information available, it appears that the occurrence of shrinkage-induced taut EPDM roof membranes may be widespread. Furthermore, it appears that the taut condition of many of these roofs has resulted in flashings that are susceptible to water infiltration, or could soon become susceptible. However, in many instances the building owner may be unaware of the leakage condition because the amount of water infiltration is slight, or in the case of re-covers, the previous membrane has prevented water from migrating inside.

  Fortunately, this type of problem is typically not catastrophic. (An exception would be a long tear extending from an equipment curb into a ponded area, which happened in another area of the roof shown in Photo 1). In many instances, if flashings have become damaged, the roof life can be extended by their replacement/repair.[23]
- In the past, many of the base securement details recommended by manufacturers have had very limited resistance to damage by membrane contraction. Many of the current details (i.e., those that do not use reinforced field sheets or reinforced sheet fastening strips) are still non-conservative. Non-conservative base securement details should be of particular concern to roofing contractors, because the quality of the installation will probably be questioned if flashing problems develop.
- During very cold or warm sunny weather, it is difficult for the roofing contractor to avoid an installation that builds in temperature-induced stress. Since these loads typically will be quite small, problems should not be anticipated with details that are well designed and installed. However, temperature-induced loads may cause flashing problems where base securements are poorly designed or installed.
- Membrane shrinkage does not appear to be the cause of the flashing problems on Roof S10 (Photo 5). The damage may be related to temperature-induced loads, however, since it was installed directly over an unreinforced PVC membrane that had shattered, perhaps the flashing damage was related to EPDM movement associated with subsequent shrinkage of the unreinforced PVC membrane. To avoid this later possibility, rather than recovering a membrane that may be susceptible to further shrinkage, the existing membrane could be removed. However, with conservative base securement details (which was not the case with this roof), flashing problems will probably not be experienced even if the old membrane remains.

RECOMMENDATIONS

Existing Roofs

It is recommended that existing roofs be inspected semiannually. (For inspection guidance, see Reference 24). If the base securement has been compromised (e.g., the batten has been displaced, or the field sheet has begun to pull out from under the batten), the building owner should have corrective action performed (providing that the remainder of the roof is in reasonably good condition).

If the batten has been slightly displaced, it may be possible to return it to approximately its original position with the installation of new fasteners (which are then flashed). If this option is chosen, the condition of the substrate should be checked to verify that it has not deteriorated.

If the batten is more than slightly displaced or no longer holds the field sheet securely, more extensive repairs are recommended. If the manufacturer is known and still in business, then consult the manufacturer for repair guidance.

ARMA, NRCA and SPRI are nearing completion of a repair manual. When it is published in 1996, its guidance for base securement repair is recommended. In the interim, recommendations in Reference 3 are available. Also, see the base securement recommendations below.

If significantly deteriorated originally uncured flashings are observed, it is recommended that the building owner have corrective action performed.

New Roofs

It is recommended that EPDM sheet manufacturers reevaluate their details. Base securement details should be conservatively engineered, with incorporation of suitable safety factors and consideration of the variety of substrates that commonly occur. It is recommended that compression securement not be relied upon for non-reinforced sheets. Either use a reinforced EPDM fastening strip (Figure 5-E), or use a reinforced field sheet behind the batten (which may then be seamed to a non-reinforced field sheet in the plane of the roof). Fasteners which are capable of pulling the fastening strip snugly to the substrate and maintaining it there, (e.g., screws) are recommended. It is recommended that base securement fasteners be capable of resisting an ultimate design contraction and wind load of at least 360 lbs/ft (5.2 kN/m). (Mechanically attached membrane systems may require a substantially higher load capacity, depending upon the wind environment and the location of the first row of membrane fasteners.)

For metal edge flashings, refer to the "General Discussion" section on "Base Securement Details." These details should be considered as requiring periodic repair.

It is recommended that designers also consider the substrate into which the batten or EPDM fastening strip fasteners are being installed—a suitable substrate should be specified. Additionally, the substrate should be firm (if the fastening strip is in the horizontal plane, rather than placing it over the insulation, a wood nailer is recommended). It is also recommended that EPDM sheet complying with the latest edition of ASTM D 4637 be specified.

Reroofing

In addition to the recommendations noted for new roofs, it is recommended that the designer determine the type of substrate and its condition. Where weak or deteriorated conditions exist, replacement/strengthening should be specified.

During application, mechanics should be alert to fastener driving conditions that may indicate the substrate is inadequate. If an inadequate substrate is encountered, the designer should be consulted for direction.

