A METHODOLOGY FOR DEVELOPING TESTS TO AID SERVICE-LIFE PREDICTION OF SINGLE-PLY ROOFING MEMBRANES

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ABSTRACT

The rapid growth in the use of single-ply roofing membranes has created a need for performance standards which include requirements and tests for evaluating their service life. A methodology is described for developing tests for aiding service-life prediction of single-ply membranes. The methodology is based on ASTM practice for developing short-term tests to aid in the prediction of the service life of building materials and components. The ASTM practice outlines a sequence of steps to be taken which are applicable to aid in predicting the service life of membrane materials. A summary of the ASTM practice is given and examples of the application of many of its steps to single-ply roofing systems are presented. Service-life prediction investigations are complex and have limitations. It is expected that the development of short-term tests according to the ASTM practice will lead to increased confidence in service-life predictions.

Key words: durability prediction; membrane; methodology roofing service life; service-life testing; single-ply membranes.

1. INTRODUCTION

The use of single-ply sheet membrane materials for waterproofing low-sloped roofs has resulted in a revolutionary change in the U.S. roofing industry. The extent of recent changes in roofing technology is indicated by the amount of single-ply materials used and the number of manufacturers producing these materials. Less than a decade ago, most membrane roofing consisted of the built-up bituminous type, and fewer than perhaps 10 manufacturers were marketing single-ply sheet materials. Today, single-ply membranes account for about 15-20 percent of the roofing applied on commercial and industrial buildings, and more than 60 manufacturers of single-ply materials are selling over 100 membrane materials[1]. Many of the currently available membrane materials are new to the market, and thus the history of their in-service performance has been limited. Although most single-ply sheet membranes have in general performed satisfactorily for the limited period of time they have been in service, the rapid growth in their use has not occurred without raising concerns about their long-term performance.

The U.S. roofing industry has usually judged long-term performance (service life) of roofing systems by evaluating them in service over an extended period of time. Techniques for reliably evaluating service-life based on short term tests have not been developed. In the case of bituminous built-up roofing, voluntary consensus standards are available which give requirements for the physical and mechanical properties of the bitumens and conventional reinforcing fabrics from which the composite membrane is fabricated. Historically, standards developed through the voluntary consensus process for roofing have been generally prescriptive, describing those initial material properties which are deemed suitable or adequate for the manufactured membrane materials. Such standards are intended to assure that the membrane materials have a prescribed level of quality. However, prescriptive standards do not, in most cases, contain provisions to assure that the values for material properties are maintained at an acceptable level over the intended service life of the membrane. For single-ply sheet membranes, standards have not been developed in the United States for either quality assurance or service-life evaluation. In view of the lack of standards, an approach is outlined here that can help in meeting the need for a methodology for evaluating single-ply membranes.

The service life of a building material has been defined as the period of time after installation during which all properties exceed the minimum acceptable values when routinely maintained[2]. Service life may be determined from an evaluation of in-service performance or from the results of short-term laboratory testing. The lack of long-term in-service performance data for single-ply membranes has, in part, created a need for performance standards which include requirements for evaluating service life based on short-term testing. The availability of performance standards would assist in the selection of membrane materials which perform satisfactorily over the intended service life.

As in the case for innovative building materials in general, it is difficult to predict service life on the basis of short-term test data[3,4]. One barrier to service-life prediction is that the operating and stress conditions (mechanical, thermal, environmental, and biological factors which cause a material to degrade over time) to which roofing membranes will be subjected are difficult to quantify. Therefore, it is difficult to design a meaningful short-term test to predict how innovative materials such as single-ply roofing will perform in service. In order to avoid or minimize possible delays in the use of some potentially satisfactory membranes, their service life should be predicted from short-term test data. Since the needed methods are not available, a methodology for developing tests for aiding service-life prediction should be developed.

Frohnsdorff and Masters[5] have listed some shortcomings of durability tests. These include: (a) methods are not usually provided for correlating short-term tests with field performance; (b) provisions are usually not made for taking into account different applications: and (c) recommendations are seldom made as to how the results of standard tests for different materials should be compared with each other. In order to overcome these shortcomings and to provide a systematic approach for conducting studies for the prediction of service life of building materials, ASTM E 632, "Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials,[2]" was developed.

