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Strain Energy of Bituminous Built-Up Membranes: An Alternative to the Tensile Strength Criterion

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ABSTRACT

This study was conducted to revise the performance criterion for tensile strength of bituminous built-up membranes. Bituminous membrane samples, fabricated from polyester fabric, polyester-glass composite fabric, and single plies of APP- and SBS-modified bitumen, were tested in tension to determine their load-elongation properties and to measure their strain energy. The results of the tensile tests of the new bituminous membranes indicated wide variability of load and elongation among the different types of materials.

As an alternative to the criterion that a bituminous built-up membrane have a tensile strength of 200 lbf/in. (35 kN/m), it was recommended that the strain energy should be a minimum of 3 lbf in./in. (13 N·m/m), when tested at 0 °F (-18 °C) in the weaker direction. The properties of the membrane samples in the study were compared to the suggested revised performance criterion. Two polyester samples (without glass), having relatively low strength and low ultimate elongation at 0 °F (-18 °C), did not conform to the revised criterion.

Key words: bituminous roofing; built-up; low-sloped; performance criterion; polyester; polymer-modified bitumen; roofs; strain energy; tensile strength

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1.0 INTRODUCTION

1.1 BACKGROUND

1.1.1 Bituminous Built-Up Roofing

Bituminous built-up membranes have been used for over a century to provide the waterproofing element in low-sloped roofing systems for industrial and commercial buildings. These membranes are normally constructed by applying hot bitumen in consecutive, continuous layers to adhere reinforcement sheets (felts or mats) to each other. Until the mid-1970s, almost all low-sloped roofing systems in the United States were the bituminous built-up type. Since that time, built-up membrane applications have declined as the use of elastomeric, thermoplastic, and polymer-modified bituminous membranes has increased [1]. Nevertheless, built-up roofing has retained a large share of the membrane market. Estimates indicate, for example, that in 1985 bituminous built-up membranes accounted for about 50 percent of those installed [2].

Although over the years the majority of bituminous built-up membranes have performed satisfactorily, premature failures have often occurred [3]. For example, the U.S. Air Force found in the mid-1970s that the built-up roofs on its Strategic Air Bases were lasting an average of 12 years, although a 20-year service life was anticipated [4].

Since the early 1970s, a number of steps have been taken by the industry to help assure the satisfactory performance of built-up roofing including:

- increasing the awareness of owners, manufacturers, and contractors of the need for proper specifications, and for quality installation and maintenance [5-7],
- the development of preliminary performance criteria [8],
- an increase in laboratory and field research to provide the basis for standards and solutions to problems [9], and
- changes in the types of reinforcements used in built-up membrane fabrication [11].

The change in the types of reinforcements has been drastic, as illustrated from survey data from the National Roofing Contractors Association (NRCA) [10,11]. In 1977, organic felts (56%) and asbestos felts (25%) had the major share of the reinforcement market. At that time, fibrous glass mat reinforcements (11%) accounted for a small share of the market and synthetic fabrics such as polyester were essentially not used. By 1983, fibrous glass (65%) was the most used, while the use of organic (17%) and asbestos (2%) felts had declined significantly. At the same time, there was also an increase in the use of polymer bituminous felts (15%) for built-up roofing. The introduction of new types of reinforcements for built-up roofing has resulted in a need to reexamine and possibly modify existing performance criteria for bituminous membranes [12,13]. This report presents the results

of a study to revise the performance criterion regarding tensile strength.

1.1.2 Performance Criteria and Splitting

Performance criteria for membranes are attempts to define performance in engineering terms for one component of the roofing system [13]. In 1974, Mathey and Cullen reported on preliminary performance criteria for bituminous membrane roofing [8]. They identified 20 performance attributes for these membranes, and suggested preliminary criteria for ten of the attributes. The ten criteria concerned tensile strength, thermal expansion, thermal movement, flexural strength, tensile fatigue strength, flexural fatigue strength, punching shear strength, impact resistance, wind resistance, and fire resistance.

The twenty attributes for bituminous built-up membranes were selected upon consideration of the membrane characteristics necessary to resist development of typical defects and premature failure in service. Typical defects include splitting, blistering, ridging, slippage, delamination, and puncturing. Splitting is tearing of the membrane resulting from tensile stress [14] (which exceeds the breaking strength of the membrane). Splitting is one of the most commonly occurring defects [2,15], and as is obvious, has disastrous consequences, since the waterproofing integrity of the membrane is lost. Griffin [16] has recently given a summary of the causes of splitting and its prevention. Lewis [17] has

applied the finite-element method (FEM) of analysis to estimate levels of temperature-induced stress in bituminous built-up membranes as a step towards understanding the stresses to which membranes may be subjected in service.

Cash [15] has described characteristic condtions under which splits frequently appear in service:

- o northern climates,
- o winter months,
- o well-insulated roofs,
- o roofing systems with poor adhesion between the deck and insulation, and
- o roofing systems with weak membranes.

The first three of these factors are unavoidable, since buildings (and thus well-insulated roofs) are constructed in northern climates. The last two factors can be avoided through proper design, material selection, and system construction.

In reporting on the factors that influence the splitting of asbestos membranes, McCorkle et al. [18] stated that membrane strength is generally overrated as a factor in splitting. They indicated that the factors affecting asbestos membrane splitting were:

- o deck type and deflection characteristics,
- o insulation anchorage technique,

- o number of felt plies in the membrane, and
- o type of mopping asphalt used in the membrane

Of the preliminary performance criteria suggested by Mathey and Cullen, the tensile strength criterion is considered important to the ability of the built-up membrane to resist stresses imposed in service [13]. This criterion has been the most widely referenced of the twenty criteria suggested. For example, the National Roofing Contractors Association (NRCA) has used it as the basis for tensile testing of bituminous built-up membranes cited in the NRCA "Roofing Materials Guide."

The suggested preliminary performance criterion [8] for tensile strength is that the membrane should have a minimum strength of 200 lbf/in. (35 kN/m), when tested at 0 °F (-18 °C) in the weakest direction of the membrane (Appendix A). The development of this criterion was based on the load-elongation properties of bituminous built-up membranes available at the time and their performance in service. For example, when tested as described in the tensile strength criterion, many traditional built-up membranes had tensile strengths greater than 200 lbf/in. (35 kN/m) and elongations at break in the range of 1-3 percent. However, some of the new (or non-conventional) membranes fabricated from synthetic reinforcements such as polyester fabrics or from polymer-modified bitumens have tensile strengths less than 200 lbf/in. (35 kN/m) and elongations at break of 20 percent or

more. For the limited time in service, the performance of many of these non-conventional materials has been satisfactory [19-21]. Concerns that they may be prone to splitting have not been reported, suggesting that the performance criterion of 200 lbf/in. (35 kN/m) is not a requisite for acceptable performance of bituminous built-up membranes in cases where they are relatively extensible (e.g., having an extensibility greater than 1-3 percent).

1.1.3 Strain Energy

A preliminary study [13] was conducted at the National Bureau of Standards (NBS) to propose possible alternative approaches which might be taken to revise the tensile strength criterion. The study suggested that a strain energy approach be used. Strain energy is the energy that a material absorbs as a result of its deformation [22]. An important advantage to the strain energy approach was that it was compatible with the original tensile strength criterion in that tensile strength and strain energy are properties measured in the same tensile test. As a consequence, previous data, developed as the basis of the original tensile strength criterion, could again be used in the development of a strain energy criterion.

The use of strain energy as an approach for revision of the tensile strength criterion can be summarized as follows. When a load (force) is applied to a material, work is done as the load moves through certain distances as the material undergoes

deformation, and energy is absorbed. In a uniaxial tensile test, the total work (W) done on the material is by definition [22]:

$$W = \int_0^e P de$$

where P is the load, and e is the deformation.

The total work (W) done in deforming the material to some value, e, is equal to the area under the load-deformation curve (Figure 1). It represents the total energy absorbed by the material during strain and is, thus, called the strain energy [23].

The area under the entire load-deformation curve is a measure of the strain energy required to rupture a material [22] and is related to the toughness of the material. Toughness represents a material's ability to resist energy loads before rupture [22]. As is evident from Figure 2, a high strength material having low capacity to deform may have less toughness than a low strength material having high capacity to deform.

Traditional built-up membranes may be considered as having relatively high strength and low deformation, while some of the non-conventional membrane materials may have relatively low strength and high deformation (Figure 2). When in place on a given building, a non-conventional membrane material would be exposed to the same environmental conditions (which can produce splitting forces) as experienced by a traditional bituminous built-up membrane. Thus, as a measure of splitting resistance which includes both strength and extensibility of the membrane,

it is considered that the non-conventional membrane materials should have strain energies at least comparable to those of the traditional bituminous built-up membranes that have historically provided acceptable long-term performance.

The use of strain energy as a criterion must also include a consideration of the watertightness of the membrane upon elongation. Some of the non-conventional bituminous built-up membranes, having greater elongation at break than the traditional ones [19], may not remain watertight when elongated at low temperatures to values approaching ultimate. The bitumen in the composite built-up membrane is brittle at low temperatures (for example, less than 40 °F or 4 °C). During low-temperature elongation of a relatively extensible membrane, the bitumen may crack before the membrane ruptures. The result would be loss of watertightness, since the bitumen provides the waterproofing for the built-up membrane. Thus, in applying the strain energy approach to the performance of bituminous built-up membranes, the membrane should remain watertight after deformation to the minimum strain energy suggested as a performance criterion.

It is noted that the strain energy of a material, determined as the area under the load-elongation curve, is dependent upon the size of the specimen (or, gage length over which strain is measured, if the specimen size is held constant) [22]. To eliminate the effect of specimen size on the determination of

strain energy as a material property, the strain energy per unit volume (sometimes called strain energy density) is often considered. Strain energy density is determined by dividing the strain energy by the initial volume of the specimen. However, for bituminous built-up membranes, the use of strain energy density is not practicable. The thickness of a built-up membrane is normally not homogeneous for the specimen, and consequently, in conducting load-deformation tests, the load is reported in force per unit specimen width [24]. For the same reason, it is thus considered that the strain energy of bituminous built-up membranes, based on unit gage length, should be reported for specimens of constant width and not strain energy density.

The application of strain energy in the specification of bituminous built-up membranes having varying load-deformation properties is not a new concept [13]. The Canadian General Standards Board (CGSB) Standard [25] and the Midwest Roofing Contractors Association (MRCA) Performance Criteria [26] for polymer modified bitumens both have requirements for minumum strain energy for these materials. However, these two documents refer to strain energy at break and do not consider the watertightness of the membrane after some limited elongation which does not reach the break point.

