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# S478-95
# Guideline on Durability in Buildings

## Structures (Design)

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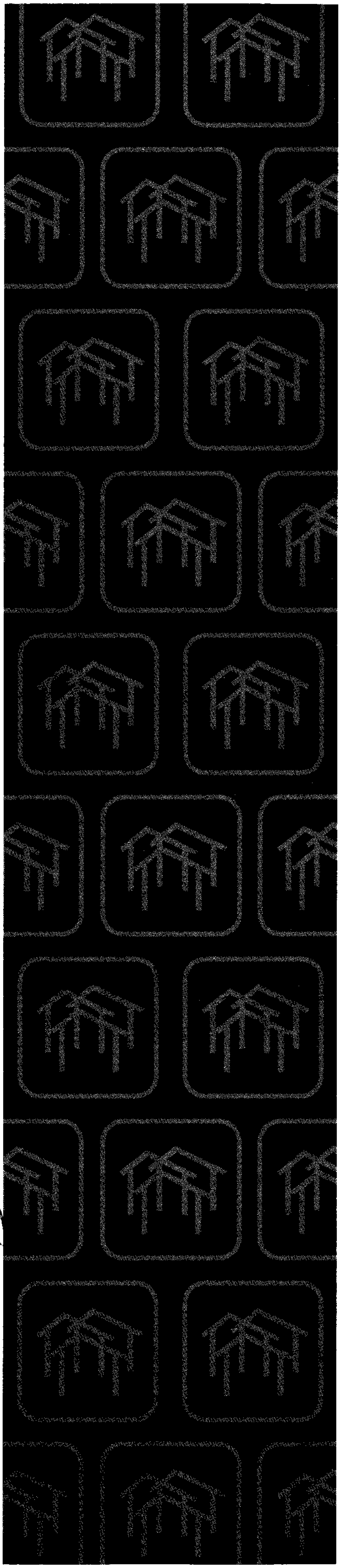

# *General Instruction No. 1*

## *S478-95*

## *December 1995*

CSA Standard S478-95, *Guideline on Durability in Buildings,* consists of **101 pages** (viii preliminary and 93 text), each dated **December 1995.**

This Standard, like all CSA Standards, is subject to periodic review, and amendments in the form of replacement pages may be issued from time to time; such pages will be mailed automatically to those purchasers who complete and return the attached card.* Some Standards require frequent revision between editions, whereas others require none at all. It is planned to issue new editions of the Standard, regardless of the amount of revision, at intervals not greater than 5 years. Except in unusual circumstances, replacement pages will not be issued during the last year of that edition.

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**Note:** *A General Instruction sheet will accompany replacement pages each time they are issued and will list the latest date of each page of the Standard.*

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*ISSN 0317-5669*
*Published in December 1995*
*by*
*Canadian Standards Association*
*178 Rexdale Boulevard*
*Etobicoke, Ontario, Canada*
*M9W 1R3*

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**Acknowledgements**

*Development of this Guideline was initiated at the request of Public Works and Government Services Canada (PWGSC). CSA acknowledges the major funding and background support provided by PWGSC, and funding support provided by the Department of National Defense, for the development of this first edition.*

*The Technical Committee acknowledges the contribution made by R.L. Booth. Through his drive and leadership until his resignation due to failing health, the draft was developed from a working concept to a near final document. This Guideline is dedicated to his memory.*

# *Preface*

This is the first edition of CSA Standard S478, *Guideline on Durability of Buildings.*

This Guideline sets forth for the first time in North America a set of recommendations to assist designers in creating durable buildings. The Guideline provides a framework within which *durability* targets may be set and suggests criteria for specifying *durability performance* of buildings in terms that are commonly used, but that were previously undefined. To do so, the Guideline contains generic advice on the environmental and other design factors that have an impact on the *durability* of building *components* and materials. It identifies the need to consider initial and longterm costs, *maintenance*, and replaceability in the selection of materials and *components.*

The Guideline makes it clear that *service life* requirements and design choices which may affect *durability* should be thoroughly discussed and agreed upon by all concerned, in particular the owner, designer, and constructor. Model documents for recording these decisions are provided in Appendix A. Later Appendices discuss and expand upon issues related to identification and (relative) quantification of environmental loading, deterioration mechanisms, and damage avoidance strategies including the need for appropriate *maintenance* over the life of the building.

This Guideline was prepared by the CSA Technical Committee on Designing for Durability, operating under the Standards Steering Committee on Structures (Design) and was formally approved by those Committees.

*December 1995*

**Notes:**

**(1)** *Use of the singular does not exclude the plural (and vice versa) when the sense allows.*

**(2)** *Although the intended primary application of this Standard is stated in its Scope, it is important to note that it remains the responsibility of the user of the Standard to judge its suitability for any particular purpose.*

**(3)** *CSA Standards are subject to periodic review, and suggestions for their improvement will be referred to the appropriate committee.*

**(4)** *All enquiries regarding this Standard, including requests for interpretation, should be addressed to Canadian Standards Association, Standards Development, 178 Rexdale Boulevard, Etobicoke, Ontario M9W 1R3.*

*Requests for interpretation should*

*(a) define the problem, making reference to the specific clause, and, where appropriate, include an illustrative sketch;*

*(b) provide an explanation of circumstances surrounding the actual field condition; and*

*(c) be phrased where possible to permit a specific "yes" or "no" answer.*

*Interpretations are published in CSA's periodical* Info Update. *For subscription details, write to CSA Sales Promotion,* Info Update, *at the address given above.*

# Foreword

Premature deterioration of buildings, resulting in costly *repairs* and disruptions in use, is an increasing problem. The annual costs related to such *repairs* and disruptions have now reached multimillion dollar levels.

To a limited degree, the issue of *durability* is addressed in numerous public documents, including the *National Building Code* (NBC), materials and installation standards, and manuals of good practice. CSA Standard CAN/CSA-S413-87, *Parking Structures* (second edition, December 1994), was the first Canadian building design standard written specifically to help designers achieve *durability* and avoid premature deterioration.

Consideration of the issue of *durability*, however, is often implicit rather than explicit, and is generally limited to particular phases in a building's life cycle and with respect to the implications of premature deterioration. The NBC, for example, is limited by its scope to addressing the issue only at the design and construction phases; it is precluded from addressing *maintenance* and *repair* or other factors that can limit deterioration after hand-over to the client. Furthermore, the Code is limited to addressing deterioration affecting the health and safety of building users. It does not address related costs and disruptions to building use.

This Guideline addresses the *durability* and premature deterioration issues throughout the life of the building, including the necessary *maintenance* procedures which should be anticipated. It expands, for new buildings, upon concepts relating *service life* expectations of owners, initial *quality*, and the impact of regular *maintenance* programs introduced in the 1993 CSA Standard S448.1, *Repair of Reinforced Concrete in Buildings.*

Explicit in this Guideline are the notions that

(a) the achievement of *durability* requires that life expectancy be considered in the design procedures for buildings and their *components*;

(b) the decisions taken during the life of a building, and even before the development of actual design documents, affect all subsequent decisions and resultant *performance*; and

(c) beginning with the initial concept for a building, the design process should take into account the environmental loads and deleterious *agents* to which the building *components* will be exposed.

When new types of materials are introduced into buildings or when traditional materials are used in new applications, these factors are even more important.

This Guideline was developed as an aid to owners and designers. The information contained is neither new nor revolutionary. It is an attempt to put together in one document a realistic method to define and design durable buildings, and to provide guidance on factors to be considered and where answers may be found. Appendices have been provided to supplement, qualify, or expand upon various topics in the Guideline.

The Guideline is a first attempt at such a document, and users are encouraged and requested to submit any and all suggestions for improving and enhancing the information covered. A *Proposal for Change* form for this purpose is found inside the back cover.

# S478-95
# Guideline on Durability in Buildings

## 1. Scope

### 1.1
This Guideline considers the *agents* and mechanisms related to *durability* and provides advice for incorporating requirements for *durability* into the design, operation, and *maintenance* provisions for buildings and their *components.*

### 1.2
The Guideline includes
(a) definitions of *performance, failure, service life,* and other concepts related to building *durability*; and
(b) guidance for designers, builders, owners, and operators on achieving *durability* by planning the design, construction, *maintenance, repair,* and *renovation* of buildings.

### 1.3
The *durability* of mechanical and electrical systems and services in buildings is not within the scope of this Guideline.

**Notes:**
**(1)** *While not addressed specifically, it is recognized that durability of these systems and services should be included in an integrated design. The principles set forth herein may be considered for application to a building's systems and services provided the effects of internal loads resulting from their operation are also taken into appropriate account.*
**(2)** *The loads on components and the building that result from the operation of the systems and services should be considered along with environmental and structural loads.*

## 2. Definitions

**Agent** — whatever acts on a building or its *components* that affects *service life* (eg, water, temperature).

**Assembly** — an arrangement of more than one *material* or *component* to serve specific overall purposes. Examples of *assemblies* include the total building *envelope* or individual walls, roofs, or parapets.

**Building science** — in the design of buildings and their *assemblies,* the study and application of principles governing physical, chemical, and electro–chemical behaviour in order to predict effects on an *assembly* due to loads placed on materials and *components* on and within the *assembly,* and their impact over time.

**Component** — any building unit. They may be manufactured, prefabricated, or built or formed onsite, and may be basic units such as nails, cladding anchors, reinforcing bars, and membranes or may be complex units such as cast reinforced concrete slabs or window and door units. A complex *component* such as a window unit can also be considered as an *assembly,* depending upon the context.

**Defect** — a deficiency in a building element that is critical to the *performance* of the element, eg, a gap in a barrier.

**Design service life** — the *service life* specified by the designer in accordance with the expectations (or requirements) of the owners of the building. For given materials and constructions exposed to identical loads, the *design service lives* for similar buildings are adjusted depending on the amount and nature of *maintenance* that the owners commit to carry out during the lives of the completed buildings.

**Durability** — the ability of a building or any of its *components* to perform its required functions in its service *environment* over a period of time without unforeseen cost for *maintenance* or *repair.*

**Envelope** — an environmental separator, generally between the inside and outside of a building (including the ground), but also between dissimilar *environments* within the building.

**Environment** — all conditions adjoining or permeating a building or any of its elements.

**Failure** — the loss of *performance*, as defined by the onset of any of the following limit states:
(a) collapse, as related to human safety or to loss of function of the building;
(b) local damage, as related to loss of function of the building *component* or to appearance;
(c) displacement, as related to loss of function of the building *component* or to appearance; or
(d) discolouration, as related to appearance of *components* having an aesthetic function.

**Maintenance** — the actions and measures taken periodically to maintain a desired level of *performance. Maintenance* includes a planned program of cleaning, *repair*, or replacement of identified *components* such as paint or gaskets.

**Performance** — the behaviour of a building or any of its *components* as related to use.

**Predicted service life** — the *service life* forecast from recorded *performance*, previous experience, tests, or modelling.

**Premature failure** — *failure* occurring prior to achievement of the *design service life.*

**Quality** — the totality of features and characteristics of products or services that bear on their ability to meet specified requirements.

**Quality assurance** — all those planned and systematic actions needed to confirm that products or services will satisfy specified requirements.

**Quality management** — the administrative system established to ensure that required *quality assurance* procedures have been followed and to direct appropriate corrective action(s) when the specified *quality* has not been achieved.

**Renovation** — a program of restoration or modernization of a building to satisfy current building code and functional requirements, with or without a change in use or occupancy of the building, and with or without structural changes.

**Repair** — action taken, including replacement, to bring the level of *performance* to a level acceptable to the designer and the owner. It may be part of the planned *maintenance* program for a building (eg, patching and painting of walls in access corridors) or may be initiated to remedy unexpected damage (eg, *repair* of a parking slab resulting from *premature failure* of part of a protective membrane).

**Service life** — the actual period of time during which the building or any of its *components* performs without unforeseen costs or disruption for *maintenance* and *repair.*

# 3. Reference Publications

## 3.1 Referenced Standards

This Guideline makes reference to the following Standards:

**CSA Standards**
S413-94,
*Parking Structures;*

S448.1-93,
*Repair of Reinforced Concrete in Buildings.*

**ISO Standard**
ISO 9001-94,
*Quality Systems Model for Quality Assurance in Design/Development, Production, Installation and Servicing.*

## 3.2 Bibliography

Appendix G is a bibliography of publications providing guidance and background information on *durability* in buildings and construction materials. It includes publications identified in the earlier Appendices to this Guideline.

# 4. Basic Durability Requirement

### 4.1

Buildings and their *components* shall be conceived, designed, constructed, and operated and maintained in such a way that, under foreseeable environmental conditions, they maintain their required *performance* during their *design service lives.*

The *predicted service life* of buildings and building *components* and *assemblies* should meet or exceed their *design service life.*

### 4.2

In the event of *renovation,* the *design service life* of the revised structure shall be reconsidered.

### 4.3

In the event of *repairs* necessary to correct damage or premature deterioration, the *repairs* shall be designed, constructed, and maintained to provide the required *performance* over the *design service life* agreed upon between the owner and the designer.

# 5. Quality Assurance

## 5.1 Durability and Quality Assurance Through the Building Life Cycle

To achieve *durability, quality assurance* is essential at every stage in the life of the building. Table 1 identifies the various stages in the life cycle and the specific *quality assurance* activities that should be completed at each stage.

## 5.2 Elements of Quality Assurance

### 5.2.1

Durability can be achieved only if
(a) the required *quality* of design is provided;
(b) the required *quality* of materials is used throughout;
(c) the required *quality* of workmanship is provided in the construction and *maintenance* of the building, its *components,* and *assemblies*; and
(d) the building is operated within the limits for which it was designed.

### 5.2.2

A fundamental principle of *quality assurance* is that all persons accept responsibility for the standard of their own work. In order to avoid *durability* problems, adequate and coordinated *quality* control obligations should be imposed upon all persons involved and during all phases in the process of defining, planning, building, and operating and maintaining the structure until the end of its *service life.*

### 5.2.3

The *quality assurance* plan of a building should be consistent with its *design service life* category (see Table 2), its complexity, and the aggressiveness of *environments* and *agents* to which it will be exposed.

### 5.2.4

*Quality assurance* requires the coordinated management of expertise, *quality* control activities, and communications between individuals responsible for different aspects in the overall *quality assurance* process, and implementation of corrective action when necessary. For this purpose, establishment of a *quality management* program in conformance with ISO Standard ISO 9001 is recommended.

## 5.3 Elements of Quality Management

### 5.3.1 Program

A comprehensive *quality management* program should be created and implemented at the initiation of every construction project. Its objective should be to verify that necessary *quality assurance* checks are made, and corrections are promptly made when specified *quality* is not provided, so that the building and all its *components* can meet expectations for their *performance* over their *design service lives.*

### 5.3.2 Documentation

Communication of *performance* objectives, expectations, and decisions between owners, designers, and others involved in the different stages of the building process is critical to *quality assurance.* The development, at the design stage, of a rational plan for the *maintenance* of building *components,* including planned *repairs* and replacements, will assist in defining the objectives for the designer and expectations of owners and operators (see Clauses 10 and 11). As an aid to this process, design life and *maintenance* data sheets are provided in Appendix A. It is recommended that these sheets or similar documentation be completed and updated as the design evolves. This documentation should reflect the objectives and expectations agreed to between the designer and the client, and should be provided on completion to the building operators who should maintain and update the information as necessary during the operation and future modifications of the building.

## Table 1
## Quality Assurance and the Building Process

(See Clause 5.1.)

| **Stage in Building Life Cycle** | **Quality Assurance Activity** | **Reference Clauses** |
|---|---|---|
| Conception | • establish appropriate levels of *performance* for building and *components* | 4, 6 |
| Design<br>– detail<br>– specify | • prescribe *performance* criteria for materials, *components,* and *assemblies*<br>• confirm acceptability and achievability of *performance*<br>• specify test options (prototype, in situ, etc) | 6, 7, 8, 10 |
| Tendering | • review design documents, including *performance* specifications<br>• accept requirements (contractor)<br>• accept tender(s) (owner) | 8, 9 |
| Construction | • control through<br>• review of process and product<br>• sampling and testing<br>• correction of deficiencies<br>• certification of work | 5, 8, 9 |
| Handover | • commissioning<br>• verification of *performance* of completed building by testing under operational loads | 10, 11 |
| Operation and Maintenance | • monitor *performance*<br>• inspect for deterioration or distress<br>• investigate problems<br>• certify work | 10, 11, 12 |
| Renovation | • same as for Conception and Design, above | 13 |

# 6. Design Service Life of Buildings and Components

## 6.1 Buildings and Components

Requirements for *durability* may vary from building to building and from one *component* to another. These requirements are related to intended use, to cost, and to frequency, difficulty, and extent of *maintenance*, replacement, and *repair.* Requirements for *durability* are expressed in terms of *design service life.* The *design service life* of the building provides one basis for the determination of the *design service life* of the building *components.*

## 6.2 Buildings

The *design service life* of the building should be determined by the designer in accordance with the requirements of the owner(s). Typical *design service life* categories for buildings are given in Table 2.

## 6.3 Components

### 6.3.1 Determination of Component Design Service Life

The appropriate *design service life* of each *component* of a building should be determined considering
(a) exposure conditions (see Appendix C);
(b) difficulty and expense of *maintenance*;
(c) the consequences of *failure* of the *component* in terms of costs of *repair*, disruption in operation, and hazard to building users (see Table 3);
(d) current and future availability of suitable *components*;
(e) the *design service life* of the building (see Appendix A); and
(f) technical or functional obsolescence.

### 6.3.2 Difficulty and Expense of Maintenance

When determining the *design service life* for building *components*, it is suggested that at least three categories (more, for more complex *components*) be used to describe necessary *maintenance* : "little or none", "significant", and "extensive". Individual *components* can then be classified under the appropriate category by considering costs, difficulty, extent, and frequency. The selection or design of *components* and the specification of the necessary *maintenance* should be determined by balancing initial costs, operations and *maintenance* costs, and acceptable levels of effort during *maintenance*. To extend the lifecycle, selection of *components* with inherent superior *durability*, implementation of a more comprehensive *maintenance* program, or both, should be specified.

