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Prediction of service life of building materials and components

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1. INTRODUCTION

1.1 Background

Throughout the history of mankind, concern for longevity of buildings and structures is evident. For example, concern for longevity is implied in the biblical instructions given to Moses on Mount Sinai for construction of the Tabernacle in Jerusalem; it is evident in the construction of the pyramids in Egypt; it is evident in the construction of the Coliseum in Rome; it is evident in the construction of thousands of ancient buildings and structures throughout the world. Even though the construction processes and the materials of construction have changed with technological advances since ancient times, concern for longevity remains.

Scientists, architects, construction engineers and others associated with construction technology in the 20th century recognize that data on the service life of building materials and components are essential to achieving longevity through the effective selection, use and maintenance of the materials of construction. Service life data are also needed to assess performance as a function of cost and thereby permit selection of the most economically attractive option.

In the building industry, the difficulties facing the materials specifier are becoming greater as a result of the demands of owners for buildings outside the usual range of experience (e.g. taller buildings and buildings with more column-free space) and for lower life-change costs, changes in the formulation of traditional materials (e.g. in response to changes in the availability of ingredients), and the needs to take advantage of new technologies (e.g. solar heating and cooling) and to respond to legislation inhibiting use of certain traditional materials (e.g. asbestos-containing fire-protective materials and some solvents used in paints). As the selection of building materials becomes more difficult, the decisions are likely to become less reliable unless there are compensating factors which make possible higher quality decisions. The number of defects in buildings [1] seems to attest to the need for improvement in the design process of which materials selection is a part.

The need to advance the state-of-knowledge of service life prediction and, thereby, reduce a barrier to innovation and improve the selection of cost-effective materials has stimulated several internationally sponsored activities. Among these are the First, Second, and Third International Conferences on the 'Durability of Building Materials and Components' held in 1978, 1981, and 1984, respectively [2–4], the formation of multinational research activities on service life, such as the studies being carried out by the Nordic countries [5], and the 1984 NATO Advanced Research Workshop on 'Problems in Service Life Prediction of Building and Construction Materials' [6].

In 1981, the Conseil International du Batiment pour la Recherche L'Etude et la Documentation (CIB) and the Réunion Internationale des Laboratoires D'Essais et de Recherches sur les Matériaux et les Constructions (RILEM) formed a joint Working Commission (Technical Committee) on Prediction of the Service Life of Building Materials and Components (CIB W80/ RILEM 71-PSL). The objectives of the joint activity are:

1. To identify methodologies for prediction of service life of materials and components used in the exterior envelope of buildings;
2. To identify areas for improvement of existing methodologies and to stimulate new developments; and
3. To develop systematic methodologies for service life prediction of exterior envelope building materials and components and to disseminate information on the state-of-the-art.

In order to address the objectives, members of the Working Commission (Technical Committee) chose, as their initial activity, to prepare a report on the current state-of-the-art of service life prediction, including identification of research needs and including a proposed systematic methodology (approach) for carrying out studies on service life prediction.

1.2 Purposes of report

This report presents the results of the initial task carried out by the Working Commission (Technical Committee). The purposes of the report are to:

1. Assess the current state-of-the-art of service life prediction;
2. Identify and describe some of the systematic methodologies (approaches) that are currently available;
3. Propose a general systematic methodology (approach) which could be used by a broad range of Working Commissions, Technical Committees and others in carrying out studies on service life prediction (it is intended that the methodology could form the basis of a CIB/RILEM Recommendation); and
4. Identify research needed to advance the state-of-the-art of service life prediction of building materials and components.

2. SUMMARY: STATE-OF-THE-ART OF SERVICE LIFE PREDICTION

The service life of a building material, component or system can be defined as the period of time after installation during which essential properties meet or exceed minimum acceptable values. Each material or component in a building system has an expected service life. Some components, such as structural members, are expected to perform their intended functions for at least the lifetime of the building. Other components, such as roofing membranes, paints and joints sealants, usually have shorter service lives and require periodic repair or replacement during the lifetime of the building. Materials and components have finite service lives because they gradually undergo chemical, physical, or mechanical changes that degrade them and reduce their ability to perform as required.

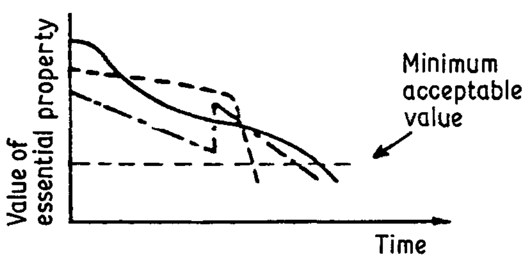

Fig. 1 Hypothetical performance over time functions.

Numerous terms have been used in describing research or test methods that relate to measurement of the longevity of building materials, components, and systems. These terms include durability, performance over time, and service life. 'Durability' is not an absolute quality of a material or item but a term expressing a human perception of a quality which changes in the environment; it implies likelihood of lasting well in expected environmental exposures but usually without quantification of the expected life. 'Performance over time' can be expressed as the function which describes how specific properties vary with time, as shown in Fig. 1. With this function established and with the definition of the limiting acceptable values, service life can be predicted. Because 'performance over time' and 'service life' are more easily quantifiable than 'durability', they more closely meet the need in describing the period of time after installation during which all properties of a material, component or system meet or exceed the minimum acceptable levels. In this report, the term 'service life' will be used.

2.1 Sources of data

Data on service life are available from both experience and testing. For traditional materials and components that have been used in buildings, some data on actual service lives are usually available from experience in actual buildings. Although these data are often poorly documented or incomplete, they are an aid to decision making. Also useful data for traditional materials used in traditional applications may be available from case-studies or field tests. But, for new or substitutional materials, or for traditional materials used in new environments, service life data based upon past experience are not available. In such cases, data must be generated from testing or from an assessment of available knowledge regarding the science and engineering of the materials and the type of application. Field exposure tests are often relied upon for reliable service life data; and, if the exposures are properly carried out, useful data can be obtained. The primary problem encountered in carrying out field exposure tests is that they can take a long time to obtain results unless the property changes leading to degradation are detected at early stages in the exposure. Other problems are that the exposure conditions cannot be controlled and the intensities of weathering factors are seldom measured, particularly at the micro-environment level. It is difficult, therefore, from field exposure tests to identify mechanisms of degradation, to isolate the effects of various degradation factors, and to generate data which are well understood. If delays in the use of potentially satisfactory new materials or traditional materials in new environments are to be minimized, service life must be predicted from short-term test data.

Regardless of the source of service life data, judgment by experts is essential in interpreting data because data are not complete enough to permit predictions without judgment.

2.2 Service life tests

Test methods to obtain service life data can involve laboratory exposure, field exposure or assessments of actual in-service performance. Typically, these tests involve measuring the rate at which specific properties change with time of exposure in the service environment (or in laboratory exposures intended to simulate the service environment). Implicit in the development or use of test methods to generate service life data are the following elements:

(i) Definition of the performance requirements
(ii) Characterization of the materials or components in terms relevant to understanding their degradation mechanisms
(iii) Characterization and quantification of the factors which may cause degradation
(iv) Identification of possible degradation mechanisms
(v) Definition of the range of conditions to which the material will be exposed
(vi) If accelerated tests are used, confirmation that the degradation mechanisms induced by these tests are correct
(vii) Determination of the rates of degradation under various environmental conditions covering the likely ranges
(viii) Development of mathematical models describing the degradation processes under various conditions and application of them to the prediction of service life
(ix) Reporting of the results of the prediction with explicit statements of the assumptions made

Despite the availability of many laboratory-based test methods for assessing the relative 'durabilities' of specific building materials, the data obtained from these methods are seldom adequate for reliably predicting service life. To a large extent, the shortcomings of many laboratory-based test methods stem from the approach or philosophy around which the methods are developed and used. Traditionally, the goal of accelerated ageing tests has been to simulate in the laboratory an accelerated version of a generic natural exposure environment. To accomplish this, researchers have selected those factors of degradation that they felt were most influential and incorporated them into an accelerated ageing test. They might also have cycled one or more of the factors of degradation to simulate the diurnal cycle. As one can easily imagine, the number of possible accelerated ageing tests is very large. It is not surprising, therefore, that many different accelerated ageing tests have been proposed and used by the industry.

Once an accelerated test has been proposed, the next step is to determine how well the results of this accelerated ageing test compare with those from an in-service exposure. The traditional way of doing this is to make sets of test materials, each consisting of a large number of the materials to be studied. One set is then exposed in the accelerated ageing test, while the other sets are placed in various outdoor exposure sites or are materials used in actual buildings. At each exposure site, the materials are checked periodically to determine their state of degradation, and once they have degraded sufficiently, the exposure test is terminated. The materials are then ranked in order of increasing degree of degradation. The rankings for each exposure are correlated with the rankings of the other exposure sites. If a high correlation exists between the ranking of the accelerated ageing test and those of the outdoor exposures, then the accelerated ageing test is considered to be successful. Unfortunately, the results are seldom, if ever, so definitive. Once in a while, a high correlation is achieved, but more often the correlations are marginal. More importantly, significant transpositions in the rankings are often observed between the accelerated and in-service exposures; that is, a material that performs well in the accelerated ageing test performs poorly in-service and vice versa.

Masters [7] has outlined a number of barriers to the development of improved test methods and to service life prediction. These include the needs for: (i) a systematic approach or methodology for treating the problem; (ii) an effective mechanism for obtaining and reporting data on the actual in-service performance of materials (feedback from practice); (iii) knowledge of the mechanisms of degradation; (iv) knowledge of the factors causing degradation; (v) the ability to simulate or account for the synergism between degradation factors, and (vi) mathematical models describing the material behaviour in specific environments or applications. Section 3 of this report will address in further detail the need for the systematic methodology mentioned above. Items (ii) through (vi) will be described briefly in the following discussions (Sections 2.3 through 2.7).

2.3 Feedback from practice

As pointed out by Sneck [8], an important element which is often lacking in service life studies is feedback on the performance of materials in service. The lack of an effective mechanism for obtaining and reporting data on the actual in-service performance of materials presents problems in: (a) disseminating, in a common format, the data that are available; (b) identifying the mechanisms of degradation under in-use conditions; (c) characterizing the various exposure environments; (d) identifying the effect of the various environments in which materials are used internationally; and (e) validating predictive models. Although standard procedures for performing outdoor exposure tests are available in many countries, these methods do not address feedback from materials under in-use conditions. In his report to RILEM, Sneck [8] recommended collaboration to establish effective feedback systems and an acceleration of work to develop methods for inspecting the state of existing buildings and structures.