1.2 OBJECTIVES

The objectives of this study are:

1) to determine the load-deformation properties including strain energy of some non-conventional bituminous membrane materials, and

2) to suggest a strain energy criterion as an alternative for the tensile strength criterion given in NBS Building Science Series 55 [8].

1.3 SCOPE

This study concerned the load-deformation properties including strain energy of bituminous built-up membrane specimens fabricated in the laboratory. The primary type of built-up membrane investigated was reinforced with polyester fabric, although specimens having organic felt and fibrous glass mat reinforcements were included. Load-deformation properties were also measured for two polymer-modified bitumens. In addition, after a strain energy criterion was suggested based on the initial test data, additional polyester-based membrane specimens were tested to compare their strain energy with that of the revised criterion.

2.0 EXPERIMENTAL

2.1 MEMBRANE SAMPLES

2.1.1 Samples Used in Determination of the Strain Energy Criterion

The bituminous membrane samples (nos. 1-9) used for the determination of the strain energy criterion are described in Table 1. All materials were commercially available for low-sloped roofing. The built-up membrane samples were fabricated using either hot asphalt or an asphaltic emulsion (Table 1) put on in quantities normally applied in practice. The procedure is given in Appendix B. The temperature of the asphalt during application was a minimum of 425 °F (218 °C). No asphalt was applied to the outer surfaces of the samples. After fabrication, the samples were kept at ambient laboratory temperature for at least 72 hours before testing. The orientations of the test specimens, relative to the direction of the manufactured roll of reinforcing fabric, were longitudinal (machine-direction), transverse (cross-machine direction), and diagonal (45° to the machine direction).

2.1.2 Samples Used for Comparison with the Suggested Strain Energy Criterion

Four other polyester-based built-up membrane samples (nos. 10-13) were prepared using asphaltic emulsion and tested in tension for comparison of their strain energy with that suggested in the revised criterion. These samples are described in Table 2. For these four samples, a coating of the emulsion was applied on either one or both outer surfaces.

2.2 TENSILE TEST

All samples were tested in tension using a universal testing machine at a rate of 0.08 in./min (2 mm/min). The machine was equipped with a microcomputer for data acquisition, reduction, and storage, as well as for calculating the strain energy of the specimens. Tests were carried out at 73, 0, and -30 °F (23, -18, and -34 °C). The test-specimen configuration was as described in ASTM D 2523 [24]. Five specimens of each membrane sample were tested at each temperature for each orientation.

For those samples that underwent relatively little extension (< 5 percent) during testing, percent elongation was determined using a 2-in. (50-mm) gage-length extensometer attached at specimen mid-length. The samples for which the extensometer was used were:

- sample nos. 1 and 2 (transverse direction) at 0 °F (-18 °C),
- sample nos. 3 and 4 (longitudinal and transverse directions) at 0 and -30 °F (-18 and -34 °C),
- sample no. 8 (all directions) at all temperatures, and
- sample no. 9 (longitudinal and transverse directions) at -30 °F (-34 °C).

In the majority of the cases using the extensometer, specimen rupture occurred within the extensometer gage length. When specimen rupture took place outside the extensometer gage length, the measured extension was considered to be indicative of the extension occurring in the area of the break.

Percent elongation of the other samples (i.e., those not listed above) at the remaining conditions of test was determined by measuring the amount of separation which occurred between the specimen grips during testing. Observation of the specimens during testing did not indicate noticeable slippage in the grips. Any slippage in the grips was considered to be negligible in relation to the total elongation of the specimen.

2.3 WATERTIGHTNESS TEST

Watertightness tests were conducted according to the procedure given in the Canadian General Standards Board (CGSB) Standard for polymer-modified bitumens [25]. Test specimens had an area of 4 $in.^2$ (2500 mm^2), and the diameter of the column holding the water was 1.8 in. (44 mm). Before conducting the watertightness tests, the specimens were elongated at 0 °F (-18 °C) at a rate of 0.08 in./min (2 mm/min) to a percent corresponding to the minimum strain energy suggested in the revised performance criterion (see section 4.2.3). Upon removal from the environmental chamber, the ends of the elongated, cold specimens were immediately nailed to a plywood substrate for conducting the watertightness test.

3.0 RESULTS

When tested in tension, the 9 membrane samples described in Table 1 showed, as expected, varying load-elongation properties. This is illustrated in Figure 3, which presents the results of the tests at 0 °F (-18 °C) for specimens tested in the transverse direction. Several samples (Nos. 1 - 4, and 8) exhibited relatively high peak loads that occurred at break with relatively little elongation. Peak load is defined as the maximum load recorded during the tension test. One sample (No. 9) gave a peak load during the initial portion of the test (due to break of the reinforcement), and had a relatively high elongation at break. For another sample (No. 7), the peak load occurred essentially at break with relatively high elongation. Two samples (Nos. 5 and 6) exhibited low load and intermediate elongation.

Tables 3, 4, and 5 present summaries of the average tensile strength, percent elongation, and calculated strain energy for the tension tests. Tensile strength is given as the peak load experienced during testing. Depending on the sample, the peak load occurred at the initial stages of elongation or at the ultimate elongation. For those cases where the peak load occurred during initial specimen elongation, the percent elongation and strain energy are given for peak loads and also for the break point of the specimens (referred to in the tables as ultimate elongation and total strain energy, respectively). When the peak load occurred at specimen break, only values of ultimate elongation

and total strain energy are reported (Tables 4 and 5). In some tests, a rapid, large loss of load occurred just prior to specimen break (for example, see Figure 3, specimen no. 7). In these cases also, only the ultimate elongation and total strain energy are reported.

Appendix C presents a summary of the coefficients of variation for all tests of samples listed in Table 1. The coefficient of variation of average tensile strength of all specimens was generally 15 percent or less. With the exception of sample nos. 4 and 5 at 0 and -30 °F (-18 and -34 °C), the coefficients of variation of average percent elongation and strain energy were generally 25 percent or less. In the case of the exceptions, the values of the coefficient of variation for several of the test conditions were in the range of 50 to 90 percent. The degree of bonding (or interlocking) of the fibers in the fabrics has a significant effect on the reproducibilty of the elongation and strain energy data.

4.0 DISCUSSION

4.1 CONVENTIONAL BUILT-UP MEMBRANES

Conventional 4-ply bituminous built-up membranes using organic and glass felts (sample nos. 1 and 2, respectively) were included in the study to compare their load-elongation properties at 0 °F (-18 °C) with those of the non-conventional membrane materials. It was particularly of interest to determine the strain energy of the conventional samples at 0 °F (-18 °C), since this property had not been reported previously by Mathey and Cullen [8] during the development of the preliminary performance criteria.

The strain energies at 0 °F (-18 °C) for the 4-ply organic and glass built-up membranes were 3.2 and 4.0 lbf·in./in. (14.0 and 17.6 N·m/m), respectively. The greater value of strain energy for the glass felt membrane was attributed, for the most part, to its greater tensile strength (Table 3). The ultimate elongations for the two conventional membrane samples were found to be similar (Table 4). The values of tensile strength of both the organic and glass felt membrane samples (Table 3) were similar to the those reported by Mathey and Cullen [8] for these types of materials.

4.2 NON-CONVENTIONAL BITUMINOUS MEMBRANE MATERIALS

Little data on the load-elongation properties of polyester reinforced bituminous built-up membranes have been reported for different test temperatures and orientations of fabric in the

membrane specimen [19]. Thus, for purposes of characterization, 3-ply specimens of polyester-based bituminous built-up membranes (sample nos. 3 - 7), oriented in the longitudinal, transverse, and diagonal directions of the fabric, were tested in tension at 73, 0, and -30 °F (23, -18, and -34 °C).

Splitting in bituminous built-up membranes usually occurs perpendicular to the weaker orientation of the reinforcement [15]. For this reason, tensile properties of built-up membranes are normally measured for the longitudinal and transverse directions of the felt to determine the stronger orientation. The membrane can be oriented on the roof to have maximum resistance to areas of stress concentration. For example, Griffin [27] has indicated that the direction of reinforcing felts applied on insulation substrates should be perpendicular to long, continuous joints between the adjacent insulation boards.

Tensile properties for the diagonal direction of conventional membrane materials are normally not measured. In this study, the tensile properties of the non-conventional membrane materials were determined for the diagonal direction, since some of these materials contained reinforcement which could contribute to strength of the fabric in the longitudinal and transverse directions, but might have little influence on strength in the diagonal direction. For such materials, the diagonal direction of the fabric would then be the weakest orientation.

The results of the study showed that the polyester fabrics having the bonded glass net (sample nos. 3 and 4) were weakest in the diagonal direction (Table 3). However, this finding should have little impact on the use of the glass-reinforced polyester fabrics for built-up membranes, since in normal practice, the fabric orientation during application would be perpendicular to the long joints between insulation boards. Thus, further discussion of the data regarding the orientation of the fabric in the test specimens will be limited to the longitudinal and transverse directions.

The APP (atactic polypropylene)- and SBS (styrene-butadiene-styrene)-modified bitumens were included in the test program to compare the load-elongation properties of typical polymer-modified bitumens to those of bituminous built-up membrane materials. In developing the scope of the study, it was intended to explore whether the revised performance criterion for tensile strength would have applicability to typical polymer-modified bitumens.

4.2.1 Tensile Strength

With one exception, the membrane samples were weaker in the transverse direction than the longitudinal direction at each of the test temperatures (Table 3). One polyester sample (no. 7) was weaker in the longitudinal direction. The method of manufacture for this polyester fabric was different than that used for the

other two polyesters (sample nos. 5 and 6). The finding that the weaker orientation of a polyester fabric may be either the longitudinal or transverse direction has significance for roofing applications. The load-elongation properties of polyesters in both directions should be known before application so that proper orientation of the weaker direction with respect to insulation boards may be achieved.

For a given orientation (e.g., transverse), all membrane samples were weakest at 73 °F (23 °C) (Table 3). At the lower test temperatures, the strength of the samples increased. Sample nos. 3, 4, and 9 had greatest tensile strengths at -30 °F (-34 °C). The polyester samples (nos. 4 - 6) were strongest at 0 °F (-18 °C), although their strengths at -30 °F (-34 °C) were not much different than those at 0 °F (-34 °C). Sample no. 8 (APP-modified bitumen) had a much greater tensile strength at 0 °F (-18 °C) than at -30 °F (-34 °C).

The load-elongation behavior of three samples (nos. 3, 4, and 8) for the transverse direction at 0 °F (-18 °C) was similar to that of the conventional built-up membranes (nos. 1 and 2), as illustrated in figure 4. The tensile strength of the three samples was greater than 200 lbf/in. (35 kN/m), indicating conformance to the preliminary performance criterion for bituminous built-up membranes [8].