### 6.3.3 Consequences of Failure

Table 3 identifies eight categories of *failure* defined by the worst consequence of a *failure* in that category. *Components* whose *failure* threatens life or health should be designed to provide a greater reliability during the *design service life* than those whose *failure* does not threaten life or health. Structural *assemblies* or members, such as roof trusses over a swimming pool or load-bearing columns supporting a parking structure, are examples of *components* that would generally require both a longer *design service life* and greater reliability in provisions specified to ensure their *durability*.

**Note:** *The consequences of failure to maintain an assembly can be illustrated by the following example: a cladding anchor that corrodes prematurely because a sealant has unbonded or cracked may fail, causing injury or property damage. The cause may be lack of maintenance. If a detail is determined to be critical to durability, it may be prudent to design redundant protection, particularly if its cost is negligible and the risk of failure is greatly reduced.*

### 6.3.4 Component Selection Related to Technical or Functional Obsolescence and Other Requirements

The *design service life* of a *component* or *assembly* will also depend on the availability of durable *components* and knowledge of construction methods required for their proper installation. Even when *components* and *assemblies* whose *predicted service lives* approach that of the building are available, other considerations such as aesthetics or environmental impact may preclude their use.

### 6.3.5 Component Service Life Related to Building Service Life

Permanent *components* of a building (foundations, basement walls, and main structural members) should be expected to perform for the life of the building. Moveable or removable *components* (partitions in an office building, interior finishes) should be designed to last only as long as they will remain useful. Exterior claddings can normally be expected to provide *service lives* of 20 or more years. A cladding system requiring little *maintenance* for temporary buildings may require extensive *maintenance* if used on "permanent" buildings.

A rational plan for *maintenance* of building *components*, including *repair* and replacement, should be set up as indicated in Clauses 10 and 11 and Appendix A.

**Note:** *Ideally, at the end of the service life of a building, each component and assembly in that building would reach the end of its service life and instantaneously biodegrade, leaving a clean site and no material disposal problems. In reality, the service lives of components vary widely, depending on their exposure to damaging agents, and will have service lives longer* *or shorter than the building. The use of components and materials which lend themselves to recycling at the end of their functional lives may be a practicable solution.*

## 6.4 Specification of Design Service Life

A statement of the *design service life*, in years, for both the building and its *components* and *assemblies* should be established between the designer and the owner. The design life statement should be accompanied by information on
(a) building, *component* and *assembly design service lives;*
(b) exposure conditions, *environments*, and limits on use;
(c) recommended *maintenance*, in accordance with Clause 10;
(d) design exposure conditions (Clauses 7 and 8).

The data sheets found in Appendix A may be modified and used to establish and record the necessary data for a building.

The information necessary to ensure that the design concept and objectives are realistic and achievable should be communicated to all parties involved in the construction process, including consulting designers, contractors, fabricators and suppliers, and construction trades.

### Table 2
### Categories of Design Service Life for Buildings

(See Clauses 5.2.3 and 6.2.)

| **Category** | **Design service life for building** | **Examples** |
|---|---|---|
| Temporary | Up to ten years | • non-permanent construction buildings, sales offices, bunkhouses<br>• temporary exhibition buildings |
| Medium life | 25 to 49 years | • most industrial buildings<br>• most parking structures* |
| Long life | 50 to 99 years | • most residential, commercial, and office buildings<br>• health and educational buildings<br>• parking structures below buildings designed for long life category* |
| Permanent | Minimum period, 100 years | • monumental buildings (eg, national museums, art galleries, archives)<br>• heritage† buildings |

* *Parking structures should have a design service life at least equal to the building they serve, except parking structures serving long life category buildings may be designed for medium life provided they are not located directly under the long life superstructure or provided deterioration of the parking structure would not adversely affect the building served. See CSA Standard S413.*

† *Buildings are not designed as a heritage structures but may be assigned the designation by virtue of their historical significance. One purpose of applying such a designation to a building is to ensure that, henceforth, it will be preserved permanently. The concepts contained in this Guideline will be of assistance in establishing appropriate maintenance and repair programs for designated buildings.*

## Table 3
## Categories of Failure*

(See Clauses 6.3.11 and 6.3.3.)

| Category | Effects of failure† | Example |
|---|---|---|
| 1 | No exceptional problems | Replacement of light fittings |
| 2 | Security compromised | Broken door latch |
| 3 | Interruption of building use | *Repair* requires discontinuation of service or dislocation of occupants |
| 4 | Costly because repeated | Window hardware replacement |
| 5 | Costly *repair* | Requires extensive materials or component replacement or extensive use of scaffolding |
| 6 | Danger to health or the ecological system | Excessive dampness, mold, soil gases, asbestos, PCBs |
| 7 | Risk of injury | Loose handrail |
| 8 | Danger to life | Sudden collapse of structure |

* *Individual failures can be in two or more categories.*

† *The effects of failure may include broader implications than indicated in the Table and for which the consequences (monetary costs, people costs, societal costs, etc) are not known. Any of these can be trivial, costly, or very expensive.*

# 7. Predicted Service Life of Components and Assemblies

## 7.1 General

The *predicted service life* of any building *component*, including repaired as well as new *components*, is approximate based on the assumed environmental conditions and on installation, operating, and *maintenance* procedures.

## 7.2 Methods to Predict Service Life

### 7.2.1

The *predicted service life* of *components* or *assemblies* may be assessed by one or more of the following three methods:

(a) demonstrated effectiveness, in accordance with Clause 7.3;
(b) modelling of the deterioration process, in accordance with Clause 7.4; and
(c) testing, in accordance with Clause 7.5.

### 7.2.2

All methods used to determine *predicted service life* should be based on a sound understanding and application of the principles of *building science*, in accordance with Clause 7.6.

### 7.2.3

For the prediction of *service life* of an *assembly*,

(a) demonstrated effectiveness may be applied where identical *assemblies* have been used
  - (i) successfully; and
  - (ii) in the same *environments;*

(b) modelling and demonstrated effectiveness should be applied where
  - (i) a similar *component* or *assembly* has been used successfully in the same environments; or
  - (ii) proven components or assemblies have been used successfully, but in moderately different environments; and

(c) modelling and testing should be applied where
  - (i) innovative *components* and *assemblies* are to be used; or
  - (ii) proven *components* or *assemblies* are to be used in significantly different environments.

The degree to which an *assembly* or its *components* are innovative or the service *environment* is dissimilar to one previously experienced should be established by the application of *building science* principles.

## 7.3 Demonstrated Effectiveness

### 7.3.1

Requirements for *durability* of specific *components* are contained, although often not explicitly identified, in current codes, standards (see Appendix D), and other sources (see Appendix G). These requirements usually imply *service lives* of *components* which are consistent with current expectations and which may be considered appropriate for buildings of medium or long *design service life.*

### 7.3.2

The prediction of *service life* may also be based on documented records of successful *performance* and from information on deterioration problems reported in the literature. The latter also is particularly useful for assessing relatively innovative *assemblies* and for innovative *components* used in conventional *assemblies.*

## 7.4 Modelling of the Deterioration Processes

The prediction of *service life* of any *component* of an *assembly* by modelling of the deterioration processes requires consideration of

(a) the function(s) of the *component* (eg, air and/or moisture barrier);

(b) the *environments* adjacent to and within the *components;*

(c) the relative movement of adjacent *components* or *assemblies;*

(d) the deterioration or damage mechanisms that occur as a consequence of the *environment,* and interactions with adjacent *assemblies;* and

(e) the limit states (eg, fracture, damage, movements, gaps, discolouration, etc) defining functional *failure* of the *component* in the *assembly.*

## 7.5 Testing

### 7.5.1

The purposes of testing are

(a) to validate and quantify conclusions from modelling described in Clause 7.4;

(b) for *quality assurance* purposes prior to and during construction; and

(c) for investigation of existing buildings.

### 7.5.2

The following types of testing may be carried out:

(a) laboratory tests to determine conditions on and within *assemblies* exposed to controlled simulated *environments* (eg, rain penetration, air leakage, and temperature differentials) adjacent to the *assemblies;*

(b) *durability* tests of materials, *components,* and *assemblies* to determine their deterioration and *failure* mechanisms and time to failure under natural or simulated *environments;* or

(c) field tests of constructed *assemblies* to determine transport and accumulation of *agents*, either during construction for *quality assurance* purposes or during the investigation of existing conditions in a building.

**Note:** *Simulated environments may represent extreme cases of natural environments or "accelerated" extreme natural environments. Special care must be taken in extrapolating the results of testing based on "accelerated" methods to the prediction of service life.*

## 7.6 Application of Building Science Principles to Modelling of the Deterioration Process

### 7.6.1 Local Environments

Modelling of the deterioration process requires an understanding of the delivery mechanisms and accumulation rates of *agents* which promote deterioration. These will be based on knowledge about the immediate surroundings of *components* and their place in specific *assemblies.*

Moisture, with or without contaminants, is the most important environmental *agent* causing premature deterioration. The application of principles of *building science* permits the generation of models for predicting the mechanisms, paths, volumes, and forms of moisture which building *assemblies* will need to accommodate and resist.

Guidance on the assessment of the *environment* and environmental *agents,* including moisture, contaminants, and temperature is contained in Appendices C, D, and E.

### 7.6.2 Movement

The relative movement of adjacent *components* is determined from a consideration of dimensional changes of individual *components* due to material characteristics, temperature, moisture changes in *materials* and the atmosphere, and stresses due to service loads.

The relative movement of adjacent *assemblies* is determined from a consideration of dimensional changes of the *assemblies* due to temperature and moisture changes in materials comprising the *assembly,* temperature and moisture changes in the atmospheres, differential movements in supporting structures, and stress.

### 7.6.3 Deterioration and Damage Mechanisms

Deterioration and damage mechanisms are consequences of the expected environmental conditions, the chemical and physical properties of the *materials* of the *components,* and the interaction of the different *components,* including chemical (eg, galvanic corrosion) and physical (eg, movements, deformations) interactions.

Corrosion is currently a very costly unforeseen *durability* problem in buildings. It is only partially addressed by current building codes and standards. An introduction to corrosion is provided in Appendix E.

Guidance on the identification of deterioration or damage mechanisms and their control is provided in Appendix D for materials and in Appendix F for building *envelope assemblies.*

### 7.6.4 Failure

*Failure* is defined not by the occurrence of deterioration or damage mechanisms but by their effects. The effects depend on the functions of the *component* (eg, moisture barrier, drainage *component*) or on its visual appearance. A deterioration mechanism occurring on or inside an *assembly* does not necessarily mean *failure.* Therefore it is important to consider not only *component environments* and deterioration and damage mechanisms, but which limit states (eg, fracture, movements, gaps, appearance, *material* weakening) correspond to functional *failure* in the intended use. Some guidance is given in Appendix D on the forms of *failure* associated with prevalent deterioration mechanisms for materials and in Appendix F for building *envelope assemblies.*

# 8. Design Considerations

## 8.1 General

Designers in particular should be aware of the issues related to *durability*. The design considerations identified herein should be of assistance in developing a strategy to assure *durability* generally. Appendix F contains additional information on the design aspects of the building *envelope*.

## 8.2 Convention and Innovation

Designs should be based on existing Standards and proven design and construction practices wherever possible. This recommendation and Clauses 8.3 to 8.7 should not be interpreted as discouraging the use of new materials or approaches to the design or construction of buildings and their *components*. However, the use of innovative technology should be based on sufficient modelling or testing (see Clause 7) to ensure the likelihood of a high level of success in the application.

## 8.3 Materials Selection

Materials should

(a) have compatible physical and chemical properties when in contact or close association;
(b) have physical and chemical properties appropriate for the *environment*; and
(b) have physical properties compatible with anticipated differential movements.

## 8.4 Detailing

Detailing should be provided using clear, concise, and complete drawings and specifications, and should, where necessary,

(a) provide barriers and seals to resist the infiltration or deposition of moisture or other deleterious *agents*;
(b) provide airseals, drainage, and venting between and through *assemblies* to minimize the accumulation of moisture or other deleterious *agents*;
(c) minimize the risk of local concentrations of moisture and deleterious materials through appropriate geometry, form, and placement of *components*; and
(d) minimize exposure of *components* to environmental loads.

## 8.5 Ease of Construction

The design concept for a building and its *components* must be buildable to achieve the necessary level of *quality*. Ease of construction may be improved when design documents

(a) incorporate the input of contractors, fabricators, and suppliers knowledgable in the use and installation of materials and systems to be specified, and of the staff who will be responsible for the operation of the completed building;
(b) use normally available and commonly used durable materials;
(c) specify a realistic and achievable level of workmanship;
(d) use standard approaches to, and methods of, construction;
(e) use simple construction techniques;
(f) consider sequence of construction;
(g) incorporate flexibility to allow response to changes in design, construction, scheduling, conditions, or *materials* availability that may arise during construction;
(h) recognize the allowable and expected construction tolerances of the *components* being designed and of adjacent building elements (which may exceed those of the *component*); and
(i) minimize the frequency and extent of interfacing between work by different trades.

*Components* and techniques which are critical or difficult to install correctly should be clearly detailed and explained in design documents.

## 8.6 Operation and Maintenance

Designs for buildings, their *components*, and *assemblies* should

(a) allow for ease of access for inspections, testing, *maintenance*, *repair*, and replacement of *components* and *assemblies*, including mechanical and electrical systems and services, during the construction phase and throughout the *service life* of the building, its *components*, and its *assemblies;*
(b) identify building *components*, including mechanical and electrical systems and services, that require special care through the construction and operation and *maintenance* phases.

### 8.7 Functional Obsolescence

Designs for buildings expected to undergo changes in usage and tenancies over the *service life* of the building should make appropriate allowance for future alterations of the contained spaces, probability of obsolescence of installed services, and the desirability of recycling or reusing *components*.

### 8.8 Life Cycle Cost

All decisions pertaining to materials selection, detailing, buildability, and operation and *maintenance* should take into consideration not only the first costs but all life cycle costs.

## 9. Construction Considerations

### 9.1 Timing

Construction contractors, their suppliers, and the building operators should be involved in the design/construction process as early as possible, to achieve better understanding of the intended functions of the building and its *components*, and for better coordination of the construction methods and their sequence.

### 9.2 Coordination

#### 9.2.1 Bid Document Review

Prior to tender, those involved in tendering should review in detail all design documents. The designers should communicate to the contractors and suppliers the intended functions of the proposed design and point out aspects critical to the proper *performance* of the design.

Prior to the start of construction, all design documents should again be reviewed in detail by the successful contractors and suppliers, and the designers should again communicate the intended functions and critical aspects of the final design. The contractors and suppliers should confirm that they have a clear understanding of the proposed building and *component* functions, specified materials, and the proposed methods for fabrication of *components* and construction of the building. Unclear items should be resolved with the designers before construction begins. The use of partial construction or mock-ups of critical building *components* prior to construction is recommended, particularly where innovative materials, products, or concepts are being introduced.

#### 9.2.2 Quality Control

Prior to the start of construction, those involved should establish *quality* control by adopting appropriate *quality management* procedures as described in Clause 5.

The designer should remind the owner and the contractor to assign appropriate resources and measures to achieve specified construction and installation details and tolerances.

There should be on-going and continuous communication between all parties involved in the construction to ensure that standards are being met and that appropriate corrective actions are selected and implemented if specifications cannot or have not been met.

#### 9.2.3 Interaction Among Trades

Prior to the start of construction, those involved should assign scopes of work to appropriate trades, establish coordination between trades, and schedule and phase the work to achieve proper construction and installation of all building *components* and *assemblies*. The trades should be briefed on any new or unusual construction procedures or design innovations to ensure that they can be built as specified.

Suppliers and fabricators should notify the designers, contractors, and installers when special construction related procedures are required to protect *components* during construction.

Before beginning its work, it is advisable that each trade examine preceding work of other trades to confirm that conditions appear to provide a satisfactory base to its own work.

New work contingent on preceding work should not be executed until preceding work identified as unsatisfactory is corrected.

### 9.2.4 Protection During Construction

During construction, those involved should provide for the proper and adequate transport, handling, and storage of materials, *components*, and *assemblies*, to protect them against damage or deterioration during the construction period. Designers should inform contractors and suppliers of *components* and *assemblies* which may require special care and protection prior to installation.

## 10. Operation, Maintenance, and Inspection Programs

**Note:** *Operation, maintenance, and inspection programs described in this Clause are intended for execution by the owner of the building.*

### 10.1 Operation

Operating conditions inside a building will have significant long-term impacts on component and *assembly* durabilities. Buildings should be operated within the design parameters of temperature, relative humidity, and pressure differentials for which the building was designed and fitted. In any event, the variance between operating and design conditions should be controlled within specified tolerances.

Operating procedures used outside of the building should be planned and carried out to avoid excessive exposure of the structure to damaging *agents*. For example, salt-laden snow should not be piled against exterior walls because the chlorides can increase the rate of deterioration, and high pressure water should not be used for cleaning where there is danger of damaging seals and sealants.

### 10.2 Maintenance and Inspections

The objective of operations and *maintenance* programs should be to provide at reasonable cost a clean, reliable, functional, safe, and healthy *environment*. Programs of routine *maintenance* and inspection are necessary to ensure that the building and its materials, *components*, and *assemblies* perform their required functions for the duration of their *design service lives*.

### 10.3 Specification of Maintenence and Inspection Programs

#### 10.3.1

It is recommended that *maintenance* and inspection programs be prepared during the production of construction documents.

This is an important exercise, especially for the owners of the completed building, in that it requires these issues to be identified and considered prior to construction. Establishment of an appropriate *maintenance* and inspection budget should be a specific consideration.

As construction proceeds, these programs should be extended and revised to reflect as-constructed needs and results. (See Appendix A and Table A3.)

#### 10.3.2

Though not currently included in the general scope of work in client-architect agreements, a *maintenance* and inspection database should be obtained by the owner and should include

(a) as-built drawings;
(b) shop drawings;

(c) Comprehensive Design Life and Maintenance Summary Table (see Appendix A);
(d) work methods and operating manuals;
(e) training information;
(f) recommended schedules of inspection, preventative and corrective *maintenance* identifying tasks, and required resources (time, personnel, tools, materials, etc); and
(g) appropriate forms for recording histories of *maintenance* and inspections conducted.