2.3.1 *Information bases containing failure and service life data*

The rapid developments in computer technology offer many new possibilities in the storage, handling and retrieval of data on building failures and on the service life of materials and components. These possibilities are, thus far, utilized to a limited extent. Two examples of activities containing computer aided information bases are (i) the Architecture and Engineering Performance Information Center (AEPIC), formed in 1982 at the University of Maryland (USA), and (ii) a reporting and feedback system for building materials failures and other technical experiences instituted by the National Swedish Institute for Building Research (SIB).

The ultimate objective of AEPIC is the prevention of structural and material failures. It is predicated on the premise that the systematic collection, collation, analysis, and dissemination of information about such failures will further the objective. But even with the formation of AEPIC, implementation of an effective system of obtaining and disseminating data in a short period of time would be difficult. One problem to be overcome is that, although data are available, they are not easily adaptable to a uniform reporting format. Another problem stems from the many gaps in the available data and the many questions of the actual in-use history.

The SIB feedback system was developed in close collaboration with major housing organizations. It was intended that these organizations would voluntarily report technical experiences in a specific format as they routinely used the data base. This goal has, thus far, not been reached and the data base is currently used primarily for storage of data from failure investigations performed by SIB researchers.

The applicability of the information from such data bases is dependent upon the quality of the collected data, and the procedure for collection and collation of the data determines the quality.

It is also important to bear in mind that many failures are caused by incorrect design, by poor construction work or by faulty maintenance. Failure studies and the collection of failure data generate important information on the quality of design, construction and management of buildings but do not necessarily give the required feedback of information on materials performance. Reliable data on the service life of materials can be generated from field performance only if the data stem from well-planned, systematic inspections of the state of thoroughly characterized existing buildings in thoroughly characterized environments.

2.3.2 *Field inspection of buildings*

Most field inspections of buildings that include an assessment of the performance of materials and components are descriptive. The purpose of such inspections is often to describe the in-service state of materials or materials combinations either for single components of buildings or for a whole, well-defined population of buildings.

If the field investigation has the limited scope of drawing conclusions regarding only those components that have been studied, the procedure of sampling houses may be non-statistical. The buildings to be inspected can be sampled systematically, observing variables such as building design, exposure environment, installation procedure, or material.

If the goal is to generalize the observations to a population of buildings, an inspection of a statistical sample of objects from the population is an effective way of performing the investigation. A statistical sample means that the probability of a particular component being included in the sample is known, and is greater than zero. It is important to recognize that a sample survey is not necessarily inferior to an investigation of the whole population. Through a careful sampling technique, an investigation of relatively few buildings can give valid results. With a decrease in the number of buildings being inspected, a greater effort can be put on the inspection routine and the evaluation techniques. A valuable asset associated with this type of investigation is the possibility of accounting for the accuracy of the results.

The type of data that can be generated by statistically designed field surveys are illustrated by the following example of a study conducted by the National Swedish Institute for Building Research. The purpose was to estimate the number of building failures (unexpected maintenance) in the population of housing units built after 1954, and to calculate the costs for their repair. A sample of 661 houses from 84 municipalities all over Sweden was investigated.

The sampling procedure was designed to ensure good confidence of the estimates of expenses for six main classes of accounting. However, when analysing the resultant data, it was also possible to estimate, with an acceptable level of confidence, the number of failures and the costs of their repair for certain parts of the building.

As an example, Fig. 2 shows the number of apartment houses with failures of certain parts of the buildings.

A closer look at the roof failures for both single family houses and apartment houses revealed (see Figs 3 and 4) how the failures involving moisture (leakage, dampness, etc.) appeared in different age classes and how the number of defects of roofing felt varied with the age of the felt.

The inspection routine and the evaluation techniques to be used in field investigations of buildings are of great importance. The evaluation techniques must be comparable to those used in laboratory studies.

The major development needs regarding methods for inspection of buildings and structures are connected with (a) the techniques for sampling, (b) the measurement and description of exposure environments, (c) the methods or routines for inspections, and (d) the procedures or measurement techniques for evaluating properties that serve as degradation indicators.

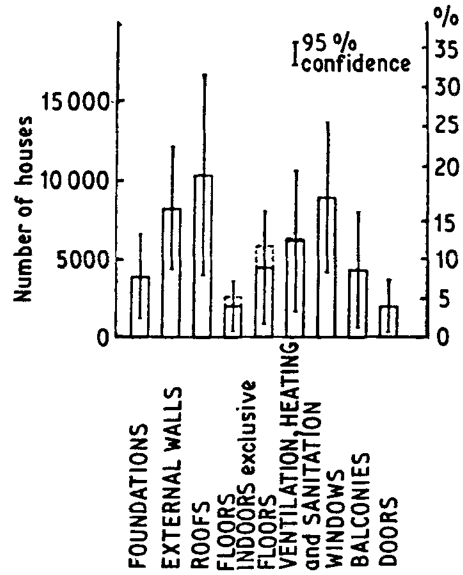

Fig. 2 Number of apartment houses with defects on certain parts of the building.

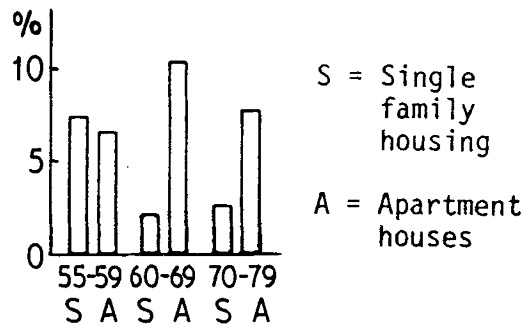

Fig. 3 Dwellings with failures of the roofing due to moisture.

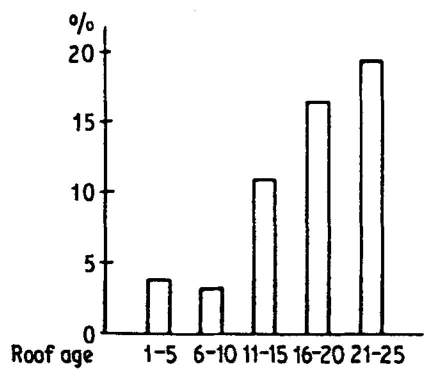

Fig. 4 Defects of roofing felt as a function of roof age.

2.4 Mechanisms of degradation

Degradation mechanisms are the processes or reactions that lead to a change in the ability of a material, component, or system to perform as intended. Degradation mechanisms can be expressed in many different ways including, for example, chemical reactions (hydrolysis, photo-oxidation) or phenomena (loss of plasticizer, swelling, shrinking). It is essential, in the design and conduct of service life studies, that one obtain sufficient knowledge of degradation mechanisms to ensure that the tests performed do not induce mechanisms which would not be encountered in service. Ramachandran [9] has stated that one reason for the fact that accelerated weathering tests frequently yield unsatisfactory data is that researchers presuppose important exposure factors and degradation mechanisms and incorporate the suppositions into the design and use of exposure chambers. He argues that it is more effective first to determine the degradation processes and then to design the test to reproduce them.

The lack of mechanistic data is an important technical barrier to service life prediction.

2.5 Degradation factors (agents)

Degradation factors (or agents) can be defined as any of the group of factors that can affect the performance of a building material, component, or system. Table 1 contains a list of agents (degradation factors) taken from ISO 6241 [10]. Table 2 lists degradation factors according to ASTM E632, 'Standard Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials' [11].

Regardless of the specific category or terminology used, it is recognized that: (i) the factors causing degradation are numerous; (ii) the importance of the factors varies with the material in question and with the geographic location of interest, and (iii) knowledge of the effect of the factors and knowledge of the range (or intensity) of the factors is needed in the development of test methods for predicting service life.

Each of the most important factors must be considered in developing or carrying out test methods to generate service life data because the service life of a material of component is affected by the degradation factors acting on it during the different stages of its life cycle.

Table 1 Degradation factors (agents) relevant to building performance

	Nature	Origin			
		External to the building		Internal to the building	
		Atmosphere	Ground	Occupancy	Design consequences
1.	Mechanical agents				
1.1	Gravitation	Snow loads, rain water loads	Ground pressure, water pressure	Live loads	Dead loads
1.2	Forces and imposed or restrained deformations (4.01)	Ice formation pressure, thermal and moisture expansion	Subsidence, slip	Handling forces indentation	Shrinkage, creep, forces and imposed deformations
1.3	Kinetic energy	Wind, hail, external impacts	—	Internal impacts, wear	Water hammer
1.4	Vibrations and noises	Wind, thunder, airplanes, explosions, traffic and machinery noises	Earthquakes, traffic and machinery vibrations	Noise and vibration from music, dancers, domestic appliances	Services noises and vibrations
2.	Electromagnetic agents				
2.1	Radiation	Solar radiation, radioactive radiation	—	Lamps, radioactive radiation	Radiating surface
2.2	Electricity	Lighting	Stray currents	—	Static electricity, electrical supply
2.3	Magnetism	—	—	Magnetic fields	Magnetic fields
3.	Thermal agents	Heat, frost, thermal shock	Ground heat, frost	User emitted heat, cigarette	Heating, fire
4.	Chemical agents				
4.1	Water and solvents	Air humidity, condensation, precipitation	Surface water, ground water	Water sprays, condensation, detergents, alcohol	Water supply, water waste, seepage
4.2	Oxidizing agents	Oxygen, ozone, oxides of nitrogen	—	Disinfectant, hydrogen peroxide	Positive electrochemical potentials
4.3	Reducing agents	—	Sulphides	Agents of combustion, ammonia	Agents of combustion, negative electrochemical potentials
4.4	Acids	Carbonic acid, bird droppings, sulphuric acid	Carbonic acid, humic acids	Vinegar, citric acid, carbonic acid	Sulphuric acid, carbonic acid
4.5	Bases	—	Lime	Sodium hydroxide, potassium hydroxide, ammonium hydroxide	Sodium hydroxide, cement
4.6	Salts	Salty fog	Nitrates, phosphates, chlorides, sulphates	Sodium chloride	Calcium chloride, sulphates, plaster
4.7	Chemically neutral	Dust, soot	Limestone, silica	Fat, oil, ink, dust	Fat, oil, dust, soot
5.	Biological agents				
5.1	Vegetable and microbial	Bacteria, seeds	Bacteria, moulds, fungi, roots	Bacteria, house plants	—
5.2	Animal	Insects, birds	Rodents, worms	Domestic animals	—