Reroofing an Existing EPDM Membrane

If an existing EPDM membrane is to be removed, it is recommended that the roofing contractor be alert to taut conditions. When ballast is removed, the membrane may contract. When cut, a long tear may result, which could leave a larger area of the roof vulnerable to infiltration than anticipated. (This situation was encountered on roof S13).

ACKNOWLEDGMENTS

The authors wish to thank those contractors who sent in the samples used in this study. We also extend our thanks to William Lei, M. Lisa DeGuzman, Peter Crowe and Wai Fai Lee for obtaining some of the experimental data presented in this paper.

REFERENCES

1. Laaly, H.O., *The Science and Technology of Traditional and Modern Roofing Systems*, Volume II, Laaly Scientific Publishing, 1992, pp. 27-1 - 27-24.
2. 1994-1995 NRCA Annual Market Survey, National Roofing Contractors Association, Rosemont, Ill.,1995.
3. Dupuis, R.M., "Repair Methods for Re-attaching EPDM Membrane and Flashing Experiencing Shrinkage," Midwest Roofing Contractors Association 1994 Convention Program - T&R Update, Kansas City, Mo., 1994.
4. Paroli, R.M., Dutt, O., Delgado, A.H. and Mech, M.N., "Characterization of Ethylene- Propylene-Diene Monomer (EPDM) Roofing Membranes Using Thermogravimetry and Dynamic Mechanical Analysis," *Thermochimica Acta*, 182, 1991, pp. 303-317.
5. Dutt, O., Paroli, R.M. and Mailvaganam, N.P., "Glass Transitions in Polymeric Roofing Membranes-Determination by Dynamic Mechanical Analysis," *Proceedings of the 1991 International Symposium on Roofing Technology*, 1991, pp. 495.
6. Turenne, R.G., Stenman, H.K., Mech, M.N. and Dutt, O., "Thermally-Induced Loads in Single Ply Membranes," *Roofing Research and Standard Development: 3rd Volume, ASTM STP 1224*, Thomas J. Wallace and Walter J. Rossiter, Jr., Eds., American Society for Testing and Materials, Philadelphia, 1994.
7. Gish, B.D. and Lusardi, K.P., "Laboratory Evaluation of EPDM Roof Membranes: A 17-Year History of Performance," *Proceedings of the 1991 International Symposium on Roofing Technology*, 1991, pp. 159.
8. Dupuis, R.M., "Research to Improve EPDM Performance," *Contractors Guide*, October 1993, pp. 36. (Reprinted in Architectural Specified, January/February 1994, pp. 40.)
9. Cullen, W.C., *Project Pinpoint Analysis: Ten-Year Performance Experience of Commercial Roofing 1983—1992*, 1993.
10. Dupuis, R.M., "From the field: A professional's observations," *Professional Roofing*, August 1994, pp. 22.
11. Baxter, D., "Insights gained from the field," *Professional Roofing*, March 1995, pp. 28.
12. Dupuis, R.M. and Haas, A.K., "Temperature-Induced Behavior of New and Aged Roof Membranes," *Proceedings of the Second International Symposium on Roofs and Roofing*, 1981, Volume 1 pp. 66.
13. "Flexible Membrane Roofing: A Professional's Guide to Specifications," Section 3.1.1, 3.1.2 and 3.1.3, SPRI, 1995, pp. 2.
14. Gillenwater, R., personal communication, August 1995.
15. Rossiter, W.J., "Tests of Adhesive-Bonded Seams of Single-Ply Rubber Membranes," ASTM STP 959, 1987, pp. 53.
16. Chmiel, C., Dupuis, R., Gillenwater, R. and Hanson, H., "EPDM Lap Adhesives: Past, Present, Future Use and Performance," Midwest Roofing Contractors Association, 1986.
17. Rossiter, W.J., Lechner, J.A. and Seiler, J.F., "Performance of Tape-Bonded Seams of EPDM Membranes: Initial Characterization," *Proceedings of the 11th Conference on Roofing Technology*, NIST/NRCA, 1995, pp. 78.
18. Martin, J.W., Rossiter, W.J. and Embree, E., "Factors Affecting The Strength And Creep-Rupture Properties Of EPDM Joints," *Proceedings of the Third International Symposium on Roofing Technology*, 1991, pp. 63.
19. Rossiter, W.J., Martin, J.W., Lechner, J.A., Embree, E. and Seiler, J.F., "Effect of Adhesive Thickness and Surface Cleanliness on Creep-Rupture Performance of Ethylene-Propylene-Diene Terpolymer (EPDM) Peel and Lap Shear Joints," ASTM STP 1224, 1994, pp. 123.
20. Rossiter, W.J., "Field Evaluation of the Quality of Newly Formed Adhesive-Bonded Seams of Single-Ply Membranes," Roofs and Roofing: New Materials, Industrial Applications, Uses and Performance, 1988, pp. 273.
21. Rossiter, W.J., Martin, J.W., Lechner, J.A. and Seiler, J.F., "Creep-Rupture Resistance of Seam Specimens Sampled From In-Service EPDM Roof Membranes," *Proceedings of the VIII International Congress*, 1992, pp. 331.
22. Gish, Brian, "Comparing Non-reinforced and Fabric-reinforced EPDM Sheeting," *Contractors Guide*, October 1990, pp. 34.
23. Hutchinson, T.W., "Restoration of Out-of-Warranty EPDM Roof Systems," *Proceedings of the IX International Congress*, 1995, pp. 366.
24. *SPRI/NRCA Manual of Roof Inspection, Maintenance and Emergency Repair for Existing Single-Ply Roofing Systems, 1992.*