The practice given in ASTM E 632 is applicable to the evaluation of new and innovative single-ply roofing membrane materials. It can provide the basis for a methodology for the development of tests to aid service-life prediction. This paper presents a summary of the practice in ASTM E 632 and gives examples of its application to single-ply roofing systems.

2. OVERVIEW OF THE PRACTICE IN ASTM E 632

The practice outlines a logical sequence of steps to be undertaken in developing tests for predicting the service life of innovative building materials or components, or for the use of existing materials or components under conditions other than normally expected. The sequence of steps given in the practice for developing predictive service-life tests is shown in Figure 1. As seen in this figure, the procedures for developing predictive service-life tests are divided into the following four parts (1) problem definition, (2) pre-testing, (3) testing, and (4) interpretation and reporting of the data. The application of ASTM E 632 to the development of short-term tests for building materials and components has recently been discussed[3,5].

Part 1 in ASTM E 632, problem definition, covers the intent of the tests and the degradation factors to be included in the aging tests. A listing of degradation factors affecting the service life of building materials and components, as given in the practice, is presented in Table 1. The purpose of part 2, pre-testing, is to demonstrate that rapid changes in the properties of the material can be induced by exposure to extreme levels of the degradation factors identified in part 1. The pre-testing provides the background for the design of the more realistic predictive service-life tests to be conducted in part 3. The purposes of testing (part 3) are to determine the relationships between the rates of degradation and exposure conditions; to perform tests under in-service conditions to confirm that degradation mechanisms occurring in the short-term tests are similar to those observed in service; and to measure the rates of change in properties in service. In part 4, interpretation and reporting of data, the data obtained in testing are assessed in order to predict the service life of the material or component or to compare the relative durabilities of various materials. Also in this part, mathematical models are needed for comparing rates of changes in properties of materials determined from short-term tests and those observed in service.

3. ILLUSTRATION OF THE APPLICATION OF ASTM E 632 TO SINGLE-PLY ROOFING

This section of the paper illustrates the broad application of the practice in ASTM E 632 to the evaluation of single-ply sheet roofing membranes as part of a roof system. A roof system consists of the deck, insulation, and membrane including seams. The membrane materials considered in the illustration include elastomeric, plastomeric, and modified bitumens. Various methods of membrane attachment are used including fully bonded, partially attached, and loose-laid. The sequence of the components within the system may also vary. For example, protected membrane systems have the membrane below the insulation. Other factors to consider in the evaluation of the system include the method of application and the environmental conditions during application and service.

Because of the number of variables describing a single-ply sheeting roofing system, a specific illustration of the practice to this type of roofing is considered beyond the scope of the paper. Rather, a broad approach with specific examples for many of the steps in the practice is given. The examples have in general been taken from the literature. The approach would be narrower and perhaps more detailed, if a specific single-ply membrane system were to be evaluated. The broad illustration of the practice, for each of the steps involved, uses definitions given in ASTM E 632 and is as follows.

Step 1. Define Performance Requirements and Criteria — The primary function of a roof system is to protect the building, its occupants, and its contents from the effects of weather, particularly water penetration. In this regard, the roof system must remain watertight and thermally efficient for 10 years or more. A period of 10 years is suggested based on the length of industry warranties for single-ply membranes. In contrast, Laaly and Sereda[6] have stated that new roofing materials should have a life expectancy similar to at least that of conventional roofing materials which they indicated was based on an average life of about 20 to 25 years.

In defining failure of the roof system, a quantitative criterion should be adopted and depend on the specific application[5]. A quantitative criterion is necessary and should be defined for the material or system under evaluation so that a rational judgment may be made as to whether or not failure has occurred. For example, a failure criterion for a roof system might vary from one opening or fissure in the membrane to a number of openings over some portion of the roof area depending on factors such as structural integrity, building contents, and thermal efficiency of the roof system. In some applications, a single leak in the membrane or disbonding of a seam may result in vast areas of wet insulation and water damage to other components of the roof system or contents of the building. Other applications may be more tolerant of leaks over a greater percentage of the roof area.

Step 2. Characterization of Membrane Materials — Characterization of a roofing membrane material is a key step in the evaluation of its long-term performance. Important indicators of degradation may go undetected if the material is incompletely characterized. As stated in

ASTM E 632 the material should be characterized as thoroughly as possible with regard to structure and composition, critical performance characteristics, properties that may serve as degradation indicators, the type and range of degradation factors encountered during exposure, and possible mechanisms of degradation during exposure.

