NISTIR 4638

A Performance Approach to the Development of Criteria for Low-Sloped Roof Membranes

U.S. Department of Commerce
National Institute of Standards and Technology
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Gaithersburg, MD 20899

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July 1991

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ABSTRACT

This report outlines a performance approach for developing criteria for the selection and use of membranes in low-sloped roof applications. An overview of previous efforts for applying the performance approach to membrane roofing is also given. A fundamental aspect of the performance approach is that selection criteria are based on an understanding of the requirements necessary for the membrane system to perform acceptably in service. The availability of performance-based criteria would greatly assist in eliminating some of the defects that have plagued low-sloped roofing over the years.

The approach consists of seven steps including identification of the key functions to be performed by a roof, identification of attributes essential to satisfactory performance, development of the requirements, criteria, and test methods, and putting in place a feedback mechanism to revise the criteria, if warranted, as new information becomes available on the performance of the system in service. Five key functions associated with the performance of the membrane in a low-sloped system are identified, and performance requirements for each function are proposed. These functions are watertightness, maintainability, health and safety, environmental impact, and appearance. Of these five functions, watertightness is the one that directly affects the major problem (i.e., leaks) associated with low-sloped roof performance. As a consequence, the majority of the requirements recommended for membrane systems in past studies, as well as in the present report, emphasize this aspect of performance.

It is recognized that considerable effort may be needed to develop criteria and test methods for the complete set of attributes. Consequently, the initial work should focus on those attributes of membrane roofing that have been associated with the most problems. Review of data from NRCA's Project Pinpoint indicated that seam defects in single-ply membranes have been the problems most frequently encountered for these types of roof systems. On this basis, it is further suggested that the application of the performance approach to membrane roofing begin with the subject of seams. As an initial step in this direction, an outline of the needed criteria is presented including attributes and suggested requirements. The development of criteria and test methods are reserved for future study.

Key words: evaluation; low-sloped roofing; membranes; performance criteria; requirements; roof functions; roofs; seams; test methods; watertightness

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1. INTRODUCTION

1.1 Background

Waterproofing of roofs of commercial and industrial buildings in the United States is primarily accomplished using low-sloped membrane roofing systems [1]. Estimates indicate that approximately 300 million square meters (3 billion square feet) of membrane roofing is installed annually [2,3]. The three main types of membranes are built-up bituminous, single-ply elastomeric and thermoplastic, and polymer-modified bitumens. In addition to the membrane, the other main components are insulation boards and the structural deck (Figure 1), with elements such as vapor retarders and membrane surfacings used in some systems.

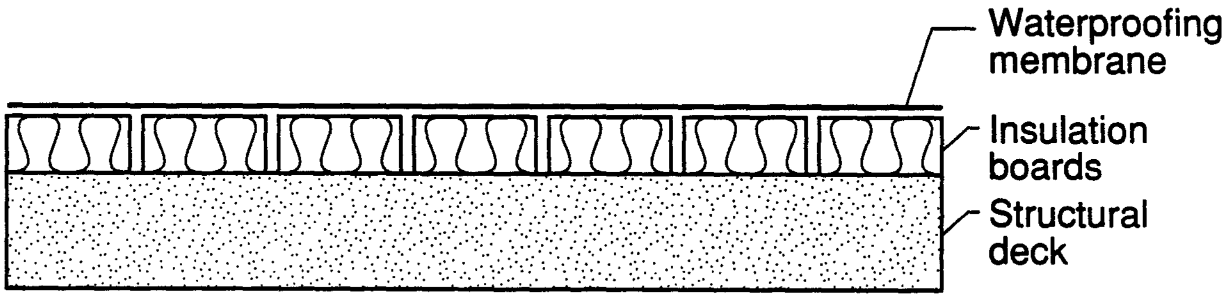

Figure 1. Main components of a low-sloped roof system: waterproofing membrane, insulation boards, and structural deck

The majority of the low-sloped roof systems perform satisfactorily [4]. Nevertheless, on the average, the early failure rate for low-sloped roofs is considerably higher than for other major components of a building [5]. Problems with membrane roofing occur frequently enough that building owners, and others, consider leaky roofs to be one of the main problems in the operation and maintenance of commercial and industrial buildings [6]. An illustration of the need to improve performance is that, although roof systems account for only 2 to 5 percent of the total cost of buildings, they give rise to about 50 percent of building lawsuits [7]. On the positive side, low-sloped roofing today is performing better than in the early 70s, although continued efforts are still needed to further performance [8].

Table 1 provides a summary listing of the major types of materials used in the fabrication of low-sloped roof systems [9]. The number of potential combinations of membrane, insulation, and deck types, as given in Table 1, is well over 400; and this figure does not include the numerous brand names that are available for each generic component. This mathematical exercise is, of course, an oversimplification. Nevertheless, it illustrates that the number of combinations of low-sloped roofs, from which a building owner, architect-specifier, or roofing contractor can make a selection is large.

Table 1. Major materials for low-sloped roof membranes, insulations, and decks

Component	Material
Built-up Membrane	Type of Reinforcement o glass mat o organic felt o polyester fabric Type of Bitumen o asphalt o coal tar pitch
Single-Ply Membrane	Synthetic Sheets o CME (chlorinated polyethylene)* o CR (polychloroprene) o CSME (chlorosulfonated polyethylene)* o EPDM (ethylene propylene diene terpolymer) o PIB (polyisobutylene) o PVC (polyvinyl chloride)
Modified Bitumen Membrane	Type of Polymeric Modifier o APP (atactic polypropylene) o SBS (styrene-butadiene-styrene) Type of Bitumen o asphalt Type of Reinforcement in the Sheet o glass mat o polyester fabric
Insulation Board	Type of Board o composite (foam plastics/mineral boards) o fibrous glass o foam glass o mineral o polyisocyanurate o polystyrene o polyurethane o wood fiber
Structural Deck	Type of Deck o concrete o lightweight concrete o metal o wood

*In roofing practice, CME and CSME are referred to as CPE and CSPE, respectively.

For this reason, it is imperative that the decision-maker be provided with reliable information on the properties and long-term performance capabilities of the individual materials, and the interactions between them. Such knowledge is needed to provide a sound basis for developing standards and criteria which the owner, specifier, or contractor may use in selecting a system. Although the emphasis here is placed on the selection of the component materials and their interactions, it is recognized that materials performance is only one of four essential elements that contribute to satisfactory roof performance. These are: good design, good materials, good workmanship, and good maintenance.