The strength of sample nos. 3 and 4 at 0 °F (-18 °C) was attributed to the glass net bonded to the polyester fabric. Peak load was achieved when the glass net failed. The polyester fabric did not break at this point. However, delamination of the three plies of polyester fabric in the specimens occurred simultaneously with the glass-net rupture. Because of the delamination, the membrane specimens were considered failed, and the tension test was terminated.

4.2.2 Percent Elongation

For all orientations at 73 °F (23 °C), the non-conventional bituminous membrane materials had, with one exception, ultimate elongations ranging from approximately 15 to 150 percent (Table 4). These values were substantially greater than the ultimate elongations of conventional built-up membranes, which may range from about 1 to 4 percent[1] at ambient temperatures. The ultimate elongation of sample no. 8 was only slightly greater than 1 percent at 73 °F (23 °C).

As the temperature was decreased below 73 °F (23 °C), the ultimate elongations of all samples except no. 8 decreased. In general, sample no. 8 exhibited little change in percent elongation over the range of test temperatures. On the average, it had its greatest percent elongation (2.6 percent) at 0 °F (-18 °C). Reasons for this finding were not investigated.

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[1]. Unpublished NBS data.

Three of the polyester-based samples (nos. 3, 4, and 7) had comparable elongations at 0 and -30 °F (-18 and -34 °C) for a given orientation. Polyester sample no. 5 had its lowest percent elongation (for all orientations) at 0 °F (-18 °C). The percent elongation was twice as great at -30 °F (-34 °C) as at 0 °F (-18 °C), as shown in figure 5, which gives load-elongation curves in the transverse direction at the three test temperatures. Polyester sample no. 6 showed similar behavior for the transverse direction, having about twice the extensibility at -30 °F (-34 °C) than at 0 °F (-18 °C).

The SBS-modified bitumen (sample no. 9) was the only material which was significantly more extensible at 0 °F (-18 °C) than at -30 °F (-34 °C). Complete embrittlement of the membrane material had apparently not occurred at 0 °F (-18 °C), because of the modification with the SBS polymer.

4.2.3 Strain Energy

The total strain energies of the non-conventional membrane materials varied considerably between some samples, which reflected the differences in their peak loads and ultimate elongations (Table 5). For the longitudinal and transverse directions, four polyester-based samples (nos. 3 - 6) were found to have their greatest total strain energy at 73 °F (23 °C), which was attributed to their relatively high elongations at this temperature. For these four samples, as the test temperature

decreased below ambient, the total strain energy decreased. For sample nos. 3 and 4, the total strain energy was comparable at 0 °F (-18 °C) and -30 °F (-34 °C). In the cases of sample no. 5 in the longitudinal and transverse directions and sample no. 6 in the transverse direction, the strain energy at -30 °F (-34 °C) was about twice as great as that at 0 °F (-18 °C). This was primarily due to the lower percent elongation at 0 °F (-18 °C), as indicated previously (section 4.2.2). From figure 5, it is evident that, for three test temperatures, the total strain energy of sample no. 5 was least at 0 °F (-18 °C).

For a given orientation, the total strain energies of polyester sample no. 7 were comparable at the three test temperatures. In this case, relative increases in load and decreases in ultimate elongation, as the temperature was reduced below 73 °F (23 °C), produced little effect on the strain energy (figure 6). In the case of both polymer-modified bitumens (sample nos. 8 and 9), the relative changes which occurred in load and ultimate elongation, as the test temperature was decreased, resulted in the samples having their greatest total strain energy at 0 °F (-18 °C) (Table 5).

At 0 °F (-18 °C) for the weaker membrane direction, two of the five polyester-based samples (nos. 3 and 7) had a total strain energy greater than that of the 4-ply organic membrane sample (no. 1) (Table 5). In contrast, for the same conditions, the

other three polyester-based samples (nos. 4, 5, and 6) had a total strain energy less than that of the organic membrane sample. Figure 7 compares typical load-elongation curves for the polyester samples (nos. 5, 6, and 7) with a curve for the organic membrane sample (no. 1). It is evident that the area under the curve for sample no. 7 is much greater than that for the organic membrane sample. It is not evident that the areas under the curves for sample nos. 5 and 6 are less than that of the organic membrane sample. It was found by calculation that the total strain energy of polyester sample nos. 5 and 6 was less than that of the organic membrane sample.

5.0 REVISED PERFORMANCE CRITERION FOR TENSILE STRENGTH

The original tensile strength performance criterion of 200 lbf/in. (35 kN/m) for bituminous built-up membranes (having relatively high strength and low extensibility) has provided a technical basis for the U.S. roofing industry in the selection of membrane materials that provide satisfactory long-term performance. The original criterion should be continued to be used. However, the original tensile strength criterion should have an alternative approach to provide applicability to the non-conventional bituminous membrane materials that have relatively low strength and high elongation, and that have shown satisfactory in-service performance regarding splitting resistance.

The approach taken for revising the tensile strength performance criterion is to use the strain energy of the membrane as an alternative to tensile strength. A major difficulty in suggesting the use of strain energy is the selection of a minimum value which the membrane material should possess under the given test conditions. As a first step to resolve this difficulty, it is considered that the minimum value of strain energy should be based on the strain energy of built-up membrane materials which have provided acceptable performance. In this regard, four-ply organic built-up membranes, properly applied and maintained, have, in general, performed satisfactorily for many years [8, 29]. Until recent times, membranes having organic felts were the most commonly used, and provided an industry

benchmark against which the performance of other types of mambrane materials was compared. For this reason, it is suggested that a minimum value of strain energy (for use as a performance criterion) be comparable to that of typical 4-ply organic bituminous built-up membranes. It is noted that 4-ply organic membranes generally have shown conformance to the tensile strength criterion of 200 lbf/in. (35 kN/m).

Although 4-ply organic built-up membranes having different brand names are generically the same type of material, they do not all have equivalent strain energies. This is due, in part, to differences in load-elongation properties imparted to the felts during the manufacturing process. Table 6 compares the tensile strength, ultimate elongation, and strain energy of some typical 4-ply organic membranes. With the exception of the sample tested in the present study, the strain energy of the other samples was estimated from load-elongation data given in the referenced papers [8, 28, and 30]. Strain-energy data were not presented in these references. Table 6 indicates that the strain energy of the samples was in general estimated to be about 3 lbf·in./in. (13 N·m/m) or greater. In one case of a coal tar pitch membrane, the estimated strain energy was 1.7 lbf·in./in (7.6 N·m/m), which was attributed to the low elongation (0.9 percent) of the sample.

Based on the limited data given in Table 5, it is suggested that a preliminary minimum value of strain energy of

3 lbf•in./in. (13 N•m/m) be used in the revision of the performance criterion for tensile strength. Additional data from load-elongation tests of 4-ply organic built-up membranes may result in a value of strain energy superseding the presently suggested value.

The revised performance criterion for tensile strength is presented in Table 7. As previously discussed, a watertightness test must be conducted on membrane materials which conform to the strain energy portion of the criterion. The watertightness test should be conducted on the specimen after it is elongated at 0 °F (-18 °C) to a percent at which the strain energy is equivalent to the criterion value of 3 lbf in./in. (13 N m/m). If the specimen is not watertight after that elongation, it is considered to be non-functional, and would not meet the criterion.

The watertightness test in the CGSB Standard for polymer-modified bitumens [25] was used in the present study to demonstrate watertightness of the elongated membrane specimens. The test was selected because it was available in a national standard developed in North America. The description of the procedure in the standard indicated that the test should be easily conducted in the laboratory. However, difficulty was encountered in sealing membrane test specimens to the vertical tubes containing the columns of water that provided pressure for the tightness test. Hot wax was found to provide the best seals, but sealing

was still difficult to accomplish. The test was considered adequate for purposes of demonstrating watertightness in this study. Because of the difficulties encountered in the present study, it is suggested that, for future application of the tensile strength criterion, another watertightness test should be used or an improved test procedure be developed.[2]

5.1 COMPARISON OF TEST SAMPLES TO THE REVISED CRITERION

Table 8 compares the bituminous membrane materials included in the study with the revised performance criterion for tensile strength. Five samples (nos. 1 - 4, and 8) showed conformance to the original criterion of having a tensile strength of 200 lbf/in. (35 kN/m). Watertightness tests were not conducted on these samples, since loss of watertightness of built-up membranes (which have relatively low extensibilty) during elongation to break has never been of concern. These materials provide waterproofing capability as long as they do not split, puncture, or incur similar damage.

Sample nos. 7 and 9 did not conform to the tensile strength criterion, but did meet the strain energy criterion of 3 lbf·in./in. (13 N·m/m). These samples were also watertight when

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[2]. During the course of the study, conversations were held with Dr. R. Booth, present chairman of the CGSB task group having responsibility for the standard. He indicated that the standard is being reviewed for possible revision. One concern being addressed is the significance of the current test procedure for demonstrating watertightness of a damaged membrane specimen.

tested according to the procedure in the CGSB Standard. Prior to the watertightness test, sample no. 7 was elongated 5 percent at 0 °F (-18 °C). Sample no. 9 was elongated to 3.5 percent. At these elongations, the strain energy of the specimens was about 3 lbf·in./in. (13 N·m/m).

Two polyester samples (nos. 4 and 5) did not show conformance to either the tensile strength or strain energy criterion. As a consequence, there was no need to conduct the watertightness test on these samples.

The two polymer-modified membrane materials met the revised performance criterion. The APP-modified bitumen (no. 8) showed conformance to both the tensile strength and strain energy portions of the criterion. The SBS-modified bitumen (no. 9) was in conformance with the strain energy section. Additional research should be conducted on other polymer-modified bituminous membranes to obtain further evidence that the revised criterion would have applicability to the many polymer-modified bitumens that are presently being marketed.

Finally, it is noted that the tests of the bituminous built-up membranes were conducted only on new samples prepared in the laboratory. The test specimens were not subjected to any exposure conditions, either in the laboratory or outdoors, which might be considered deleterious to the membranes. The minimum

strain energy of 3 lbf•in./in. (13 N•m/m) should be maintained by a membrane as it ages. Changes in membrane properties that occur due to weathering and diurnal cycling should not result in a strain energy less than the suggested minimum. Further research is needed to investigate whether the non-conventional bituminous built-up membranes maintain an acceptable minimum value of strain energy after performance in service.