Table 2 Degradation factors (agents) affecting the service life of materials and components

1. Weather factors	Radiation
	  Solar
	  Nuclear
	  Thermal
	Temperature
	  Elevated
	  Depressed
	  Cycles
	Water
	  Solid (such as snow, ice)
	  Liquid (such as rain, condensation, standing water)
	  Vapour (such as high relative humidity)
	Normal air constituents
	  Oxygen and ozone
	  Carbon dioxide
	Air contaminants
	  Gases (such as oxides of nitrogen and sulphur)
	  Mists (such as aerosols, salt, acids,and alkalies dissolved in water)
	  Particulates (such as sand, dust, dirt)
	Freeze–thaw
	Wind

2. Biological factors	Microorganisms Fungi Bacteria

3. 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

4. Incompatibility factors	Chemical Physical
5. Use factors	Design of system Installation and maintenance procedures Normal wear and tear Abuse by the user

Climatic agents, such as solar radiation, temperature, water, air constituents, air contaminants and wind, are particularly important to the degradation of materials used in the exterior envelope of buildings. Most test methods that have been developed throughout the world for generating service life data focus upon climatic agents as the factors which cause degradation. But the range and importance of these agents vary widely with type of climate, geographic location, time of the year, time of day and even within a relatively small area of single building (i.e. micro-environment). Thus, climatic agents are difficult to quantify and to incorporate meaningfully into accelerated test methods. Masters and Wolfe [12] have pointed out the need to quantify climatic agents if reliable service life data are to be generated.

The approach of ISO/TC 156 (Working Group 4) in quantifying climatic agents has been to develop a classification system. Although the classification developed to date addresses the corrosion of metals, the general approach may be relevant to service life prediction studies of other materials.

In the approach, a restricted number of climatic areas are first defined based on quantitative meteorological parameters, such as cold, mild, wet, and dry. In the next step, a restricted number of pollution classes are defined based on quantitative data of concentrations and depositions of primary pollutants. Sulphur dioxide and chlorides are assumed to be the primary corrosion-inducing substances in the atmosphere. Thus, air pollution is graded with respect to quantitative levels of these two air contaminants and pollution classes of the atmosphere are listed. These first two steps of the approach are valid irrespective of the metallic material considered. They define the environment with respect to two corrosion stimulants, SO_2 and chlorides.

As the third step of the ISO/TC 156 approach, each pollution class in a certain climatic area is classified with respect to corrosion aggressivity. Because the corrosion stimulants in the environment affect different materials in different ways, it may be necessary to create individual classification systems of corrosion aggressivity for every material. With knowledge of both the climate area and the pollution class, it is possible to arrive at a corrosion aggressivity index. The type of exposure, e.g., the location of the surface in open exposure, under shelter or in a closed space, must be considered. The list of important corrosion characteristics of the atmosphere consists of:

- Air temperature
- Relative humidity
- Precipitation
  - amount
  - pH
  - SO_4
  - Cl
- Time of wetness
- Air contamination
  - concentration of SO_2
  - deposition of SO_2
  - deposition of Cl
  - other pollutants
- Dust amount

A Task Group within RILEM 31-PCM on 'Performance Criteria for Building Materials' has suggested that the processes of corrosion and deterioration are controlled by the micro-environment (the conditions of the building material and the immediate layer of liquid or gas which prevails at the site where chemical or physical processes of deterioration take place). The implication of the findings of the Task Group is that the micro-environment, not just the environment, must be characterized and quantified if reliable service life data are to be generated.

2.6 Synergistic effects of degradation factors

Short-term tests, particularly those using accelerated ageing, are usually designed to evaluate the effect of a small number of degradation factors. Although such test results may be useful for screening or ranking materials, they are only of limited value for predicting service life, unless the degradation factors studied are those that are responsible for all (or nearly all) of the in-service degradation. In actual service, degradation factors may interact to increase the rate of degradation or, less often, to decrease the rate by one factor cancelling the effect of others. Synergistic interaction between degradation factors complicates predictions of service life based upon short-term test data because the synergistic actions are difficult to simulate or account for. If progress is to be made in the development of reliable service life tests, it is essential that the synergistic effects of degradation factors be understood and accounted for.

In research at the US National Bureau of Standards, Martin and co-workers [13, 14] are utilizing rigidly controlled accelerated exposure conditions to obtain data on the synergistic effects of UV radiation, heat and moisture in degrading a 'model' plastic material, poly(methyl methacrylate). Similar work is also being carried out with protective coatings for steel and single-ply roofing membranes. The rate and mechanistic data are being incorporated into stochastic models for service life prediction. Although the specific models may not be directly applicable to all polymeric materials, the approach to service life prediction being used is generically applicable and thus relevant to this document. Experimentally, the approach is difficult to carry out for more than three degradation factors because of the large number of combinations of exposure conditions that would have to be studied. This limitation may present problems in some service life prediction studies, but, in general, the primary factors causing degradation are usually few in number. If the primary degradation factors are clearly identified, therefore, it is believed that the approach can be used to account for almost all the degradation that would occur in service.

2.7 Mathematical models

Recent international conferences [6, 15] have explored both deterministic and probabilistic modelling approaches to service life prediction. The American Society of Mechanical Engineers (ASME) conference [15] was heavily focused upon metals while the NATO-sponsored workshop [6] addressed organic and inorganic building and construction materials, as well as metals.

Fracture mechanics has been widely used in modelling the creep/fatigue/fracture degradation of metals. For polymers and for inorganic construction materials, such as concrete, other mechanisms of degradation are important and fracture mechanics approaches have not been as widely applied.

Because service life is often represented by a failure distribution, it has been suggested [6] that reliability theory can be an effective and powerful modelling tool, particularly for predicting early times to failure using short-term test data. Reliability theory is a systematic probabilistic procedure having wide acceptance in the electronics, nuclear, aerospace and medical industries for quantitatively predicting the service lives of materials, components and systems. Application of the procedure to construction materials has been carried out by NBS researchers [13]; the research has demonstrated that, by (a) understanding the fundamental mechanisms of degradation, (b) measuring properties that effectively indicate materials performance, (c) utilizing well-planned and carefully-controlled ageing tests, and (d) utilizing an iterative research approach, reliable data can be generated and utilized in the development of stochastic models for service life prediction. The iterative nature of the proposed approach is particularly important because it provides service life data and testing procedures that are based upon the best knowledge available at any particular time in the course of conducting the research. As the knowledge base increases, the reliability of the service life prediction increases, but the user always has data and procedures available which reflect the state-of-the-art.

3. SYSTEMATIC METHODOLOGIES (APPROACHES) TO SERVICE LIFE PREDICTION

Systematic approaches or methodologies for addressing service life prediction have been proposed by several researchers and, to some extent, these approaches are used either in specific laboratories or in specific countries. But on an international basis, no such methodology exists. The lack of an internationally accepted methodology for systematically treating the problem of service life prediction leads to a number of problems. It makes it difficult for participants in joint research activities to communicate; it hinders the ability of researchers to link the various segments of their research in a clear and concise manner; it minimizes the opportunity for identifying and sharing data which are available for inclusion in the development of new or revised test methods; and it hinders the identification of research needs.

This chapter will seek to provide the basis for a proposed systematic methodology or approach that can be used in a wide range of applications. It will: (i) identify the essential elements of a systematic methodology, and (ii) describe a number of methodologies that have been proposed or used in service life prediction.

3.1 Essential elements of a systematic methodology

The essential elements of a systematic methodology for prediction of service life are identified below:

1. It must be *generic*; that is, it must be applicable to a broad range of building materials and components. This will permit its use throughout CIB and RILEM as Working Commissions and Technical Committees seek to study service life and develop improved predictive tests for many different materials and components used in many different applications. Acceptance in CIB and RILEM of a uniform and systematic methodology for approaching research on service life prediction and for developing improved predictive tests will: (i) aid communication between participants in various activities; (ii) aid researchers in linking various segments of their research in a clear and concise manner; (iii) aid in identifying and sharing data; and (iv) aid in identifying research needs.
2. It must *lead to identification of the data needed* including data on environmental degradation factors in service, possible degradation mechanisms for the material or component, quantitative performance requirements (minimum requirements), intended maintenance methods and frequency, and design features including information about fabrication, transport, storage, erection, workmanship, and supervision.
3. It must *be based upon the use of reliable test methods or upon use of reliable feedback data*. Test methods, whether laboratory-based or field exposure-based, must be designed according to the information mentioned in item 2 above and methods used for assessing the performance or properties as a function of time must yield quantitative, rather than qualitative, data. Test results should be repeatable and reproducible. Feedback data, such as may be obtained from actual in-service performance, may be useful in predicting performance beyond the time of the observation.
4. It must *provide guidance on interpretation of data*. Information must be given to aid in predicting service life from the available data. Suitable methods and tools for this purpose, e.g., mathematical models, must be listed.
5. It must *lead to documentation of assumptions made*. Documentation is particularly important to other researchers who may use the research findings.

3.2 Description of some systematic methodologies used in service life prediction

Systematic methodologies for dealing with problems of service life prediction have been proposed by several laboratories and international organizations. To date, however, no internationally accepted approach for systematically treating the problem of service life prediction exists. Below, a number of proposed methodologies will be summarized to illustrate different approaches to the problem.

3.2.1 *Methodology under consideration by RILEM TC 31-PCM on performance criteria for building materials*

RILEM Technical Committee 31-PCM on 'Performance Criteria for Building Materials' has developed a systematic methodology which has been presented by Sneck [4]. The current version of the methodology, which is included in a draft report of the Committee, is illustrated schematically in Fig. 5 and depicts the evaluation or prediction of performance as being divided into these steps: performance analysis, evaluation and decision making. Expert judgment is emphasized as an essential part of evaluations. As pointed out by the Committee, the complexity of evaluating the interactions of materials or systems with their environments requires expertise that cannot be fully replaced by test methods.