APPENDICES

Appendix 1

Summary of Project Pinpoint Analysis

Through 1993, the problem job database contained 237 reports of EPDM shrinkage. The following is a summary of these reports:

1. Receipt of reports by year:

1993:	46	1988:	24
1992:	45	1987:	24
1991:	11	1986:	8
1990:	35	1985:	2
1989:	38	1984:	4

2. Age of roof at time of report:

<1 year:	5%	7 years:	7%
1 year:	11%	8 years:	13%
2 years:	6%	9 years:	5%
3 years:	4%	10 years:	5%
4 years:	7%	> 10 years:	5%
5 years:	13%	Unknown:	12%
6 years:	7%		

Median age at time of report is approximately 5.5 years.

3. In addition to shrinkage, many reports also indicated other problems:

Lap:	61%
Flashing:	46%
Puncture/tear:	23%

4. Type of construction:

New:	30%
Tear-off:	25%
Recover:	40%
Unknown/not reported:	5%

Baseline data indicate that 49 percent of the EPDM membrane jobs are installed on new construction. Therefore, it appears that contraction-related problems may occur more frequently on reroofing projects than on new construction (i.e., contraction problems may not be correlated with market share).

5. Type of deck:

Metal:	49%
Concrete:	19%
Wood/plywood:	15%
Gypsum:	6%
Other/unknown:	11%

EPDM membrane/deck baseline data are highly correlated with the problem job data. Type of deck does not appear to influence shrinkage problems.

6. Type of insulation:

Polystyrene:	31%
Wood fiberboard:	29%
Polyisocyanurate:	19%
Other/unknown:	12%
None:	8%
Perlite:	6%

(The total percentage exceeds 100 because some reports indicated more than one type of insulation.)

EPDM membrane/insulation baseline data are not highly correlated with the problem job data. However, the type of insulation does not appear to influence shrinkage problems.

7. Vapor retarder:

Yes:	6%
No:	29%
Unknown/not reported:	65%

Baseline data indicates that 10 percent of the EPDM membrane jobs incorporate vapor retarders. The presence, or lack thereof, of a vapor retarder does not appear to influence shrinkage problems.

8. Membrane attachment:

Ballasted:	48%
Mechanically attached:	35%
Fully adhered:	17%

Correlation with EPDM baseline data is uncertain because 20 percent of the baseline jobs did not identify the type of attachment.

9. Problem severity:

Minor:	7%
Moderate:	46%
Severe:	47%

(If multiple problem types were reported, it is unknown if the problem severity identification is applicable to shrinkage or to another problem.)

10. Number of problem squares (m^2):

<10%:	14%
10-50%:	47%
>50%:	39%

(If multiple problem types were reported, it is unknown if the number of problem squares is applicable to shrinkage or to another problem.)

11. Problems were reported in 41 states. Five percent of the reports do not indicate the state. Of the reports indicating the state, 46 percent were received from the following eight states, with each state representing from 5 to 6 percent of the reports: Florida, Illinois, Indiana, Iowa, Michigan, Minnesota, Missouri and Wisconsin.

12. The jobs were supplied by twelve different manufacturers (the manufacturer was unknown/not reported on 18 percent of the jobs). Five of the manufacturers no longer supply EPDM roof sheets in North America. (These five manufacturers represented 3 percent of the problem jobs.)

Of the reports that identified the manufacturer, 22 percent of the jobs were by one manufacturer and 16 percent were by another manufacturer. It appears that these relatively high numbers are related to market share factors, rather than performance factors.