5.2 Comparison of Additional Samples to the Revised Criterion

Table 9 presents the tensile strength, ultimate elongation, and total strain energy for the additional polyester-based membrane samples (nos. 10-13). As previously indicated, these samples were tested for comparison of their strain energy with that suggested for the revised performance criterion. Three replicate specimens of each sample were tested at 0 °F (-18 °C) in the transverse direction of the fabric. Coefficients of variation for these tests are given in Appendix D. As is evident in Table 9, the total strain energies of the four specimens were found to be greater than the suggested criterion value of 3 lbf•in./in. (13 N•m/m). Watertightness tests were not conducted on the four specimens. To determine conformance to the revised criterion, a watertightness test of the samples would need to be conducted.

In conducting the additional tests, it was of interest to investigate whether a surface coating of asphaltic emulsion would influence the sample tensile strength. Sample nos. 10 and 11

were prepared from the same fabric and were identical except that one outer surface of no. 10 was coated, whereas the two surfaces of no. 11 were coated (Table 9). Sample nos. 12 and 13 also formed an identical pair except for surface coating. Strict comparison of the effect of the surface coating is difficult to make because of the limited number of replicate specimens tested. As given in Table 9, the former pair (nos. 10 and 11), had comparable tensile strengths, whereas the latter pair (nos. 12 and 13) had tensile strengths differing by about 25 percent. Visual examination of the test specimens seemed to indicate that the asphaltic emulsion penetrated the polyester fabric used for sample nos. 12 and 13 more than it penetrated the fabric used to prepare sample nos. 10 and 11. The penetration of the asphaltic emulsion into the fabric could provide increased fabric strength.

6.0 SUMMARY AND RECOMMENDATIONS

This study was conducted to revise the performance criterion for tensile strength of bituminous built-up membranes. This criterion is that the tensile strength of the membrane should be a minimum of 200 lbf/in. (35 kN/m), when tested in the weaker direction at 0 °F (-18 °C). The development of this criterion was based on the load-elongation properties of traditional built-up membranes available in the early 1970s and their performance in service. Alternative bituminous membranes, based on synthetic reinforcements and polymer-modified bitumens are now available. The non-conventional materials have generally performed satisfactorily, particularly with regard to splitting resistance. However, many of them do not have tensile strengths conforming to the minimum value suggested in the original criterion. They have relatively low strength (< 200 lbf/in. or 35 kN/m) and high elongation in relation to the traditional bituminous built-up membranes, which may be considered as relatively high strength and low elongation materials.

Bituminous membrane samples, fabricated from 3 plies of polyester fabric, 3 plies of polyester-glass composite fabric, and 1 ply of APP- and SBS-modified bitumen, were tested in tension to determine their load-elongation properties and to measure their strain energy. The tests were conducted in the longitudinal, transverse, and diagonal directions at 73, 0, and -30 °F (23, -18, and -34 °C). The single-ply materials were included to investigate the

applicabilty of the revised criterion to these types of membranes. Limited tensile tests of conventional 4-ply organic and glass built-up membrane specimens were also carried out to compare the load-elongation properties with those of the non-conventional membrane materials.

The results of the tensile tests of the non-conventional bituminous membranes indicated wide variability of load and elongation among the different types of materials. The polyester and SBS-modified materials generally exhibited relatively low strength and high elongation; whereas, particularly at the lower temperatures, the polyester-glass composite materials and APP-modified bitumen showed load-elongation properties similar to those of conventional built-up membranes.

A strain energy approach was taken to revise the tensile strength criterion. A strain energy criterion considers both the strength and extensibility of the membrane, and is related to the toughness of the material to withstand energy loads before rupture. As an alternative to the criterion that a bituminous built-up membrane have a tensile strength of 200 lbf/in. (35 kN/m), it was recommended that the strain energy should be a minimum of 3 lbf·in./in. (13 N·m/m), when tested at 0 °F (-18 °C) in the weaker direction. This value of strain energy was selected based on a summary of limited load-elongation data for conventional 4-ply organic bituminous built-up membranes.

When strain energy is used as a criterion, it is necessary to conduct a watertightness test to assure that limited strain of the membrane at low temperatures does not occur to an extent that cracks the bitumen, resulting in loss of waterproofing integrity. It was recommended that a watertightness test be conducted on specimens after partial elongation to a percent corresponding to the minimum strain energy of 3 lbf•in./in. (13 N•m/m).

The properties of the membrane samples in the study were compared to the suggested revised performance criterion. Two polyester samples (without glass), having relatively low strength and low ultimate elongation at 0 °F (-18 °C), did not conform to the revised criterion. The other samples showed conformance due to minimum tensile strength, minimum strain energy, or both. Two samples (a 3-ply polyester without glass and the SBS-modified bitumen), which conformed due to minimum strain energy, were shown to remain watertight after less-than-ultimate elongation ($<$ 5 percent) at 0 °F (-18 °C).

The data on which the strain energy criterion was developed were obtained from tests of new laboratory-prepared specimens. A membrane should maintain a strain energy above the suggested minimum throughout its service life. Further research is needed to investigate whether the non-conventional bituminous built-up membranes maintain an acceptable minimum value of strain energy after long-term in-service performance.

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Table 1. Membrane Materials Used for Test Specimens for Determination of the Strain Energy Criterion

Sample No.	Plies No.	Membrane Reinforcement[a]	Interply Bitumen[b]
1	4	Organic Felt	Asphalt
2	4	Glass Felt	Asphalt
3	3	Polyester/Glass Fabric[c,d] (2 ounce/square yard)	Asphalt
4	3	Polyester/Glass Fabric[e] (2 ounce/square yard)	Asphalt
5	3	Polyester Fabric (2 ounce/square yard)	Asphaltic Emulsion
6	3	Polyester Fabric (2 ounce/square yard)	Asphaltic Emulsion
7	3	Polyester Fabric (3 ounce/square yard)	Asphaltic Emulsion
8	1	APP-Modified Bitumen[f]	None
9	1	SBS-Modified Bitumen[g]	None

a. The organic felt was ASTM D 226, Type I; the glass felt was ASTM D 2178, Type IV; there were no ASTM standards available for the polyester or polymer modified bitumen materials.

b. The asphalt was ASTM D 312, Type III; the asphaltic emulsion did not conform to an ASTM standard.

c. This material was a composite of a filament glass net (5 strands to the inch) bonded between two layers of polyester fabric.

d. The parenthetical expression is a fabric descriptor. The textile industry describes fabrics by mass per unit area, normally ounces per square yard or grams per square meter.

e. This material was a composite of a filament glass net (6 strands to the inch) bonded on one surface of a polyester fabric.

f. APP indicates that the modifier was atactic polypropylene.

g. SBS indicates that the modifier was styrene-butadiene-styrene.

Table 2. Membrane Materials Used for Samples Tested in Comparison to the Strain Energy Criterion

Sample No.	Plies No.	Membrane Reinforcement[a]	Interply Bitumen[b]	Surface Coating[c]
10	3	Polyester Fabric (3 ounces/sq yard)[d]	Asphaltic Emulsion	1 side
11	3	Polyester Fabric (3 ounces/sq yard)	Asphaltic Emulsion	2 sides
12	3	Polyester Fabric (3 ounces/sq yard)	Asphaltic Emulsion	1 side
13	3	Polyester Fabric (3 ounces/sq yard)	Asphaltic Emulsion	2 sides

a. There were no ASTM standards available for the polyester fabric materials.

b. The asphaltic emulsion did not conform to an ASTM standard.

c. Emulsion was applied to one or both outer surfaces of the test specimens in addition to the interply application.

d. The parenthetical expression is a fabric descriptor. The textile industry describes fabrics by mass per unit area, normally ounces per square yard or grams per square meter.

Table 3. Tensile Strength of Membrane Samples Used in the Determination of the Revised Criterion, lbf/in. (kN/m)

Sample No.	73°F (23°C) Peak Load[a]			0°F (-18°C) Peak Load[a]			-30°F (-34°C) Peak Load[a]		
	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]	L[b]	T[c]	D[d]
1.					287 (50.3)				
2.					370 (64.8)				
3.	211 (36.9)	154 (27.0)	79.0 (13.8)	342 (59.8)	288 (50.5)	144 (25.3)	392 (68.7)	317 (55.6)	113 (19.8)
4.	170 (29.7)	147 (25.7)	68.5 (12.0)	279 (48.9)	202 (35.4)	92.5 (16.2)	315 (55.2)	235 (41.2)	72.2 (12.7)
5.	43.6 (7.6)	33.1 (5.8)	40.7 (7.1)	55.9 (9.8)	44.9 (7.9)	53.7 (9.4)	45.1 (7.9)	33.8 (5.9)	41.1 (7.2)
6.	74.5 (13.0)	26.3 (4.6)	38.6 (6.8)	105 (18.5)	32.9 (5.8)	51.7[e] (9.1)	99.0 (17.3)	29.1 (5.1)	44.3 (7.8)
7.	62.6 (11.0)	90.7 (15.9)	67.0 (11.7)	101 (17.7)	16Ɛ (23.4)	106[d] (18.6)	95.6 (16.7)	130 (22.7)	107 (18.7)
8.	125 (21.9)	93.5 (16.4)	89.6 (15.7)	289 (50.6)	251 (44.0)	265 (46.5)	195 (34.1)	152 (26.5)	167 (29.3)
9.	94.3 (16.5)	55.4 (9.7)	72.2 (12.6)	217 (38.1)	144 (25.2)	156 (27.3)	295 (51.6)	204 (35.6)	219 (38.3)

[a] Unles otherwise indicated, average of five tests.
[b] Longitudinal direction.
[c] Transverse direction.
[d] Diagonal direction.
[e] Average of four tests.

Table 4. Elongation of Membrane Samples Used in the Determination of the Revised Criterion, percent

Sample No.	73°F (23°C)						0°F (-18°C)						-30°F (-34°C)					
	At Peak Load			At Ultimate Elongation			At Peak Load			At Ultimate Elongation			At Peak Load			At Ultimate Elongation		
	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D
1.								--[d]			1.5							
2.								--			1.7							
3.	3.3	2.4	34.2	22.9	15.6	40.5	--	--	4.3	2.3	1.8	8.5	--	--	2.3	3.0	2.0	5.9
4.	2.3	2.9	30.8	19.4	23.1	35.8	--	--	4.5	1.8	2.1	5.4	--	--	2.5	2.2	2.7	5.5
5.	--	--	--	70.0	74.9	71.1	4.5	1.4	3.3	9.7	6.6	9.7	--	--	--	26.7	13.9	27.3
6.	--	--	--	38.4	148	97.8	--	3.2	10.8[e]	15.4	12.4	16.5[e]	--	--	--	15.2	28.7	16.2
7.	--	--	--	42.0	49.6	51.1	--	--	--	21.7[f]	30.0[e]	25.3[e]	--	--	--	21.2	28.9	24.2
8.	--	--	--	1.4	1.2	1.3	--	--	--	2.4	2.6	2.4	--	--	--	1.6	1.6	1.6
9.	5.1[e]	--	--	33.6[e]	36.8[e]	43.6	2.9	3.0	16.7	14.6	18.6	23.7	--	--	--	2.6	2.3	7.1

a. Longitudinal direction.
b. Transverse direction.
c. Diagonal direction.
d. The dashed lines indicate that the peak load occurred essentially at the ultimate elongation.
e. Average of four tests.
f. Average of three tests.