### 10.4 Implementation

Once the building is completed and occupied, this comprehensive *maintenance* and inspection program should be implemented by the owner. Allowance for an adequate budget to do the necessary work will be required.

### 10.5 Inspection to Verify Maintenance

Visual inspections should be conducted at regular intervals to verify that the *maintenance* is being carried out as required and to identify and document any signs of deterioration at the earliest possible stage. Frequency of inspection of a given building *component* should be specified based on the recommendation of the professional responsible for the design of that *component*. This recommendation is often based on manufacturer criteria, and depends on the installation and function of the *component*.

Significant changes in the conditions of a material, *component*, or *assembly* observed between successive visual inspections or over a series of inspections generally indicates the need for a more thorough visual inspection with additional data collection, or for a more detailed investigation.

The prolonged presence of moisture should generally be a concern.

Where a problem is identified during a regular inspection, a professional should be called in (see Clause 11) to investigate.

### 10.6 Timing

The timing of *repairs* with respect to the development of the *defects* is of paramount importance. Early detection of deterioration symptoms and determination and correction of the cause of problems is recommended.

## 11. Investigation of Deterioration

**Note:** *This Clause is intended for implementation by an appropriately qualified professional when the owner has identified symptoms of deterioration that may indicate problems that cannot be corrected by routine maintenance and repair work, or when a general assessment of the health of the building is wanted.*

### 11.1 Investigation

#### 11.1.1 Purpose

The proper identification of the *agents* and mechanisms responsible for the deterioration is essential for the appropriate *repair* to be devised. An investigation is usually required for an accurate diagnosis and includes
(a) recording the extent of the deterioration and the way in which the *agent* of the *defect* has manifested itself (the symptoms);
(b) collecting and recording of all relevant data;
(c) comparing the symptoms and the known behaviour of the materials, *components*, and *assemblies* involved; and
(d) relating the symptoms to the *environment* to which the materials, *components*, and *assemblies* have been exposed.

All of these require the application of *building science* principles.

### 11.1.2 Use of Routine Records of Inspection

Routine documented visual inspections, recommended to be part of a regular *maintenance* program, provide the simplest means for identifying deterioration in materials, *components*, and *assemblies*.

### 11.1.3 Monitoring

Monitoring of the damaged *components* through instrumentation and comparison against known benchmarks should be considered where it is not certain from visual inspections whether identified damage can be considered stabilized or can be expected to deteriorate further.

### 11.1.4 Testing

Tests and measurements of conditions, properties, and *performance* of materials, *components*, and *assemblies*, may include
(a) moisture determination;
(b) chemical analysis;
(c) physical analysis; and/or
(d) simulation.

### 11.1.4.1 Non-Destructive Testing

Non-destructive test methods, causing little or no disruption of the material, *component*, or *assembly*, may provide additional information on the extent of deterioration where visual inspection indicates an area of concern. Accuracy of the tests generally increases with the uniformity of the material. Since the assessment is largely qualitative, the amount and usefulness of the information gained generally increases with the knowledge and judgement of the investigator.

### 11.1.4.2 Partially Destructive Testing

Partially destructive test methods may be preferred over non-destructive methods where greater accuracy or additional information is required. These tests usually involve the removal and destruction on-site of small samples from a representative area of the material, *component*, or *assembly*.

### 11.1.4.3 Off-Site Testing

Off-site testing requires sampling, transporting, and testing of representative sections of the material, *component*, or *assembly*. It involves quantitative evaluation and usually provides a greater degree of accuracy than non-destructive or partially destructive testing. More properties can be evaluated under controlled laboratory conditions than in the field.

### 11.1.4.4 In-situ Testing

In-situ testing provides a means of evaluating a full scale, undisturbed sample of the material, *component*, or *assembly* and provides an in-service measure of *performance* and conditions under a defined controlled constant or varying *environment*. The resistance of the *component* to both structural and environmental loads can be tested and measured. Sacrificing representative sections may be necessary to determine the current condition and extent of deterioration throughout a larger section or *assembly*.

### 11.2 Assessment of Deterioration

The data obtained through investigation, monitoring, and testing requires assessment by qualified personnel to determine
(a) the significance of the deterioration or *failure* in the context of the *performance* of the material, *component*, or *assembly* and of the building;
(b) the cause and source of the deterioration; and
(c) the scope and nature of *repair* work which may be required.

**Note:** *Frequently more than one contributing factor may be responsible for the particular deterioration or failure being considered, and sources may be interactive.*

## 11.3 Recommendations for Actions

Based on the assessment, the investigator should prepare a written report including, when appropriate
(a) the assessment of the effects of the damage or deterioration on the safety, serviceability, and intended *durability* of the building;
(b) recommendations for needed *repairs* or replacement of deteriorated *components;*
(c) recommendations for correction of conditions which caused the deterioration;
(c) recommendations for additional protection systems required to achieve the required *design service life;* and
(e) recommendations for *maintenance* procedures required to achieve the *design service life.*

**Note:** *The design service life in this context is intended to be compatible with that originally scheduled for the component(s) affected, and may extend only until the next planned replacement date.*

# 12. Repair Work

## 12.1

*Repair* work must be based on as accurate a diagnosis of the cause of the deterioration or *failure* as is reasonably possible. Unless this is done, the *repair* work may prove to be inappropriate or short-lived, or may lead to other deterioration or *failures.*

The scope and nature of *repair* depends upon
(a) the precise nature of the deterioration or *failure* and its impact on immediate and long-term use of the building;
(b) the *design service life* for the *repair;*
(c) the cost and disruption to use of the building during the course of the *repair* work; and
(d) funding allocated in the maintenance budget.

**Note:** *The general concepts set forth in CSA Standard S448.1 may be of use in considering the repair of buildings of all materials as well as those of reinforced concrete.*

# 13. Renovation

## 13.1 General

*Renovation* design should take fully into account the uses (and *occupancies,* in the context of the applicable building code) for which the building was originally designed and uses (*occupancies*) for which the design is to be altered.

The renovated building and its *components* should be conceived, designed, constructed, and operated and maintained so as to satisfy the *durability* guidelines of Clauses 4 to 10.

## 13.2 Assessment of the Existing Building

The current condition of the building should be assessed in terms of its ability to provide acceptable *performance* to satisfy the uses for which the *renovation* will be designed. Such assessment must include
(a) identification of all architectural and structural changes necessary to meet current codes and standards with respect to
    (i) structure;
    (ii) environmental separators;
    (iii) serviceability;
    (iv) mechanical systems; and
    (v) electrical systems; and
(b) identification of needed *repairs.*

## 13.3 Environmental Changes

Changes to the indoor *environment(s)* resulting from changes to the use and *occupancy* or changes to interior heating, ventilation, and humidification systems should be identified and, so that the expected *performance, predicted service life,* and operating and *maintenance* requirements are appropriate for the revised *design service life* of the renovated building,

(a) it should be confirmed that the existing *envelope* will provide the required separation between the altered interior and exterior *environments;* or

(b) any alterations required to *components* of the building *envelope* should be identified and specified; and

(c) the *maintenance* procedures necessary to attain that *design service life* should be identified and documented for the building operators.

# *Appendix A*
# How to Use the Guideline

**Note:** *This Appendix is included for information purposes only.*

## A1. General

This Guideline provides a framework within which design considerations related to building life and *durability* can be organized and addressed. The Guideline assumes that the objective of the designer will be to provide a building which will be durable and functional for at least the time period required by the owner.

Building codes do not currently establish explicit targets for the life of buildings. Table 2 in the Guideline identifies and defines (in years) categories of *design service life* for typical building types. The building *design service life* should be specified by the owner.

While the specified *design service life* establishes the overall objective for the design, it is neither necessary nor desirable that all *components* of the building have the same design life. For example, the interior spaces of most commercial office buildings are expected to become functionally obsolescent, perhaps several times during the building's *service life*. If this will be the case, owners and designers should plan, therefore, for periodic redecoration and internal rearrangement to satisfy the needs of tenants. In this instance it is more cost efficient to set a target life for interior partitions based on the expected time until redecoration. Other factors which have an impact on *design service life* decisions are identified in the Guideline.

The Guideline views the process of designing for *durability* as following a decision tree model, with the determination of the final design being an iterative process that begins with the overall concept and culminates in working drawings which will ensure the required *durability* as well as meeting structural and other building code needs. The Guideline also identifies that the realization of *design service life* is dependent on the operational practices and *maintenance* programs enacted by the owner.

When conformance to this Guideline is specified, all parties involved in the design, construction, and ownership of a building are required by Clause 4 to conscientiously carry out their respective responsibilities to ensure a reasonable probability that *service life* at least achieves *design service life*.

## A2. Design Information

### A2.1 General

To ensure the intended degree of *durability* is achieved, decisions related to the *design service life* of the structure, its *components*, and *assemblies*, and to the operational and *maintenance* constraints acceptable to the owner should be documented and used as the basis for design. The use of Tables **A1 to A3** is recommended as a means of recording and explaining *durability* design targets and assumptions for a building and its *components* and for communicating this information to future owners of the building.

The sample documentation tables contained in this Appendix, or other formats providing the same information, should be completed by the designer during the conceptual stage, and updated as required throughout the design, tendering, and construction process (see Clause 5). Such tables identify clearly the designer's intentions for the design *durability* of the building and its *assemblies*. They should advise the client and subsequent owners of

- the designer's response to the client's stated needs;
- the need for *maintenance* of *components* of the building;
- the building's operational parameters and tolerances; and,
- the frequency and nature of recommended *maintenance* programs.

The sets of documentation tables, described below in more detail, comprise

(a) Table A1, Building Design Data;

(b) Table A2, Preliminary Design and Maintenance Options; and
(c) Table A3, Comprehensive Design and Maintenance Summary.

To illustrate the process of documenting decisions, the tables contained in this Appendix are in the form of completed examples for two typical structures — a highrise office building (Tables A (HRO)) and a lowrise residential condominium building (Tables A (LRR)). In practice, these design documentation tables are to be adapted and expanded as necessary to reflect the actual building and the structural and other systems to be utilized in its construction.

## A2.2 Table A1 — Building Design Data

Tables A1(HRO) and A1(LRR) are completed examples of Building Design Data sheets. Their intended function is to document the basic requirements for the building and the design variables the designer will need to work with, as agreed with the owner. The two aspects of the Building Design Data table that are uniquely necessary to the *durability* design process are the specification of *design service life* (see Clause 6.2 and Table 2) and the documentation of environmental variables for the purpose of identifying potentially harmful *agents* (Clause 7.6 and Appendices C, D, E, and F).

Once completed and accepted by both the designer and owner, the Building Design Data table would normally not be altered unless there is a major alteration in the owner's requirements for use of the building or the construction system proposed, or unless the attendant operational and *maintenance* obligations are found to be too onerous or unworkable.

## A2.3 Table A2 — Preliminary Design and Maintenance Options

Table A2 is intended to record, in summary form, the *assemblies* and *components* options to be considered for design of the building documented in Table A1. Table A2 adds detail to the structural and other construction systems initially proposed in Table A1.

In addition to describing the *assemblies* and principal *components* under consideration, the table identifies their individual *design service life.* As noted previously, the *service life* of non-critical or readily replaceable *components* can be much shorter than that of the building. Clauses 6.3 and 8 and Table 3 in the Guideline provide information on the factors that need to be taken into account when determining (a) the *design service life* to be met by *components* or *assemblies* and (b) the materials and construction methods selected for preliminary design detailing.

Initially the "costs" to be identified (capital and *maintenance*) could be stated either as rough estimates or, if more than one option is being examined, in relative terms. The consequences of *failures* on the safety and serviceability of the building should be identified at this stage. As the design becomes more refined, insertion of actual projected capital and *maintenance* costs may be important in determining final materials, *component,* and *assembly* selections.

Non-typical environmental separators should be identified and addressed when their *environment* signals the needs for particular consideration to ensure protection against premature deterioration. *Assemblies* enclosing indoor swimming pools, walk-in freezers, chimneys, or manufacturing operations using acids or other caustic chemicals are four examples where special precautions to protect against premature deterioration, or to allow for economical replacement, may need to be taken.

## A2.4 Table A3 — Comprehensive Design and Maintenance Summary

Table A3, as shown for the two completed examples, provides a detailed summary of the principal *components* and their recommended *maintenance* and replacement schedules. This table also includes provision for indicating the nature of *maintenance* that will need to be done and to indicate any particular problems associated with carrying out the work. Minor components critical to the durability of *assemblies* or the building, or critical to the safe functioning of the building (eg, sealants required to control moisture or air leakage, and corrosion resistant structural hangers and connectors) should be identified. Completion of the *component maintenance* sections of Table A3 will serve to verify or correct the *maintenance* costs forecast in Table A2.

The designer can indicate for each *component* in Table A3 the level of *maintenance* necessary to realize their *design service lives.* The level and nature of the planned *maintenance* relate to cost, difficulty, or frequency of the planned work. A benefit of the A3, Summary tables is that they identify explicitly for the client and subsequent owners the extent of *maintenance* necessary to ensure that *design service lives* are achieved. These *maintenance* activities may range in scope from simple regular inspection, to occasional cleaning, to unscheduled minor or major *repairs*, to planned *component* replacements. If Table A3 is reviewed with the owner during the detailing and specification stages of the design process (see Table 1 of the Guideline), decisions may be made to specify more durable *components* initially, substituting (normally) higher capital costs for reduced *maintenance* costs.

## A3. Consequences of Failure

The categories of *failure*, as suggested in Clause 6.3.3 and Table 3 of the Guideline, reflect the consequences of *failure* on the safety and serviceability of a building. This information also is intended to assist owners in arriving at the appropriate *design service life* and *maintenance* programs for the building and its *components.*

## A4. Provision of Maintenance and Inspection Data Base

On handover of the building, the Guideline recommends that complete documentation of the building's design and construction, as well as recommended *maintenance* schedules, be obtained by the owner. Tables A1 and A3 described in this Appendix and completed for the specific building are part of the database that should be provided to the future owners together with other relevant supporting documentation (see Clause 10.3.2). This information is expected to form the basis for an "owner's manual" which identifies the nature and extent of post-commissioning work necessary to ensure achievement of the *design service life.*

## A5. Owner Responsibilities

Because the operation of the building is not the responsibility of the designer, the fulfilment of the necessary *maintenance* program should be verified by the owners by inspection and documentation. To minimize *maintenance* costs, *repairs* should be undertaken early and as necessary to prevent progressive acceleration of deterioration, following correction of the root cause of the problem.

# Table A1 (LRR)
# Building Design Data

## Building Identification
*(Complete in all cases.)*

| | |
|---|---|
| Name and location of building | *The Mews*<br>*Anytown*<br>*Canada* |
| Designer (or Design Organization) | *ABC Design* |
| Date (current) | |
| Replaces (previous date) | |
| Related Documents<br>(Client's brief, standard requirements, etc.) | *CSA Guideline S478-95,* |

## Design Service Life of Building
*(Complete in all cases.)*

| | |
|---|---|
| Category *(Table 2)* | *long* |
| Design service life, in years (minimum period for the category or specified other) | *50* |
| Basis for choice of design service life (eg, owner's requirement, normal for category) | *normal, for residential building* |

## General Building Information
*(Complete in all cases.)*

| | |
|---|---|
| Occupancy(ies); building uses | *residential* |
| Primary structural system for building | *concrete foundations; block firewalls; wood frame* |
| Other construction systems to be used | *brick and stained wood veneer*<br>*low energy consumption* |

*(continued)*

## Table A1 (LRR) (Continued)

**General Building Information** *(Continued)*

| | |
|---|---|
| Height above grade | *10 m approx. (3 storeys)* |
| Depth below grade | *2 m approx.* |
| Areas in building requiring special consideration, eg, agents potentially causing deterioration or damage | *none* |

**Environment**
***(Complete in all cases. See the Supplement to the National Building Code of Canada.)***

| | | | |
|---|---|---|---|
| Outdoor Design Temperatures | | Indoor Design Conditions | |
| 2.5% January | *– 25°C* | indoor temperature | *– 22°C* |
| 2.5% July | *30°C* | indoor humidity | *30% RH* |
| degree days below 18°C | *4634* | | |
| | | Seismic Data | |
| Soil temperatures | *°C at mm* | Za | *4* |
| | *°C at mm* | Zv | *2* |
| | *°C at mm* | Zonal velocity ratio, v | *0.10* |
| Air-borne contaminants | | Other Vibration Sources and Loads | |
| | | vehicular | |
| | | rail/subway | |
| Precipitation | | Wind | |
| 15 minute | *23 mm* | design wind speed | *km/h* |
| one day | *93 mm* | 1/10 hourly pressure | *0.30 kPa* |
| total annual | *846 mm* | 1/30 hourly pressure | *0.37 kPa* |
| driving rain index | | 1/100 hourly pressure | *kPa* |
| snow load ($S_S$) | *2.2 kPa* | | |
| snow load ($S_R$) | *0.4 kPa* | | |
| Ground conditions | | | |
| soil type(s) | *silt* | to depth of | *8 m* |
| | *shale* | to depth of | *20 m* |
| | | to depth of | *m* |

*(Continued)*

# Table A1 (LRR) (Concluded)

Environment *(continued)*

Ground conditions

depth to water table *10 m*

contaminants *none*

site investigation report *(cross reference)*

*Agents* resulting from proposed uses (eg, industrial processes, large crowds, housing livestock) likely to have an adverse effect on *durability*

Other relevant environmental *agents* and factors (such as pollutants, flooding, vibrations, or mining subsidence)