3.2.2 *Methodology under consideration by RILEM TC 60-CSC on corrosion of steel in concrete*

Within RILEM TC 60-CSC on 'Corrosion of Steel in Concrete' and CEB, a systematic methodology has been proposed and discussed [16]. The approach is outlined in Fig. 6. According to the methodology, the knowledge necessary to provide service life data encompasses: (i) an exact definition of the service life

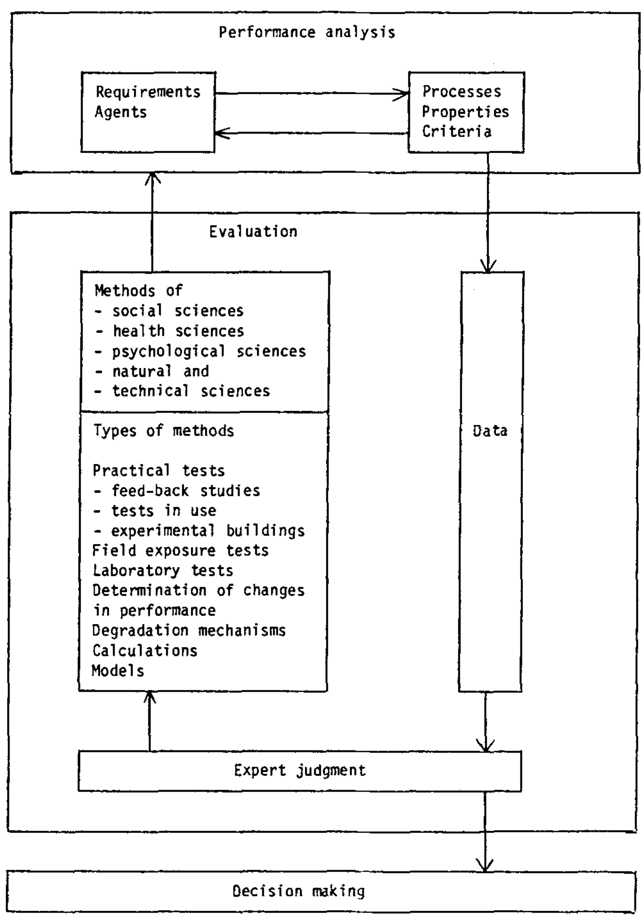

Fig. 5 Methodology under consideration by RILEM TC 31-PCM.

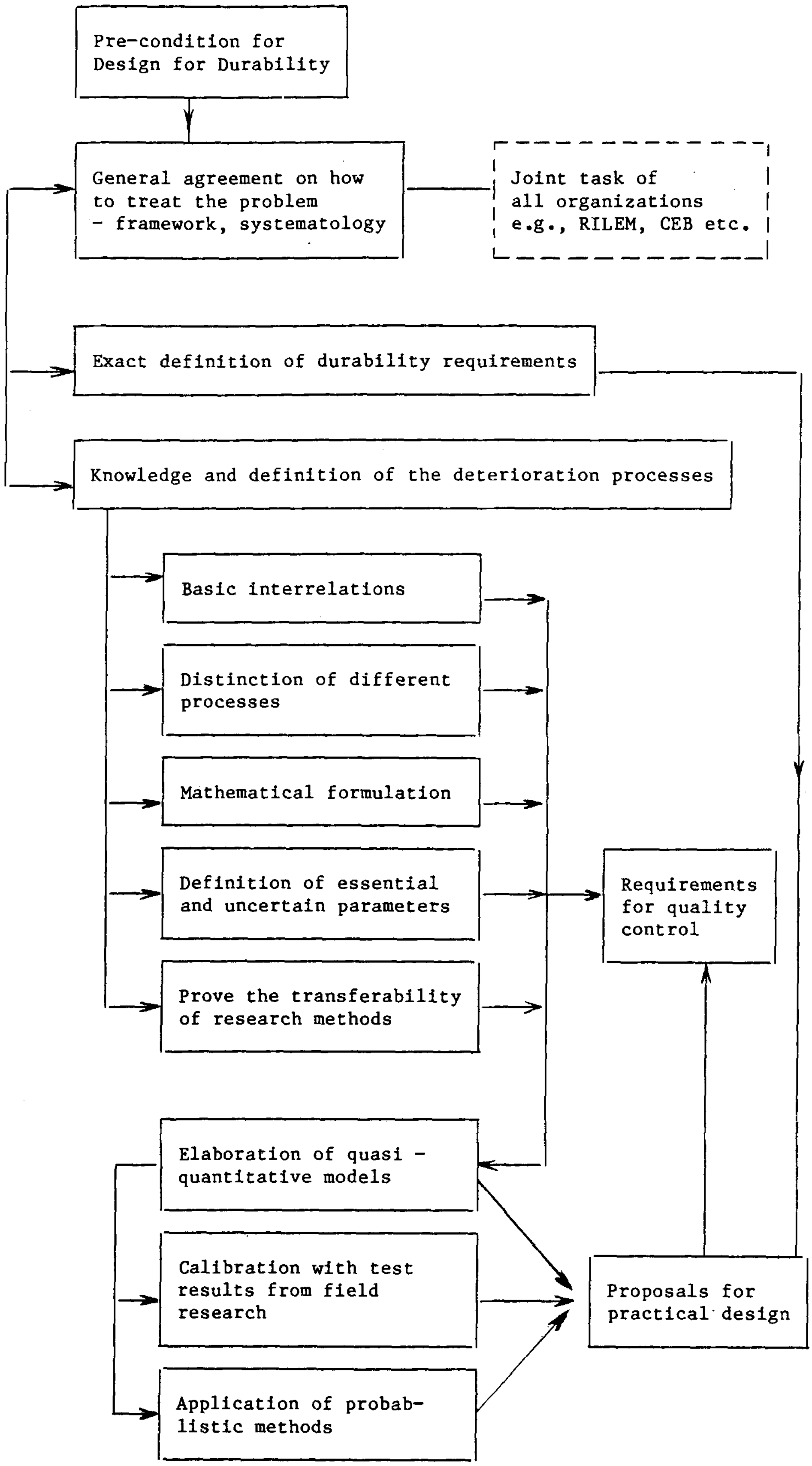

Fig. 6 Methodology for discussion within RILEM TC 60-CSC.

requirements, and (ii) knowledge about the deterioration processes. In order to achieve the latter, it is necessary to define the environmental stresses and the important performance parameters. It is suggested that the material behaviour be treated on the materials science level and that mathematically formulated 'micro-models' be developed to describe the materials behaviour on an exact basis. The formulation of probabilistic methods and simplified mathematical models for use in practical design are the last steps in this framework.

3.2.3 *Methodology under consideration by CIB W60 on the performance concept in buildings*

A framework which has been discussed by CIB W60 on the 'Performance Concept in Building' [17] suggests that the concept of durability (or service life) can be made manageable by dividing it into a series of sub-items. The main sub-items suggested are (i) in-use conditions, (ii) material(s), (iii) design, and (iv) maintenance.

For each of the four main sub-items, further detailing or subdivisions are possible and often necessary. This framework provides a systematic means of developing a 'durability profile' based upon considerations of data from the four main categories. Each property is evaluated using banded levels; e.g., materials can be rated from the extremes of 'perishable' to 'imperishable', design can be rated from 'bad' to 'excellent' and in-use conditions from 'severe' to 'light'. This methodology is intended as an aid in evaluation and selection of materials. A table for the recording of data and an example of a durability profile are shown in Figs 7 and 8, respectively.

3.2.4 *Methodology developed by the Jet Propulsion Laboratory*

The Jet Propulsion Laboratory [18] has developed a methodology for service life prediction which uses a sequence shown in Fig. 9. The sequence describes analysis of the degradation processes of solar photovoltaic (PV) modules in six steps: (i) identification of the load subjected to the component from the environment and the application; (ii) consideration of the

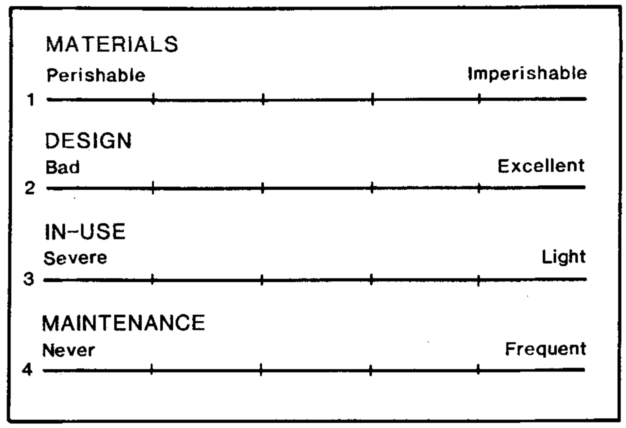

Fig. 7 The concept of durability split into four sub-items.

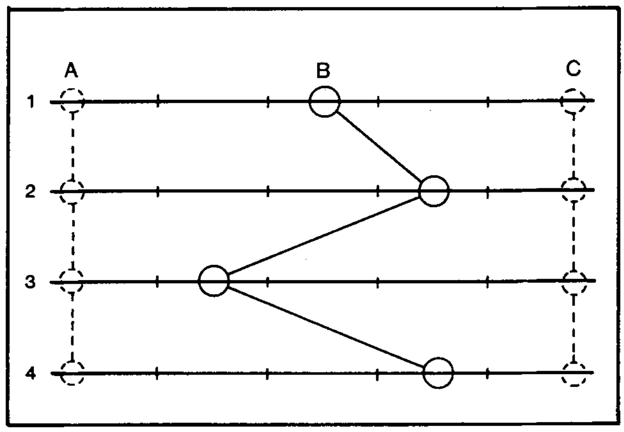

Fig. 8 A durability profile.

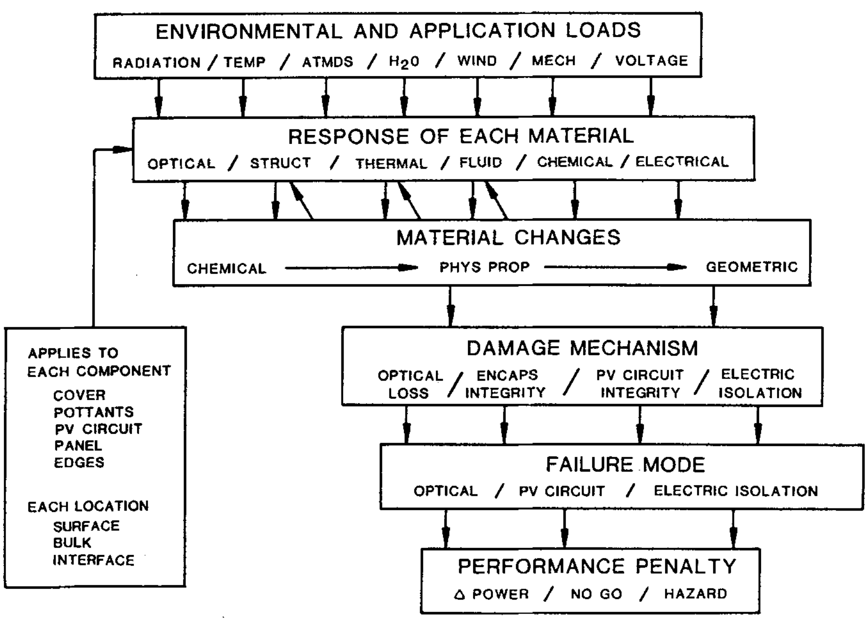

Fig. 9 PV module failure-analysis matrix.

response to the loads of each material or component (this response may be active or passive and may occur at the surface, in the bulk material, or at the interface); (iii) determination of the material changes, i.e., non-reversible response to loads (changes may be physical, chemical, or geometrical and they may also be benign); (iv) consideration of the damage mechanisms, i.e., loss of integrity or decrease in performance; (v) consideration of the failure mode (failure is defined as a performance decrement large enough to require repair or replacement); and (vi) assessment of the performance penalty, i.e., value loss or consequences. While this approach is discussed in detail for photovoltaic modules, its methodology appears to be broadly applicable to other service life problems.