Historically, in the United States, selection of roof membranes has been based chiefly on prescriptive specifications, each of which applies to a particular type of material. The specification implies that a given material will have the basic properties to provide for waterproofing the roof. However, it generally lacks full consideration of the requirements necessary for the material to perform as the membrane component of a roof system subjected to a wide variety of environmental and use conditions. In 1984, Cullen [4] reviewed the status of the development of criteria for the selection of roof membranes in the United States. He was critical of the U.S. industry for being content to develop prescriptive specifications; he urged that a performance approach be used in developing selection criteria for membrane materials. In his paper, Cullen summarized efforts made to use a performance approach in selecting membranes. He expressed the opinion that sufficient information was available to support such an approach, if only the roofing industry would pursue it. As an example, he mentioned that performance criteria for bituminous built-up roofing (BUR) membranes were proposed in 1974 yet, a decade later, the industry had still not adopted a consensus performance standard for the completed built-up membrane.

At nearly the same time that Cullen wrote his review on standards development, the National Institute of Standards and Technology (NIST)[1] published NBS Special Publication 659, "Low-Sloped Roofing Research Plan" [10]. This document was developed to outline research which would contribute to significant improvements in the quality and performance of low-sloped roofing membranes and systems. A major component of the research recommended in the plan was the development of performance criteria for membrane roofing.

As the U.S. roofing industry enters the 1990s, a performance approach for membrane selection has still not been adopted through the consensus standards process. This is unfortunate, because such an approach can foster innovation by having selection criteria based, not on the type of material comprising the membrane and its methods of manufacture and application, but on an understanding of the requirements which must be met by a membrane system to perform well in service. Its adoption within the voluntary consensus

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[1]Formerly the National Bureau of Standards (NBS)

standards process in the United States could enhance the competitiveness of the roofing industry.

1.2 Objective and Scope of this Report

This report outlines a performance approach for developing criteria for membranes used in low-sloped roof applications. An overview of previous efforts in applying the performance approach to membrane roofing is given. Criteria developed in previous studies may be incorporated in a general set of criteria having applicability to all types of membranes. However, criteria have not been suggested in the present report. Such suggestions will be the subject of future study.

Considerable effort may be needed to develop the criteria and test methods for the set of attributes given in the outline presented herein. Collectively, the U.S. roofing industry has an extensive database on the performance of low-sloped roof systems. One purpose in preparing the present report is for industry organizations such as ARMA, ASTM, NRCA, RCI, RMA, and SPRI[2] to consider the outline and take a lead role in developing the needed criteria and test methods.

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[2]The acronyms are: Asphalt Roofing Manufacturers Association (ARMA), American Society for Testing and Materials (ASTM), National Roofing Contractors Association (NRCA), Roof Consultants Institute (RCI), Rubber Manufacturers Association (RMA), and Single-Ply Roofing Institute (SPRI).

2. PERFORMANCE CRITERIA FOR MEMBRANE ROOFING

2.1 The Performance Approach

In 1972, Wright reviewed the history of the performance approach as applied to buildings [11]. He defined the approach as follows:

> "an organized procedure within which it is possible to state the desired attributes of a material, component, or system in order to satisfy the requirements of the user without regard to the specific means employed in achieving the results."

In accord with this definition, a specification developed according to the performance approach defines, from the user's perspective, a product in terms of the functions it must perform; in contrast, a prescriptive specification defines a product in terms of elements not necessarily related to performance such as constituents, physical properties, or method of manufacturer [12]. A performance specification describes a product less narrowly than a prescriptive specification, and thus has the benefits of fostering innovation and facilitating the development and evaluation of new products [4]. Nevertheless, performance and prescriptive specifications should not be looked upon as mutually exclusive, but as complementary. For example, prescriptive specifications frequently have the advantage of incorporating analyses (test methods) which can be conducted more rapidly than performance tests [12]. Test methods associated with prescriptive requirements are more apt to be used routinely for product identification or quality control.

Wright's review [11] emphasized that the key to the approach was the satisfaction of user needs. He pointed out that the performance approach was not a new concept and offered as evidence the observation that, throughout history, materials and components were chosen for structures because "they did the job."

Wright [11] wrote his review during a time period when the application of the performance approach to the design, construction, and operation of buildings held considerable interest for the U.S. industry. Since then, two international organizations[3], CIB and ISO, have prepared publications that provide guidance for using the approach for the development of standards for buildings, and their components and materials. The CIB publication is entitled "Working with the Performance Approach in Building" [13]. ISO has two International Standards, "6240 -- Performance Standards in Building: Principles for Their Preparation and Factors to be Considered" [14], and "6241 -- Performance Standards in Building: Contents and Presentation" [15].

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[3]The International Council for Building Research Studies and Documentation (CIB), The Netherlands, and the International Organization for Standardization, Switzerland.

Since the approach rests on providing end performance without prescribing the means of reaching this end, it is undertaken by formulating a statement on what is expected, quantifying the statement, and setting evaluative procedures that determine conformance. As such, the performance approach has three key elements -- the requirement, the criterion, and the test method -- with an optional fourth element, the commentary.

The format used for presentation of performance-based criteria is:

1. the requirement -- a qualitative statement which describes what the product is to accomplish.

2. the criterion -- a quantitative expression of the level of performance which the product must meet to perform acceptably.

3. the test -- the evaluative method used to determine that the product conforms to the stated criterion.

4. commentary -- explanatory comments on the reason for, or intent of, the stated criterion.

2.2 The Performance Approach Applied to Roofing

The point of departure for applying the performance concept to membrane roofing is the definition of the key functions to be performed by the system [16]. The next step is the identification of the requirements essential to the satisfactory performance of each of the functions.

Table 2 gives examples of two sets of key functions[4] expected of roofing systems. The first set was taken from a paper by Hoiberg [17] in the 1972 Symposium on the "Performance Concept in Buildings." The second set was included in a 1987 RILEM Technical Committee report [18] on "Performance Criteria for Building Materials." An examination of Table 2 indicates that there are major similarities between the two sets (for example, resistance to weather, wind, and hail), but there is not a one-to-one correspondence with regard to the functions. Hoiberg [17] did not define durability in terms of preventing water ingress into the building, and did not include, as key functions, heat flow and moisture migration. On the other hand, he made reference to appearance which was a function not included in the RILEM set.