The sheet membranes consist of various generic types, and have seams made from different processes in the factory and in the field. The roofing systems will be exposed to a wide range of environmental conditions. Although some of the sheet membranes are generically the same, their composition may vary depending on fillers, plasticizers, and other additives which may affect their performance. The waterproofing ability of the membrane is of utmost importance regarding the performance of the roofing system. Thus, the characterization of the membrane material and its interactions and compatibility with other components of the roof system are essential for planning laboratory tests. Seams in the membrane should also be well characterized. Many of the single-ply sheet membrane materials are composites, for example, containing reinforcing fabrics or carrier films, or consisting of blends of bitumens and polymers. In the case of composites, not only should the individual materials be well characterized, but also the interfaces between the materials. Changes occurring at interfaces during exposure may be important indicators of degradation.

Step 3. Critical Performance Characteristics — Critical performance characteristics are the properties of the roofing membrane that must be maintained above a certain minimum level if the membrane is not to lose its ability to perform its intended function. Critical performance characteristics may include mechanical, chemical, and physical properties. In this step the critical performance characteristics are identified, along with properties of the membrane which may be used as indicators of degradation. In some cases the properties used as indicators of degradation may be the same as the critical performance properties. For single-ply membranes, the critical performance characteristics may vary depending on factors such as the type of roofing system and the method of membrane attachment to the substrate. With regard to single-ply roofing, an illustration of the selection of critical performance properties and degradation indicators may be taken from Laaly and Sereda[6]. They considered that the membrane material must withstand movements of the roof systems, wind actions, penetration by sharp objects, and low temperatures. Thus, they selected the following properties which may be considered as critical performance characteristics: tensile strength, elongation at break, elastic limit (recovery after stretching), low temperature flexibility, crack bridging, cone penetration resistance, and static and dynamic impact tests at different temperatures. They indicated that these properties could also be used as degradation indicators when the membrane materials were exposed to moisture. They also indicated that tensile strength and change in length were considered as degradation indicators upon exposure of the materials to combined temperature and humidity.

An important technique to assist in the identification of critical performance characteristics is mathematical modeling. For example, in a preliminary analytical study of temperature-induced stresses in loose-laid and totally-adhered single-ply membranes, it was confirmed from the model that the modulus of the membrane material was a key property reflecting the magnitude of the induced stresses accompanying the thermal strains[7].

Step 4. Expected Type and Ranges of Degradation Factors — Degradation factors are external conditions or factors that adversely affect the performance of building materials and components. To delimit the range of degradation factors to which the membrane material may be exposed, the climatic conditions at the locations where the roofing system will be installed should be determined.

Wherever possible, the range of degradation factors should be quantified by means of meteorological and related information. Masters and Wolfe[8] have presented in a review how weather and climate data can be used to aid in quantifying weathering factors in the design of service-life tests for building materials and components. The types of many degradation factors to which building materials may be exposed have been classified in ASTM E 632 into five categories: weathering factors, biological factors, stress factors, incompatibility factors, and use factors (Table 1). Most of these factors are considered applicable to the evaluation of roofing systems. Due to experimental constraints, it may not be feasible to conduct an extensive study which includes the effects of all degradation factors on the roofing material properties and judgments must be made to select those factors most pertinent for a specific study. A set of degradation factors identified by Kelly and May[9] as important to roofing performance include: heat, ultraviolet radiation, water, oxygen, ozone and other gaseous pollutants, bacteria, and compatibility with other materials and components of the roofing system and of the building construction. Koike and Tanaka[10] chose heat and light only to study degradation of plastic and rubber roofing membranes.

Step 5. Identification of Possible Degradation Mechanisms — A degradation mechanism is the sequence of chemical or physical changes, or both, that leads to detrimental changes in one or more properties of a building material or component when exposed to one or more degradation factors. It is important to identify the possible mechanisms of degradation so that accelerated aging tests conducted in the laboratory would induce degradation in the test specimens representative of the mechanisms by which the membrane material ages in service.