Table 5. Strain Energy per Unit Gage Length of the Membrane Samples Used in the Determination of the Revised Criterion, lbf·in./in. (N·m/m)

Sample No.	73°F (23°C)						0°F (-18°C)						-30°F (-34°C)					
	At Peak Load			Total			At Peak Load			Total			At Peak Load			Total		
	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D
1.								--[d]			3.2 (14.0)							
2.								--			4.0 (17.6)							
3.	4.3 (19.3)	2.2 (9.6)	20.6 (91.5)	26.7 (119)	11.3 (50.1)	25.1 (112)	--	--	5.0 (22.2)	4.6 (20.2)	3.3 (14.7)	10.1 (44.7)	--	--	1.7 (7.6)	6.1 (27.1)	3.6 (15.8)	5.1 (22.5)
4.	2.3 (10.4)	2.6 (11.6)	16.4 (73.1)	17.3 (76.9)	15.4 (68.6)	19.0 (84.5)	--	--	3.2 (14.0)	3.2 (14.0)	2.8 (12.2)	3.9 (17.3)	--	--	1.3 (5.8)	3.9 (17.3)	3.4 (14.9)	3.4 (14.9)
5.	--	--	--	23.3 (104)	18.4 (82.0)	21.9 (97.2)	2.2 (9.7)	0.5 (2.1)	1.5 (6.5)	4.3 (19.0)	2.1 (9.3)	4.0 (17.6)	--	--	--	11.3 (50.1)	4.3 (19.3)	10.2 (45.3)
6.	--	--	--	17.4 (77.5)	16.3 (72.4)	18.3 (81.3)	--	0.9 (3.9)	4.7[e] (21.1)	12.6 (56.2)	2.9 (13.0)	7.2[e] (31.8)	--	--	--	10.9 (48.4)	6.7 (30.0)	5.5 (24.7)
7.	--	--	--	19.3 (85.1)	29.7 (132)	23.7 (106)	--	--	--	18.7[f] (83.2)	31.3[e] (139)	22.1[e] (98.5)	--	--	--	15.9 (70.5)	28.6 (127)	20.9 (92.8)
8.	--	--	--	1.0 (4.2)	0.6 (2.7)	0.6 (2.7)	--	--	--	4.2 (18.5)	4.2 (18.5)	4.0 (17.6)	--	--	--	2.3 (10.0)	1.8 (8.0)	1.9 (8.2)
9.	3.2[e] (14.2)	--	--	22.3[e] (73.1)	16.4[e] (96.0)	21.6 (99.1)	3.6 (15.9)	2.6 (11.5)	21.6 (96.0)	23.3 (104)	22.4 (99.8)	30.6 (136)	--	--	--	5.1 (22.5)	3.4 (15.1)	13.0 (57.8)

a. Longitudinal direction.
b. Transverse direction.
c. Diagonal direction.
d. The dashed lines indicate that the peak load occurred essentially at the ultimate elongation.
e. Average of four tests.
f. Average of three tests.

Table 6. Tensile Strength, Elongation, and Strain Energy of Typical 4-Ply Organic Built-up Membranes

Interply Bitumen	Tensile Strength lbf/in. (kN/m)	Ultimate Elongat. %	Strain Energy lbf in./in. (N m/m)	Comment
Asphalt	287 (50.3)	1.5	3.2 (14.0)	Strain energy determined in the present study.
Asphalt	267 (46.8)	2.1	3.9 (17.3)	Strain energy estimated from Mathey and Cullen data [8].
Asphalt	208 (36.4)	1.9	2.8 (12.5)	Strain energy estimated from Rissmiller data [30].
CT Pitch[1]	265 (46.4)	0.9	1.7 (7.6)	Strain energy estimated from Mathey and Cullen data [8].
CT Pitch	181 (31.7)	3.8	4.9 (21.8)	Strain energy estimated from NRCA data [28].
CT Pitch	305 (53.4)	1.6	3.5 (15.6)	Strain energy estimated from Rissmiller data [30].

1. Coal Tar Pitch

Table 7. Revised Performance Criterion for Load-Elongation Properties

Requirement	The roof membrane shall withstand, without rupture, the normal stresses imposed from internal or external causes.
Criterion	The tensile strength shall not be less than 200 lbf/in. (35 kN/m) in the weaker direction (longitudinal or transverse) of the membrane when tested at 0 °F (-18 °C). OR The strain energy shall not be less than 3 lbf in./in. (13 N m/m) in the weaker direction (longitudinal or transverse) of the membrane when tested at 0 °F (-18 °C); in addition, the membrane shall remain watertight after elongation at 0 °F (-18 °C) to a percent at which the strain energy is equivalent to the criterion strain energy of 3 lbf in./in. (13 N m/m).
Test	ASTM D 2523, Testing Load-Strain Properties of Roof Membranes.
Commentary	Certain membranes exhibit anisotropic behavior. Therefore, the results of tests in the weaker direction should apply. For conventional bituminous built-up membranes, the transverse direction is usually weaker; whereas for the new membrane materials, the weaker direction may be either longitudinal or transverse. Excessive elongation of the membrane may cause cracking of the interply bitumen and loss of watertightness. Thus, a watertightness test is conducted at a percent elongation corresponding to the minimum strain energy. The watertightness test used in the present study was based on that given in the CSGB Standard for polymer-modified bitumens. Because of difficulties encountered in conducting this test, it is suggested that, for future application of the proposed criterion, another test be used or an improved watertightness test be developed.

Table 8. Comparison of the Properties of the Membrane Samples With the Revised Performance Criterion

Sample No.	Weaker Direction	Conformance to Tensile Strength	Conformance to Strain Energy	Conformance to Watertightness
1.	T[1]	Yes	Yes	Not needed[3]
2.	T	Yes	Yes	Not needed[3]
3.	T	Yes	Yes	Not needed[3]
4.	T	Yes	No	Not needed[3]
5.	T	No	No	Not needed[4]
6.	T	No	No	Not needed[4]
7.	L[2]	No	Yes	Yes
8.	T	Yes	Yes	Not needed[3]
9.	T	No	Yes	Yes

1. Transverse direction.
2. Longitudinal direction.
3. The watertigthness test is not needed since the membrane specimen conforms to the criterion for tensile strength.
4. The watertigthness is not needed since the membrane specimen does not conform to either the tensile strength or strain energy criterion.

Table 9. Load-Elongation Properties of Additional Samples Tested in Comparison to the Strain Energy Criterion[a]

Sample No.	Tensile Strength Peak Load	Elongation Ultimate	Strain Energy Total
	lbf/in. (kN/m)	percent	lbf·in./in. (N·m/m)
10	72.5 (12.7)	19.6	12.6 (55.8)
11	77.6 (13.6)	20.9	14.9 (66.4)
12	141 (24.7)	11.4	11.8 (52.5)
13	190 (33.3)	12.9	17.6 (78.3)

a. Average of three tests. Tests were conducted at 0 °F (-18 °C) in the transverse direction of the sample.

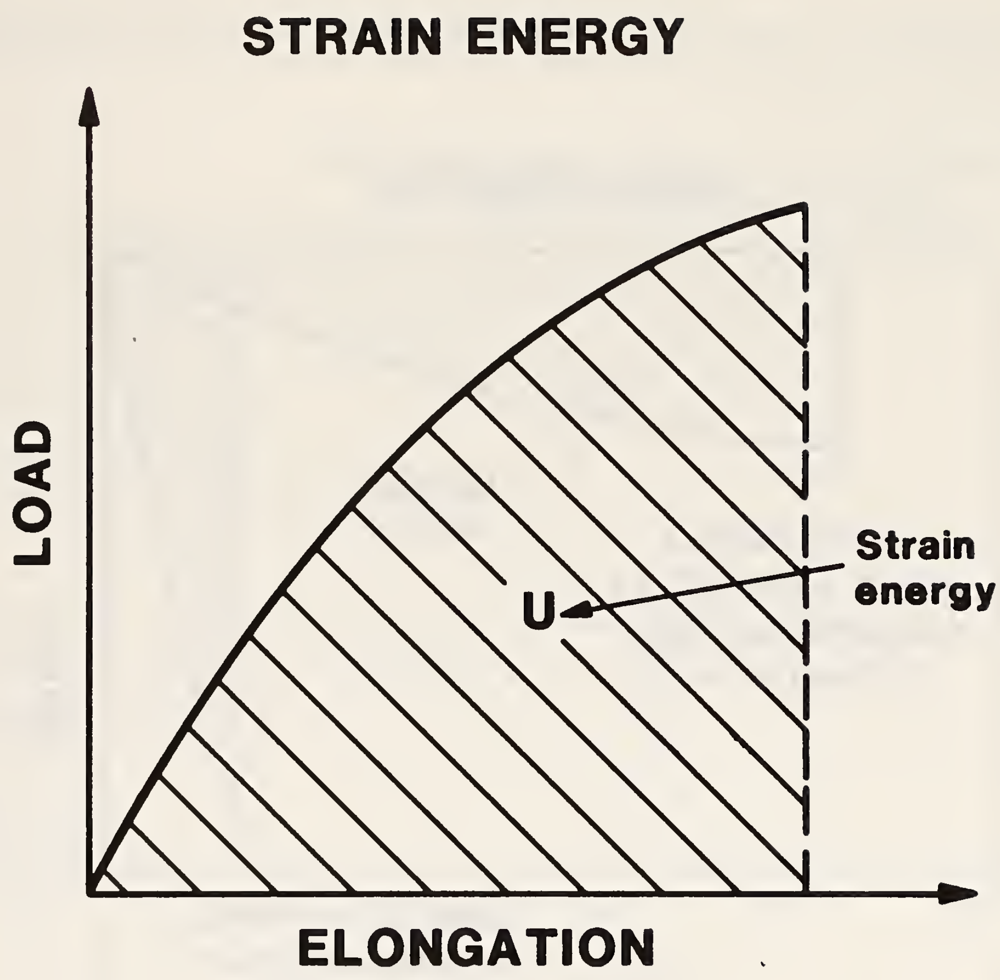

Figure 1: Strain energy: the area under the load-elongation curve.