The lesson to be learned from Table 2 is that proper identification of the key functions of roofing systems is an essential first step in applying the performance concept to roofing. Skipping this step, or not giving it sufficient attention, may lead to omissions in defining the requirements for the roof.

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[4]Some authors (e.g., ref. [15]) refer to these functions as general requirements, but the term "key functions" is used in the present report.

Table 2. Examples of past recommendations on the key functions expected of a membrane roofing system

Source	Functions[a]
1. NBS SP 361 Ref. [17]	1. Durability - resistance to movements in membranes - weather resistance - wind resistance - fire resistance - resistance to hail damage 2. Other Considerations - roof traffic resistance - roof appearance
2. RILEM 31-PCM Ref. [18]	1. Prevent water ingress through the top of the building 2. Resist environmental loads such as wind, snow, sunshine, temperature extremes, and dynamic variations for the intended service life 3. Reduce heat exchange between the building and the exterior environment 4. Withstand without rupture the normal stresses from internal or external causes 5. Prevent condensation within the building

[a]Some authors refer to the functions as general requirements.

Table 3 includes a list of the documents [16,19-23] published in the United States which have taken a performance approach to setting criteria for specific types of membrane roofing. The initial endeavor was undertaken in the early 1960s by a Committee working under the auspices of the Building Research Advisory Board (BRAB) of the National Academy of Sciences [16]. This Committee defined 18 requirements needed of the roof system of which the majority pertained to the membrane. For each requirement, a test method was suggested for evaluation; however, this early effort fell short of recommending criteria for each of the requirements. Although the BRAB document set the basis for future activities in the United States, there are still no documents written in the United States that fully address the application of the performance concept to membrane roofing. All published to date (Table 1; refs [19-23]) are limited in so far as they consider a specific type of membrane roofing (for example, built-up, single-ply, or modified bitumen).

Table 3. Documents applying the performance approach to membrane roofing

Designation[a]	Title	Crit[b]	Ref.
BRAB (1964)	Study of Roof Systems and Constituent Materials and Components	No	[16]
BSS 55 (1974)	Preliminary Performance Criteria for Bituminous Membrane Roofing	Yes	[19]
MRCA/PVC (1981)	Recommended Performance Criteria for PVC Single Ply Roof Membrane Systems	Yes	[20]
MRCA/ELAS (1982)	Recommended Performance Criteria for Elastomeric Single Ply Roof Membrane Systems	Yes	[21]
MRCA/MB (1983)	Recommended Performance Criteria for Modified Bitumen Roof Membrane Systems	Yes	[22]
BSS 167 (1989)	Interim Criteria for Polymer-Modified Bituminous Roofing Membrane Materials	Yes	[23]
SIA 280 (1981)	Plastic Waterproofing Sheets: Requirements and Test Methods	Yes	[24]
UEAtc (1983)	General Directive for the Assessment of Roof Waterproofing Systems	Yes	[25]

[a]The year of publication is given in parentheses.
[b]This column indicates whether the document contains recommended criteria.

For comparison, Table 3 also lists two European documents [24,25] that were developed on the basis of the performance approach. In many ways, the European roofing community has been more progressive in using the performance approach to setting membrane criteria. The UEAtc[5] document [25], "General Directive for the Assessment of Roof Waterproofing Systems," has been used since 1983 by the UEAtc member countries for the characterization and evaluation of membrane roofing, often in lieu of national standards. Of the documents listed in Table 3, the UEAtc document is the only one that recommends criteria that are independent of the type of membrane material.

Table 4 lists requirements for which criteria were suggested in each of the documents referenced in Table 3. Where criteria have been proposed, test methods for determining conformance have also been developed. As can be seen in Table 4, the requirements primarily address the performance of the membrane as the waterproofing component of the system. As listed in Table 4, not all requirements are treated in each of the documents. This may be explained by a number of reasons. In some cases, the authors of a given document may not have considered a particular requirement to be sufficiently important. In others, the authors felt that insufficient data were available to suggest criteria associated

[5]UEAtc is a French acronym for the European Union of Agrément. Member countries are Austria, Belgium, Denmark, France, Germany, Ireland, Italy, Netherlands, Portugal, Spain, and the United Kingdom.

Table 4. Summary of requirements given in documents that take a performance approach to setting criteria for membrane roofing

Requirement	Document[a]							
	BRAB	UEAtc Gen	SIA 280	BSS 55	BSS 167	MRCA PVC	MRCA ELAS	MRCA MB
<u>Mechanical Loads</u>								
Abrasion Resistance	x	·	·	·	·	x	x	x
Adhesion	x	·	·	·	·	·	·	·
Cyclic Movement Resistance	x	x	·	·	·	x	x	x
Dimensional Stability	·	x	x	·	x	x	x	x
Elongation	x	·	x	·	·	x	x	x
Fatigue Strength	·	·	·	x	·	·	·	·
Flexural Strength	x	·	·	x	·	·	·	·
Flow Resistance	x	x	·	·	x	·	·	x
Impact Resistance	·	·	x	x	x	x	x	x
Pliability (low temperature flexibility)	·	x	x	·	x	x	x	x
Puncture Resistance - Dynamic	x	x	x	x	·	x	x	x
Puncture Resistance - Static	·	x	x	·	·	x	x	x
Tear Resistance	x	·	·	·	·	·	x	·
Temperature-Induced Load	·	·	·	·	·	x	x	x
Tensile Strength	·	·	·	x	·	x	x	x
Thermal Expansion	·	·	·	x	·	·	·	·
Thermal Shock Resistance	x	x	·	x	·	·	·	x
Seam Strength	·	x	x	·	·	x	x	x
Strain Energy	·	·	·	·	x	·	·	x
<u>Environmental Loads</u>								
Chemical Resistance	·	·	x	·	·	x	x	x
Moisture Absorption	·	·	·	·	x	·	·	·
Moisture Resistance	x	x	x	·	·	x	x	x
Permeability	x	x	x	·	·	x	x	x
Seam Leakage	·	x	·	·	·	·	·	·
Surfacing Durability	·	·	·	·	·	·	·	x
Weathering Resistance (durability)[b]	x	x	x	·	x	x	x	x
<u>Biological Loads</u>								
Resistance to Microbial Attack	x	·	x	·	·	x	·	·
Resistance to Plant Growth	x	x	·	·	·	·	·	·
<u>Wind Loads</u>								
Peel (wind)	·	x	·	·	·	·	·	·
Uplift (wind)	x	x	·	x	x	x	x	x
<u>Fire</u>								
Fire Resistance	·	x	x	x	x	x	x	x
Number of Requirements	15	16	13	9	9	18	18	21