Appendix 2
Summary of 1993 NRCA Survey on EPDM Shrinkage

1. In November 1993, a survey was sent to all 49 contractor members of NRCA technical committees. Seven members responded with problem reports (a return rate of 14 percent). They reported 25 shrinkage problem jobs in 10 states (Alabama, Colorado, Georgia, Illinois, Louisiana, Minnesota, New York, North Carolina, Pennsylvania and Texas).

2. Type of deck:

Metal:	72%
Concrete:	12%
Wood:	12%
Lightweight insul. conc.	4%

3. Type of insulation:

Polyisocyanurate:	36%
Wood fiberboard:	36%
Expanded polystyrene:	16%
Perlite:	4%
None:	4%
Unknown:	4%

4. Vapor retarder:

Yes:	8%
No:	88%
Unknown:	4%

5. Membrane attachment:

Ballasted:	80%
Mechanically attached:	20%

6. The following types of perimeter securement were reported for the 25 problem jobs:
wood battens—40%, metal battens—36%, polymer battens—8%, membrane secured with metal edge flashing—8 percent, and fasteners through the membrane (no battens)—4 percent. One job (4 percent) did not identify the type of perimeter securement. Forty percent of the jobs reported that the perimeter securement was attached to the horizontal plane (i.e., the roof deck), and 20 percent reported that it was attached to the vertical plane (i.e., parapet). Forty percent of the jobs did not identify the plane of securement.

7. All 25 jobs reported perimeter securement problems. The type of problem reported is as follows:

Fastener pull-out:	76%
Membrane tear at fasteners:	76%
Batten pulled over fastener heads:	12%

(The total percentage exceeds 100 percent because several jobs reported multiple problems.)

8. In addition to shrinkage, the following additional items were reported:

Bridging:	88%
Holes through the base flashing:	64%
Base flashing seam problems:	44%
Field lap problems:	8%

(The total percentage exceeds 100 percent because several jobs reported multiple problems.)

9. Eighty-four percent of the 25 jobs were reported to be susceptible to water infiltration.

10. Sixty-four percent of the 25 jobs reported that shrinkage was experienced on most of the sheets.

11. The median age at the time the problem was observed was 7 years, with a maximum of 11 years and a minimum of one year.

12. The 25 jobs were supplied by eight different manufacturers (the manufacturer of two jobs was not identified). Two of the manufacturers no longer supply EPDM roof sheets in North America (two jobs were supplied by these manufacturers).

Appendix 3
Summary of Sampled Roofs with Problems

Table 2 provides information on the membrane manufacturer, roof age, attachment method, substrate, presence of a vapor retarder, the state in which the roof is located and the problem severity (as reported by the person who took the sample). Samples from roofs S1–S4 were submitted by three NRCA contractor members. The other roofs were investigated by NRCA staff. (All dimensions are approximate.)

- S-1, S-2 and S-3: Base securement details are unknown.
- S-4: Perimeter base securement was provided by metal battens on the parapet. The type and spacing of the batten fasteners is unknown. Some of the fasteners had been pulled out and there were membrane tears at the fasteners. The membrane was susceptible to water infiltration. Contraction was experienced on most of the sheets. As the ballast was removed during reroofing, the membrane soon became more taut and began pulling loose from its anchoring points.
- S-5: Perimeter base securement was provided by wood battens on the parapet. The batten was fastened into the CMU with plastic sleeve inserts/drive pins, which had a 1 in. (25 mm) embedment. At the area shown in Photo 2, the fasteners were spaced at 12 in., 11½ in. and 9½ in. (305 mm, 290 mm and 240 mm). In this area, the field sheet pulled out from under the batten. Along another parapet, the fasteners were spaced at 15 in. and 14½ in. (380 mm and 370 mm). In this area, the fasteners pulled out of the CMU—the batten pulled inward 6 in. (150 mm). In some areas, the end of the batten had pulled away from the parapet and punctured the originally uncured flashing. The originally uncured flashing was deteriorated. The roof was vulnerable to leakage.
- S-6: Perimeter base securement was provided by wood battens on the parapet. Several of the battens had pulled away from the parapet. Minor water infiltration was possible.
- S-7: Contraction of the membrane caused parapet damage (Photo 3). Membrane securement was as noted on the photo. The originally uncured flashing was very deteriorated. Minor water infiltration was possible.
- S-8: The majority of the base flashings had recently been replaced on this roof because of contraction-related base securement problems. At an area where the flashing had

not been replaced, a base flashing seam was open.

- S-9: Perimeter base securement was provided by wood battens on the brick parapet. The flashing was removed along a 53 in. (1,345 mm) length of one of the battens. One powder-driven fastener was found (it had ¾ in. [19 mm] penetration into the brick). The fastener was 19 in. (480 mm) from one end of the sample cut and 34 in. (865 mm) from the other end. The batten had pulled away 1 in. (25 mm) from the parapet.