3.2.5 *Methodology of ASTM E632-81*

In the American Society for Testing and Materials (ASTM) Method E632-81, 'Practice for Developing Accelerated Tests to Aid Prediction of the Service Life of Building Components and Materials' [11], another systematic methodology is presented. The suggested procedure outlines a systematic approach to prediction of service life. The methodology is divided into four main parts: (i) problem definition, (ii) pre-testing, (iii) testing, and (iv) interpretation and reporting of data. Figure 10 shows a chart where the four main parts are further subdivided into a sequence of steps recommended for use in developing or using predictive tests. Examples of the application of this procedure are given

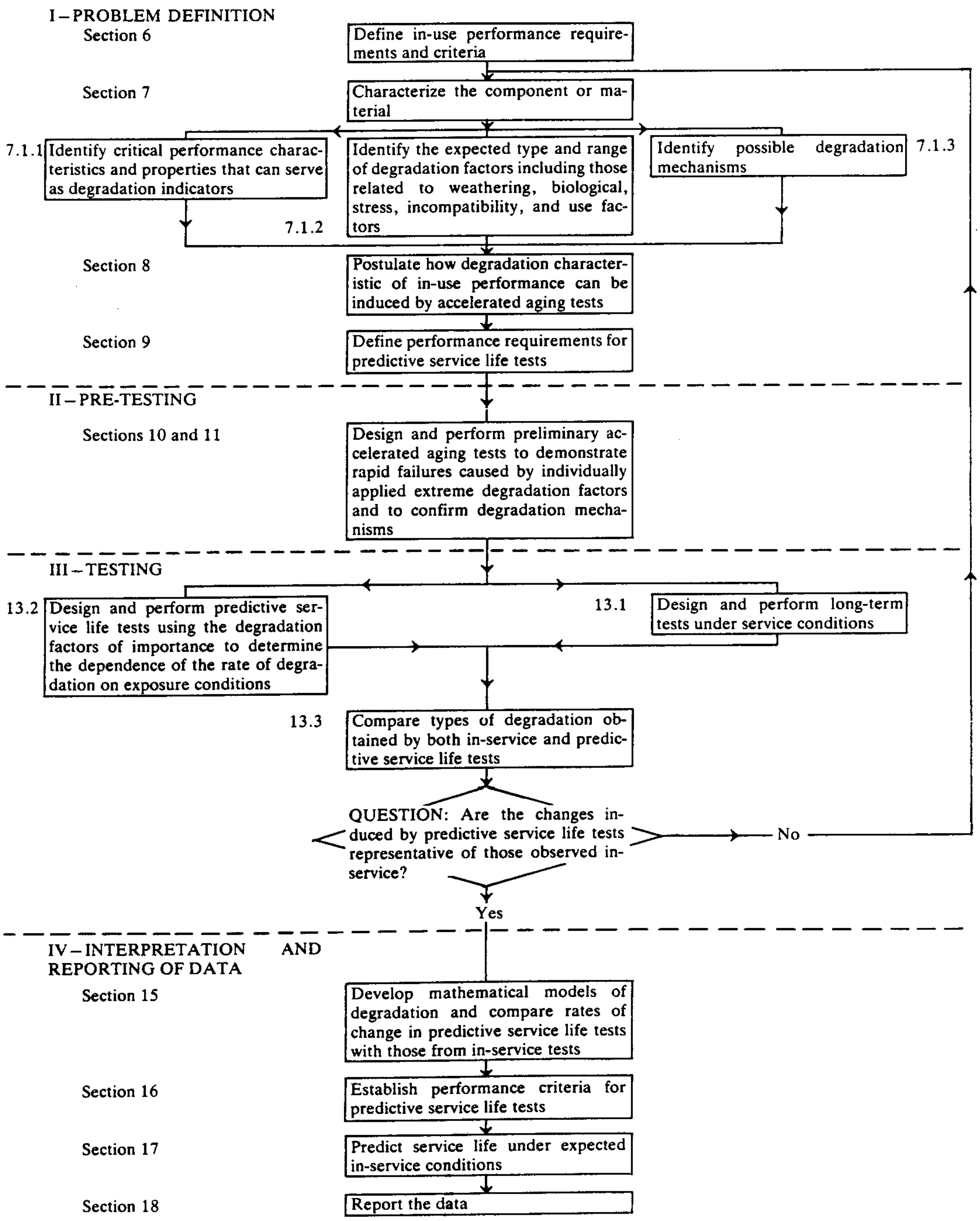

Fig. 10 Procedure for service life prediction as outlined in ASTM E632.

in [19]. The practice identifies the need for knowledge on: (i) critical performance characteristics that can serve as indicators of degradation; (ii) the range and type of factors that can cause degradation; and (iii) the mechanisms of degradation. Also, the practice recognizes the need for mathematical models to aid in predicting service life.

3.2.6 *Methodology of the CSTB (France)*

The Centre Scientifique et Technique du Batiment (CSTB) [20] uses, in its Commission for Durability Problems, a procedure which is similar to that proposed in ASTM E632-81. The approach used by CSTB is shown in Fig. 11. Minor modifications to the procedure

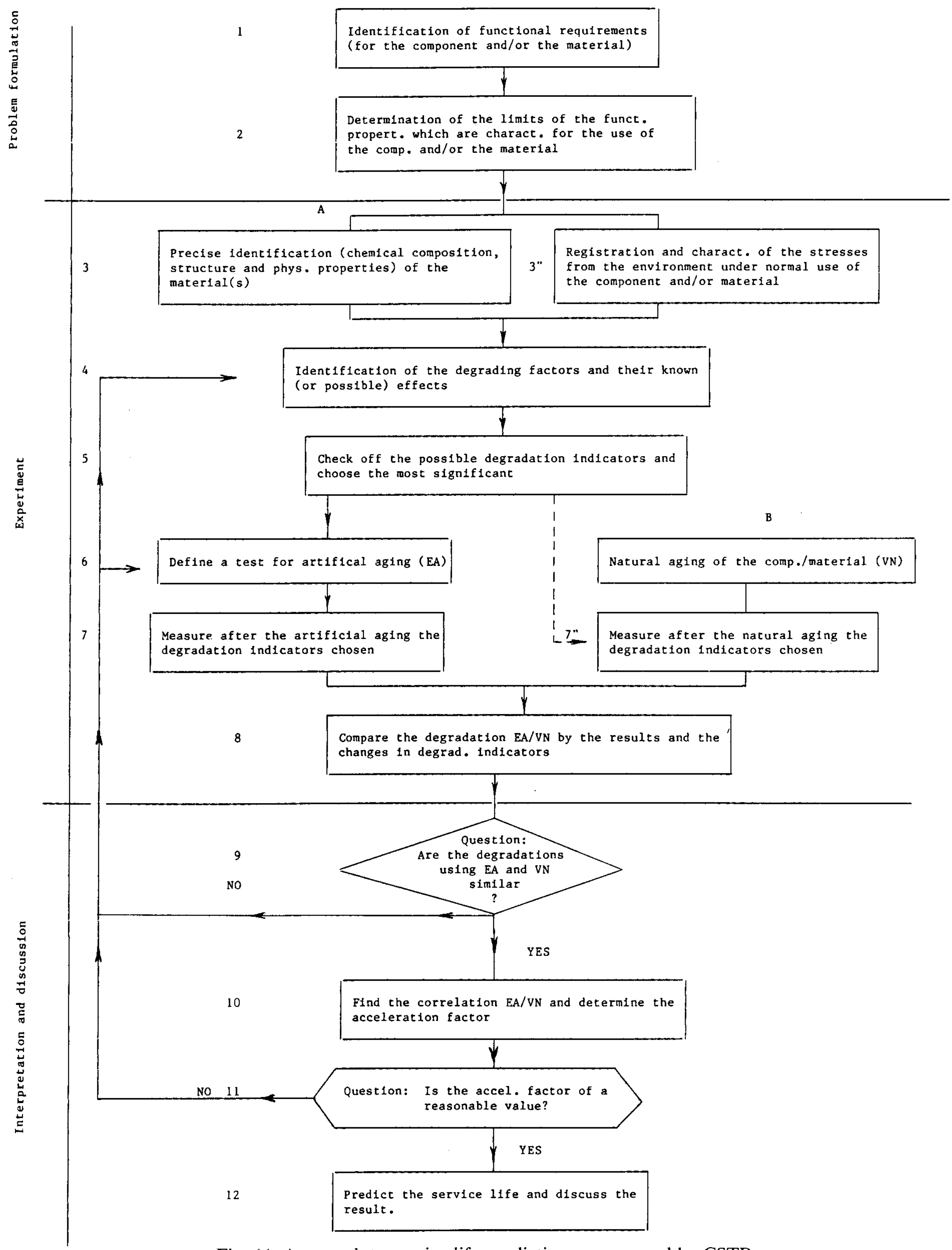

Fig. 11 Approach to service life prediction as proposed by CSTB.

of ASTM E632 have been made by CSTB because of comments from others.

3.2.7 *Methodology of Australian Standard 1745, Part 2 (1975)*

In Australian Standard 1745, Part 2 (1975) [21], another framework for prediction of service life is outlined. The procedure suggested is outlined in Fig. 12 and encompasses four main parts: (i) scope, (ii) definitions, (iii) guidelines for the preparation of data sheets, and (iv) guidelines for the use of data sheets.