[a]Titles of the documents are given in Table 3. With the exception of the BRAB report, all documents include suggested criteria for the requirements indicated by the "x" in the present table.
[b]This requirement generally includes reference to long-term resistance to agents such as heat, UV, and pollutants (e.g., ozone), although criteria for all agents are not given in every document.

with a given requirement. For example, the authors of BSS 55 [19] recommended that criteria be developed for 20 attributes of built-up membranes; however, they only suggested criteria for nine, because of lack of supporting data. Finally, there is the artificial reason that basically the same requirement might be expressed in different ways in various documents, for example, cyclic movement and fatigue strength.

Tables 3 and 4 show that, since 1980, considerable effort has been expended, both at home and abroad, toward the application of the performance concept to roofing. Table 4 supports Cullen's contention that "the technology exists to describe the desired attributes of a quality membrane in terms of requirements, criteria, and test methods for generic products of both multi-ply and single-ply types" [4]. In the following sections, an approach built on these past efforts is suggested for the development of performance criteria for membrane roofing.

A final point to be emphasized in considering the performance approach to criteria development is that membrane requirements, such as those listed in Table 4, may vary depending upon factors such as building use and environmental exposure. Although often overlooked when the performance approach is discussed, this aspect represents one of its strengths. It allows users to select a membrane product for use in a given situation, whereas under other circumstances, it might be less acceptable. As a case in point, after suggesting a criterion for the hail resistance of built-up membranes, Mathey and Cullen [19] provided commentary that lower limits of hail resistance could be established for membranes installed in areas that experience little hail. Similarly, the criteria given in the Swiss document SIA 280 [24] vary according to whether the membrane is installed exposed to, or protected from, the effects of weather. As a final example, the CIB/RILEM[6] Joint Committee on Roofing [26] outlined a classification system regarding a membrane's resistance to puncture loads and splitting due to cyclic movement of the membrane substrate. The higher the classification, then the more resistant is the membrane to these potential modes of failure. This classification system was based on work conducted in France, and has been fully described in publications from the Centre Scientifique et Technique du Bâtiment (CSTB) [27,28].

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[6]International Union of Testing and Research Laboratories for Materials and Structures (RILEM), France.

3. A PERFORMANCE APPROACH TO CRITERIA FOR ROOFING MEMBRANES

The steps for undertaking a performance approach to the development of criteria for membranes in low-sloped roofing systems are given in Figure 2. These steps are consistent with the recommendations of the BRAB Committee [16] when a performance approach to membrane selection was first proposed in the United States, and other reports which have addressed the performance approach toward materials and systems evaluation [11,18].

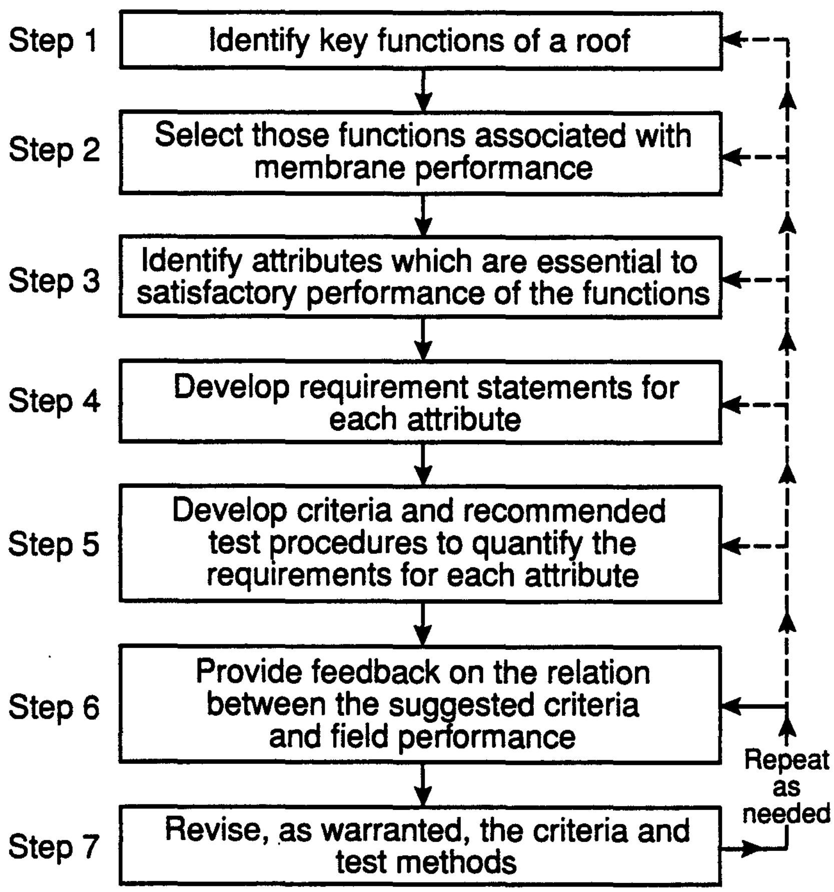

Figure 2. Steps in the performance approach for developing roof membrane criteria

3.1 Functions of the Roof System and Membrane (Steps 1 & 2)

The initial step is to identify key functions to be performed by the roof. Key functions have been listed by others [16-18], but will be considered again for completeness in defining a performance approach for the development of membrane criteria. Moreover, as illustrated by the examples in Table 2, not all past efforts have been consistent with each other.

In his Manual of Built-Up Roofing, Griffin [2] stated that:

> "the [roofing] system is an assembly of interacting components designed, as part of the building envelope, to protect the building interior, its contents, and its occupants from the weather."

Accepting this statement, it follows that the key functions required to be performed by a roof system include:

- Watertightness -- the prevention of water ingress through the top of the building.
- Heat Transfer Control -- the prevention of excessive heat exchange between the interior of the building and the exterior environment.
- Condensation Control -- the prevention of water vapor condensation within the roof system either by controlling water vapor diffusion or air convection.
- Load Accommodation -- the ability of the roof system to sustain dead and live loads experienced during normally expected service conditions.
- Maintainability -- the long-term capability to have the roof system repaired effectively and economically as it weathers under the given environmental conditions, or in the event that leaks occur due to unexpected service loads.
- Noise Control -- the minimization of noise generated by response of the roof to the external environment, or the control of noise through the roof from the external environment.