  Several other battens had also pulled away from the parapet (Photo 4). In some locations, patches had been placed where the ends of the battens had punctured the flashing. The originally uncured flashing was deteriorated. Minor water infiltration was possible where some of the ruptured originally uncured flashing had not been repaired.
- S-10: At one area, perimeter base securement was provided by 1 in. (25 mm) wide aluminum battens, placed on the horizontal plane of the roof. The batten was fastened with screws at 12 in. (305 mm) on center. In this area, the field sheet tore at the fasteners and the originally uncured flashing over the batten was stretched until it tore (Photo 5). The other perimeters of the roof used different base securement details. Problems were not observed in these other areas. Water infiltration was possible.

  From the laboratory evaluation, it appears that the contraction force was not caused by shrinkage. The concentration load may have been induced at the time of application (which was in June) or perhaps it was related to EPDM membrane movement associated with shrinkage of the unreinforced PVC membrane.
- S-11: This roof had a metal termination bar at the top of the flashing, but no base securement (except possibly for bonding adhesive). The termination bar was fastened into brick with plastic sleeve inserts/drive pins, spaced at 6 in. (150 mm). The taut membrane was susceptible to puncture and tearing at the sharp ends of some of the bars (Photo 6).
- S-12: This roof was in the process of being torn off at the time of observation. The field sheet was fastened to wood blocking that was in the plane of the roof. It was nailed with capped-head nails spaced at 4½ in. (115 mm). In one area, the nails were very corroded (an adjacent base flashing seam had opened up). In this area, the bridging was only minor.
- S-13: This roof was in the process of being torn off at the time of observation. It was secured with a metal edge flashing (Photo 7). Roofing nails spaced at 5 in., 5 in. and 4 in. (125 mm, 125 mm and 100 mm) attached the horizontal metal flange and the field sheet. The field sheet turned down at the wall and was fastened by the continuous cleat fasteners (spacing was not determined). In addition to the cleat fasteners, the sheet may or may not have had additional fasteners. The originally uncured flashing was deteriorated. Water infiltration was possible.

  After the ballast was removed, the contractor reported that long tears developed along the perimeter and extended from some of the equipment curbs.
- S-14: This roof had a reinforced membrane. It was terminated with a metal edge flashing on a raised curb. Roofing nails spaced at 12½ in. and 27½ in. (320 and 700 mm) attached the horizontal metal flange and the field sheet. It was not determined if the field sheet turned down at the wall. The originally uncured flashing had ruptured along the metal flange, similar to what is shown in Photo 7. The fastener holes through the field sheet had some minor elongation. The originally uncured flashing was deteriorated. Minor water infiltration was possible.
- S-15: This job was not sampled. It was by manufacturer E, was nine-years-old, ballasted, located in Iowa and the problem severity was typically minor, with one area being moderate. In some areas, the base flashings were secured with wood battens, and in other areas, the membrane was secured with metal edge flashing. Several of the wood battens had pulled away, and in one area, the batten's screw had penetrated the flashing.

Samples from S-5–S11 and S-14 were typically 12 in. x 12 in. (300 mm x 300 mm). (S-9 was 14 in. x 14 in.[350 mm x 350 mm], and S-10 was 12 in. x 16 in. [300 mm x 400 mm].) After cutting the samples, they were allowed to relax for approximately 20 to 60 minutes. The width of the gap between the sample and the membrane was then measured. The results are as follows: S5-A: ⅛ in. (3 mm) gap along two opposite sides and ½ in. (13 mm) gap along the other two sides. S-5B: ⅜ in. (10 mm) gap all around. S-6, S-7, S-8 and S-9: in. ¼ in. (6 mm) gap all around. S-10: Essentially no gap. S-11: ⅛ in. (3 mm) gap along to opposite sides and essentially no gap along the other two sides. S-14 (reinforced membrane): 1⁄16 in. (1.5 mm) gap all around.

Appendix 4
Summary of Sampled Roofs without Problems

Table III provides information on the membrane manufacturer, roof age, attachment method, substrate, presence of a vapor retarder and the state in which the roof is located.

- SG-1: Perimeter base securement was provided by wood battens on the parapet. The battens were fastened into CMU at 12 in. (300 mm) on center, with metal or plastic sleeve inserts/drive pins. There was some membrane bridging near the base of battens.
- SG-2: Perimeter base securement was provided by wood battens on the parapet. The battens were fastened into CMU at 16 in. (400 mm) on center, with metal or plastic sleeve inserts/drive pins. There was some very minor membrane bridging near the base of wood strip.
- SG-3: Information not available.
- SG-4: Information not available.
- SG-5: Perimeter base securement was provided by polymer battens on the parapet. The battens were fastened into CMU at 12 in. (300 mm) on center, with 1¼ in. (32 mm) long screws that were designed for use in concrete and masonry.