Each main part is subdivided into a number of steps recommended for use in evaluation. An example of the use of this procedure is given in the standard. Even though the standard is restricted to plastic materials and natural weathering, the approach might be expanded to a more general use. Regarding the natural weathering tests, the above mentioned standard recommends use of Australian Standard CK 24 [22].

3.2.8 *Summary*

Even though the approaches used in the above-mentioned methodologies are different, they have several common themes, particularly the needs to: (i) perform well-characterized in-use exposure tests of the materials/components under investigation; (ii) identify the performance requirements for the materials; (iii) identify the possible degradation mechanisms; and (iv) thoroughly characterize the properties and performance attributes of the material or component being studied. ASTM E632 (and the modified CSTB version) and the AS 1745 are the only methodologies which include a specific step on prediction of service life. But the generation of service life data is implicit in all the methodologies. The methodology of RILEM TC 60-CSC specifically recommends the use of probabilistic methods and micro-models to describe materials behaviour at a fundamental level. The methodology of RILEM 31-PCM has the uniqueness of formally recognizing the importance of 'judgment' in service life prediction although judgment is certainly an important part of each methodology. The methodology suggested by CIB W60 may be useful in the selection of materials, but is unlikely to lead to a quantitative assessment of service life.

1. SCOPE

2. DEFINITIONS

   2.1 Unit manufacturing process
   2.2 Grade - the material used in the unit manufacturing process
   2.3 Solar exposure period (recorded in h. of sunshine)
   2.4 Total exposure period (recorded in months or days)
   2.5 Failure - when the conditions of the article are no longer acceptable

3. GUIDELINES FOR PREPARATION OF DATA SHEETS

   3.1 General - possible manufacturing processes, applications, etc.
   3.2 Guidelines for the selection of suitable tests
      .1 grades for general application
      .2 grades for special application
      .3 the effect of unit manuf. process on weathering performance
   3.3 Samples for exposure
      .1 grades for general application
      .2 grades for specific applications
   3.4 Climate data to be recorded during tests
   3.5 Exposure of samples
   3.6 Presentation of data for design and selection purposes
      a. material
      b. unit manufacturing process
      c. application envisaged for grade
      d. changes in properties with exposure
      e. exposure data
      f. location of test site
      g. climate data

4. GUIDELINES FOR THE USE OF DATA SHEETS

   4.1 General
   4.2 Use factor
   4.3 Anticipated modes and criteria of failure
   4.4 The relationship of failure with exposure test data (including examples)
   4.5 Geographic adjustment of weathering results
      .1 introduction
      .2 sunshine hours
      .3 rainfall zone, slope and orientation effects
      .4 overall site severity rule

Fig. 12 Procedure for predicting service life as recommended in AS 1745.

4. PROPOSED SYSTEMATIC APPROACH (METHODOLOGY) TO SERVICE LIFE PREDICTION

Based upon the essential elements of a systematic approach or methodology identified in Section 3.1 and upon an analysis of the approaches described in section 3.2, a proposed systematic methodology for service life prediction is presented in Appendix A to this report and outlined in Fig. 13.

The methodology is divided into five primary parts: (i) definition, (ii) preparation, (iii) pre-testing, (iv) testing, and (v) interpretation and discussion.

The first three steps in the methodology are in accordance with the recommendations of CIB W60 on the 'Performance Concept in Buildings [23]. It may be helpful to use the checklists suggested by CIB W60 to confirm that all relevant factors have been considered. CIB Master Lists [24] and ISO 6241 [10] provide sets of detailed subheadings for user-needs, context, and behaviour in use.

A particularly significant feature of the methodology is that it is consistent with an iterative research approach. As mentioned earlier in the report, the iterative approach is important because it provides service life data and testing procedures that are based upon the best knowledge available at any particular time in the course of conducting the research. As the knowledge base increases, the reliability of the service life prediction increases, but the user always has available data and procedures which reflect the state-of-the-art. Another noteworthy feature of the methodology is the recognition that sound scientific and professional judgment is an essential part of service life predictions.

5. RESEARCH NEEDS

In Section 2.2 of this report, a number of barriers to service life prediction were listed. These barriers, although formidable, offer challenging opportunities for research to groups within international organizations such as CIB and RILEM.

In general, there is a need for the development of improved test methods for generating service life data. The development of such methods, however, is dependent on gaining knowledge in other more specific areas. For example, research is needed to:

(i) Develop an effective mechanism for obtaining and reporting data on actual in-service performance – the use of expert systems/artificial intelligence [25] may be useful in this regard
(ii) Develop improved knowledge of the mechanisms by which materials degrade
(iii) Develop improved tools and methods for measuring the degradation
(iv) Develop knowledge of the environmental factors causing degradation and improved methods to measure the intensity of the factors
(v) Develop methods to simulate or account for the synergism between degradation factors
(vi) Develop mathematical models describing the material or component behaviour in specific environments or applications

6. CONCLUSIONS

Data on the service life of building materials and components are essential to the cost-effective use of materials. For this reason, it is important that methods be available for reliably predicting service life. In the current state-of-the-art, test methods are most often useful for comparing the relative 'durabilities' of building materials as opposed to predicting quantitatively the service life.

The need to advance the state-of-the-art of service life prediction of building materials has stimulated considerable interest in national and international activities in recent years. The technical barriers to meeting the need for improved predictions are numerous and formidable. Therefore, it is not practicable for one laboratory or even one country to pursue, on its own, the long-term, complex and costly research needed to address the barriers. But the barriers offer the opportunity for continued and increased international interactions and the opportunity for performing challenging research on building materials and their degradation processes. In this way, the needs can be met.

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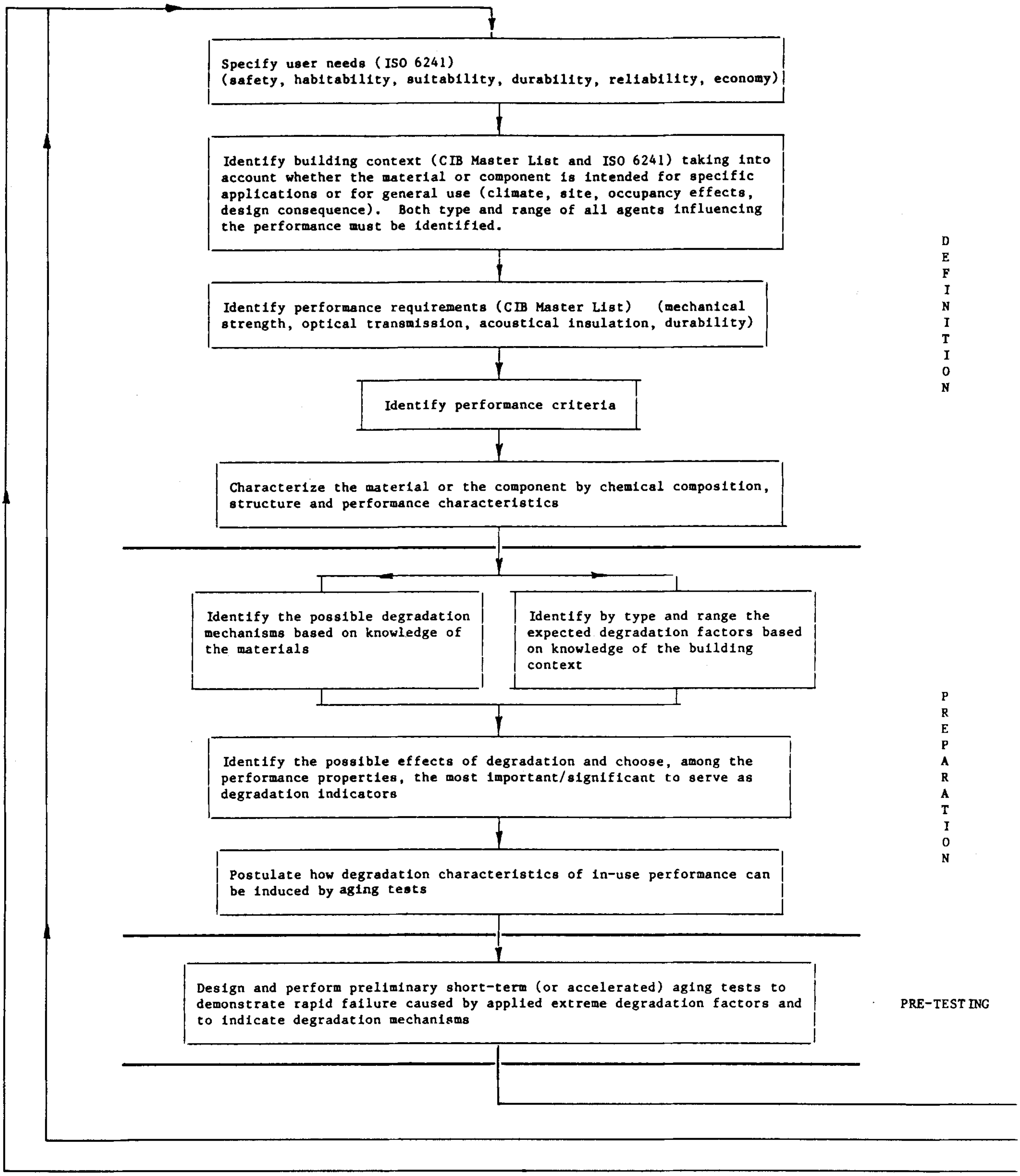
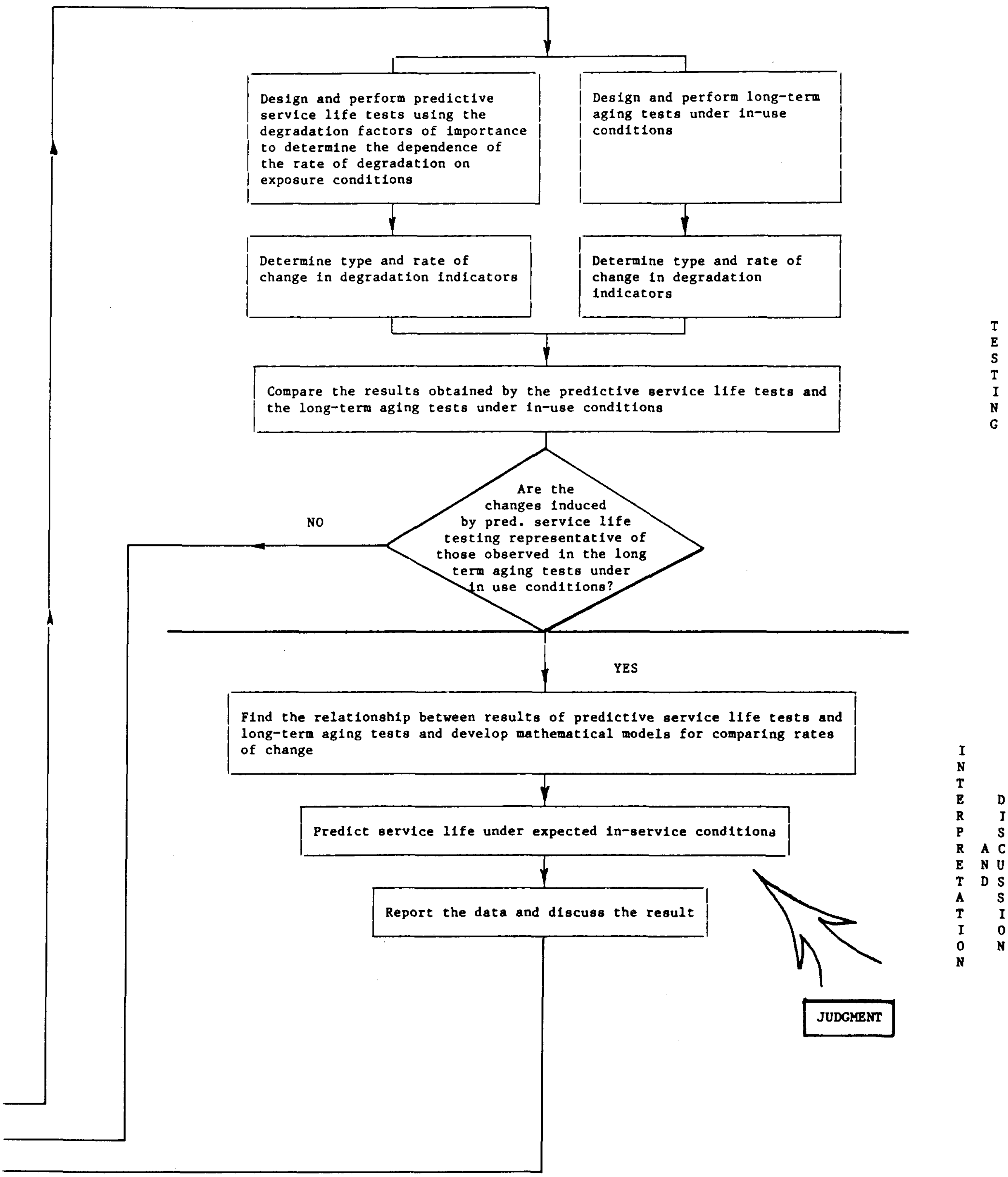