Of these functions, watertightness (and the ability of the system to be restored to watertightness in the event that unforeseen circumstances cause leaks) is provided by the membrane working in concert with the other components of the system. Heat transfer control, moisture vapor control, and load accommodation are provided primarily by the insulation, vapor retarder (if present), and structural deck, respectively. Noise may be controlled by the system itself, or through the addition of other components such as acoustic ceilings. Suggestions on the development of criteria regarding functions listed above that are not associated with watertightness are beyond the scope of the present report.

In addition to the functions given above, there are others which the user may expect of the roof system. These additional functions do not necessarily concern "weather protection," but can be important and should be included when considering performance. Such additional functions are:

- Health and Safety -- prevention of undue risk to the health and safety of the installers of the roof or the users of the building.

- Environmental Impact -- prevention of undue harm to the environment, either during installation or service.

- Appearance -- preservation of the roof appearance during installation and throughout its service life, when designed to be aesthetically attractive.

Note that the combination of these three functions with the six given previously in this Section not only includes the suggestions given by Hoiberg [17] and the RILEM Technical Committee [18] (Table 2), but goes beyond them.

Step 2 in the performance approach to membrane performance is to select those key functions to be performed by the roof which are associated with the membrane. These are:

- Watertightness
- Maintainability
- Health and Safety
- Environmental Impact
- Appearance

Without understating the importance of the last four functions, watertightness is the major concern, because it is the most difficult to ensure and the cost of failure can be high. As stated in the introduction, the unacceptably high frequency of roof leaks is the most common problem in commercial and industrial buildings [6]. It is because of the importance of the roof remaining leak-free that criteria developed to date for membranes in low-sloped roofing systems have emphasized the requirements given in Table 4.

The approach suggested here for development of performance criteria for low-sloped roof membranes also emphasizes the requirements in Table 4. However, requirements associated with roof functions other than watertightness are also included because they can be of special significance to the user. Inclusion of additional requirements is necessary, because the performance approach is based on consideration and satisfaction of user needs.

3.2 Membrane Attributes and Requirements (Steps 3 & 4)

The next step is the identification of the attributes which the membrane must possess to ensure satisfactory performance with regard to each membrane function. These may be taken sequentially for the functions identified in Step 2.

3.2.1 Watertightness. One method to identify essential performance attributes associated with this function is to consider ways by which loss of watertightness may come about. In the worst case, loss of watertightness occurs due to catastrophic failure by means such as fire or wind. Consequently, the membrane system must have adequate fire resistance and wind uplift resistance. These two attributes consider not only watertightness, but also life safety. Not surprisingly, requirements pertaining to fire and wind are always included in documents on membrane roofing performance (Table 4), as well as model, state, and local building codes. Other mechanisms of catastrophic failure include roof collapse. In this case, it is an essential attribute of the structural deck, and not the membrane, to guard against such happenings.

Apart from catastrophic failure, long-term experience with the performance of low-sloped roof systems has indicated that leaks due to inadequate membrane performance can occur in a number of ways. These include that the membrane may:

- become permeable
- delaminate
- be subjected to chemical attack
- be subjected to attack by biological agents
- tear
- erode
- split
- crack
- slip
- be punctured
- be abraded
- be penetrated by plant roots.

A satisfactorily-performing membrane system will have adequate properties to resist failure in any of these ways, either when new or during performance over the long term. This latter aspect, of course, concerns the attribute of durability or weather resistance. A list of essential membrane attributes, associated with loss of watertightness, is presented in Table 5 along with performance requirement statements (Step 4) for the attributes. Note that this table is consistent with Table 4 which, as described, was assembled from past documents that have suggested a performance approach to the development of criteria for low-sloped roof membranes.

Table 5. Membrane attributes and performance requirement statements associated with loss of watertightness

Attribute		Performance Requirement Statement
Abrasion resistance	1.	The membrane shall withstand wear from normally expected abrasive actions such as wind blown materials or foot traffic.
Biological agent resistance	1.	The membrane material shall not be weakened or made more permeable to water by biological agents normally encountered during service.
Chemical resistance	1.	The membrane material shall not be weakened or made more permeable to water by chemical agents to which it is expected to be exposed during its design service life.
Dimensional stability	1.	The roof membrane shall not exhibit dimensional change detrimental to the performance of the roof when exposed to moisture and heat under normally expected service conditions.
Fire resistance	1.	The roofing system shall not pose an undue safety hazard when exposed to any foreseeable fire conditions.
Flow resistance	1.	The membrane system shall resist slippage-producing forces generated during service due to factors such as roof slope and the mass of the membrane and its surfacing.
	2.	Base flashing materials must be capable of resisting flow, creep, and tearing forces generated under service conditions.
Interlaminar adhesion	1.	Adhesion between components of composite sheets such as reinforced synthetic single-ply materials or polymer-modified bitumens shall be adequately maintained over the membrane service life.
Interply adhesion	1.	Sheets of multi-ply membranes shall remain adequately bonded together to prevent adverse effects such as blistering and splitting.
Plant root resistance	1.	The membrane system shall resist penetration of plant roots when used under circumstances permitting plant growth on the roof, e.g., roof top terraces.
Pliability	1.	The membrane material must be capable of being readily unrolled, flexed, and bent without damage during application under normally expected environmental conditions.
Puncture resistance	1.	The roof system shall be capable of withstanding, without loss of integrity, the normally encountered static and dynamic puncture loads due to use and environmental exposure, including hail.
Resistance to water transmission	1.	The membrane shall prevent the passage of water through the roof system under expected service conditions.
Seam adhesion	1.	Seams in single-ply membranes shall remain watertight over their design service lives.
Splitting resistance	1.	The membrane shall withstand, without rupture, the normal stresses which are likely to be imposed on it from internal or external causes.
	2.	The membrane shall resist the movement of the substrate encountered during normal service conditions without splitting, cracking, or undue deformation.
Tear resistance	1.	The membrane material shall have sufficient strength to allow handling without damage under normal installation conditions, and withstand normally expected tear loads encountered in service.
Uplift resistance	1.	The roof system shall withstand design uplift forces without adverse effect.
Weathering resistance	1.	The membrane shall be capable of sustaining exposure to normally encountered environmental agents including ultraviolet (UV) radiation, moisture, and chemical pollutants without change of performance properties beyond prescribed limits.
	2.	Factory-applied protective surfacings shall provide protection to the membrane over the design life of the roof system.