Sample	Tg E''_{max} °C	Weight Loss, % Polymer and Oils (25-500°C)	Residue (>500°C)	% Oil Lost	Degree of Shrinkage*	Number of Problems per squares*
STC-1	-55	57.4	42.7	—	n/a	n/a
STC-2	-55	58.4	41.6	—	n/a	n/a
STC-3	-53	56.0	44.0	—	n/a	n/a
STC-4	-54	55.8	44.2	—	n/a	n/a
S1 Top sheet	-55	53.8	46.2	2.8	severe	10-50%
S1 Botton sheet	-55	56.6	43.4	—		
S2 Top sheet	-51	56.0	44.0	0.5	moderate	>51%
S2 Bottom sheet	-52	57.5	42.5	—		
S3-A Top sheet	-50	50.3	49.7	3.7		
S3-A Bottom sheet	-51	54.0	46.0	—	severe	51%
S3-B Top sheet	-51	51.8	48.2	1.1		
S3-B Bottom sheet	-52	52.9	47.1			
S4-A Top sheet	-49	57.2	42.8	0.2		
S4-A Bottom sheet	-49	57.4	42.6	—	severe	>51%
S4-B Top sheet	-51	57.0	43.0	2.6		
S4-B Bottom sheet	-48	59.6	41.4	—		
S5-A Top sheet	-49	53.5	46.5	5.9		
S5-A Bottom sheet	-54	59.4	40.6	—	severe	>51%
S5-B Top sheet	-48	54.9	45.1	4.7		
S5-B Bottom sheet	-49	59.6	40.4	—		
S6 Top sheet	-49	60.0	40.0	-2.5	moderate	>51%
S6 Bottom sheet	-49	57.5	42.5			
S7 Top sheet	-55	51.6	48.4	4.0	moderate	>10-50%
S7 Bottom sheet	-56	55.6	44.4	—		
S8 Top sheet	-53	53.7	46.3	-0.3	severe	>51%
S8 Bottom sheet	-55	53.4	46.6	—		
S9 Top sheet	-55	54.9	45.1	0.9	severe	>51%
S9 Bottom sheet	-55	55.8	44.2	—		
S10 Top sheet	-57	57.6	42.4	-0.2	severe	>51%
S10 Bottom sheet	-57	57.4	42.6	—		
S11 Top sheet	-57	52.5	47.5	1.1	moderate	>51%
S11 Bottom sheet	-58	53.6	46.4	—		
S112 Top sheet	-55	53.3	46.7	2.2	severe	>51%
S12 Bottom sheet	-54	55.5	44.5	—		
S13-A Top sheet	-55	53.9	46.1	2.4		
S13-A Bottom sheet	-57	56.3	43.7	—	moderate	>51%
S13-B Top sheet	-49	55.4	44.6	4.6	to	
S13-B Middle sheet	-49	57.0	43.0	2.0	severe	
S13-B Bottom sheet	-58	59.0	41.0	—		
S14 Top sheet (md)	-48	58.2	41.8	2.8		
S14 Top sheet (xd)	-49	N/A	N/A	N/A	very	<10%
S14 Bottom (md)	-49	61.0	39.0	—	minor	
S14 Bottom (xd)	-48	N/A	N/A	N/A		
SG1 Top sheet	-49	52.9	47.1	8.0	no	
SG1 Bottom sheet	-53	60.9	39.1	—	problems	
SG2 Top sheet	-56	58.7	41.3	-0.5	no	
SG2 Bottom sheet	-55	58.2	41.8	—	problems	
SG3 Top sheet	-55	56.4	43.6	0.7	no	
SG3 Bottom sheet	-56	57.1	42.9	—	problems	
SG4 Top sheet	-53	53.6	46.4	1.7	no	
SG4 Bottom sheet	-53	55.3	44.8	—	problems	
SG5-A Top sheet	-55	53.0	47.0	2.0		
SG5-A Bottom sheet	-54	55.0	45.0	—		
SG5-B Top sheet	-55	53.8	46.2	0.2	no	
SG5-B Bottom sheet	-56	54.0	46.0	—	problems	
SG5-C Neoprene flashing	-33	55.3	44.7	N/A		
SG5-C Top sheet	-55	55.3	44.7	3.5		
SG5-C Bottom sheet	-53	58.8	41.2	—		

*as reported by the person who took the sample

Appendix 5. Analysis of EPDM membranes by thermogravimetry and dynamic mechanical analysis.