# Table A2 (LRR)
# Preliminary Design and Maintenance Options

| | Building Assembly | Materials or Type | Design Life, Years | Capital Cost | Maintenance Cost | Notes |
|---|---|---|---|---|---|---|
| The Mews, Anytown, Canada — 50 Year Design Service Life | | | | | | |
| 1. | **Structure** | | | | | |
| 1.1 | **Footings** | *concrete strip* | 100 | | *none* | |
| 1.2 | **Basement** | *poured concrete with some reinforcing* | 100 | | | |
| 1.3 | **Garage** | *reinforced concrete or reinforced block* | 50 | | | |
| 1.4 | **Above Basement** | *block firewalls, wood frame construction* | 100 | | | |
| 2. | **Environmental Separations** | | | | | |
| 2.1 | **Interior-to-Ground** | | | | | |
| 2.1.1 | *basement walls* | *waterproofing of concrete wall, soil drainage* | 50 | | | |
| 2.1.2 | *floor* | *gravel below slab* | 50 | | | |
| 2.2 | **Interior-to-Exterior** | | | | | |
| 2.2.1 | *walls* | *brick/cedar siding,*<br>*building paper over plywood,*<br>*R20 batt insulation,*<br>*poly barrier,*<br>*gypsum board* | 20–50 | | | |
| 2.2.2 | *roof* | *shingles + flashings over plywood,*<br>*R32 batt insulation,*<br>*poly barrier,*<br>*gypsum board* | 20–50 | | | |
| 2.2.3 | *floor over garage* | *plywood on sleepers,*<br>*rigid insulation,*<br>*reinforced concrete slab* | 50–100 | | | |
| 2.2.4 | *deck* | *cedar deck,*<br>*rigid insulation,*<br>*membrane,*<br>*reinforced concrete slab* | 20–100 | | | |
| 2.2.5 | *roof deck* | *cedar deck,*<br>*rigid insulation,*<br>*membrane & drain,*<br>*plywood on joists* | 20–30 | | | |
| 2.2.6 | *windows, sliding glass doors* | *double or triple glazed wood* | 50 | | | |

*(Continued)*

## Table A2 (LRR) (Concluded)

| | Building Assembly | Materials or Type | Design Life, Years | Capital Cost | Maintenance Cost | Notes |
|---|---|---|---|---|---|---|
| **The Mews, Anytown, Canada — 50 Year Design Service Life** | | | | | | |
| *2.2.7* | *doors* | *insulated wood or metal* | *50* | | | |
| *2.2.8* | *junctions* | *flashings, sealants* | *5–20* | | | |
| **2.3** | **Interior–to–Interior** | | | | | |
| *2.3.1* | *firewalls between units* | *gypsum board on wood strapping,*<br>*sound insulation,*<br>*concrete* | *50–100* | | | |
| *2.3.2* | *partitions* | *gypsum on studs* | *50–100* | | | |
| *2.3.3* | *floors* | *flooring,*<br>*plywood on joists,*<br>*gypsum board ceiling* | *10–100* | | | |
| *2.3.4* | *junctions* | *taped, nailed* | *20* | | | |
| **3.** | **Finishes, Furnishings, Fixtures** | | | | | |
| **3.1** | **Interior Finishes** | | | | | |
| *3.1.1* | *ceilings, walls* | *paint* | *10* | | | |
| *3.1.2* | *floors* | *wall to wall carpet,*<br>*resilient flooring* | *15,*<br>*10* | | | |
| *3.1.3* | *bathrooms* | *ceramic tile floors and shower walls,*<br>*sealants* | *5–20* | | | |
| **3.2** | **Fixtures** | | | | | |
| *3.2.1* | *stair rails* | | | | | |
| *3.2.2* | *handrails* | | | | | |
| **4.** | **Site** | | | | | |
| **4.1** | **Hard Surfaces** | | | | | |
| *4.1.1* | *walks* | *brick and gravel* | *10* | | | |
| *4.1.2* | *stairs* | *PT wood* | *15* | | | |
| *4.1.3* | *retaining walls* | *6X6 PT wood* | *25* | | | |
| *4.1.4* | *deck walls* | *PT plywood* | *20* | | | |
| **4.2** | **Soft Surfaces** | | | | | |
| *4.2.1* | *planters over garage* | *LW soil on filter,*<br>*pea gravel,*<br>*membrane,*<br>*concrete slab* | *15–50* | | | |

## Table A3 (LRR)
## Comprehensive Design Life and Maintenance Summary

| The Mews, Anytown, Canada — 50 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building Assembly | Materials/Type & Manufacturer | DSL, Years | Failure Category | Category | Type | Frequency | Access | Capital | Mainten-ance |
| **1.** | **Structure** | | | | | | | | | |
| **1.1** | **Footings** | | | | | | | | | |
| *1.1.1* | *footings* | *concrete strip* | *100* | *cost, safety* | *none* | | | *excavate* | | |
| **1.2** | **Basement** | | | | | | | | | |
| *1.2.1* | *slab* | *concrete* | *100* | *disruption, appearance* | *significant* | *clean /repair* | *yearly /10 yrs* | *OK* | | |
| *1.2.2* | *walls* | *concrete* | *100* | *safety, health, appearance* | *little* | | | *OK inside, excavate outside* | | |
| *1.2.3* | *connectors* | *some reinforcing* | *100* | *safety* | *little* | | | | | |
| **1.3** | **Garage** | | | | | | | | | |
| *1.3.1* | *slab* | *R/C (mesh)* | *50* | *disruption, appearance* | *significant* | *clean /repair* | *yearly /10 yrs* | *OK* | | |
| *1.3.2* | *walls* | *R/C or R/block* | *50* | *safety, appearance* | *little* | *clean* | *10 yrs* | *OK* | | |
| *1.3.3* | *roof* | *precast hollow-core* | *100* | *safety, appearance* | *little* | *clean* | *10 yrs* | *OK below, removals above* | | |
| *1.3.3* | *connectors* | *some reinforcing* | *100* | *safety* | *little* | | | *removals* | | |
| **1.4** | **Above Basement** | | | | | | | | | |
| *1.4.1* | *floors* | *plywood on wood joists* | *100* | *safety* | *none* | | | *removals* | | |
| *1.4.2* | *walls* | *plywood on wood studs* | *100* | *safety, health* | *none* | | | *removals* | | |
| *1.4.3* | *firewalls* | *concrete block* | *100* | *safety, health* | *none* | | | *removals* | | |
| *1.4.4* | *roof* | *plywood on wood trusses* | *100* | *safety, health* | *none* | | | *removals* | | |
| *1.4.5* | *connectors* | *nails, hangers* | *100* | *safety* | *none* | | | *removals* | | |

*(Continued)*

## Table A3 (LRR) (Continued)

| The Mews, Anytown, Canada — 50 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building Assembly | Materials/Type & Manufacturer | DSL, Years | Failure Category | Category | Type | Frequency | Access | Capital | Mainten-ance |
| 2. | **Environmental Separation** | | | | | | | | | |
| 2.1 | **Environmental Separations** | | | | | | | | | |
| *2.1.1* | *basement walls* | *concrete with 2 coats waterproofing* | *50* | *health* | *little* | | | *excavate to repair* | | |
| | | *drain to storm sewer* | *50* | *health* | *little* | *clean* | *4 yrs* | *excavate to repair* | | |
| *2.1.2* | *slab-on-ground* | *concrete slab on 8" gravel* | *50* | *health* | *significant* | *clean /seal* | *yearly /10 yrs* | *OK* | | |
| *2.1.3* | *junction* | *cast against* | *50* | *health* | *little* | *seal* | *10 yrs* | *OK* | | |
| 2.2 | **Interior–to–Exterior** | | | | | | | | | |
| *2.2.1* | *walls* | *brick veneer* | *50* | *cost, appearance* | *significant* | *repair, repoint* | *50 yrs* | *OK (stage)* | | |
| | | *cedar siding* | *25* | *cost, appearance* | *significant* | *restain* | *25 yrs* | *OK (ladder)* | | |
| | | *building paper on 1/2" plywood* | *50* | *safety, cost, appearance* | *none* | | | *removals (see above)* | | |
| | | *R20 batt insulation* | *50* | *cost, disruption* | *none* | | | *removals* | | |
| | | *6 mil vapour barrier* | *50* | *cost, disruption* | *none* | | | *removals* | | |
| | | *1/2" gypsum board* | *50* | *disruption* | *little* | *repair, paint* | | *OK* | | |
| | *parapets* | *flashing on top of brickwork* | *20* | *disruption, appearance* | *significant* | *replace* | *20 yrs (with roofing)* | *OK (ladder to roof)* | | |
| | | *rigid insulation around blockwork* | *50* | *cost* | *none* | | | *removals* | | |
| *2.2.2* | *roof/ceiling* | *210 asphalt shingles* | *20* | *disruption, health, appearance* | *extensive* | *replace* | *20 yrs* | *OK (ladder or scaffold to roof)* | | |

*(Continued)*

## Table A3 (LRR) (Continued)

| The Mews, Anytown, Canada — 50 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Maintenance** |
| | *roof/ceiling (cont'd)* | *48" shield/flashing at eave* | 20 | *disruption, appearance* | *significant* | *repair* | *20 yrs* | *remove shingles (ladder)* | | |
| | | *soffit/ridge vents* | 50 | *appearance* | *little* | | | *OK (ladder)* | | |
| | | *eavestroughing & leaders* | 20 | *appearance* | *significant* | *clean /replace* | *6 mths /20 yrs* | *OK (ladder)* | | |
| | | *1/2" plywood* | 50 | *safety, cost, disruption* | *little* | | | *removals* | | |
| | | *R32 batt insulation* | 50 | *cost, disruption* | *none* | | | *removals* | | |
| | | *6 mil air/vapour barrier* | 50 | *cost, disruption* | *none* | | | *removals* | | |
| | | *1/2" gypsum board* | 50 | *disruptions* | *little* | *paint* | | *OK* | | |
| *2.2.3* | *floor over unheated garage* | *plywood on sleepers* | 50 | *cost, disruption* | *little* | *renailing* | *10-20 yrs* | *removals (above)* | | |
| | | *8" rigid insulation* | 50 | *cost, disruption* | *none* | | | *removals (above)* | | |
| | | *7" precast* | 100 | *safety, cost* | *none* | | | *removals (above)* | | |
| *2.2.4* | *outside deck over unheated garage* | *2×4 cedar on sleepers* | 15 | *safety, appearance* | *extensive* | *repair /replace* | *yearly /15 yrs* | *OK* | | |
| | | *1" rigid insulation* | 50 | – | *little* | | | *removals* | | |
| | | *bituthene membrane* | 15 | *cost, disruption* | *extensive* | *repair /replace* | *15 yrs* | *removals* | | |
| | | *7" precast* | 100 | *safety, cost* | *none* | | | *removals* | | |
| | | *sloped gravity drainage to ground* | | | | | | | | |

*(Continued)*

## Table A3 (LRR) (Continued)

| The Mews, Anytown, Canada — 50 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building Assembly | Materials/Type & Manufacturer | DSL, Years | Failure Category | Category | Type | Frequency | Access | Capital | Mainten-ance |
| 2.2.5 | roof deck | 2×4 cedar on sleepers | 15 | safety, appearance | extensive | repair /replace | yearly /15 yrs | OK | | |
| | | 6" rigid insulation | 50 | cost, disruption | little | | | remove deck | | |
| | | bituthene membrane | 15 | cost, disruption | extensive | repair /replace | 15 yrs | removals | | |
| | | plywood | 50 | safety, cost | none | | | removals | | |
| | | drain & ABS pipe to storm sewer | 15 | disruption | significant | repair | 15 yrs | removals above or in wall below | | |
| 2.2.6 | windows, sliding glass doors | triple-glazed redwood | 50 | health, security, appearance | significant | replace panes | panes as req'd, units 50 yrs | OK | | |
| | | skylight | 20 | health | significant | replace panes | 20 yrs | OK | | |
| 2.2.7 | doors, front/back | metal, insulated | 50 | security, appearance | significant | repair, replace | as req'd | OK | | |
| 2.2.8 | junctions | flashings | 20 | cost | significant | replace | 20 yrs | OK (ladder) | | |
| | | sealants | 5 | | extensive | replace | 5 yrs | OK (ladder) | | |
| 2.3 | **Interior-to-Interior** | | | | | | | | | |
| 2.3.1 | firewalls between units | 1/2" gypsum board each side | 50 | disruption | little | repairs, paint | as req'd, 5 yrs | OK | | |
| | | 2" sound blanket each side | 50 | cost | none | | | removals | | |
| | | 2×2's shimmed 1/2" | 100 | cost, disruption | none | | | removals | | |
| | | 8" concrete block | 100 | safety, cost, disruption | none | | | major removals | | |
| 2.3.2 | partitions | 1/2" gypsum board each side | 50 | disruption | little | repairs, paint | as req'd, 5 yrs | OK | | |
| | | 2×4 studs | 100 | safety, disruption | little | repairs, alterations | as req'd | removals | | |

(Continued)

## Table A3 (LRR) (Continued)

| The Mews, Anytown, Canada — 50 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Maintenance** |
| *2.3.3* | *floors* | *1/4" subfloor (some areas)* | *100* | *appearance, disruption* | *none* | | | *remove floor cover* | | |
| | | *5/8" plywood* | *100* | *safety* | *little* | *renail* | *as req'd* | *remove floor cover* | | |
| | | *2×10 joists* | *100* | *safety* | *none* | | | *removals* | | |
| | | *1/2" stippled gypsum board* | *100* | *disruption, appearance* | *little* | *repairs* | *as req'd* | *OK* | | |
| *2.3.4* | *junctions* | *taped, nailed* | *20* | *disruption, appearance* | *significant* | *crack repair* | *as req'd* | *OK* | | |
| **3.** | **Finishes, Furnishings, Fixtures** | | | | | | | | | |
| **3.1** | **Interior Finishes** | | | | | | | | | |
| *3.1.1* | *ceilings, walls* | *paint* | *10* | *appearance* | *significant* | *touch-up repaint* | *as req'd, repaint* | *OK* | | |
| *3.1.2* | *floors* | *wall to wall carpet* | *15* | *appearance* | *significant* | *clean/repair* | *2 weeks* | *OK* | | |
| *3.1.3* | *bathrooms* | *tile shower walls* | *20* | *health, appearance* | *significant* | *repairs, regrout* | *20 yrs* | *OK* | | |
| | | *tile floors* | *20* | *disruption, appearance* | *significant* | *repairs* | *20 yrs* | *OK* | | |
| | | *sealants* | *5* | *appearance, health* | *extensive* | *replace* | *5 yrs* | *OK* | | |
| **3.2** | **Fixtures** | | | | | | | | | |
| *3.2.1* | *stair rails* | *painted metal* | *50* | *safety, appearance* | *significant* | *paint* | *5 yrs* | *OK* | | |
| *3.2.2* | *exterior handrails* | *square steel anchored to wood parapet* | *20* | *safety, appearance* | *significant* | *paint* | *5 yrs* | *OK* | | |

*(Continued)*

## Table A3 (LRR) (Concluded)

| The Mews, Anytown, Canada — 50 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building Assembly | Materials/Type & Manufacturer | DSL, Years | Failure Category | Category | Type | Frequency | Access | Capital | Mainten-ance |
| **4.** | **Site** | | | | | | | | | |
| **4.1** | **Hard Surfaces** | | | | | | | | | |
| 4.1.1 | walks | brick, gravel | 10 | injury, appearance | extensive | reset | yearly | OK | | |
| 4.1.2 | stairs | PT wood, certifed for above ground use | 15 | injury, appearance | significant | replace | 15 yrs | OK | | |
| 4.1.3 | retaining walls | PT wood 6×6, certified for ground contact, joined by 1" steel rods | 25 | appearance | significant | reset, replace | 25 yrs | OK | | |
| 4.1.4 | deck walls | brick (6" TTW) | 50 | safety, security | little | | | OK | | |
| | | PT plywood, certified for above ground use, on studs anchored to masonry | 20 | security, appearance | significant | stain | 5 yrs | OK | | |
| 4.1.5 | garage wall | metal grillage | 50 | security, appearance | significant | paint | 10 yrs | OK | | |
| **4.2** | **Soft Surfaces** | | | | | | | | | |
| 4.2.1 | planters over garage | 12" LW soil | 20 | – | little | | | OK | | |
| | | 2" fibreglass filter | 50 | drainage | none | | | OK | | |
| | | 2" pea gravel | 100 | drainage | none | | | removals | | |
| | | bituthene membrane | 15 | cost, disruption | extensive | repair/ replace | 15 yrs | removals | | |
| | | 7" precast | 100 | safety, cost | none | | | removals | | |
| | trees | | | appearance | | trim | as req'd | | | |

# Table A1 (HRO)
# Building Design Data

## Building Identification
*(Complete in all cases.)*

| | |
|---|---|
| Name and location of building | *The Office Block* |
| | *Othertown* |
| | *Canada* |
| | |
| Designer (or Design Organization) | *DEF Consortium* |
| | |
| Date (current) | *20 September 1994* |
| Replaces (previous date) | |
| Related Documents<br>(Client's brief, standard requirements, etc.) | *CSA Guideline S478-95,*<br>*(see file 94-03-08)* |
| | |

## Design Service Life of Building
(Complete in all cases.)

| | |
|---|---|
| Category *(Table 2)* | *long* |
| Design service life, in years (minimum period for the category or specified other) | *60 years* |
| Basis for choice of design service life (eg, owner's requirement, normal for category) | *owner specified* |

## General Building Information
*(Complete in all cases.)*

| | |
|---|---|
| Occupancy(ies); building uses | *upper levels: offices*<br>*ground level: mercantile & assembly (restaurant)*<br>*below ground: parking garage* |
| Primary structural system for building | *cast-in-place concrete* |
| Other construction systems to be used | |

*(Continued)*

## Table A1 (HRO) (Continued)

### General Building Information *(Continued)*

| | |
|---|---|
| Height above grade | *14 storeys (54 m) plus penthouse* |
| Depth below grade | *2 storeys (7.2 m)* |
| Areas in building requiring special consideration, eg, agents potentially causing deterioration or damage | *none* |

### Environment

*(Complete in all cases. See the Supplement to the National Building Code of Canada.)*

| | | | |
|---|---|---|---|
| Outdoor Design Temperatures | | Indoor Design Conditions | |
| 2.5% January | *– 25 °C* | indoor temperature | *22 °C* |
| 2.5% July | *30 °C* | indoor humidity | *30% RH* |
| degree days below 18°C | *4634* | | |
| | | Seismic Data | |
| Soil temperatures | *°C at mm* | Za | *4* |
| | *°C at mm* | Zv | *2* |
| | *°C at mm* | Zonal velocity ratio, v | *0.10* |
| Air-borne contaminants | | Other Vibration Sources and Loads | |
| | | vehicular | |
| | | rail/subway | |
| Precipitation | | Wind | |
| 15 minute | *23 mm* | design wind speed | *km/h* |
| one day | *93 mm* | 1/10 hourly pressure | *0.30 kPa* |
| total annual | *846 mm* | 1/30 hourly pressure | *0.37 kPa* |
| driving rain index | | 1/100 hourly pressure | *0.46 kPa* |
| snow load ($S_S$) | *2.2 kPa* | | |
| snow load ($S_R$) | *0.4 kPa* | | |
| Ground conditions | | | |
| soil type(s) | *blue clay* | to depth of | *6 m* |
| | *shale* | to depth of | *10 m* |
| | | to depth of | *m* |