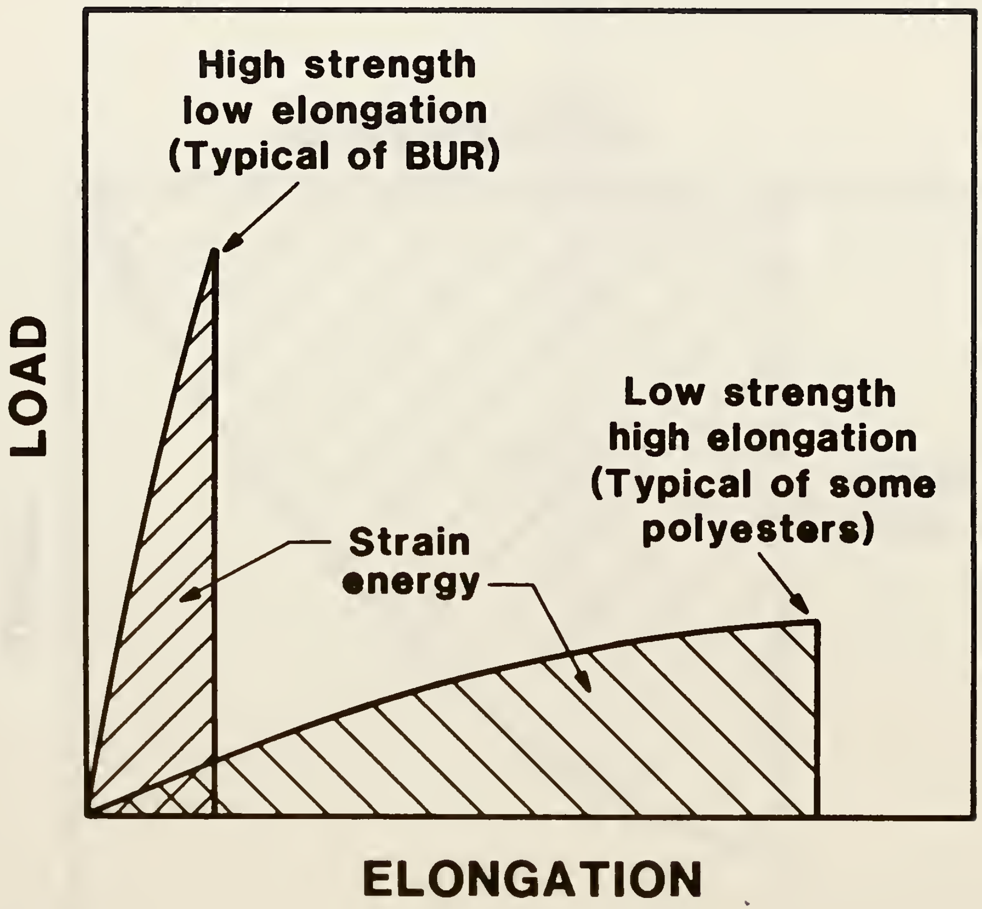

Figure 2. Comparison of strain energy for materials having variable load-elongation properties.

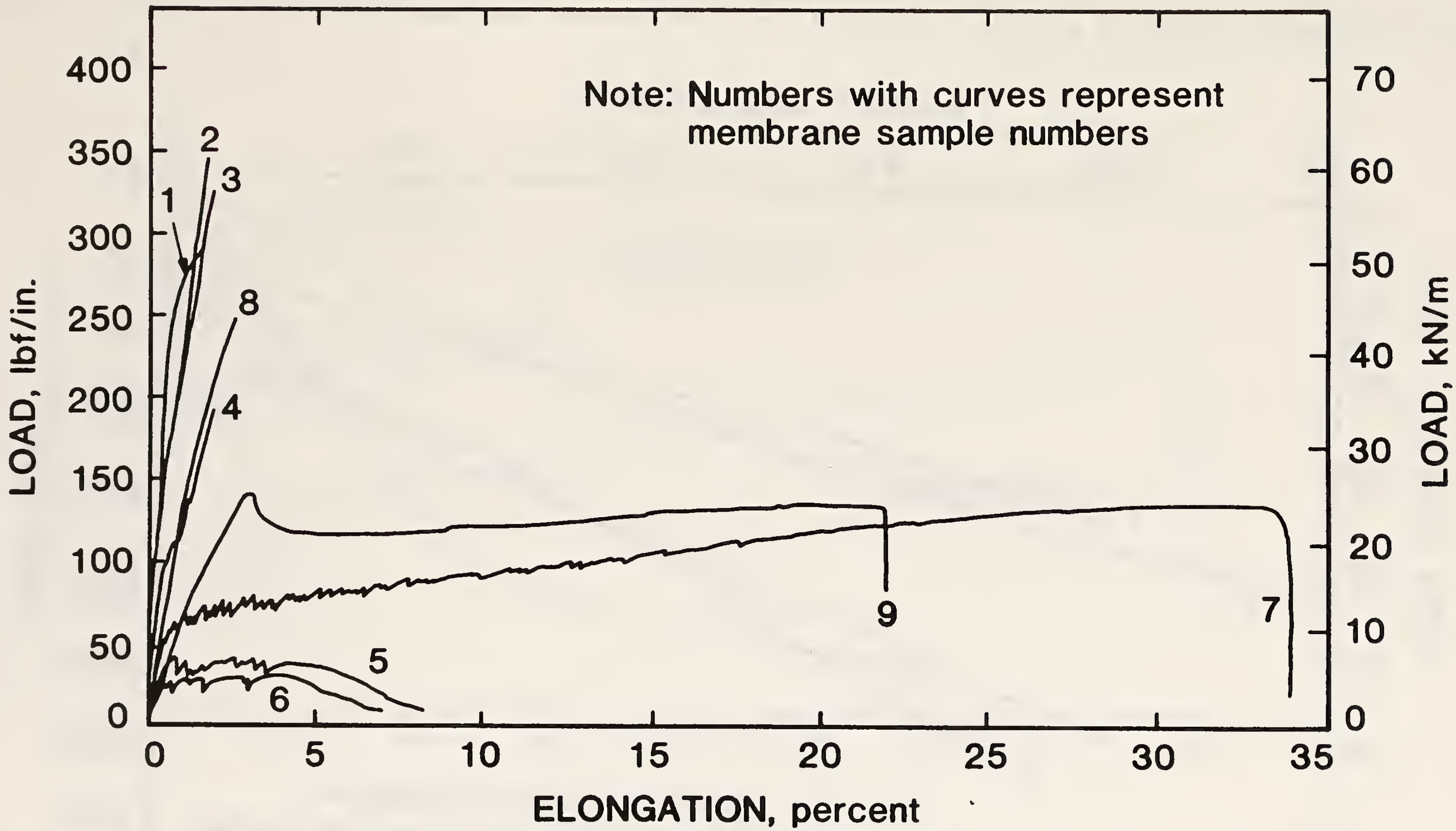

Figure 3. Load-elongation curves of the membrane samples, when tested at 0°F (-18°C) in the transverse direction.

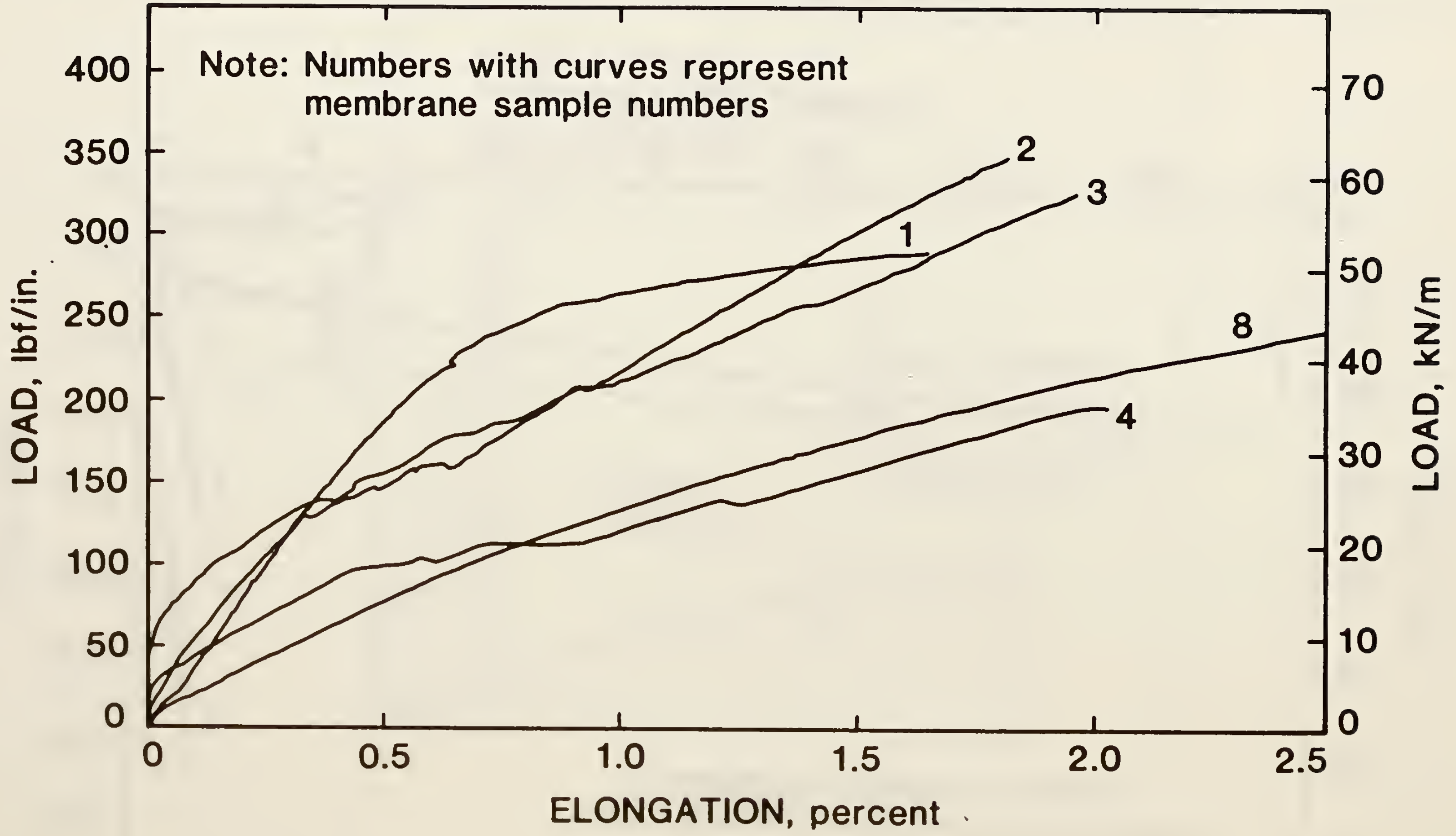

Figure 4. Illustration showing that the load-elongation properties of some new bituminous membranes are comparable to those of conventional built-up membranes, when tested at 0°F (-18°C).