By way of illustration, in evaluating the performance of a seam in a single-ply membrane, many possible mechanisms of degradation may be listed. Possible mechanisms which may contribute to or result in seam failure include: induced stress due to membrane shrinkage caused by material degradation, thermal contraction, and building movement; stress due to externally-applied loads such as foot traffic, impact, wind, and building vibration; creep at the seam lap; degradation of the adhesive and membrane materials resulting in lower bond strength; and lower initial bond stength due to incorrect installation resulting from factors such as surface contaminants, and improper adhesive thickness and application temperature.

Step 6. Postulations Regarding Accelerated Aging Tests — This step forms the basis for the design of the preliminary accelerated aging tests. In this step, ways of accelerating the degradation of the membrane are postulated in accord with the degradation factors and possible degradation mechanisms identified in steps 4 and 5, respectively.

For example, if failure of a seam is considered to be due to deterioration of the adhesive bond because of poor resistance to temperature and moisture, then this mechanism might be accelerated by exposing the seam to temperature and moisture conditions higher than those expected in-service. On the other hand, if a seam is thought to fail because it cannot resist prolonged periods of induced stress, then the seam should be exposed to stress levels higher than expected in service. In addition, the synergistic effects of combined temperature, humidity, and stress exposure should also be considered. To evaluate the effects of incorrect adhesive application, seams might be tested which are made with materials having both clean and contaminated surfaces, or with varying thicknesses of adhesive.

Precautionary advice must be given here regarding the exposure of the materials to levels of degradation factors greater than those experienced in service. Care must be exercised not to expose the materials to such extreme levels that the mechanism of degradation in the accelerated exposure is likely to be different than that encountered in service.

Step 7. Define Performance Requirements for Predictive Service-Life Tests — The performance requirements for the roofing membrane material in the accelerated aging tests are defined in qualitative terms. As indicated by Frohnsdorff and Masters[5] the accelerated tests should produce failure by the same mechanisms as in service, but in a shorter time. Also, if many materials are tested, the tests selected should, to the extent possible, rank the materials in the same order of durability as the in-service exposures.

Step 8. Design and Perform Accelerated Aging Tests and Confirm Degradation Mechanisms — The purpose of this step is to determine whether or not accelerated degradation of the membrane material will occur, as postulated in the previous steps, under the influence of the degradation factors applied at extreme levels of intensity. If the roofing material or system exhibits rapid degradation it should either be eliminated from further evaluation or tested under less severe conditions. The rapid degradation may have occurred by a mechanism which may not produce deterioration under service conditions. An obvious example would be the exposure of modified bitumen materials to temperatures above those which would cause the materials to flow. As indicated in ASTM E 632, this step in the evaluation of the membrane material provides information concerning: (1) property changes that are likely to be useful as degradation indicators; (2) the order of importance of the degradation factors; (3) mechanisms by which properties change, and (4) the intensities of degradation factors needed to induce rapid property changes.

Pre-tests of roofing materials may also provide information or direction as to which degradation factors need not be examined in further detail as to their effect on the membrane's durability. For example, Kelly and May[9] considered that ozone might have a deleterious effect on some bitumen-polymer membrane materials because of the rubbers incorporated in them. However, they reported that the bitumen-polymer membrane materials in their study were not deteriorated under relatively high concentrations of ozone when the materials were tested under strain. They did not conduct further tests at lower ozone concentrations.

Step 9. Design and Perform Predictive Service Life Tests Using the Degradation Factors of Importance — The predictive service life tests are based on the results of the pre-tests in step 8. The predictive service-life tests are conducted to provide a relatively rapid means of measuring the rate of property changes typical of those which occur in service. The levels of intensity of the degradation factors used in the predictive service-life tests are lower than those in the pre-tests. In addition, different levels of each of the degradation factors should be incorporated to provide data which may be used as the basis for mathematical models (step 13) for describing rates of changes of the materials during exposure. Key material properties identified as degradation indicators (step 3) are measured before and after exposure to the degradation factors for certain periods of time. The predictive service-life tests should also consider the effects of synergism between the degradation factors, and such tests should be included as necessary.

Step 10. Long-Term In-Service Tests — It is very desirable to conduct long-term in-service tests so that degradation mechanisms occurring in service can be compared with those in accelerated (predictive service-life) tests. Data from outdoor exposures are also needed to enable comparisons of rates of change of material properties from the accelerated and outdoor exposure tests. The outdoor exposure sites should be selected so that the membrane materials are subjected to environments which have relatively high levels of intensity of the specific degradation factors to be investigated. Although it may not always be achieved, the intent is to produce measurable rates of change in the membrane properties in the relatively short time that the in-service test may be conducted. In this regard, microstructural analytical techniques which are capable of detecting incipient changes in materials structure or properties should be selected, whenever possible, as degradation indicators.