Fig. 13 Methodology for service life prediction.


Design and perform predictive service life tests using the degradation factors of importance to determine the dependence of the rate of degradation on exposure conditions
Design and perform long-term aging tests under in-use conditions
Determine type and rate of change in degradation indicators
Determine type and rate of change in degradation indicators
Compare the results obtained by the predictive service life tests and the long-term aging tests under in-use conditions
Are the changes induced by pred. service life testing representative of those observed in the long term aging tests under in use conditions?
NO
YES
Find the relationship between results of predictive service life tests and long-term aging tests and develop mathematical models for comparing rates of change
Predict service life under expected in-service conditions
Report the data and discuss the result
JUDGMENT
TESTING
INTERPRETATION AND DISCUSSION

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APPENDIX A

Proposed systematic methodology for service life prediction of building materials and components

A1. Scope

This document outlines a systematic approach or methodology to service life prediction of building materials and components, including the identification of needed information, the selection or development of tests, the interpretation of data, and the reporting of results*. It utilizes an iterative research approach, thereby permitting improved predictions to be made as the base of knowledge grows. Although mathematical analyses needed for prediction of service life are not described in detail, either deterministic or probabilistic analyses may be used.

A2. Field of application

This document is intended to be generic and, therefore, applicable to all types of building materials and components. Specific test methods and test equipment used to develop service life data vary with the materials and components to be evaluated and with the user requirements; therefore, specific test methods and equipment are not included in this document.

A3. Definitions

A3.1 *Ageing test*

A test in which building components or materials are subjected or exposed to factors believed or known to cause degradation.

A3.2 *Accelerated ageing test*

An ageing test in which the degradation of building components or materials is intentionally accelerated over that expected in service.

A3.3 *Biological degradation factor*

Any of the group of degradation factors that are directly associated with living organisms, including micro-organisms, fungi, and bacteria.

A3.4 *Biological growth*

Growth of organisms on the surface or in the body of a material. These are generally fungi (moulds) or algae, but other life forms are not excluded.

* Comparative testing is an alternative to the steps identified in this document; it involves qualitative comparison of the results of a test material or component with the results of a similar control material or component when exposed to identical conditions.

A3.5 *Building component*

A building element using industrial products that are manufactured as independent units capable of being joined with other elements.

A3.6 *Building material*

An identifiable material, such as brick, concrete, metal, or timber, that may be used in a building component.

A3.7 *Control samples*

Samples retained in an environment that is believed or known not to induce degradation for the purpose of determining initial performance characteristics.

A3.8 *Critical performance property*

A property of a building material or component that must be maintained above a certain minimum level if the material or component is to retain its ability to perform its intended functions.

A3.9 *Degradation factor (or agent)*

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

A3.10 *Degradation mechanisms*

The sequence of chemical, mechanical or physical changes that lead to detrimental changes in one or more properties of a building material or component when exposed to one or more degradation factors.

A3.11 *Deterioration*

The process of becoming impaired in quality or value.

A3.12 *Durability*

The capability of a building, assembly, component, product or construction to maintain serviceability over at least a specified time.

A3.13 *Incompatibility factor*

Any of the group of degradation factors that lead to detrimental chemical and physical interactions between building materials or components.

A3.14 *In-service test*

A test in which building materials or components are exposed to degradation factors under actual in-service conditions.

A3.15 *Performance over time*

The function which describes how the measured values of the chosen properties vary with time.

A3.16 *Performance criterion*

A statement of a limiting condition or a quantitative level of performance for a selected performance characteristic or property of a material or component needed to ensure compliance with a performance requirement.

A3.17 *Performance requirement*

A statement of the performance required from a building material or component.

A3.18 *Predictive service life test*

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

A3.19 *Property measurement test*

A test for measuring one or more properties of building materials or components; it can be used to measure the change in performance as a function of time or some other variable.

A3.20 *Reference samples*

Samples of known performance which are exposed simultaneously and under identical conditions as the samples under study to provide comparative data.

A3.21 *Serviceability*

The capability of a building, assembly, component, product or construction to perform the function(s) for which it is designed and used.

A3.22 *Service life (of a building material or component)*

The period of time after installation during which all essential properties meet or exceed minimum acceptable values, when routinely maintained.

A3.23 *Stress factor*

Any of the group of degradation factors that result from externally applied sustained or periodic loads.

A3.24 *Use factor*

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

A3.25 *Weathering factor*

Any of the group of degradation factors associated with the environment, including radiation, temperature, rain and other forms of water, freezing and thawing, normal air constituents, air contaminants, and wind.

A4. Procedure

Figure 13 contains an outline of the steps described below.

A4.1 *Problem definition*

A4.1.1 Scope

The problem definition step† covers an analysis of the problem under study including an identification of essential data.

A4.1.2 Specification of user needs

User requirements define attributes to be provided by the object under study. Included are attributes such as safety, habitability, suitability, durability, reliability, and economy. These requirements are independent of the location in which the object is used.

A4.1.3 Identification of the building context

Identify the building context, taking into account whether the building material or component is intended for specific applications or for general use. The context comprises the climate and/or the site at which the building is located, the incidental effects of occupancy (such as water vapour, heat, or abrasion), the principles on which the building functions (e.g., high or low thermal inertia), and, in particular, for products and materials, the 'design consequences' of the built form. Both type and range of all agents influencing the performance must be identified. The range should include mean values as well as extreme values.

A4.1.4 Identification of performance requirements

Identify performance requirements for the material, component or system in question. Requirements may include, for example, strength, optical transmission, acoustical insulation and durability. The performance requirements should be based on information obtained in Sections A4.1.2 and A4.1.3.

A4.1.5 Identification of performance criteria

Identify the performance criteria, including methods for determining compliance with performance requirements.

A4.1.6 Characterization of the material or component

Characterize the material or component to be evaluated as thoroughly as possible in terms of structure, chemical composition and performance values (corresponding to the performance criteria identified in Section 4.1.5).

A4.2 *Preparation*

A4.2.1 Scope

The preparation step covers treatment of the information obtained in Section 4.1 to identify or postulate degradation factors and possible degradation mechanisms and to postulate how degradation can be accelerated or induced by ageing tests.

† Judgment plays an important part in many of the problem definition steps outlined below.

A4.2.2 Identification of degradation factors

Identify the type and range of the expected degradation factors based on knowledge of the building context as obtained in Section A4.1.3. A list of some degradation factors is presented in Table A1. This list is not exhaustive and other possible important factors should be sought in each specific case. The listed factors include weathering, biological, stress, incompatibility, and use factors.

Table A1 Degradation factors affecting the service life of building components and materials

Weathering factors	Radiation
	  Solar
	  Nuclear
	  Thermal
	Temperature
	  Elevated
	  Depressed
	  Cycles
	Water
	  Solid (such as snow, ice)
	  Liquid (such as rain, condensation, standing water)
	  Vapour (such as high relative humidity)
	Normal air constituents
	  Oxygen and ozone
	  Carbon dioxide
	Air contaminants
	  Gases (such as oxides of nitrogen and sulphur)
	  Mists (such as aerosols, salts, acids, and alkalies dissolved in water)
	  Particulates (such as sand, dust, dirt)
	Freeze–thaw
	Wind

Biological factors	Micro-organisms Fungi Bacteria

Stress factors	Stress, sustained
	Stress, periodic
	  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

A4.2.2.1. Weathering factors include radiation, temperature (elevated, depressed, and cycles), water (solid, liquid, and vapour), normal air constituents, air contaminants (gases, mists, and particulates), freeze–thaw, and wind. Some quantitative information on weathering factors is available from published weather and climatological data. These data are usually sufficient to indicate the ranges of intensities to which the material or component will be exposed in service.