Sample	Elongation (%)	Tensile Strength (kN/m)
STC1	555 ± 9	10.7 ± 0.4
STC2	557 ± 29	14.4 ± 0.5
STC3	511 ± 12	15.1 ± 0.4
STC4	484 ± 30	11.8 ± 0.2
S1 Top	375 ± 12	12.9 ± 0.5
S1 Bottom	459 ± 11	18.3 ± 0.2
S2 Top	376 ± 6	12.7 ± 0.1
S2 Bottom	471 ± 16	12.5 ± 0.1
S3-A Top	271 ± 16	15.3 ± 0.5
S3-A Bottom	253 ± 29	13.9 ± 1.2
S3-B Top	302 ± 11	16.5 ± 0.4
S3-B Bottom	328 ± 16	15.9 ± 0.5
S4-A Top	446 ± 18	10.9 ± 0.3
S4-A Bottom	468 ± 38	11.1 ± 0.4
S4-B Top	439 ± 7	11.7 ± 0.1
S4-B Bottom	475 ± 33	11.9 ± 0.5
S5-A Top	332 ± 17	12.9 ± 0.2
S5-A Bottom	467 ± 11	16.0 ± 0.6
S5-B Top	317 ± 19	12.6 ± 0.5
S5-B Bottom	372 ± 33	12.9 ± 0.4
S6 Top	309 ± 23	14.4 ± 0.8
S6 Bottom	328 ± 5	15.3 ± 0.1
S7 Top	392 ± 29	10.6 ± 0.4
S7 Bottom	530 ± 25	10.8 ± 0.3
S8 Top	438 ± 20	15.4 ± 0.3
S8 Bottom	536 ± 35	15.7 ± 0.6
S9 Top	430 ± 14	13.6 ± 0.4
S9 Bottom	436 ± 28	13.3 ± 0.5
S10 Top	560 ± 1	12.2 ± 0.1
S10 Bottom	582 ± 26	12.2 ± 0.3
S11 Top	266 ± 9	16.9 ± 0.2
S11 Bottom	333 ± 27	15.6 ± 0.3
S12 Top	436 ± 20	13.8 ± 0.1
S12 Bottom	535 ± 21	14.3 ± 0.5
S13-A Top	327 ± 28	11.2 ± 0.5
S13-A Bottom	360 ± 13	10.8 ± 0.1
S13-B Top	194 ± 14	11.4 ± 0.3
S13-B Bottom	286 ± 11	9.0 ± 0.1
S14* Top	448 ± 19	9.5 ± 0.2
S14* Bottom	258 ± 14	7.9 ± 0.1
SG1 Top	362 ± 16	13.2 ± 0.7
SG1 Bottom	305 ± 11	11.8 ± 0.4
SG2 Top	305 ± 10	11.9 ± 0.2
SG2 Bottom	393 ± 20	12.9 ± 0.4
SG3 Top	488 ± 26	11.8 ± 0.4
SG3 Bottom	501 ± 14	11.2 ± 0.2
SG4 Top	281 ± 25	10.0 ± 0.4
SG4 Bottom	328 ± 9	13.4 ± 0.1
SG5-A Top	451 ± 22	13.7 ± 0.3
SG5-A Bottom	524 ± 9	12.9 ± 0.3
SG5-B Top	407 ± 22	14.5 ± 0.3
SG5-B Bottom	441 ± 17	14.0 ± 0.2
SG5-C Top	421 ± 15	14.0 ± 0.1
SG5-C Bottom	414 ± 11	13.4 ± 0.2

* Reinforced

Appendix 6. *Tensile strength and elongation values for EPDM samples.*

Appendix 7. *Induced load measurements.*

Temperature (°C)	kN/m
0	0.18
-10	0.21
-20	0.27
-30	0.35
-40	0.46
-50	0.71
-60	1.76
-70	4.77

STC 1. *Induced load/width.*

Temperature (°C)	kN/m
0	0.08
-10	0.10
-20	0.12
-30	0.15
-40	0.21
-50	0.32
-60	0.69
-70	2.07

STC 2. *Induced load/width.*

Temperature (°C)	kN/m
0	0.09
-10	0.12
-20	0.15
-30	0.19
-40	0.29
-50	0.52
-60	1.32
-70	2.78

STC 3. *Induced load/width.*

Temperature (°C)	kN/m
0	0.18
-10	0.20
-20	0.25
-30	0.34
-40	0.51
-50	1.00
-60	2.61
-70	6.00

STC 4. *Induced load/width.*

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.08	0.07
-10	0.10	0.09
-20	0.11	0.11
-30	0.14	0.15
-40	0.19	0.19
-50	0.33	0.32
-60	0.90	0.84
-70	2.42	2.24

S1. *Induced load/width.*

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.06	0.08
-10	0.08	0.10
-20	0.10	0.13
-30	0.14	0.17
-40	0.23	0.27
-50	0.41	0.53
-60	1.32	1.49
-70	2.55	2.81

S2. *Induced load/width.*

Appendix 7. Induced load measurements (continued).