Rossiter and Mathey[11] reported that in-service performance was the usual method for assessing the durability of single-ply membranes. They indicated that many manufacturers of new materials conduct field testing before introducing them to the market for general use. However, the use of such in-service tests of complete systems in conjunction with accelerated aging tests for predicting service life has not been reported in the literature.

Step 11. Comparison of Types of Degradation — In this step, a comparison is made of the types of degradation occurring in the accelerated aging and long-term in-service tests. It is imperative that the accelerated aging tests induce degradation according to the same mechanisms as occur in service. If the mechanisms are different, the accelerated aging tests should be re-designed. Accelerated aging tests which cause materials deterioration by mechanisms other than those experienced in service have little value in the prediction of service life. A prime reason why the mechanisms of degradation in the two types of tests may be dissimilar is that the level of intensity of the key degradation factors in the accelerated aging tests is too high.

In this regard, Laaly and Ashton[12] reported that heating samples of unreinforced and reinforced poly(vinyl chloride) (PVC) membrane materials for 5 hours at 163°C (325°F) had no effect on tensile strength. The unreinforced PVC showed little change in tensile strength after 8 years outdoor exposure, while the tensile strength of the reinforced PVC membrane material increased by 100 percent after 11 years exposure. Moreover, the changes in elongation of both PVC materials caused by laboratory heating were not representative of those which occurred in service. Thus, Laaly and Ashton[12] concluded that heating at 163°C (325°F) for 5 hours was too severe and caused degradation different than encountered in natural exposure. They lessened the laboratory heating exposure to 130°C (266°F) for 24 hours.

Marechal[13] has studied the aging of styrene butadiene styrene (SBS) modified bitumen membrane materials. Accelerated aging was performed in a ventilated oven at 70°C (158°F) for periods of time up to 6 months. Changes induced in the heated specimens were determined using gel permeation chromatography (GPC) and by creep testing. The results indicated that the oven exposure thermally oxidized the membrane material causing scissions of the SBS chains in the polymer component and hardening of the bitumen component. GPC analysis and creep testing of the SBS-modified bitumen membrane materials exposed outdoors indicated similar changes in the SBS polymer and bitumen. On this basis, Marechal[13] concluded that mechanisms of degradation in the accelerated and in-service tests were comparable.

Step 12. Determine Whether the Mechanisms of Degradation in the Predictive Service-Life Tests are Representative of Those Occurring in the In-Service Tests — The determination of whether differences exist between the mechanisms of degradation occurring in the predictive service-life (accelerated) tests and in-service tests is based on the analysis undertaken in step 11. If the mechanisms of degradation in the accelerated and in-service tests are found to be different, the accelerated aging tests should be altered after a reassessment of the information obtained in steps 2 through 8 (see loop in Figure 1). If the degradation mechanisms in the two types are not found to be different, step 13 may be undertaken.

Step 13. Development of Mathematical Models for Comparing Rates of Changes in the Predictive Service-Life and In-Service Tests — Using the data from the predictive service-life and in-service tests, mathematical models of the rates of degradation of the membrane materials should be developed. These models should be consistent with the mechanisms of degradation and consider the effect of the key degradation factors on the rate of deterioration. Development of the mathematical models enables the comparison or correlation of the rate of degradation in the predictive service-life test with that in the in-service test.

For example, in both accelerated aging and in-service tests, Koike and Tanaka[10] studied the effect of the exposure of combined heat and ultraviolet light on the performance of rubber and plastic roofing membrane materials. In both tests, it was necessary to measure the temperature and the intensity of the ultraviolet radiation. These degradation factors produced a decrease in the elongation of the membrane materials. Mathematical models (empirical equations) were developed relating the decrease in elongation with time to the temperature and intensity of the ultraviolet radiation. The equations were found to be valid for the degradation of some rubber and plastic membrane materials exposed outdoors for two years. In the case where water had collected on the surface of a plastic membrane specimen the equations were not found to be valid. It is assumed that the presence of water altered the mechanism of degradation and was not accounted for in the mathematical models based on only temperature and the intensity of ultraviolet radiation.