A4.2.2.2. Biological factors include micro-organisms, fungi, and bacteria.

A4.2.2.3. Stress factors consist of sustained stress, such as those developed by the weight of a building or its systems, and periodic stress, such as wind loads. The intensities of stress factors can usually be estimated from engineering calculations.

A4.2.2.4. Chemical and physical incompatibility between dissimilar materials include, for example, corrosion caused by contact between dissimilar metals or stress caused by the different thermal expansion coefficients of rigidly connected dissimilar materials.

A4.2.2.5. Use factors include the design of the system, installation and maintenance procedures, normal wear and tear, and abuse.

A4.2.2.6. It is difficult to quantify the in-service intensity of biological, incompatibility, and use factors, but upper limits within the normal range can usually be established by engineering judgment. Consider each of the degradation factors that may affect the performance of a building system material or component in selecting or designing predictive service life tests.

A4.2.3 Identification of possible degradation mechanisms

Identify all reasonable possible mechanisms by which the identified degradation factors induce changes in the properties of the component or material. The mechanisms can be identified at various levels. If much is known about the chemistry of the material(s), it may be possible to identify mechanisms based upon specific chemical reactions, such as hydrolysis and photo-oxidation. On the other hand, if little is known about the chemical reactions of the material, mechanisms may be defined in more general terms as, for example, thermal decomposition, volatilization of constituents, constituent diffusion, corrosion, and shrinking/swelling. Limitations on the knowledge available will always exist. However, it is important to identify as many possible degradation mechanisms as possible. This reduces the possibility for error and improves the basis for establishing that mechanisms induced by the accelerated or other short-term ageing tests are representative of those that occur in service.

A4.2.4 Identification of possible effects of degradation

Identify, on the basis of data obtained in Sections A4.2.2 and A4.2.3, the possible effects of degradation on the performance characteristics of the material or components. Identify and choose the characteristics or properties that are essential or can best serve as effective indicators of the degradation. It is important that quantitative measurements of characteristics or properties are obtained if the data are to be used in quantitative service life predictions.

A4.2.5 Postulations regarding ageing tests

Once the information from Sections A4.2.2, A4.2.3 and A4.2.4 has been obtained, postulations can be made regarding specific procedures for inducing the identified mechanisms of degradation using the identified degradation factors. For example, if accelerated ageing tests are used and if thermal degradation is identified as a possible degradation mechanism, then it may be postulated that this type of degradation can be accelerated by exposure to temperatures higher than those expected in service. However, it would need to be ensured that extreme levels of degradation factors do not result in degradation mechanisms that would not be experienced in service. The postulations that are made in this step lay the groundwork for selecting or designing preliminary ageing tests.

A4.3 *Pre-testing*

A4.3.1 Scope

Pre-testing is used to demonstrate that rapid changes in the selected properties of the material or component can, in fact, be induced by exposure to extreme levels of the degradation factors. These changes, if observed, support (or rule out) the previously identified mechanisms by which property changes occur. They may also contribute to a better understanding of the primary degradation factors leading to property changes and indicate properties that are likely to be useful as measures of the extent of degradation.

A4.3.2 Design of pre-tests

Pre-tests should be based upon the postulates made in Section A4.2.5. The tests should provide for various properties to be measured before and after ageing to determine which properties can best be used as degradation indicators. Also, evaluate the effect of degradation factors, identified in Section A4.2.2, to which the material or component will be exposed in service, to determine which factors are the most important.

A4.3.2.1. The intensity of degradation factors used in pre-tests should be based upon the quantitative ranges identified in Section A4.2.2. Weather and climatological data for the most extreme climates in which the component or material will be used can form the basis for the intensities of these factors in the pre-tests. Calculations of sustained stress due to the weight of a building and periodic stress due to wind and impact can also be used.

A4.3.2.2. Biological and incompatibility factors may not be important unless combined with extreme values of weathering factors. For example, fungi and bacteria are most active in warm, moist locations; chemical incompatibility may only be important as long as liquid water is present between the joined materials; physical incompatibility may not be important unless there are large temperature changes. The effects of incompatibility factors can, therefore, usually be evaluated along with tests to determine the effect of weathering factors.

A4.3.2.3. Use factors are not often included in predictive service life tests. Installation and maintenance practices are assumed to be provided as recommended by the manufacturer, and abuse is usually considered to be beyond the scope of test methods. Although use factors are not often included in ageing tests, they can affect the service life of building materials and components and should be evaluated if deemed critical.

A4.3.3 Performing pre-tests

The results of the pre-tests should be used to make adjustments, as needed, of previous assumptions regarding: (i) property changes that are likely to be useful as degradation indicators, (ii) the order of importance of the degradation factors, (iii) mechanisms by which properties change, and (iv) the intensities of degradation factors needed to induce property changes.

A4.4 *Testing*

A4.4.1 Scope

The primary purpose of this step is to perform tests to obtain the data needed in predicting service life (or comparing relative durabilities) of building materials or components. The tests must be in accordance with information and data obtained in the previous section.

If adequate methods do not exist, the outlined procedure can be an aid to design and perform new or improved predictive service life tests by: (a) determining the relationships between the rates of degradation and the exposure conditions; (b) designing and performing tests under in-use conditions to confirm that degradation mechanisms induced by accelerated or short-term ageing tests are the same as those observed in service; and (c) measuring the rates at which properties change in service.

A4.4.2 Design and performance of tests

A4.4.2.1 Long-term ageing tests under in-use conditions. Long-term ageing tests under in-use conditions should emphasize the degradation factors of importance for the material or component. These tests may be actual in-service tests of the complete system in which feedback information on the performance of materials and components is obtained over time or they may involve exposure of selected materials. It is essential to design the tests so that all factors of importance are considered. Where possible, the tests should permit the most important degradation mechanisms to be identified in a relatively short period of time. However, information obtained during longer exposures is also needed to aid in relating the rates of change in the predictive tests to those obtained in ageing test under in-use conditions and in ensuring that mechanisms do not change with time of exposure. The intensity or magnitude of the degradation factors should be measured during the tests‡.

A4.4.2.2 Predictive service life tests. The goal of predictive service life tests is to provide a relatively rapid means of measuring the rate of property changes typical of those that occur in long-term ageing tests under in-use conditions. Predictive tests are usually, but not always, based upon accelerated ageing. An example in which predictive tests are not necessarily based upon accelerated ageing is cited‡. Predictive tests should normally be designed from information obtained in pre-tests. In general, the intensity of factors in these tests will be less than in the pre-tests to reduce the likelihood of causing degradation by mechanisms that are not encountered in service. The properties measured before and after ageing should be those that have been identified as most useful or most important for indicating degradation. All important degradation factors should be included in the exposure conditions§.

A4.4.3 Comparison of types of degradation

Compare the types and range of degradation obtained in the predictive service life tests and the tests under in-use conditions. If the initial accelerated or short-term ageing tests do not induce mechanisms representative of those obtained under in-use conditions, alter the ageing tests after reassessing the information obtained under Definition, Preparation and Pre-testing (see innermost loop in Fig. 13).

A4.5 *Interpretation and discussion*

A4.5.1 Scope

This section addresses the interpretation and reporting of data to assess the data obtained in testing, and either predict the service life of the material or component

‡ It is often possible to make reliable predictions of expected long-term performance of materials and components from limited data using these tests. This is particularly true if property changes leading to degradation can be detected at early stages. In such cases, the long-term tests would be utilized as the predictive service life tests.

§ The possibility of synergism should always be borne in mind in the development and conduct of ageing tests. For example, the combined effects of weathering factors, such as solar radiation, temperature cycles, and moisture, may be greater than the sum of the effects of the individual factors. The intensity or magnitude of the degradation factors in the accelerated ageing test should be measured to aid in determining the effects of increased intensity and in relating the rates of change in the in-service and predictive tests.

based upon the results of the predictive service life tests or compare the relative durabilities of materials and components. An essential part of data interpretation is judgment by experts. Despite efforts throughout this document to quantify results and to base decisions upon scientific information, judgment is ever-present and is recognized in Fig. 13.

A4.5.2 Comparing rates of change

A4.5.2.1. After establishing that the mechanisms induced by the predictive service life tests are the same as those observed in service, compare the rates of change of properties in the two tests. For the simplest case, where degradation proceeds at a constant rate, determine the acceleration factor, K, as follows

$$K = \frac{R_{AT}}{R_{LT}}$$

where R_{AT} is the rate of change obtained from the predictive service life test, and R_{LT} is the rate of change obtained from the long-term ageing test under in-use conditions.

A4.5.2.2. However, the relationship between the results of the two types of test is seldom so simple. For nonlinear relationships, mathematical modelling of observed degradation in terms of the known or assumed degradation mechanisms or data analysis using the principles of reliability analysis or other mathematical analysis procedures may be necessary to establish a satisfactory relationship between the rates of change. Such models must be able to account for quantitative data about the degradation factors in calculations of the rates of change during the test period.

A4.5.3 Prediction of service life

The expected service life of the material or component can be predicted based upon the results of the predictive service life tests. Obtain the predicted service life by using the information in Section A4.5.2 to compare the rates of change in the predictive service life tests and ageing tests under in-use conditions. An alternative to predicting service life actually is to compare the relative durabilities of several materials or components that have been tested in a similar manner. Such comparisons are often made to rank materials or components.

A4.5.4 Reporting of data

A report summarizing all assumptions and the findings of all analysis should be prepared. Accelerated or short-term ageing tests typically involve a certain degree of uncertainty and the results have to be considered with care. If possible, the uncertainty should be expressed quantitatively. The test report should, insofar as is possible, include the following information:

(a) Name and address of the testing laboratory
(b) Name and address of the person or organization who requested the test
(c) Purpose of the test
(d) Date and identification number of the report
(e) Date of supply of the materials or components
(f) Name and address of manufacturer or supplier of the materials or components which are tested
(g) Name or other identification marks of the tested materials or components
(h) Designation of the materials or components according to criteria expressed in official standards or regulations
(i) Description of the materials or components
(j) Properties of the materials such as performance data and model descriptions should be given
(k) Description of the test situation
(l) Date of test
(m) Test method
(n) Deviations from test method, if any
(o) Test results

A4.5.5 Iterative process

The use of the iterative research or decision-making process is recommended; this is illustrated by the outermost loop in Fig. 13. The advantage of the iterative process is that predictions and decisions can be made based upon the best knowledge available. As the knowledge base increases, the reliability of the service life predictions increases, but the user always has available data and procedures which reflect the state-of-the-art.