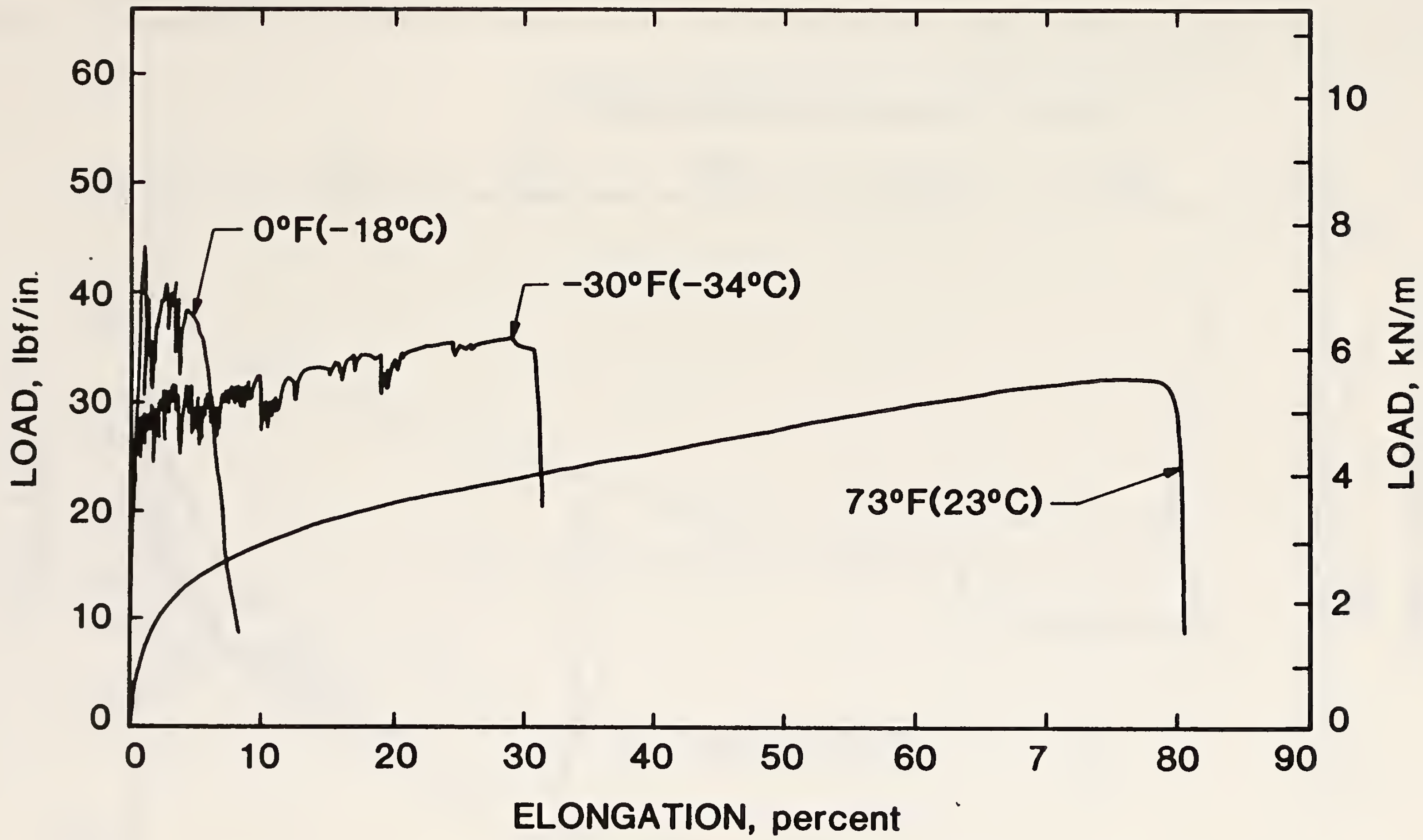

Figure 5. Load-elongation curves for sample no. 5, when tested in the transverse direction at 73, 0, and -30°F (23, -18, and -34°C).

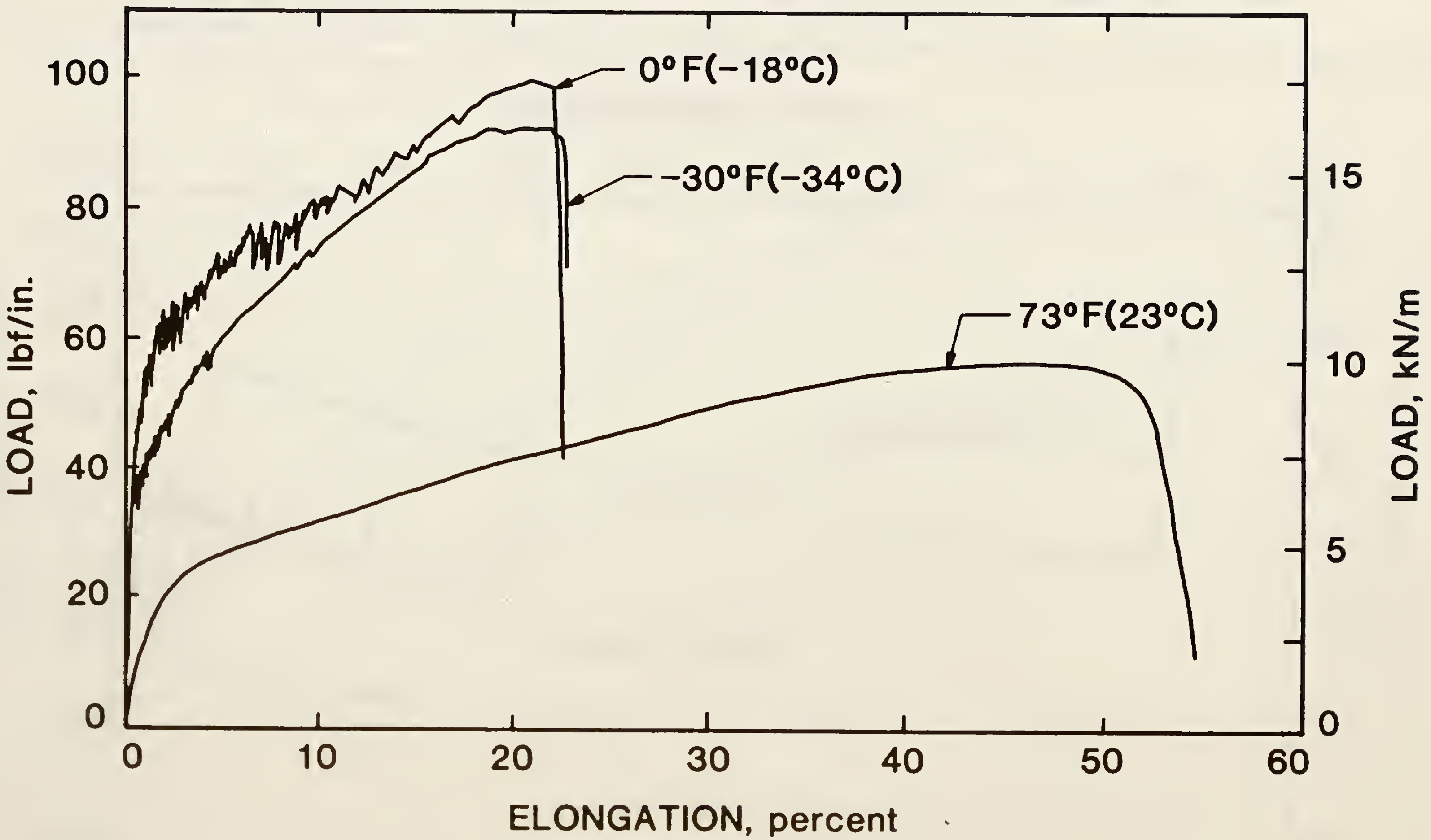

Figure 6. Load-elongation curves for sample no. 7, when tested in the longitudinal direction at 73, 0, and -30°F (23, -18, and -34°C).

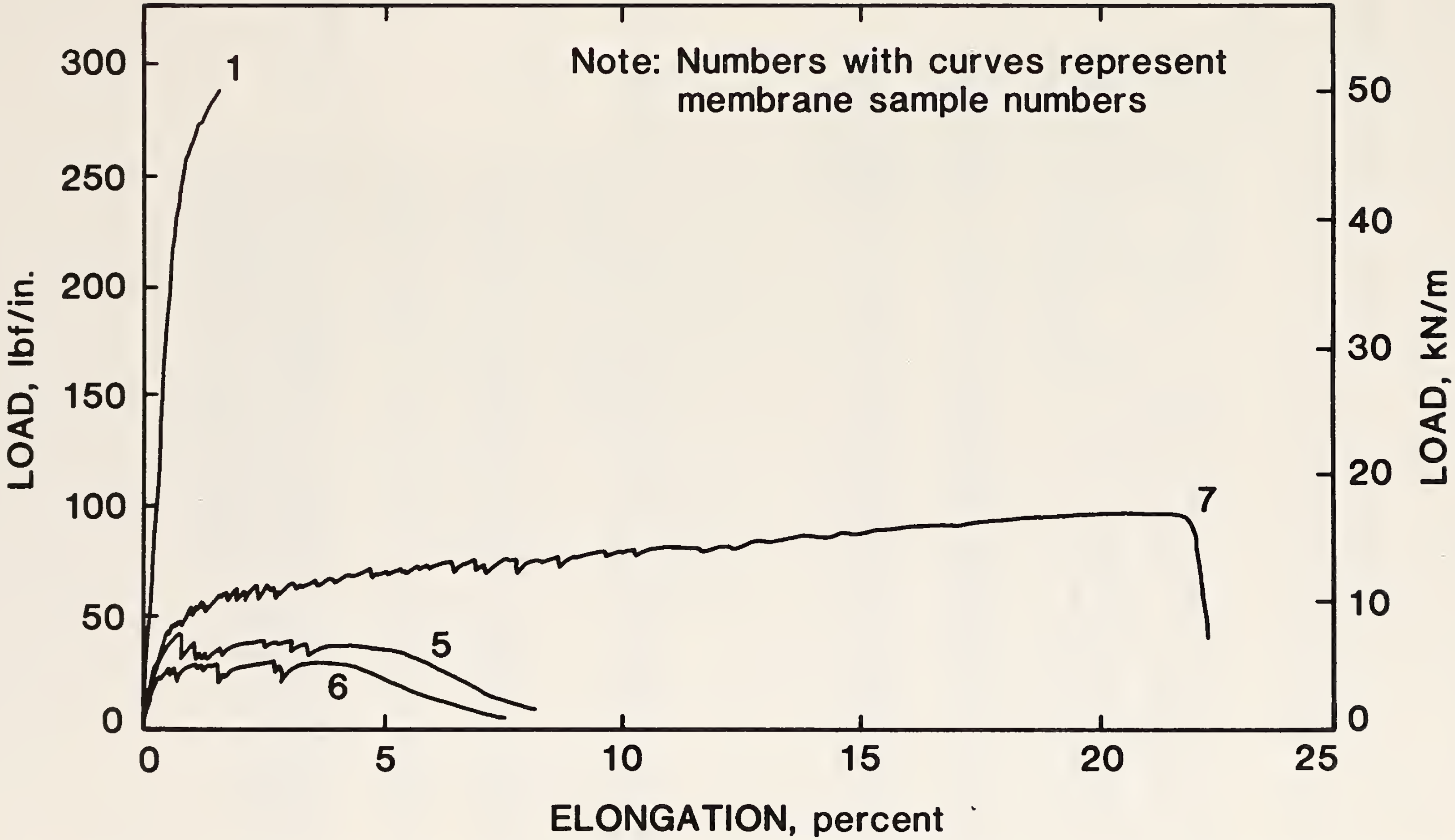

Figure 7. Comparison of the load-elongation curves of the polyester samples with that of the organic membrane sample; tests are compared for the weaker direction of the membrane sample at 0°F (-18°C).