3.2.2 Maintainability. Attributes and performance statements for maintainability are given in Table 6.

Table 6. Membrane attributes and performance requirement statements associated with maintainability

Attribute		Performance Requirement Statement
Repairability	1.	The membrane surface shall be capable of being patched effectively and economically over its design service life.
Capability for re-coating	1.	The membrane surface shall be able to be re-coated, as warranted, over the design life of the roof in cases where coatings are part of the membrane roofing system.

3.2.3 Health and Safety. Attributes and performance statements for health and safety are given in Table 7.

Table 7. Membrane attributes and performance requirement statements associated with health and safety other than fire and wind

Attribute		Performance Requirement Statement
Safety during use	1.	The roof system shall not impose undue hazard on those who use the roof, the building, and its occupants and others in the building vicinity during its service life.
Installation safety	1.	Installation of the membrane roof system shall not impose undue hazards to the workers, building occupants, or the building.

3.2.4 Environmental Impact. Attributes and performance statements for environmental impact are given in Table 8.

Table 8. Membrane attributes and performance requirement statements associated with environmental impact

Attribute		Performance Requirement Statement
Impact during installation	1.	Installation of the membrane roof system shall not impose undue hazards to the environment.
Impact during use	1.	The roof system shall not impose undue hazards to the environment during its service life.

3.2.5 Appearance. Attributes and performance statements for appearance are given in Table 9.

Table 9. Membrane attributes and performance requirement statements associated with appearance

Attribute		Performance Requirement Statement
Aesthetic appearance	1.	The installation of the roof system shall not detract from the design appearance of the finished roofing.
	2.	Long-term performance of the roof system shall not detract from its aesthetic appearance.

3.3 Criteria and Test Methods (Step 5)

Step 5 includes the development of criteria that will quantify the level of performance expected. Also included in this step is the selection (or development) of the test method for assessing that the membrane material, either alone or as part of the system, satisfies the criteria.

This step is perhaps the most difficult to achieve, because of the complexity of characterizing a material in combination with its interactions with other system components and its response to the environment. Often the information needed to support the development of a criterion may not be available. Step 5 involves not only characterizing the membrane before and during use, but also requires characterization of the environment. This may necessitate the development of new or improved test methods. For example, methods are currently not available for determining stresses and strains experienced by a membrane in service. In addition, the important question of long-term performance, or durability, cannot be overlooked. It is expected that techniques for reliably evaluating service-life would need to be developed on a rational basis such as outlined in ASTM Practice E 632, "Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials," [29,30].

In characterizing membranes in service, it would be advantageous to have available nondestructive evaluation (NDE) methods. To date, little application of NDE methods to roof membranes in service has occurred. The application of thermal analysis (TA) methods, such as dynamic mechanical analysis and thermogravimetry, has been suggested for membrane characterization because only small samples are needed [26]. This may limit damage to the membrane. However, this aspect of using TA methods has not been explored for in-place membranes. Finally, the use of mathematical models developed in recent years on roof performance [31] can assist in understanding the interactions between membranes and other components of the system. However, for some criteria, the application of the existing models to criteria development may need to be demonstrated or, for other criteria, validation of the models may need to be conducted. It may also be that new models may need to be developed for some criteria.

Because of the complexity of the development process, newly-set criteria often use existing ones re-cast in performance language [11]. In this regard, the criteria previously recommended in the documents summarized in Table 4 should help to provide a starting point for the set of criteria needed for membrane roofing in the United States.

3.4 Feedback and Revision of Proposed Criteria (Steps 6 & 7)

In his review on the history and status of the performance approach, Wright [11] wrote that "criterion levels must be thought of as indeterminably tentative." One reason for such a comment is that the performance approach builds in a mechanism of feedback whereby performance in service is monitored in relation to the recommended criteria. Consequently, as performance in service is more fully understood, the lessons learned are used primarily as the basis for revising the criteria. Steps 6 and 7, the final two in the performance approach, involve the use of feedback from the field and the revision of the criteria, where warranted.

The feedback mechanism in the performance approach is illustrated in Figure 2 as the solid line re-linking Steps 6 and 7. Note also the dashed line linking Step 7 with those of 1 to 5. Although past authors have emphasized that feedback is mostly used to update criteria, it may be that in-service performance also provides evidence that the early steps leading to the development of criteria need revision. The dashed line in Figure 7 represents such a situation.

4. DISCUSSION

An examination of the attributes and requirements listed in Tables 4 through 9 shows that the list is extensive. As a result, considerable effort may be needed to develop criteria and to recommend associated test methods for each of the requirements. To achieve an immediate return on the efforts expended in developing criteria for improving roof performance, the work should begin with those attributes of membrane roofing that have been associated with the most problems. NRCA's Project Pinpoint provides information on performance problems and membrane deficiencies.

Table 10 lists, from the 1990 Project Pinpoint results [32], the five most common problems for the following types of membrane roofing: elastomeric, thermoplastic, modified bitumen, and bituminous built-up. As is evident, seam defects in elastomeric and modified bitumen membranes occur more frequently than other problems for these types of membranes. Moreover, even in the case of thermoplastic membranes where unsatisfactory seam performance is generally not considered to be a problem, the Project Pinpoint returns indicate seam defects among the five most common problems reported. In the case of built-up membranes, blistering and splitting are reported as the two main problems. This is not unexpected as blistering and splitting have long been reported as two of the major problems recurring with BUR membranes [2].

On the basis of the Project Pinpoint results, it is logical that the application of the performance approach to membrane roofing should start with seams. It has been the main area of concern with the newer membrane materials, but criteria have not yet been developed. A task group within ASTM Committee D 08 on "Roofing, Waterproofing, and Bituminous Materials" has been assembled to address the need. Moreover, the technology associated with seam performance is expected to change in the near future in answer to concerns raised on the basis of past performance and recognition of needs for environmental protection. For example, efforts to reduce solvent emissions into the atmosphere may result in use of low-VOC[7] adhesives or tapes in place of current solvent-based adhesives used to fabricate seams of some systems. The availability of performance-based criteria for seams would be beneficial in facilitating the development and evaluation of the new products [4].