*(Continued)*

## Table A1 (HRO) (Concluded)

**Environment** *(continued)*

Ground conditions

depth to water table *8 m*

contaminants *none*

site investigation report *(cross reference)* ______

*Agents* resulting from proposed uses (eg, industrial processes, large crowds, housing livestock) likely to have an adverse effect on *durability*

- ***none critical***

Other relevant environmental *agents* and factors (such as pollutants, flooding, vibrations, or mining subsidence)

- ***chlorides on parking garage ramps from road salt***

# Table A2 (HRO)
# Preliminary Design and Maintenance Options

| | Building Assembly | Materials or Type | Design Life, Years | Capital Cost | Maintenance Cost | Notes |
|---|---|---|---|---|---|---|
| <u>The Office Block</u>, Othertown, Canada — <u>60 Year</u> Design Service Life | | | | | | |
| 1. | **Structure** | | | | | |
| 1.1 | **Foundation** | *cast-in-place reinforced concrete* | *60+* | | *none* | *note implications of failure* |
| 1.2 | **Parking Garage** | *cast-in-place reinforced concrete* | *60+ for vertical elements; 20 for slabs* | | *high* | *discuss slab protection to determine service life and capital vs maintenance costs* |
| 1.3 | **Typical Storey** | *cast-in-place reinforced concrete* | *60+* | | *none* | |
| 1.4 | **Balconies** | *none* | | | | |
| 2. | **Environmental Separations** | | | | | |
| 2.1 | **Interior–to–Ground** | | | | | |
| *2.1.1* | *roofs* | *waterproof bituminous membrane over reinforced concrete slab* | *20* | | | |
| *2.1.2* | *basement walls* | *waterproof bituminous membrane on concrete* | *60* | | | |
| *2.1.3* | *floor* | *reinforced concrete over granular fill* | *60* | | | |
| *2.1.4* | *junctions* | *air, vapour, & water barriers* | | | | |
| 2.2 | **Interior–to–Exterior (Above Ground)** | | | | | |
| *2.2.1* | *curtain wall – type 1* | *glass curtain wall* | *30* | | | *major half-life replacement program* |
| *2.2.2* | *windows* | *all tinted, sealed double glazed, non-opening* | *30* | | | |
| *2.2.3* | *curtain wall – type 2* | *granite & glass curtain wall* | *30–60* | | | *DSL depends on mechanical support system selected; may be greater or less than half-life of building* |
| *2.2.4* | *roof* | *single ply membrane over rigid insulation over reinforced concrete* | *15* | | | *membrane is weak link; detailing is critical to DSL* |
| *2.2.5* | *roof openings* | | | | | |
| *2.2.6* | *roof junctions* | *water barriers* | *3–15* | | | *detailing is critical* |

(Continued)

## Table A2 (HRO)(Continued)

| | Buiding Assembly | Materials or Type | Design Life, Years | Capital Cost | Maintenance Cost | Notes |
|---|---|---|---|---|---|---|
| **The Office Block, Othertown, Canada — 60 Year Design Service Life** | | | | | | |
| **2.3** | **Interior–to–Interior** | | | | | |
| *2.3.1* | *walls<br>– core, parking levels* | *concrete block* | *60* | | *low* | |
| | *– core, upper levels* | *gypsum board on c. block* | *20* | | *low* | *periodic redesign to revitalize public areas* |
| | *– suite separations* | *steel stud, acoustical separation* | *20* | | *low* | *periodic removal or replacement with changes in tenants* |
| | *– other partitions* | *by tenant* | — | | | *changes by tenants* |
| *2.3.2* | *wall openings (in mall)* | | | | | |
| | *– windows* | *– tempered glass* | *30* | | *low* | *periodic removal or replacement with changes in tenants* |
| | *– doors* | *– security doors or by tenant* | *60* | | *low* | |
| | *(in suites)* | *– windows, by tenant* | — | | *N/A* | |
| | | *– doors, hinged metal or by tenant* | *60* | | *low* | |
| *2.3.3* | *floors, ceilings* | *concrete slab, suspended* | *60* | | *low* | *periodic replacement of ceiling panels and fixtures* |
| **3.** | **Finishes, Furnishings, Fixtures** | | | | | |
| **3.1** | **Interior Finishes** | | | | | |
| *3.1.1* | *ceilings<br>– parking level* | *finished* | — | | *low* | *cleaning, inspect for leakage, delam, spalling* |
| | *– mall level* | *paint or by tenant* | *5* | | *low* | |
| *3.1.2* | *walls<br>– parking level* | *paint* | | | *low* | |
| | *–mall level* | *paint, ceramic tile, or by tenant* | | | *low* | |
| | *– office levels* | *paint, or by tenant* | | | *low* | |
| | *– office levels* | *paint or by tenant* | *5–10* | | *low* | *painting, acoustic tile replacement* |

*(Continued)*

## Table A2 (HRO) (Concluded)

| | Buiding Assembly | Materials or Type | Design Life, Years | Capital Cost | Maintenance Cost | Notes |
|---|---|---|---|---|---|---|
| The Office Block, Othertown, Canada — 60 Year Design Service Life | | | | | | |
| *3.1.3* | *floors*<br>*– parking level* | | *5*<br>*60* | | *low*<br>*low* | |
| | *– mall level* | | *60*<br>*5–20* | | *low*<br>*low* | |
| | *– office levels* | | *10* | | *low* | |
| 3.2 | **Furnishings** | | | | | |
| *3.2.1* | *fixed mall furniture* | | | | | |
| 3.3 | **Fixtures** | | | | | |
| *3.3.1* | *handrails* | | *60* | | *low* | *cleaning, painting* |
| *3.3.2* | *guards* | | *60* | | *low* | *cleaning, painting, inspection* |
| 4. | **Site** | | | | | |
| 4.1 | **Hard Surfaces** | | | | | |
| *4.1.1* | *pedestrian* | *pavers, cast-in-place concrete* | *60* | | | *resetting* |
| *4.1.2* | *vehicular* | *asphalt over concrete* | *60* | | | *resurfacing* |
| *4.1.3* | *other* | | | | | |
| **4.2 Soft Surfaces** | | | | | | |
| *4.2.1* | *grassed areas* | | | | | |
| *4.2.2* | *flower and tree beds* | | | | | |

## Table A3 (HRO)
## Comprehensive Design Life and Maintenance Summary

| The Office Block, Othertown, Canada — 60 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Maintenance** |
| **1.** | **Structure** | | | | | | | | | |
| **1.1** | **Foundations** | | | | | | | | | |
| *1.1.1* | *piles* | *cast-in-place r/c (reinforced concrete)* | *60* | *costly, danger to life* | *none, extensive if failure* | *underpinning* | | *slab removal & excavation* | | |
| | *footings* | *cast-in-place r/c* | *60* | *costly, disruptions* | *none, extensive if failure* | | | *remove slab edge inside, excavate outside* | | |
| *1.1.2* | *columns* | *cast-in-place r/c* | *60* | *costly, danger to life* | *little/none, extensive if failure* | | | *OK* | | |
| *1.1.3* | *beams, arches* | *cast-in-place r/c* | *60* | *costly, danger to life* | *little/none, extensive if failure* | | | *OK* | | |
| *1.1.4* | *walls* | *cast-in-place r/c* | *60* | *costly, danger to life* | *little/none, significant if failure* | *epoxy injection* | *as req'd* | *OK inside, excavate outside* | | |
| *1.1.5* | *connectors, anchorages* | *re-bar* | *60* | *costly, danger to life* | *little/none, extensive if failure* | | | | | |
| **1.2** | **Parking Garage** | | | | | | | | | |
| *1.2.1* | *suspended slabs* | *cast-in-place r/c* | *25* | *costly, loss of use, danger to life* | *extensive* | *reseal, patch, resurface /replace* | *as req'd,*<br>*25 yrs* | *OK, scaffolding and formwork req'd from below* | | |
| *1.2.2* | *slabs-on-ground* | *(see 2.1.3)* | | | | | | | | |

*(Continued)*

## Table A3 (HRO) (Continued)

| The Office Block, Othertown, Canada — 60 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Mainten-ance** |
| **1.3** | **Typical Storey** | | | | | | | | | |
| *1.3.1* | *slabs & decks*<br>*– slabs-on-ground* | *cast-in-place r/c* | *60* | *costly, loss of use* | *none, extensive if failure* | | | | | |
| | *– suspended slabs* | *cast-in-place r/c* | *60* | *costly, loss of use* | *none, extensive if failure* | | | | | |
| *1.3.2* | *columns* | *costly, danger to life* | *60* | *costly, danger to life* | *none, extensive if failure* | | | | | |
| *1.3.3* | *beams, arches, trusses, joists* | *cast-in-place r/c* | *60* | *costly, danger to life* | *none, extensive if failure* | | | | | |
| *1.3.4* | *shear walls* | *cast-in-place r/c* | *60* | *costly, danger to life* | *none, extensive if failure* | | | | | |
| *1.3.5* | *connectors, anchorages* | *re-bar* | *60* | *costly, danger to life* | *none, extensive if failure* | | | | | |
| **2.** | **Environmental Separations** | | | | | | | | | |
| **2.1** | **Interior–to–Ground** | | | | | | | | | |
| *2.1.1* | *roofs below ground (under landscaped plaza)* | *monolithic cast-in-place r/c slab* | *60* | *loss of use, danger to life* | *none* | | | | | |
| | *– air & vapour barrier, moisture protection* | *exterior waterproof membrane* | *35* | *loss of use, appearance* | *extensive* | *patch, replace* | *as req'd, 35 yrs* | *removal (all materials above)* | | |
| | *– insulation* | *type 4 polystyrene* | *35* | *cost (damage to plants)* | *none* | *replace with work on membrane* | | | | |
| | *– drainage* | *granular fill under filter fabric* | — | *damage to plants* | *none* | *replace fabric* | *as req'd* | | | |
| | *– landscaping* | *(see 4.2)* | | | | | | | | |

*(Continued)*

## Table A3 (HRO) (Continued)

| **<u>The Office Block,</u> Othertown, Canada — <u>60 Year</u> DSL** | | | | | **Maintenance** | | | | **Cost** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Mainten-ance** |
| *2.1.2* | *walls* | *cast-in-place r/c* | *60* | *health (soil gas or humidity), loss of use* | *none, extensive if failure* | | | *excavation outside, OK inside* | | |
| | *– air & vapour barrier, moisture protection* | *exterior waterproof membrane* | *60* | *health, appearance* | | | | *excavation* | | |
| | *– capillary break /drainage layer* | *1/2" manufactured drainage layer with filter fabric* | *60* | *health* | | | | *excavation* | | |
| *2.1.3* | *slabs-on-ground* | *cast-in-place r/c with breathing sealer* | *25* | *loss of use, appearance* | *significant* | *clean, patch, reseal;*<br>*resurface, replace* | *yearly*<br>*25 yrs* | | | |
| | *soil gas protection* | *6 mil poly air barrier* | *60* | *health* | *none, significant if failure* | *replace* | | *remove slab* | | |
| | *under-slab drainage* | *granular fill, filter fabric* | *60* | *health* | *none* | | | | | |
| | *construction joints* | *gaskets* | | | | | | | | |
| *2.1.4* | *junctions* | | | *health, loss of use, appearance* | | | | | | |
| | *– roof to wall* | *gaskets* | | | *significant* | *replace* | | | | |
| | | *waterproof membrane* | *35* | | *see 2.1.1 & 2.1.2* | | | | | |
| | *– wall to floor* | *drainage tile* | *60* | | *none* | *replace if failed* | | *excavate* | | |
| | | *waterproof membrane* | *60* | | *see 2.1.2* | | | | | |
| | | *gaskets* | | | *significant* | *replace* | | | | |

*(Continued)*

## Table A3 (HRO) (Continued)

| The Office Block, Othertown, Canada — 60 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Maintenance** |
| **2.2** | **Interior–to–Exterior (Above Ground)** | | | | | | | | | |
| *2.2.1* | *type 1 (glass) curtain walls* | | *30* | *costly, appearance, loss of use, loss of life* | *significant* | | *30 yrs* | *swing stage* | | |
| | *– thermal insulation* | *75 mm rigid glass fibre* | *60* | *costly* | *extensive if failure* | *replace* | *30 yrs* | | | |
| | *– air/vapour barrier* | *22 ga prefinished metal pan* | *30* | *costly, risk of injury* | *extensive if failure* | *replace* | *30 yrs* | | | |
| | | *membrane between pan & window frame* | *15* | *costly, loss of use, danger to life* | *extensive* | *replace* | *15 yrs* | *removal of interior finish* | | |
| | *– moisture protection* | | | | | | | | | |
| | *– cladding* | *6 mm tempered spandrel glass* | *30* | *costly, danger to life* | *extensive* | *clean, replace* | *yearly, 30 yrs* | *swing stage* | | |
| | *– flashing* | | | | | | | | | |
| | *– seals* | | | | | | | | | |
| | *– drainage* | | | | | | | | | |
| | *– connectors, anchorages* | *stainless steel* | *60* | *danger to life* | *none* | *replace* | *30 yrs* | | | |
| *2.2.2* | *windows* | | | | | | | | | |
| | *– glazing* | *tinted sealed double glazed units* | *30* | *costly* | *significant* | *clean, replace* | *seasonally, 30 yrs* | *swing stage* | | |
| | *– flashing* | *prefinished aluminum* | *60* | *costly* | *extensive if failure* | *replace* | | | | |
| | *– seals* | *glazing beads* | *10* | *costly* | *significant* | *replace* | *10 yrs* | | | |

*(Continued)*

## Table A3 (HRO) (Continued)

| The Office Block, Othertown, Canada — 60 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Maintenance** |
| 2.2.3 | *type 2 (granite & glass) curtain walls* | | | *costly, appearance, loss of use, loss of life* | *significant* | | *30 yrs* | *swing stage* | | |
| | *– thermal insulation* | *50 mm rigid glass fibre* | *60* | *costly* | *extensive if failure* | *replace* | *30 yrs* | | | |
| | *– air/vapour barrier* | *sealant between precast backup panels* | *5* | *costly, danger to life* | *significant* | *replace sealant* | *5 yrs* | | | |
| | | *sealant between precast and window frame* | *5* | *costly, danger to life* | *significant* | *replace sealant* | *5 yrs* | *removal of interior finish* | | |
| | *– moisture protection* | | | | | | | | | |
| | *– cladding* | *granite panels* | *60* | *costly, danger to life* | *extensive* | *replace* | *as req'd* | *crane, swing stage* | | |
| | *– flashing* | *prefinished aluminum* | *60* | *costly* | *extensive* | *replace* | *as req'd* | | | |
| | *– seals* | *sealant* | *5* | *costly* | *significant* | *replace* | *5 yrs* | | | |
| | *– connectors, anchorages* | *stainless steel* | *60* | *danger to life* | *none* | *replace* | *30 yrs* | | | |
| | *– windows (see 2.2.2)* | | | | | | | | | |
| | *– doors*<br>*– swinging*<br>*– revolving* | *metal, metal & glass*<br>*metal & glass* | *60* | *loss of use, security, risk of injury* | *significant* | *clean, lubricate, adjust hardware* | *weekly*<br>*6 mths*<br>*6 mths* | | | |

*(Continued)*

## Table A3 (HRO) (Continued)

| <u>The Office Block</u>, Othertown, Canada — <u>60 Year</u> DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building Assembly | Materials/Type & Manufacturer | DSL, Years | Failure Category | Category | Type | Frequency | Access | Capital | Mainten-ance |
| 2.2.4 | *roof* | | *15* | *health, loss of use, costly* | | | | | | |
| | *slab/air barrier* | *cast-in-place r/c* | *60* | *danger to life, costly* | *none* | | | | | |
| | | *membranes at junctions* | *15* | *health, loss of use, costly* | *extensive* | *replacement* | *w/roofing replacement* | *removal of roofing* | | |
| | *thermal insulation* | *75 mm rigid* | *15* | *costly* | *extensive* | *replacement* | *15 yrs* | *removal of roofing* | | |
| | *moisture control – roofing* | *single ply membrane over membrane* | *15* | *costly, loss of use* | *significant* | *patching, replacement* | *as req'd, 15 yrs* | *disposal & delivery to roof* | | |
| | *– flashing (see also 2.2.6)* | *prefinished aluminum* | *15* | *costly, loss of use* | *significant* | *patching, replacement* | *as req'd, 15 yrs* | *removal of roofing* | | |
| | *– drains* | *aluminum* | *60* | *costly, loss of use* | *little* | *clean* | *annual* | *none* | | |
| | *ballast* | *filter fabric* | *15* | *costly* | *significant* | *replace* | *15 yrs* | *remove ballast* | | |
| | | *gravel ballast* | *60* | *danger to life, risk of injury from blow-off* | *little* | *remove & reinstall* | *15 yrs* | *storage during repair* | | |
| | *anchorages* | *mechanical fastening at perimeter* | *15* | *danger to life, risk of injury from blow-off* | *significant* | *replace* | *15 yrs* | *removals* | | |
| 2.2.5 | *roof openings* | | | | | | | | | |