APPENDIX A. PERFORMANCE CRITERION FOR TENSILE STRENGTH

This appendix presents the performance criterion for tensile strength for bituminous built-up membranes as suggested in 1974 by Mathey and Cullen [8]. The format considered in the performance approach had four key elements:

1. the requirement -- This was a qualitative statement which describes what the membrane was to accomplish.

2. the criterion -- This was a quantitative express of the level of performance which the membrane should have to perform acceptably.

3. the test -- This was the test method which was used to determine that the membrane conforms to the stated criterion.

4. commentary -- This was to provide comment concerning an explanation of the reason for, or intent of, the stated criteria.

The tensile strength criterion is as follows:

Requirement	The roof membrane shall withstand, without rupture, the normal stresses imposed from internal or external causes.
Criterion	The tensile strength shall not be less than 200 lbf/in. (35 kN/m) in the weakest direction of the membrane when tested at 0 °F (-18 °C).
Test	ASTM D 2523, Testing Load-Strain Properties of Roof Membranes.
Commentary	This criterion is based on performance in service. Certain membranes exhibit anisotropic behavior. Therefore, the results of tests in the weakest direction (usually transverse or "cross machine" direction) should apply.

APPENDIX B. PREPARATION OF BUILT-UP MEMBRANE SPECIMENS

The built-up membrane test specimens were prepared from the materials described in Tables 1 and 2. Sheets of reinforcement, having dimensions of 8 x 10 in. (200 x 250 mm), were cut from the rolls of felt or fabric. The 10-in. (25-mm) dimension corresponded to the orientation of the felt or fabric (longitudinal, transverse, and diagonal) in the test specimen. One sheet of the reinforcement was coated with the between-ply bitumen (hot asphalt or asphaltic emulsion), and a second sheet was immediately applied on the bitumen. The resulting 2-ply membrane sandwich specimen was placed in a laboratory press. Two spacing rods, having diameters approximately equal to the desired thickness of the resultant 2-ply membrane sandwich specimen, were set at the two edges of the lower platen of the press. A minimum force of 500 lbf (4.90 kN) was applied to the membrane specimen and spacing rods. In this manner, the between-ply bitumen layer was pressed to the desired thickness, and excess bitumen was forced to flow out of the edges of the membrane specimen. Additional plies of membrane were in turn built-up from the 2-ply specimen in a similar way using spacing rods having appropriately selected, larger diameters. Tensile test specimens were cut from the membrane sandwiches using the die described in ASTM D 2523 [24].

APPENDIX C. COEFFICIENTS OF VARIATION OF MEMBRANE SAMPLES TESTED FOR DETERMINATION OF THE STRAIN ENERGY CRITERION

Appendix C gives a summary of the coefficients of variation for the average values of tensile strength, percent elongation, and strain energy for the tests (sample nos. 1-9) conducted to revise the tensile strength criterion. Unless otherwise noted in the tables, five membrane specimens were tested for each condition.

Table C1. Coefficients of Variation for Tensile Strength of Membrane Samples Used in the Determination of the Revised Criterion

Sample No.	73°F (23°C)			0°F (-18°C)			-30°F (-34°C)		
	Peak Load			Peak Load			Peak Load		
	a L	b T	c D	a L	b T	c D	a L	b T	c D
1.					0.8				
2.					6.9				
3.	8.8	14.7	5.0	4.5	27.0	3.7	8.1	16.8	12.0
4.	12.9	9.8	5.2	4.0	2.9	5.3	6.7	4.0	2.9
5.	4.9	5.9	3.8	5.1	4.8	4.3	17.2	12.2	7.6
6.	2.2	3.1	5.0	6.8	5.2	13.3	7.9	11.4	12.5
7.	6.5	12.9	4.3	6.2	1.9	7.5	3.3	5.9	4.5
8.	3.0	14.2	9.7	5.7	2.0	4.6	14.7	9.5	8.9
9.	9.4	6.5	4.5	2.7	3.4	7.1	1.9	7.4	3.0

a. Longitudinal direction.
b. Transverse direction.
c. Diagonal direction.

Table C2. Coefficients of Variation for the Percent Elongation of Membrane Samples Used in Determination of the Revised Criterion

Sample No.	73°F (23°C)						0°F (-18°C)						-30°F (-34°C)					
	At Peak Load			Ultimate			At Peak Load			Ultimate			At Peak Load			Ultimate		
	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D
1.								--[d]			13.9							
2.								--			14.2							
3.	19.9	16.0	9.4	16.3	17.8	6.2	--	--	13.3	6.3	21.8	18.1	--	--	15.6	3.3	24	32.2
4.	9.9	13.7	4.9	8.9	27.0	6.2	--	--	14.1	7.1	25.0	25.1	--	--	46.9	10.0	3.4	28.2
5.	--	--	--	7.8	5.6	4.1	34.3	80.0	60.3	24.1	25.8	23.0	--	--	--	27.5	67.8	24.5
6.	--	--	--	4.3	3.6	4.9	--	52.0	44.7[e]	6.7	36.1	24.6[e]	--	--	--	7.9	19.3	36.1
7.	--	--	--	5.5	5.8	8.6	--	--	--	8.4[f]	4.0[e]	10.6[e]	--	--	--	6.7	4.4	9.4
8.	--	--	--	5.2	24.7	11.5	--	--	--	10.7	5.0	1.0	--	--	--	23.8	12.8	15.6
9.	12.7[e]	--	--	14.4[e]	11.4[e]	5.9	4.3	5.3	40.6	34.9	21.8	20.7	--	--	--	7.1	24.2	8.5

a. Longitudinal direction.
b. Transverse direction.
c. Diagonal direction.
d. The dashed lines indicate that the peak load occurred essentially at the end of test.
e. Average of four tests.
f. Average of three tests.

Table C3. Coefficients of Variation for Strain Energy of Membrane Samples Used in the Determination of the Revised Criterion

Sample No.	73°F (23°C)						0°F (-18°C)						-30°F (-34°C)					
	At Peak Load			Total			At Peak Load			Total			At Peak Load			Total		
	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D	a L	b T	c D
1.								--[d]			16.2							
2.								--			17.7							
3.	31.6	29.3	13.0	22.0	18.7	12.3	--	--	18.6	10.2	31.6	14.1	--	--	29.0	10.5	34.5	33.7
4.	22.6	25.3	9.7	17.6	28.9	9.5	--	--	16.7	12.1	23.2	27.8	--	--	60.8	14.5	5.0	29.7
5.	--	--	--	8.8	11.2	5.9	34.7	89.0	64.8	29.2	33.0	25.0	--	--	--	43.4	73.9	28.0
6.	--	--	--	3.1	3.9	3.6	--	50.5	54.7[e]	10.9	38.6	36.2[e]	--	--	--	10.4	26.6	27.7
7.	--	--	--	5.1	16.6	12.5	--	--	--	14.5[f]	5.3[e]	16.5[e]	--	--	--	10.1	10.2	13.6
8.	--	--	--	4.8	37.7	18.9	--	--	--	12.2	7.7	4.9	--	--	--	29.3	22.5	13.8
9.	18.4[e]	--	--	19.3[e]	14.7[e]	7.4	7.5	9.7	49.6	37.7	24.3	27.6	--	--	--	8.4	27.1	10.8

a. Longitudinal direction.
b. Transverse direction.
c. Diagonal direction.
d. The dashed lines indicate that the peak load occurred essentially at the end of test.
e. Average of four tests.
f. Average of three tests.

APPENDIX D. COEFFICIENTS OF VARIATION OF ADDITIONAL SAMPLES TESTED IN COMPARISON TO THE REVISED CRITERION

Appendix D gives the coefficients of variation for the average values of tensile strength, percent elongation, and strain energy for the tests on the additional membrane samples. (Table 2). Three replicates were tested for each sample at 0 °F (-18 °C) in the transverse direction of the specimen.

Table D1. Coefficients of Variation for Tensile Strength, Elongation, and Strain Energy of the Additional Membrane Samples, percent

Sample No.	Tensile Strength Peak Load	Elongation Ultimate	Strain Energy Total
10	5.3	49.2	50.8
11	5.8	37.7	43.3
12	11.8	14.0	21.7
13	12.8	13.5	22.9

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11. ABSTRACT (A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)

This study was conducted to revise the performance criterion for tensile strength of bituminous built-up membranes. Bituminous membrane samples, fabricated from polyester fabric, polyester-glass composite fabric, and single plies of APP- and SBS-modified bitumen, were tested in tension to determine their load-elongation properties and to measure their strain energy. The results of the tensile tests of the new bituminous membranes indicated wide variability of load and elongation among the different types of materials.

As an alternative to the criterion that a bituminous built-up membrane have a tensile strength of 200 lbf/in. (35 kN/m), it was recommended that the strain energy should be a minimum of 3 lbf·in./in. (13 N·m/m), when tested at 0 °F (-18 °C) in the weaker direction. The properties of the membrane samples were compared to the suggested revised performance criterion. Two polyester samples (without glass), having relatively low strength and low ultimate elongation at 0 °F (-18 °C), did not conform to the revised criterion.

12. KEY WORDS (Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)

bituminous roofing; built-up; low-sloped; performance criterion; polyester; polymer-modified bitumen; roofs; strain energy; tensile strength

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