[7] volatile organic compounds

Table 10. The five most common problems for each of the main types of roof membranes, as reported from Project Pinpoint in 1990[a]

Membrane Type	Problem	Percent[b]
Elastomeric	Seam Defects	50
	Puncture/Tear	21
	Shrinkage	13
	Wind Related	10
	Blistering	5
Modified Bitumen	Seam Defects	36
	Shrinkage	11
	Blistering	10
	Embrittlement	8
	Wind Related	2
Thermoplastic	Shrinkage	42
	Blistering	29
	Puncture/Tear	17
	Seam Defects	9
	Wind Related	3
Built-Up	Blistering	24
	Splitting	22
	Ridging	18
	Slippage	6
	Wind Related	3

[a]This table was assembled from data given by Cullen [32]
[b]Percent of problems reported for the given type of membrane.

As an initial step toward the development of criteria for seams, Appendix A presents an outline in performance format. Note that the outline includes suggestions for requirements, criteria, and evaluative procedures for membrane attributes other than watertightness. At the present time, only the requirement statements are proposed. Development of the criteria and evaluative procedures are left for future study.

In the case of watertightness, criteria suggested for development not only include mechanical-load resistance, which addresses delamination of the seam, but also permeability and puncture resistance. These last two requirements consider ways for a membrane to lose watertightness in a seam in a manner comparable to that through the membrane material itself. They are included in the seam criteria so that the set will be complete and stand alone. In practice, the criteria and test methods for permeability and puncture resistance should not differ from those suggested for the membrane material.

Finally, as mentioned, ASTM Committee D08 has a task group working on the development of performance-based criteria for seams. Suggestions for completing the outline given in Appendix A would be of assistance to the work of this task group.

5. SUMMARY

Low-sloped membrane roof systems have been one of the most problem-prone components of commercial and industrial buildings. Although the first efforts toward using a performance approach for developing criteria for membrane roofing were undertaken in the United States in 1964, over 25 years later such criteria have not been issued through the consensus standards process. A standard specification developed according to the performance approach defines a product in terms of the functions it is to perform, as required by the user, whereas a prescriptive specification defines a product in terms of parameters such as its constituents, physical properties, or method of manufacture. Performance and prescriptive specifications should be considered as complementary. In the latter case, the required tests may be conducted more rapidly than performance tests, which can be beneficial for product identification or quality control.

A fundamental aspect of the performance approach is that selection criteria are based on an understanding of the requirements necessary for the membrane system to perform acceptably in service. Moreover, requirements may be variable depending upon factors such as building use and environmental exposure, which provides use of a product under favorable circumstances. The availability of performance-based criteria would greatly assist in eliminating some of the defects that have plagued low-sloped roofing over the years.

As usually formalized, the performance approach uses four main statements in a specification:

1. the requirement -- a qualitative statement which describes what the product is to accomplish.

2. the criterion -- a quantitative expression of the level of performance which the product must meet to perform acceptably.

3. the test -- the evaluative method used to determine that the product conforms to the stated criterion.

4. commentary -- explanatory comments on the reason for, or intent of, the stated criterion.

This report outlines a performance approach for developing criteria for membranes used in low-sloped roof applications. An overview of previous efforts for applying the performance approach to membrane roofing is given. The approach consists of seven steps including identification of the key functions to be performed by a roof, identification of attributes essential to satisfactory performance, development of the requirements, criteria, and test methods, and putting in place a feedback mechanism to revise the criteria, if warranted, as new information becomes available on the performance of the system in service.

Five key functions associated with the performance of the membrane in a low-sloped system were identified, and attributes and performance requirements for each function were proposed:

1. Watertightness -- the prevention of water ingress through the top of the building.

2. Maintainability -- the long-term capability to have the roof system repaired effectively and economically as it weathers under the given environmental conditions, or in the event that leaks occur due to unexpected service loads.

3. Health and Safety -- prevention of undue risk to the health and safety of the installers or the users of the building.

4. Environmental Impact -- prevention of undue harm to the environment, either during installation or service.

5. Appearance -- preservation of the roof appearance during installation and throughout its service life, when designed to be aesthetically attractive.

Of these five functions, watertightness is the one that directly affects the major problem (i.e., leaks) associated with low-sloped roof performance. As a consequence, the majority of the requirements recommended for membrane systems in past studies, as well as in the present report, have emphasized this aspect of performance. In the present study, 17 attributes associated with watertightness were identified as essential to satisfactory performance of the membrane.

It is recognized that considerable effort may be needed to develop criteria and test methods for the complete set of attributes. Consequently, it is suggested that initial work should focus on those attributes of membrane roofing that have been associated with the most problems. Review of data from NRCA's Project Pinpoint indicated that seam defects in single-ply and polymer-modified bitumens have been the problems most frequently encountered for these types of membrane systems. On this basis, it was further suggested that the application of the performance approach to membrane roofing begin with the subject of seams. As an initial step in this direction, an outline of the needed criteria was presented including attributes and suggested requirements. The development of criteria and test methods are reserved for future study.

6. ACKNOWLEDGMENTS

The authors acknowledge the valuable contributions of their colleagues who reviewed the report. Thanks are expressed to the reviewers: William C. Cullen, Research Associate, NRCA; James Pielert, Building Materials Division, NIST, and Paul E. Stutzman, Building Materials Division, NIST.

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APPENDIX A. PRELIMINARY OUTLINE FOR CRITERIA FOR SEAMS OF LOW-SLOPED ROOF MEMBRANES

This Appendix suggests, in performance format, the key requirements for seams in single-ply membranes. The requirements are listed for five attributes: watertightness, maintainability, health and safety, environmental impact, and appearance. Each requirement statement is followed by a skeleton outline of criteria, evaluation method, and commentary. However, no criteria nor test methods are suggested at present; they are to be completed in the future.

A.1 ATTRIBUTE: WATERTIGHTNESS OF A SEAM

A.1.1 Requirement — Resistance to Mechanical Loads. The seam shall be capable of sustaining, without loss of watertightness, the mechanical loads expected to be imposed in service from internal or external causes.

a) Criterion[a] Peel strength
Evaluation
Commentary

b) Criterion Shear strength
Evaluation
Commentary

c) Criterion Creep resistance in peel
Evaluation
Commentary

d) Criterion Creep resistance in shear
Evaluation
Commentary

e) Criterion Cyclic movement resistance
Evaluation
Commentary

f) Criterion Flexure resistance
Evaluation
Commentary

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[a]The criteria, evaluations, and commentaries for all requirements are to be completed.