*(Continued)*

## Table A3 (HRO) (Continued)

| The Office Block, Othertown, Canada — 60 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building Assembly | Materials/Type & Manufacturer | DSL, Years | Failure Category | Category | Type | Frequency | Access | Capital | Mainten-ance |
| 2.2.6 | *roof/wall junctions* | | | | | | | | | |
| | *– inner parapet and roof penetrations to roof moisture protection* | *prefinished aluminum flashing* | *15* | *costly, loss of use* | *significant* | *reseal, replace* | *15 yrs* | *removals* | | |
| | | *membrane vertical-surfaces-to-flashing* | *15* | *costly, loss of use* | *significant* | *reseal, replace* | *15 yrs* | *removals* | | |
| | | *membrane flashing-to-single-ply roofing* | *15* | *costly, loss of use* | *significant* | *reseal, replace* | *15 yrs* | *removals* | | |
| | *– outer parapet to curtain walls* | *prefinished aluminum flashing* | *15* | *costly* | *significant* | *replace* | *15 yrs* | *removal of materials* | | |
| | | *membrane, flashing sealed to glazing pocket* | *3* | *costly, loss of use* | *significant, extensive* | *replace* | *3 yrs* | *safety harnesses* | | |
| 2.3 | **Interior–to–Interior** | | | | | | | | | |
| 2.3.1 | *walls* | | | | | | | | | |
| | *– core, parking levels* | *concrete block* | *60* | *loss of life (smoke spread)* | *none* | | | | | |
| | *– core, upper levels* | *gypsum board* | *20* | *appearance, loss of use* | *significant* | *repair, redecorate* | *20 yrs* | | | |
| | | *on concrete block* | *60* | *loss of life (smoke spread)* | *none* | | | | | |
| | *– suite separations* | *Type X gypsum board both sides* | *20* | *appearance, loss of use, security* | *significant* | *repair, redecorate* | *20 yrs* | | | |
| | | *steel studs & resilient channels* | *20* | *loss of use* | *significant* | *relocate* | *20 yrs* | | | |
| | | *sound absorbing batts* | *60* | | | *relocate* | *20 yrs* | | | |
| | *– other partitions* | *(by tenants)* | | | | | | | | |

*(Continued)*

## Table A3 (HRO) (Continued)

| **The Office Block**, Othertown, Canada — **60 Year** DSL | | | | | **Maintenance** | | | | **Cost** | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Mainten-ance** |
| 2.3.2 | *wall openings* | | | | | | | | | |
| | *-windows*<br>*-in mall*<br>*-in suites* | <br>*by tenant*<br>*by tenant* | | *security, loss of use, danger to life (smoke spread)* | *little* | *clean* | *per tenant contract* | | | |
| | *-doors* | *hinged metal security doors,*<br>*or by tenant* | *60* | *security, loss of use, danger to life* | *little* | *cleaning, servicing, replace/ relocate* | *6 mths, annual* | | | |
| 2.3.3 | *floors* | *cast-in-place r/c slab* | *60* | *danger to life, loss of use* | *none* | | | | | |
| | *ceilings, mall & office levels* | *suspended gypsum board* | *60* | *loss of use, appearance* | *little* | *repair* | *20 yrs* | | | |
| | *ceilings, office level corridors* | *suspended acoustic tile* | *60* | *loss of use, appearance* | *little* | *replace panels* | *20 yrs* | | | |
| 3. | **Finishes, Furnishings, Fixtures** | | | | | | | | | |
| 3.1 | **Interior Finishes** | | | | | | | | | |
| *3.1.1* | *ceilings* | | | | | | | | | |
| | *– parking levels* | *none* | | | | | | | | |
| | *– mall level*<br>*– entrances, lobbies, concourse, washrooms* | *paint* | *10* | *cost* | *significant* | *repaint* | *10 yrs* | *ladders, scaffolding* | | |
| | *– rental space* | *fit-up by tenant* | | | | | | | | |
| | *– office levels*<br>*– corridors* | *acoustic tile* | *60* | *appearance, cost* | *little* | *replace* | *as req'd* | *ladders* | | |
| | *– washrooms* | *paint* | *10* | *appearance, cost* | *significant* | *repaint* | *10 yrs* | *ladders* | | |
| | *– offices* | *fit-up by tenant* | | | | | | | | |

*(Continued)*

# Table A3 (HRO) (Continued)

| The Office Block, Othertown, Canada — 60 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Maintenance** |
| *3.1.2* | *walls*<br>*– parking levels* | *painted concrete & block* | *5* | *appearance, cost* | *significant* | *repaint* | *5 yrs* | *ladders* | | |
| | *– mall level*<br>*– entrances, lobbies, concourse, washrooms* | *paint* | *5* | *appearance, cost* | *significant* | *repaint* | *5 yrs* | *ladders* | | |
| | | *tile* | *60* | | *little/none* | *clean* | *3 mths* | *OK* | | |
| | *– rental space* | *fit-up by tenant* | | | | | | | | |
| *3.1.3* | *– office levels*<br>*– corridors, washrooms* | *paint* | *5* | *appearance, cost* | *significant* | *repaint* | *5 yrs* | *ladders* | | |
| | *– offices* | *fit-up by tenant* | | | | | | | | |
| | *floors* | | | | | | | | | |
| | *parking levels*<br>*– stair & elevator lobbies* | *terrazzo* | *60* | *loss of use, danger of injury* | *little* | *cleaning, waxing* | *daily, monthly* | | | |
| | *– vehicle areas* | *sealer* | *5* | *loss of use* | *significant* | *sweeping, washing, resealing* | *seasonally,*<br>*5 yrs* | | | |
| | *mall level*<br>*– entrances/exits* | *steel grill* | *60* | *danger of injury* | *little* | *cleaning* | *monthly* | | | |
| | *– lobbies, concourse, washrooms* | *terrazzo* | *60* | *loss of use, danger of injury* | *little* | *cleaning, waxing* | *daily, monthly* | | | |
| | | *tile (concourse)* | *60* | *loss of use* | *little* | *cleaning, waxing* | *daily, monthly* | | | |
| | *– rental space* | *fit-up by tenant* | | | | | | | | |

*(Continued)*

## Table A3 (HRO) (Continued)

| The Office Block, Othertown, Canada — 60 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | **Building Assembly** | **Materials/Type & Manufacturer** | **DSL, Years** | **Failure Category** | **Category** | **Type** | **Frequency** | **Access** | **Capital** | **Maintenance** |
| | *office levels – corridors* | *carpet* | *10* | *cost, appearance* | *significant* | *clean, replace* | *daily, 10 yrs* | | | |
| | *– washrooms* | *terrazzo* | *60* | *loss of use, danger of injury* | *little* | *cleaning, waxing* | *daily, monthly* | | | |
| | *– offices* | *fit-up by tenant* | | | | | | | | |
| **3.2** | **Furnishings** | | | | | | | | | |
| *3.2.1* | *fixed mall furniture – information desk* | | *20* | *loss of use, appearance* | *little* | *cleaning* | *daily* | | | |
| | *– directory board* | | *10* | *loss of use, appearance* | *little* | *cleaning* | *daily* | | | |
| | *– seating* | | *60* | *danger of injury* | *little* | *cleaning* | *daily* | | | |
| 3.3 | Fixtures | | | | | | | | | |
| *3.3.1* | *handrails* | *painted tubular metal* | *60* | *danger of injury or to life* | *little* | *cleaning, painting* | *daily, annually* | | | |
| *3.3.2* | *guards* | *painted metal* | *60* | *danger of injury or to life* | *little* | *cleaning, painting* | *daily, annually* | | | |
| **4.** | **Site** | | | | | | | | | |
| **4.1** | **Hard Surfaces** | | | | | | | | | |
| *4.1.1* | *pedestrian* | *pavers,*<br>*cast-in-place concrete* | *60*<br>*60* | *injury, loss of use*<br>*injury, loss of use* | *little*<br>*little* | *resetting*<br>*repair* | *5 yrs*<br>*5 yrs* | | | |
| *4.1.2* | *vehicular* | *asphalt over cast-in-place concrete* | *60* | *injury, loss of use* | *significant* | *resurfacing* | *5 yrs* | | | |
| *4.1.3* | *other* | | | | | | | | | |

*(Continued)*

## Table A3 (HRO) (Concluded)

| The Office Block, Othertown, Canada — 60 Year DSL | | | | | Maintenance | | | | Cost | |
|---|---|---|---|---|---|---|---|---|---|---|
| | Building Assembly | Materials/Type & Manufacturer | DSL, Years | Failure Category | Category | Type | Frequency | Access | Capital | Mainten-ance |
| 4.2 | Soft Surfaces | | | | | | | | | |
| *4.2.1* | *grassed areas* | *grass over artificial hummocks* | *10* | *loss of use, appearance* | *significant* | *cut, water,<br>fertilize,<br>resod* | *weekly<br>annually<br>10 yrs* | | | |
| | | *drainage (see 2.1.1)* | | | | | | | | |
| *4.2.2* | *flower and tree beds* | *trees in flower beds* | *30* | *appearance, danger of injury* | *little* | *pruning* | *annually* | | | |
| | | *flower displays* | *1* | *appearance* | *significant* | *planting, weeding* | *annually* | | | |
| | | *drainage (see 2.1.1)* | | | | | | | | |

# *Appendix B*
# ***Costs of Premature Deterioration in Buildings***

**Note:** *This Appendix is included for information purposes only.*

## B1. The Costs of Repairs

The costs arising from failing to achieve durability in buildings are both direct and indirect. The costs of unplanned major repairs or renovations required to reached the desired service life of a building are direct, but there are often substantial losses in revenue associated with disruptions to normal business while renovations and repairs take place. Information is hard to find on either category, but some indication of direct costs can be offered through two quite different approaches.

One approach, used to assess the impact of ageing assets for the Advisory Board on the National Research Council's (NRC) Construction Program (Dalgliesh, 1992), was to collect reports of rehabilitation projects, giving costs on a case-by-case basis. These reports indicated that the building envelope is generally the system most vulnerable to premature deterioration. In 1989, unsettled claims against Canadian architects and engineers for failing facades reached $50 million, and the Ontario New Home Warranty paid out $29 million for facades over a two year period. Only roofs give rise to more claims, but if the trend continues, facades will move into the lead. Office renovations deemed newsworthy usually report costs in the range of $5 – $30 million each, with some (Amoco Building in Chicago) going as high as $80 million (Clinton, 1991; Chevin, 1991). Upon identifying the building envelope as particularly vulnerable to durability problems, the Institute for Research in Construction of the NRC engaged a consultant to conduct a national assessment of the Canadian roofing and exterior cladding market (NRC, 1993), with instructions to estimate how much is being spent to correct premature failures. In the end, this second approach was based on establishing expected service life benchmarks for roofing and cladding systems (Dell'Isola & Kirk, 1981). Premature failure was then defined as any performance condition requiring repair or replacement of the system before the benchmark date. The results of the study gave an average annual expenditure (in 1993 dollars), for roofing and exterior wall systems combined, of $7.5 billion. A conservative estimate of premature failure rate was calculated as 3% to 5%, ie, $235 – $380 million per year.

## B2. Further Reading

For reports referred to above and for further reading on the costs of premature deterioration, see Clause G2 in Appendix G.

# Appendix C
# Assessment of Environmental Conditions

**Note:** *This Appendix is included for information purposes only.*

## C1. General

Environmental conditions are those chemical and physical exposures to which materials, *components,* or *assemblies* are subjected and which may result in *failure* due to material deterioration or movements. *Service life* of materials is determined by the interaction of the materials with their *environments.* Designing for *durability* implies the need to control or eliminate those *agents* promoting *failure.*

In dealing with *durability,* two scales of *environment* must be considered: the macro-environment adjacent to the *assembly* (atmospheric and ground conditions, including pollution, outside the building; heating, humidification, and ventilation conditions inside the building) and the micro-environment at the surface of, and within, materials and *components.*

This Appendix provides information on
(a) the environmental *agents* which potentially can damage building materials and *assemblies;*
(b) the assessment of *component* conditions and parameters; and
(c) classifications of environmental severity for some common building materials.

## C2. Environmental Agents That Can Affect Service Life

Chemical action takes place continuously in many construction materials. These actions may be beneficial (gradual increase in concrete strength due to chemical changes in the cement) or detrimental (embrittlement of plastics exposed to ultraviolet radiation). Some chemical actions are entirely dependent upon constituents of the material but many are in response to *agents* such as moisture, temperature, and chemicals present in their *environment,* such as carbon dioxide ($CO_2$) and sulphur dioxide ($SO_2$). Frequently the action of one *agent* is dependent on the presence of another, moisture and oxygen being a common pairing. Table C1 lists the most common *agents* that may affect the *durability* of building *components.*

Physical action of environmental *agents* plays an important role in the deterioration of materials, *components,* and *assemblies.* The physical action of temperature and moisture fluctuation and/or gradient can either be direct (eg, cracking and joint movement (Beall, 1990; BRE, 1991) or indirect (eg, separation between cladding panels due to temperature drop or drying shrinkage can facilitate ingress of water and other *agents* into the wall *assembly* (ASTM, 1991) with the resulting damage being either chemical in nature (corrosion of cladding ties and anchors) or physical in nature (loss of thermal efficiency of insulation)).

## C2.1 Water

Water in the atmosphere in its various states (gas, liquid, or solid) interacts with material surfaces in several forms: adsorbed moisture (low relative humidity); condensed water (high relative humidity eg, dew); and precipitation (eg, fog, rain, snow). Water plays a major role in the corrosion of metals, the decay of wood, and the deterioration of other materials, either as an *agent* of change or a means of transport of other *agents.* In the case of corrosion and other deterioration inside buildings and *assemblies,* the presence of water is usually a result of condensation on material surfaces.

Most organic and many inorganic materials are porous and absorb moisture to varying degrees. Porous materials which are saturated or nearly saturated may be fractured by the expansive forces exerted when the contained water freezes. Fluctuations in the moisture content of porous materials can cause them to expand and contract as moisture is absorbed and given off. These movements must be accommodated in the design. Thermal properties of insulation materials are detrimentally affected by absorption of water. Organic materials such as wood will also decay if exposed to excessive moisture in the presence of oxygen and fungi.

The formation of and growth of ice lenses in moist fine grained soils can lift buildings and cause serious structural damage through frost heave of foundations and supported structures or by lateral displacement of retaining walls.

The source of water may be from rainfall, moisture migration from the ground or the interior of a building, or melt water when frost or ice formed on a surface melts. This latter source of water can be more damaging than the others since it produces saturation at just above the freezing point while leaving little opportunity for evaporation.

## C2.2 Air

Air, like water, is both an active environmental *agent* and a means of transport.

Atmospheric oxygen ($O_2$) acts as an *agent* which causes corrosion when present with moisture, and allows decay to develop when in the presence of both fungi and adequate moisture. Carbon dioxide ($CO_2$) acts as an *agent* of corrosion of reinforcing steel by reducing the alkalinity of concrete and, as a consequence, the passivity of the rebar surface.

Air provides a means of transport of other environmental *agents* such as water and chlorides, with air leakage through the building *envelope* being a major cause of problems.

## C2.3 Air Contaminants

The major air pollutants causing deterioration problems are oxides of nitrogen and sulphur, and salts. Precipitation becomes acidified as a result of dissolution of gases (Lipfert, 1987). Particulate matter in the air deposited on building surfaces can contribute to material deterioration. Hygroscopic deposits (eg, salts, dust, pollen) on material surfaces have been found to decrease the relative humidity at which a moisture film will form on a surface (ASTM, 1982).

### Sulphur Dioxide

The sulphur compounds, and especially sulphur dioxide ($SO_2$), constitute the most important pollutant in the atmosphere today. The main source of sulphur dioxide has been identified as the use of fossil fuels (mainly coal with a relatively high sulphur content), including motor vehicle traffic. Consequently, the concentration of sulphur dioxide varies considerably depending on the distance from the sources of emission and the time of year. Its concentration in industrial areas and densely populated areas is sufficient to accelerate the deterioration of materials. The effect of $SO_2$ on the deterioration of materials is dependent on its deposition on material surfaces which in turn is dependent on other factors such as wind flow near the surface of the material, the presence of a film of moisture on the surface, and the nature of the surface. Proximity to a source of $SO_2$ has been demonstrated to be a major factor affecting deterioration of building materials.

### Oxides of Nitrogen

Oxides of nitrogen enter the atmosphere as a result of natural processes such as lightning and microbiological processes, through agricultural activities involving the use of nitrogen fertilizers, and by combustion of fossil fuel. In the presence of water, oxides of nitrogen can form nitric acid which could be detrimental for most building materials. However, the amount of nitric acid in the atmosphere is very small and its role on the deterioration of building materials is not clear.

### Chlorides

Although not normally considered as pollutants, chlorides from sea spray may be regarded as a form of particulate pollution. The carriage of sea-salt inland from coastal regions has long been recognized as an important contributor to atmospheric corrosion problems and stone deterioration in most maritime regions. It has been found that chloride deposition decreases with distance inland, with a consequent decrease in rate of corrosion. Although most of the decrease occurs within one to two kilometres from the shore, the effect can be significant at much greater distances. Since sodium chloride can take up water from the atmosphere at relatively low relative humidity, sea-salt deposits can pose severe *durability* hazards to metal building claddings, especially on surfaces sheltered from rain.

Chlorides can also originate from industrial sources such as hydrochloric acid manufacturing plants and from the combustion of coal, paper, and chlorine-containing plastics. These latter sources are also responsible for the presence of hydrochloric acid in the atmosphere. Chlorides from deicing salts are also found in abundance and are a major cause of much deterioration on North American roadway infrastructure.

## C2.4 Soils and Ground Contaminants

Any material placed in contact with contaminated soils and contaminated groundwater may be affected by the presence of the contaminants. The effect of soil contaminants depends on their combination, on their concentration, and on the soil type. Contaminants such as solvents (eg, gasoline) and oxidizing *agents* (eg, acids) can react chemically and dissolve or degrade plastics. Bacterial activity can affect directly or indirectly the deterioration of materials in soils. Sulphate reducing bacteria, found mostly on wet clay, boggy soils, and marshes, are a typical example of bacteria affecting corrosion of metals.

Naturally occurring constituents of the soil may promote deterioration of building materials, particularly in moist conditions. Salts dissolved in groundwater can migrate in porous materials in contact with the ground and cause efflorescence, a common problem with masonry in contact with the soil. Naturally occurring sulphates in some soils require the use of specially formulated concretes and masonry mortars to avoid their destruction due to the effects of the sulphates.