Step 14. Performance Criteria for Predictive Service Life Tests — A performance criterion is a quantitative statement of a level of performance for a selected performance characteristic for a material or component. Performance criteria are needed to ensure compliance with performance requirements. In this step, based on the results of the predictive service-life tests, performance criteria are established that define quantitative minimum acceptable levels of performance for the performance requirements defined in step 7.

Step 15. Predict Service Life Under Expected In-Service Conditions — In this step, the expected service life of the roofing membrane material may be predicted based on the results of the predictive service-life tests. Using the mathematical models developed in step 13, the rates of change of the material properties in the accelerated aging and long-term in-service tests are compared. This comparison provides the basis for the prediction of the expected service life.

As indicted in ASTM E 632, an alternative to the actual prediction of service life is to compare the relative performance of a number of materials in a series of similar tests. This comparison may result in ranking the materials in order of their expected long-term performance.

Step 16. Report the Data — The final step in ASTM E 632 is to report the data. The report should summarize the findings and assumptions made in the previous steps. This has importance for an understanding of the rationale upon which the predictive service-life tests were established. The report should also include the predictions or rankings of durability of the materials which are tested.

4. SUMMARY AND CONCLUSIONS

Single-ply materials presently account for a significant percentage of the waterproofing membranes used for low-sloped roofing. Many of these materials have a limited history of in-service performance as roofing membranes. Voluntary consensus standards and performance standards for single-ply membranes have not yet been developed in the United States to enable evaluation of the service life of these materials. Moreover, it is difficult to quantify the specific environments and stresses to which the membrane will be subjected during its service life. The practice given in ASTM E 632 was developed to aid in the prediction of the service life of building materials and components. This paper presented a summary of the practice and illustrated many of the steps using examples from the literature. The practice in ASTM E 632 is applicable to the evaluation of single-ply membrane materials and can provide the basis for a methodology for tests to aid their service-life prediction. Among the benefits of evaluating service life according to the practice given in ASTM E 632 are: the investigation is conducted in a logical manner and attempts to include all relevant factors affecting service life; and uniformity is achieved in planning and conducting tests.

The prediction of service life of building materials is complicated and has many possible sources of errors[5]. The process to aid in service life prediction as outlined in ASTM E 632 involves characterization of the material under investigation and of its service environment, as well as knowledge of the mechanisms of materials degradation. Confidence in the predictions will be higher in cases where materials are well characterized and their degradation mechanisms are well understood. Assumptions will always have to be made about degradation mechanisms, the less well understood the greater the amount of testing required to attain a high confidence in the predictions[5]. Service life prediction investigations, as outlined in ASTM E 632, require a large number of complex tests. Thus, these investigations are limited to facilities staffed with qualified personnel and having specialized equipment.

Even though service-life prediction investigations are complex and have limitations, methods for evaluating the long-term performance of single-ply membranes on the basis of short-term tests are needed. This need has been created, in part, by the lack of long-term in-service performance data for many of these membrane materials. Performance standards for single-ply membranes should include requirements for evaluating service life based on short-term tests. It is expected that the development of short-term tests according to the logical sequence outlined in ASTM E 632 will lead to increased confidence in the service life predictions.

5. ACKNOWLEDGEMENT

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Weathering Factors
- Radiation
  - Solar
  - Nuclear
  - Thermal
- Temperature
  - Elevated
  - Depressed
  - Cycles
- Water
  - Solid (such as snow, ice)
  - Liquid (such as rain, condensation, standing water)
  - Vapor (such as high relative humidity)
- Normal Air Constituents
  - Oxygen and ozone
  - Carbon dioxide
- Air Contaminants
  - Gases (such as oxides of nitrogen and sulfur)
  - Mists (such as aerosols, salt, acids, and alkalies dissolved in water)
  - Particulates (such as sand, dust, dirt)
- Freeze-thaw
- Wind

Biological Factors
- Microorganisms
- Fungi
- Bacteria

Stress Factors
- Stress, sustained
- Stress, periodic
- Stress, random
  - Physical action of water, as rain, hail, sleet, and snow
  - Physical action of wind
  - Combination of physical action of water and wind
  - Movement due to other factors, such as settlement or vehicles

Incompatibility Factors
- Chemical
- Physical

Use Factors
- Design of system
- Installation and maintenance procedures
- Normal wear and tear
- Abuse by the user

TABLE 1
Degradation Factors Affecting the Service Life of Building Materials and Components[3].