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.09	0.13
-10	0.11	0.18
-20	0.14	0.23
-30	0.18	0.31
-40	0.28	0.46
-50	0.48	0.79
-60	1.34	1.79
-70	2.77	3.23

S3-A. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.11	0.25
-10	0.14	0.32
-20	0.17	0.40
-30	0.22	0.52
-40	0.30	0.74
-50	0.48	1.14
-60	1.17	2.29
-70	2.69	3.89

S3-B. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.06	0.06
-10	0.07	0.07
-20	0.08	0.09
-30	0.12	0.14
-40	0.22	0.25
-50	0.49	0.50
-60	1.57	1.52
-70	2.90	2.81

S4-B. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.15	0.13
-10	0.21	0.19
-20	0.30	0.27
-30	0.45	0.40
-40	0.64	0.66
-50	1.09	1.14
-60	2.24	2.21
-70	3.74	3.54

S5-A. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.05	0.08
-10	0.07	0.11
-20	0.08	0.13
-30	0.10	0.18
-40	0.13	0.32
-50	0.21	0.58
-60	0.57	1.36
-70	1.76	2.54

S5-B. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.07	0.04
-10	0.07	0.03
-20	0.08	0.04
-30	0.10	0.06
-40	0.18	0.14
-50	0.37	0.38
-60	1.25	1.28
-70	2.63	2.74

S6. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.05	0.08
-10	0.07	0.11
-20	0.08	0.13
-30	0.10	0.18
-40	0.13	0.32
-50	0.21	0.58
-60	0.57	1.36
-70	1.76	2.54

S7. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.11	0.11
-10	0.13	0.14
-20	0.15	0.16
-30	0.19	0.20
-40	0.26	0.29
-50	0.43	0.47
-60	0.99	1.15
-70	2.28	2.42

S8. Induced load/width.

Appendix 7. Induced load measurements (continued).

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.06	0.11
-10	0.07	0.13
-20	0.08	0.15
-30	0.10	0.18
-40	0.15	0.24
-50	0.25	0.39
-60	0.78	0.99
-70	2.01	2.18

S9. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.06	0.05
-10	0.07	0.07
-20	0.08	0.08
-30	0.11	0.10
-40	0.18	0.15
-50	0.31	0.28
-60	0.76	0.69
-70	2.11	1.82

S10. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.08	0.11
-10	0.10	0.13
-20	0.11	0.14
-30	0.14	0.18
-40	0.17	0.23
-50	0.26	0.34
-60	0.61	0.78
-70	1.92	2.04

S13-A. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.03	0.08
-10	0.02	0.09
-20	0.00	0.11
-30	0.00	0.14
-40	0.03	0.21
-50	0.13	0.39
-60	0.66	1.15
-70	1.89	2.41

SG2. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.07	0.07
-10	0.08	0.09
-20	0.11	0.12
-30	0.15	0.16
-40	0.21	0.22
-50	0.32	0.36
-60	0.77	0.81
-70	1.94	2.01

SG3. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.08	0.07
-10	0.11	0.08
-20	0.14	0.10
-30	0.20	0.15
-40	0.29	0.24
-50	0.55	0.46
-60	1.38	1.19
-70	2.47	2.49

SG4. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.07	0.09
-10	0.08	0.11
-20	0.10	0.14
-30	0.12	0.18
-40	0.17	0.27
-50	0.27	0.44
-60	0.71	0.92
-70	1.90	2.05

SG5-A. Induced load/width.

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.07	0.12
-10	0.09	0.15
-20	0.11	0.17
-30	0.14	0.21
-40	0.19	0.29
-50	0.31	0.44
-60	0.75	1.01
-70	2.04	2.32

SG5-B. Induced load/width.

Appendix 7. Induced load measurements (continued).

Temperature (°C)	Unexposed kN/m	Exposed kN/m
0	0.09	0.09
-10	0.11	0.12
-20	0.13	0.14
-30	0.17	0.17
-40	0.23	0.24
-50	0.37	0.37
-60	0.96	0.87
-70	2.50	2.05

SG5-C. Induced load/width.