Stray currents are extraneous direct electrical currents in the ground. When a metallic object is placed in a strong current field, a potential difference develops across the object and accelerated corrosion occurs at points where current leaves the object and enters the soil. This is especially pronounced in densely populated oil production fields and within industrial complexes containing numerous buried pipelines.

## C2.5 Biological Agents

Building materials can suffer from the direct action of living organisms (eg, deterioration of wood by fungi) or from the action of by-products of plant or animal life (eg, corrosion of metals by the action of sulphate reducing bacteria).

Microorganisms are usually classified according to their ability to grow in the presence or absence of oxygen. Fungi that cause deterioration of timber need oxygen and moisture (CBD 111, 1969). A moisture content of less than about 20% in timber is usually sufficient to prevent fungi from flourishing. Sulphate reducing bacteria are most prevalent in *environments* depleted of oxygen.

Insect attack is predominantly a problem with timber and timber-based materials. The best known insect problem with timber is attack by termites.

Rodents such as mice and rats can cause considerable damage by gnawing organic materials and PVC casings to electric cables. Birds and their nests and droppings can cause either mechanical damage (by pecking of soft materials) or by chemical damage (corrosion of steel bridges exposed to bird droppings).

The major cause of damage from plants takes the form of disruption of foundations or clogging of drains and gutters by roots. Trees absorb water from the soil which, for some soils, may result in differential settlement.

## C2.6 Temperature

One of the most significant effects of temperature is the thermal stress that is placed on all materials subject to variations in temperature. Roofing systems and cladding *components* are subjected to high temperatures in summer and very cold temperatures in winter and must expand and contract as the temperature cycles. Thermal stresses can cause buckling, bowing, and sometimes breakage of building *components*.

Although most chemical processes are accelerated by an increase in temperature, a decrease in temperature can also have a similar effect. This is the case for corrosion of metals where low surface temperatures promote the condensation of vapour on the surface, providing an *environment* favourable to corrosion. However, if the surface temperature is high, drying of the surface will impede corrosion.

### C2.7 Solar Radiation

Organic materials such as polymers and wood may deteriorate if exposed to solar radiation. Solar radiation at the earth's surface has been considerably altered by filtration through the atmosphere. The highest energy wavelengths, corresponding to the shortest ultraviolet wavelengths emitted by the sun, are absorbed by ozone in the upper atmosphere so that only UV radiation having the lowest energy is received at ground level.

When a material absorbs radiation, the energy level of one particular atom is raised. The excited atom may return to its unexcited state by dissipating the energy by heat or other types of radiation without damage to the molecules. This is what usually happens when materials are irradiated with longer wavelength radiation such as visible light or infra-red radiation. If radiation contains enough energy, however, it may cause a chemical reaction which is manifested by a gradual change of the material properties such as embrittlement, yellowing, or fading of the colour. Sealants, as a result of long molecule scission when exposed to UV and subsequent cross-linking of the shorter molecular chains, may either crack or lose adhesion at the interface.

Before solar radiation can affect a material it is necessary for radiation to be absorbed. The opacity, texture, and colour of the surface has a considerable effect on the ability of materials to absorb radiation. The molecular arrangement of the materials determines the amount and type of waves that are absorbed. The amount of high energy UV reaching the ground decreases as the sun angle decreases. Consequently, shading organic material surfaces when the sun is high is an effective way to decrease deterioration due to UV radiation.

UV radiation also interacts with other *agents* such as temperature and moisture to produce an effect greater than the sum of individual effects (CBD 122, 1970).

Solar radiation on building surfaces has a very important effect on surface temperatures. The daily cycle of solar radiation can cause building surfaces to experience large temperature swings. This in turn results in cyclic dimensional changes to the building materials and it may also increase the number of freeze-thaw cycles.

### C2.8 Chemical Incompatibility

Two materials in contact may cause or accelerate deterioration as a result of chemical interaction. Some examples are

(a) galvanic corrosion between dissimilar metals (see Appendix E);
(b) crazing or fracture of plastic in contact with certain sealants (BRANZ 242, 1985);
(c) accelerated corrosion of steel and zinc in certain woods and wood containing certain preservative chemicals (ASTM STP 691, 1980); and
(d) corrosion of lead and some aluminum alloys in contact with moist concrete or mortar.

## C3. Environmental Parameters

### C3.1 Time-of-Wetness

Time-of-wetness has been found to be one of the most important parameters in materials deterioration. Corrosion, for example, takes place when the surface of the metal is covered by a film of water. The presence of that film of water on the surface of metals exposed to the atmosphere has been found to occur when the relative humidity is above 80 to 90 percent and the temperature is above freezing. Also, the time-of-wetness depends on details (eg, retention of moisture between surfaces; gravity water traps). With natural ventilation, the indoor relative humidity (RH) can approach the outdoor relative humidity, whereas with air-conditioning and space heating, the indoor relative humidity can be significantly lower than the outdoor relative humidity, especially during cold weather.

## C3.2 Driving Rain Index (and Driving Rain Wind Pressure)

In the absence of wind, rain does not generally wet vertical walls; it is the combination of rain and wind that wets vertical surfaces. Wind impinging on a facade during a rain storm will cause water to migrate to vertical troughs and cavities and to accumulate as it channels its way downwards over a building facade. The product of the annual average rainfall and annual average wind speed is an indicator of the likelihood of rain penetration. Figure C1 shows the driving rain index (the product of annual rainfall, m, and average wind speed, m/sec) across Canada (Boyd, 1963). The regions of sheltered, moderate, and severe conditions are based solely on the index figures, and should be modified as follows according to local conditions:

(a) sheltered conditions are in districts where the driving rain index is 3 or less, excluding areas that lie within 8 km of the sea or large estuaries, where the exposure should be regarded as moderate;

(b) moderate conditions are located in districts where the driving rain index is between 3 and 7, except in areas which have an index of 5 or more and which are within 8 km of the sea or large estuaries, in which exposure should be regarded as severe; and

(c) severe conditions are located in areas with driving-rain index of 7 or more.

Also, in areas of sheltered or moderate exposure, high buildings which stand above their surroundings or buildings of any height on hill slopes or hill tops should be regarded as having an exposure one grade more severe than that indicated by the map.

A less well known but possibly more useful measure for assessing wind/rain effects is the new Driving Rain Wind Pressure (DRWP) data from Environment Canada. It is incorporated with explanation for its application in CSA Special Publication A440.1-M1990.

## C3.3 Acidity of Precipitation

Acidity of precipitation, expressed as pH, is determined by the quantities of substances in the atmosphere. The normal pH of rain, as a result of equilibrium with carbon dioxide and carbonic acid, is approximately 5.6. Organic acids and background air pollution levels can act to reduce pH levels to below 5.0 In general, pH levels much greater than 5.0 will have been influenced by alkaline particles. Figure C2 is a plot of pH levels as measured by current networks operating for various agencies in North America. Urban pH levels, because of local sources of pollutants, can be somewhat below the values shown in Figure C2. The importance of pH with respect to metallic corrosion is discussed in Appendix E.

# C4. Macro-Environments

The outdoor macro-environment is characterized by climatological and ground conditions, including pollution. *Environments* in the ground are affected not only by climatological conditions and pollution sources, but also by the nature of the ground constituents. As a result, *environments* in the ground are very complex and very variable both in space and time.

The nature of the indoor *environment* depends primarily on the operational conditions for heating, humidification, and air conditioning of the building, and the presence of moisture sources such as swimming pools and contaminants such as chlorides. There may be several distinct indoor *environments* within any multi-functional building.

# C5. Micro-Environments

Materials are influenced by the *environment* in their immediate vicinity, ie, the micro-environment. The micro-environment to which a material or *component* is exposed reflects the macro-environment acting adjacent to the *assembly*, modified by the *assembly* itself and the porosity and permeability of the materials and *components*. The micro-environment results from the complex interaction between the macro-environment and the building *component* and *assembly*. Although little can be done to modify the macro-environment (except indoors), the micro-environment can be controlled. Control of the micro-environment can be achieved from a fundamental appreciation and understanding of the various transport mechanisms by which *agents* in the macro-environment gain access to building *components*.

The mechanisms of concern are those which govern the flow of air, water, and heat. Further guidance on environmental transport mechanisms through building *envelopes* is contained in the *Commentary to Part 5* of the *NBCC.*

In designing for *durability* one can either select a material to resist the effects of the *environment*, or the *environment* must be altered to suit the material. Figure C3 illustrates some instances where the micro-environment can be altered to suit the material by simple alterations in the design of a detail. Figure C3 (a) shows that by a relatively simple change in the design of a lap joint, an undesirable water trap can be avoided. A similar condition where a channel member, placed in a position which favours collection of water, can be modified in various ways to alter the micro-environment which would cause deterioration of the member. Figure C3 (e) shows a condition where a material resistant to the detrimental micro-environment is used to alter the micro-environment at the base of a column.

## C6. Classification of Environmental Severity

Once the micro-environment has been assessed, by educated guess, by environmental simulation test, or by monitoring of existing buildings, the *environment* can be classified in terms of severity. Since different materials are affected differently by different environmental *agents*, it is hardly conceivable that a single *environment* classification system could be used for all materials in a building. The Decay Hazard Map for North America, Figure C4, shows the decay potential, based on the combined effects of average daily precipitation and temperatures above threshold levels, for exposed wood in above-ground applications.

Table C2 presents the classification system used in the CIB-FIP Model Code for reinforced concrete. Essentially, the level of humidity, chloride concentration, temperature, and the presence of chemical *agents* are the main factors affecting the rate of deterioration of reinforced concrete.

Table C3 presents an *environment* classification system for metals (eg, steel, zinc, copper, aluminum) based on time-of-wetness (Table C3 (a)), level of $SO_2$ contamination (Table C3 (b)), and concentration of chlorides in the atmosphere (Table C3 (c)). Table C3 (d) makes use of the categories obtained from the first three tables to classify the *environment* in terms of its corrosivity. The lowest level of corrosivity corresponds to an *environment* in which negligible amounts of metal loss would take place whereas the highest level, designated as very severe (VS), would result in a fast deterioration of the metal. The corresponding level of protection necessary to ensure adequate *durability* should be selected based on the severity of the *environment*. Metals in *environments* classified as VL would probably not need protection while a metal in an *environment* with a VS classification would probably need an elaborate protection system. The level of protection necessary, however, also depends on local rates of deposition of $SO_2$ (see Clause C2.3) and the type of metal.

## C7. References

For reports referred to above and for further reading on the assessment of environmental conditions affecting building components, see Section G3 in Appendix G.

# Table C1
# Environmental Agents That Can Affect Service Life

(See Clause C2.)

| Agent | Type | Clause No. |
|---|---|---|
| Moisture | solid (ice, snow),<br>liquid (rain, condensation),<br>gas (water vapour, humidity) | C2.1 |
| Air constituents | $O_2$, $CO_2$ | C2.2 |
| Air contaminants | oxides,<br>particulates,<br>sea spray | C2.3 |
| Ground constituents | sulphates and other salts,<br>acids (from decomposition of organic matter) | C2.4 |
| Ground contaminants | chemicals from spills and leaks,<br>chlorides from road salt,<br>induced electrical currents | C2.4 |
| Biological *agents* | microorganisms,<br>insects,<br>other animals,<br>plants | C2.5 |
| Temperature | | C2.6 |
| Solar radiation | UV (ultraviolet) radiation | C2.7 |
| Incompatible chemicals | | C2.8 |
| Differential movements | between *components* (shrinkage and swelling),<br>within massive materials (temperature gradient response),<br>creep/flow | |
| Use or exposure | loading,<br>abrasion,<br>overloading | |

# Table C2
# Exposure Classification for Reinforced Concrete

(Source: CIB-FIP Model Code for Reinforced Concrete)
(See Clause C6.)

| **Exposure** | | **Environmental Conditions** |
|---|---|---|
| Dry *environment* | | – interior of buildings for normal habitation or offices* |
| Humid environment | without frost | – interior of buildings where humidity is high<br>– exterior *components*<br>– *components* in non-aggressive soils and/or water |
| | with frost | – exterior component exposed to frost<br>– *components* in non-aggressive soils and/or water and exposed to frost<br>– interior *components* when the humidity is high and exposed to frost |
| | with frost & de-icing *agents* | – interior and exterior *components* exposed to frost and de-icing *agents* |
| Seawater environment | without frost | – *components* completely or partially immersed in seawater, or in the splash zone<br>– *components* in saturated salt air (coastal area) |
| | with frost | – *components* partially immersed in seawater or in the splash zone and exposed to frost<br>– *components* in saturated salt air (coastal area) |
| ***The following classes may occur alone or in combination with the above classes.*** | | |
| Aggressive chemical *environment* | slightly aggressive | pH between 6.5 and 5.5; or<br>15–40 mg/l carbonic acid dissolving lime ($CO_2$); or<br>15–30 mg/l ammonium ($NH_4^+$); or<br>300–1000 mg/l magnesium; or<br>200–600 mg/l sulphate |
| | moderately aggressive | pH between 5.5 and 4.5; or<br>40–100 mg/l carbonic acid dissolving lime ($CO_2$); or<br>30–60 mg/l ammonium ($NH_4^+$); or<br>1000–3000 mg/l magnesium; or<br>600–3000 mg/l sulphate |
| | highly aggressive | pH less than 4.5; or<br>more than 100 mg/l carbonic acid dissolving lime ($CO_2$); or<br>more than 60 mg/l ammonium ($NH_4^+$); or<br>more than 3000 mg/l magnesium; or<br>more than 3000 mg/l sulphate |

** This exposure class is valid only as long as, during construction, the structure or some of its components is not exposed to more severe conditions over a period of several months.*

## Table C3
## Environmental Classification for Corrosion of Metals

(adapted from ISO/DP 9223)
(See Clause C6.)

### (a) Classification of Time-of-Wetness of Corroding Metallic Surfaces

| Category | Time-of-wetness<br>Hours/year | % of year | Examples |
|---|---|---|---|
| $\tau_1$ | < 10 | < 0.1 | indoor air without climatic control |
| $\tau_2$ | 10–250 | 0.1–3 | indoor air without climatic control except for indoor non-air-conditioned space in humid regions |
| $\tau_3$ | 250–2500 | 3–30 | outdoors in dry and very cold regions; well ventilated sheds in temperate zones |
| $\tau_4$ | 2500–5500 | 30–60 | outdoors in all zones except for dry tropical zones and extremely cold zones |
| $\tau_5$ | > 5500 | > 60 | very damp regions;<br>unventilated closed sheds in humid conditions |

### (b) Classification of Pollution by Sulphur-containing Substances Represented by $SO_2$

| Category | Deposition rate of $SO_2$ mg/m$^2$/day | Concentration of $SO_2$ ppb | Examples |
|---|---|---|---|
| $P_1$ | < 35 | < 15 | clean, unpolluted rural air |
| $P_2$ | 35–80 | 15–30 | polluted urban area |
| $P_3$ | 80–200 | 30–85 | heavily polluted area near a chimney stack or other local emission source |

*(Continued)*

## Table C3 (Concluded)

### (c) Classification of Pollution by Airborne Salinity Represented by Chloride

| Category | Deposition rate of chloride, mg/m$^2$/day | Examples |
|---|---|---|
| $S_1$ | < 60 | inland, at a good distance from the sea shore |
| $S_2$ | 60–300 | |
| $S_3$ | 300–900 | within 1 to 2 km from the sea shore;<br>exposed to use of de-icing salts |

### (d) Estimated Corrosivity Categories of the Atmosphere from Environmental Characteristics

| | $P_1$ | | | $P_2$ | | | $P_3$ | | |
|---|---|---|---|---|---|---|---|---|---|
| | $S_1$ | $S_2$ | $S_3$ | $S_1$ | $S_2$ | $S_3$ | $S_1$ | $S_2$ | $S_3$ |
| $\tau_1$ | VL | VL | L | VL | VL | L | L | L | L |
| $\tau_2$ | VL | L | M | L | M | M | L | M | S |
| $\tau_3$ | M | S | S | S | S | S | S | VS | VS |
| $\tau_4$ | M | S | VS | S | S | VS | VS | VS | VS |
| $\tau_5$ | S | VS | VS | VS | VS | VS | VS | VS | VS |

**Notation:**

*VL — very light to negligible corrosion*
*L — light corrosion*
*M — moderate corrosion*
*S — severe corrosion*
*VS — very severe corrosion*