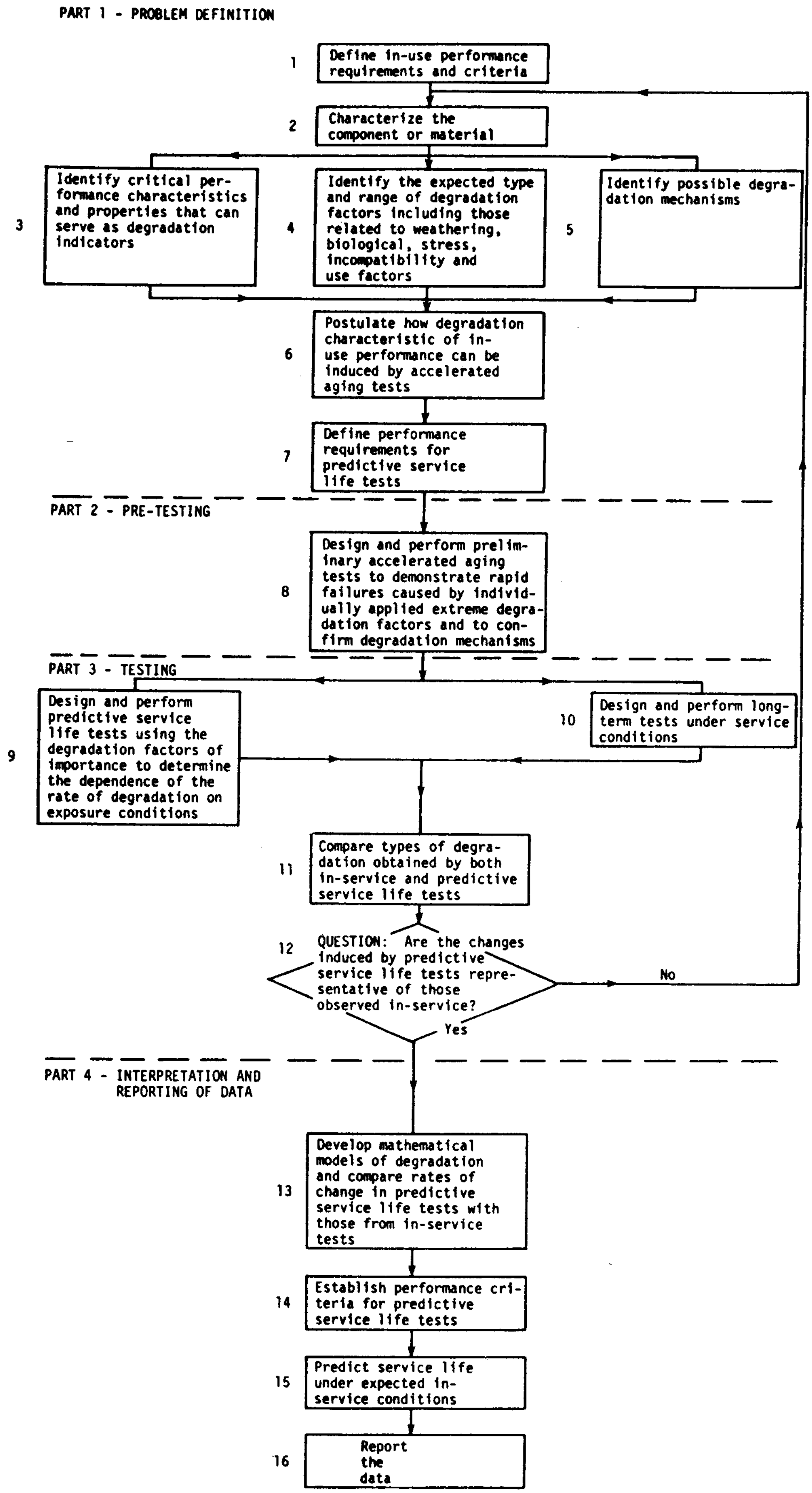

FIGURE 1
Steps in the Practice in ASTM E 632 for Developing Predictive Service Life Tests[3].