A.1.2	Requirement	Puncture Resistance. The seam shall be capable of withstanding, without loss of watertightness, the static and dynamic puncture loads expected to be encountered in service.
a)	Criterion Evaluation Commentary	Static puncture
b)	Criterion Evaluation Commentary	Dynamic puncture
c)	Criterion Evaluation Commentary	Hail resistance

A.1.3	Requirement	Resistance to Water Transmission. The seam shall prevent the passage of water through the roof under expected service conditions.
a)	Criterion Evaluation Commentary	Permeability to liquid water

A.1.4 Requirement — Effects of the Environment. Seams shall not be affected by internal and external environmental factors expected to be encountered in service to an extent that their ability to prevent water ingress will be impaired over the design life of the membrane.

a) Criterion — Heat
Evaluation
Commentary

b) Criterion — Moisture
Evaluation
Commentary

c) Criterion — Solar radiation
Evaluation
Commentary

d) Criterion — Airborne pollutants
Evaluation
Commentary

e) Criterion — Chemicals
Evaluation
Commentary

A.2 ATTRIBUTE: MAINTAINABILITY

A.2.1 Requirement — Sheet Condition. The properties of the membrane materials shall not be altered during exposure to the extent that a seam cannot effectively and economically be patched or otherwise repaired in the event of an unforeseen leak.

a) Criterion — Peel strength
Evaluation
Commentary

b) Criterion — Shear strength
Evaluation
Commentary

c) Criterion — Creep resistance in peel
Evaluation
Commentary

d) Criterion — Creep resistance in shear
Evaluation
Commentary

e) Criterion — Cyclic movement resistance
Evaluation
Commentary

f) Criterion — Flexure resistance
Evaluation
Commentary

A.3 ATTRIBUTE: HEALTH AND SAFETY

A.3.1 Requirement — Health and Safety During Installation. Installation of the seams shall not impose undue risks to the health and safety of the installers and users of the building, or of damage to the building itself.

a) Criterion — Combustible materials
Evaluation
Commentary

b) Criterion — Toxic materials
Evaluation
Commentary

c) Criterion — Ignition
Evaluation
Commentary

d) Criterion — Burns (thermal)
Evaluation
Commentary

A.4 ATTRIBUTE: ENVIRONMENTAL IMPACT

A.4.1 Requirement — Installation Effects on the Environment. Installation of the seams shall not cause undue damage to the environment.

a) Criterion — Volatile Organic Components.
Evaluation
Commentary

A.5 ATTRIBUTE: APPEARANCE

A.5.1 Requirement — Installation Effects on Appearance. Installation of seams shall not detract from the appearance of the building, in those cases when building attractiveness is of importance.

a) Criterion — Uniform appearance.
Evaluation
Commentary

NIST-114A (REV. 3-89)	U.S. DEPARTMENT OF COMMERCE NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY **BIBLIOGRAPHIC DATA SHEET**	1. PUBLICATION OR REPORT NUMBER NISTIR 4638 2. PERFORMING ORGANIZATION REPORT NUMBER 3. PUBLICATION DATE JULY 1991

4. TITLE AND SUBTITLE

A Performance Approach to the Development of Criteria for Low-Sloped Roof Membranes

5. AUTHOR(S)

Walter J. Rossiter, Jr., Geoffrey Frohnsdorff, Larry W. Masters, Jonathan W. Martin

6. PERFORMING ORGANIZATION (IF JOINT OR OTHER THAN NIST, SEE INSTRUCTIONS)

U.S. DEPARTMENT OF COMMERCE
NATIONAL INSTITUTE OF STANDARDS AND TECHNOLOGY
GAITHERSBURG, MD 20899

7. CONTRACT/GRANT NUMBER

8. TYPE OF REPORT AND PERIOD COVERED

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS (STREET, CITY, STATE, ZIP)

10. SUPPLEMENTARY NOTES

[ ] DOCUMENT DESCRIBES A COMPUTER PROGRAM; SF-185, FIPS SOFTWARE SUMMARY, IS ATTACHED.

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 report outlines a performance approach for developing criteria for the selection and use of membranes in low-sloped roof applications. An overview of previous efforts for applying the performance approach to membrane roofing is also given. A fundamental aspect of the performance approach is that selection criteria are based on an understanding of the requirements necessary for the membrane system to perform acceptably in service. The availability of performance-based criteria would greatly assist in eliminating some of the defects that have plagued low-sloped roofing over the years.

The approach consists of seven steps including identification of the key functions to be performed by a roof, identification of attributes essential to satisfactory performance, development of the requirements, criteria, and test methods, and putting in place a feedback mechanism to revise the criteria, if warranted, as new information becomes available on the performance of the system in service. Five key functions associated with the performance of the membrane in a low-sloped system are identified, and performance requirements for each function are proposed. These functions are watertightness, maintainability, health and safety, environmental impact, and appearance. Of these five functions, watertightness is the one that directly affects the major problem (i.e., leaks) associated with low-sloped roof performance. As a consequence, the majority of the requirements recommended for membrane systems in past studies, as well as in the present report, emphasize this aspect of performance.

It is recognized that considerable effort may be needed to develop criteria and test methods for the complete set of attributes. Consequently, the initial work should focus on those attributes of membrane roofing that have been associated with the most problems. Review of data from NRCA's Project Pinpoint indicated that seam defects in single-ply membranes have been the problems most frequently encountered for these types of roof systems. On this basis, it is further suggested that the application of the performance approach to membrane roofing begin with the subject of seams. As an initial step in this direction, an outline of the needed criteria is presented including attributes and suggested requirements. The development of criteria and test methods are reserved for future study.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)

evaluation; low-sloped roofing; membranes; performance criteria; requirements; roof functions; roofs; seams; test methods; watertightness

13. AVAILABILITY

[X] UNLIMITED

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[X] ORDER FROM NATIONAL TECHNICAL INFORMATION SERVICE (NTIS), SPRINGFIELD, VA 22161.

14. NUMBER OF PRINTED PAGES

36

15. PRICE

A03

ELECTRONIC FORM