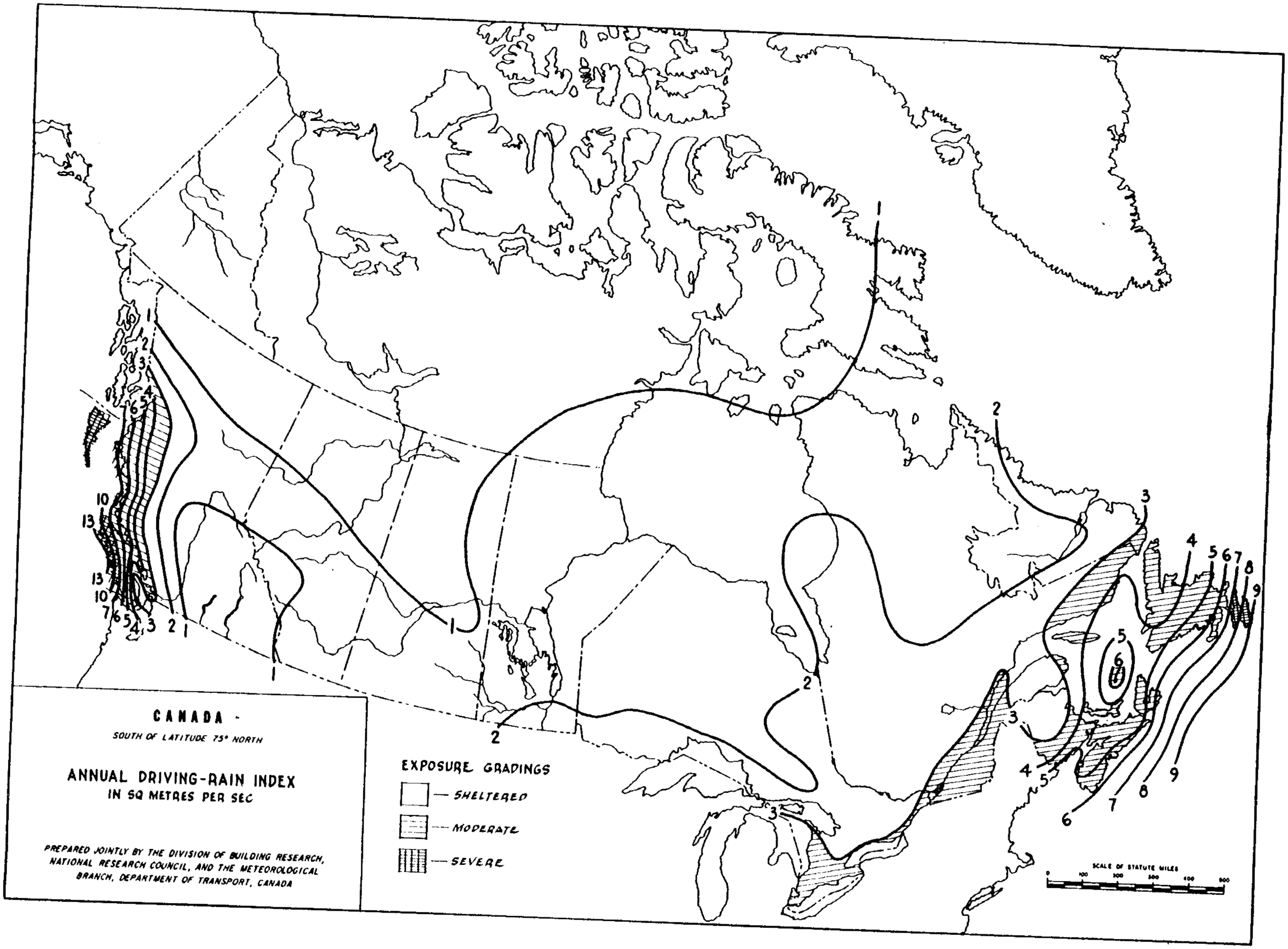


**Figure C1**
**Annual Rain Index**
(See Clause C3.2.)

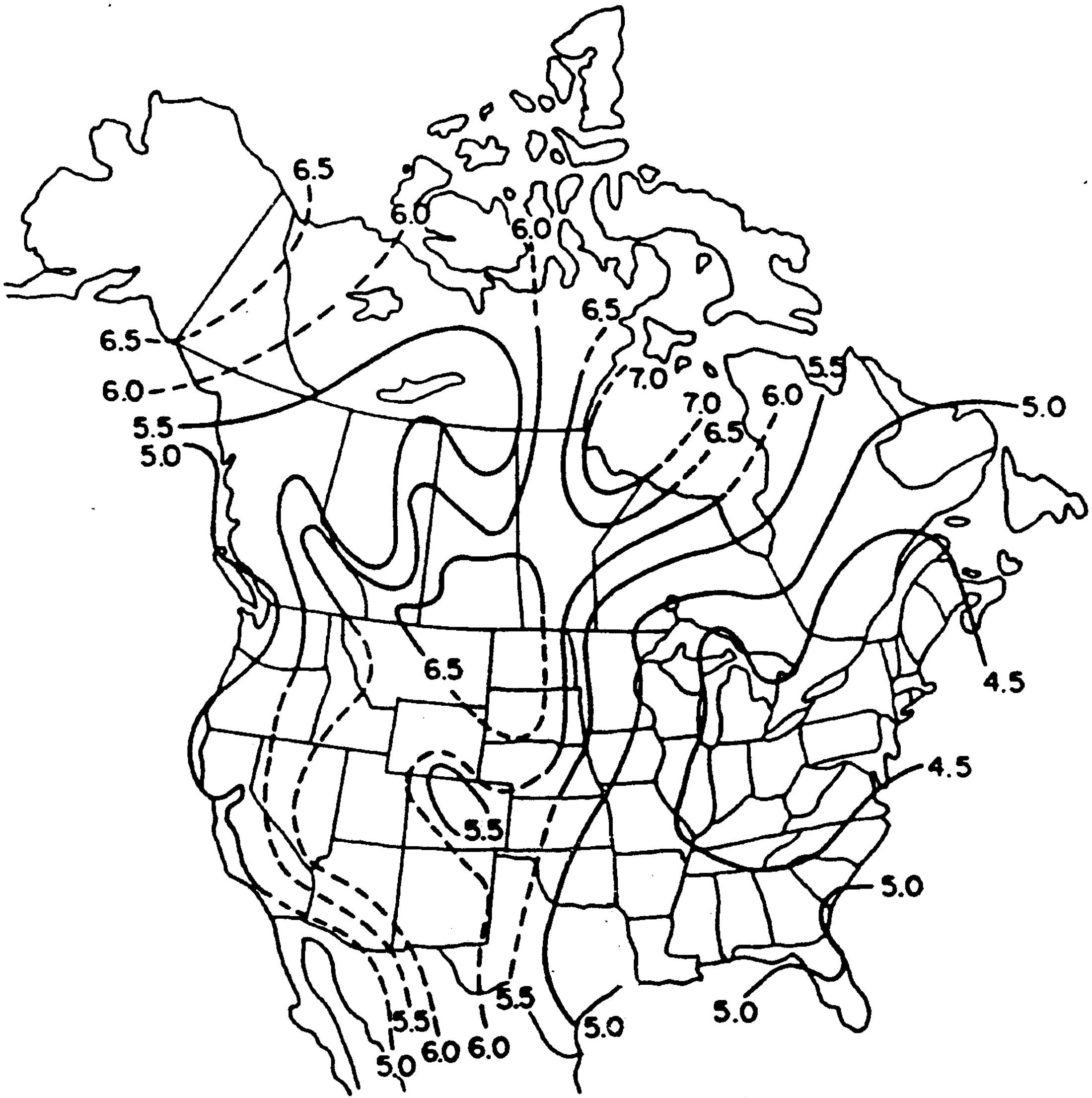
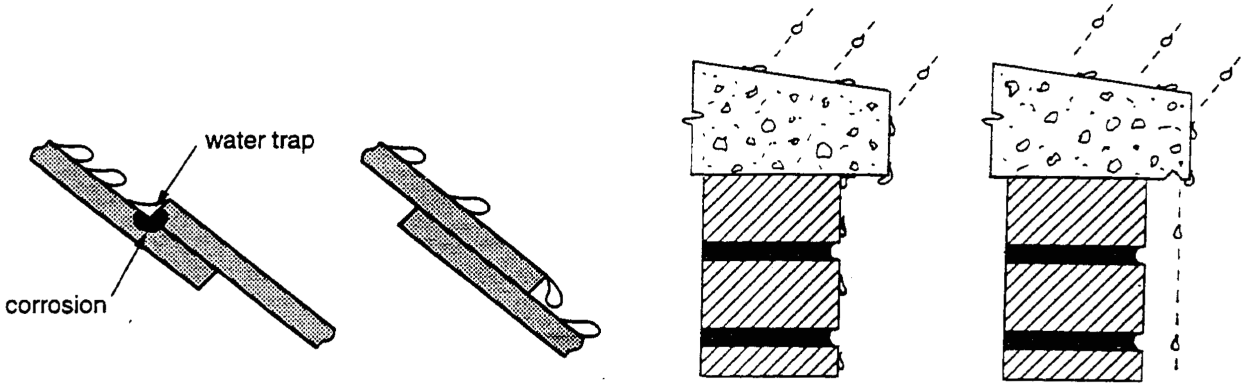
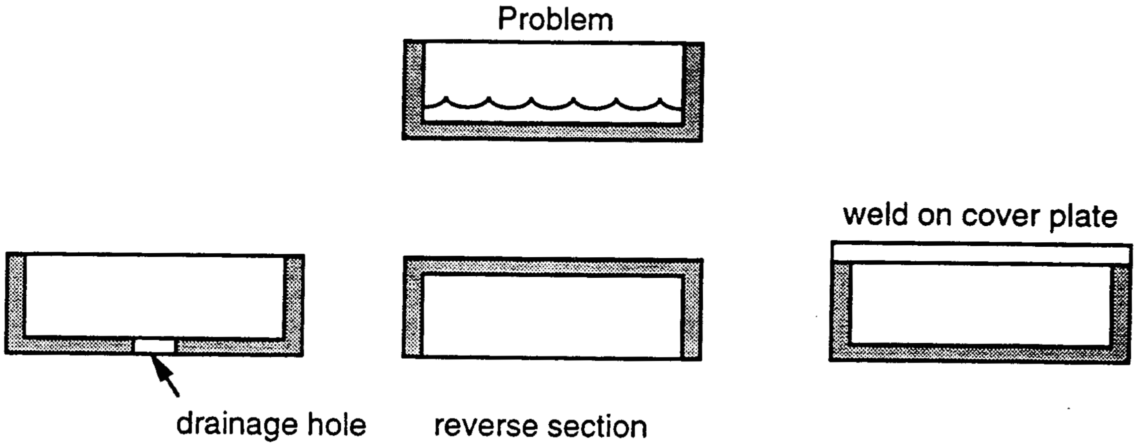


**Figure C2**
**Weighted Mean pH of Precipitation for North America for the Period 1976 – 1979**
(See Clause C3.3.)

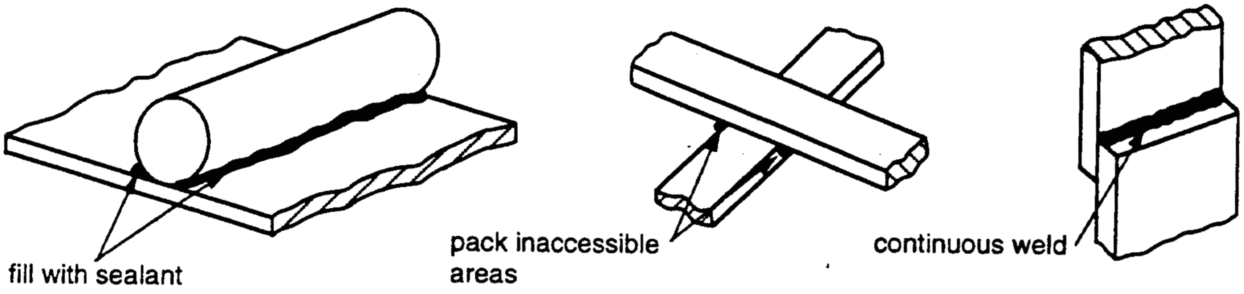


(a) Lap Joint

(b) Drip Edge



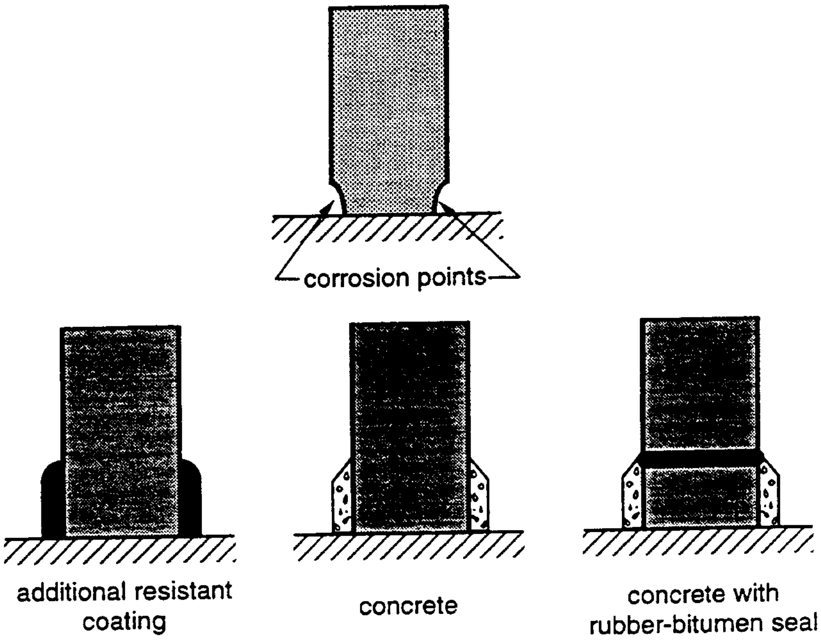
(c) Controlling Water Accumulation in Channel Section



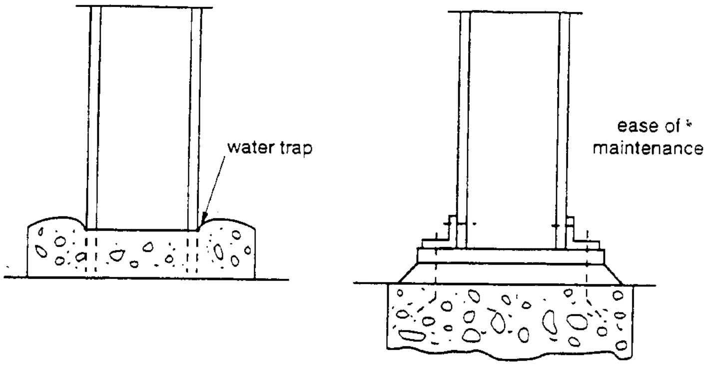
(d) Filling Crevices Where Water or Dirt Can Collect

*(Continued)*

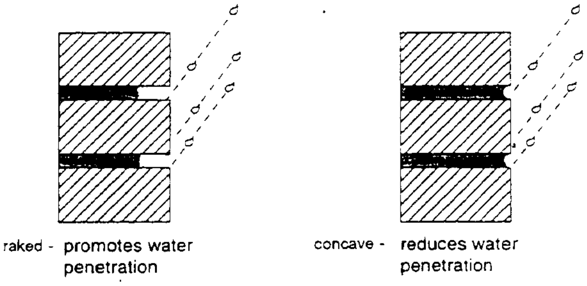
**Figure C3**
**Micro-Environment Changes Through Changes in Detailing**
(See Clause C5.)



(e) Protection of Environment-Sensitive Column Base

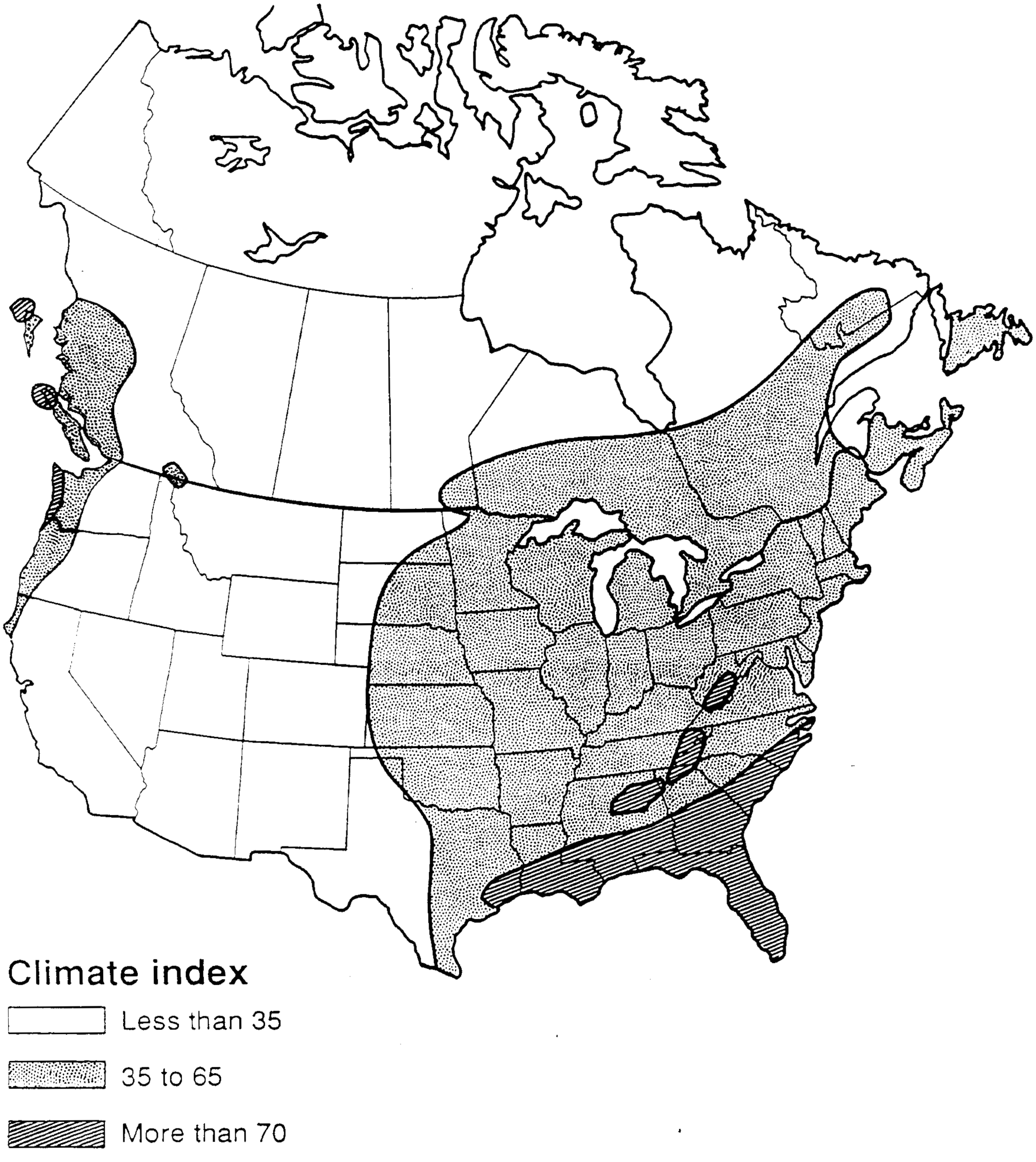


(f) Avoidance of Water Trap at Column Base



(g) Reducing Water Penetration Through Brick Veneer

**Figure C3 (Concluded)**



(Sources: Scheffer, 1971; DeGroot & Esenther, 1982; Setliff, 1986)

**Figure C4**
**Decay Hazard Map for North America**
**(For Wood in Above-Ground, Exposed Applications)**
(See Clause C6.)

# Appendix D
# Deterioration Mechanisms for Building Materials and Their Control

**Note:** *This Appendix is included for information purposes only.*

## D1. General

This Appendix summarizes, in tabular form, the various possible mechanisms which may lead to the deterioration of building materials, conditions under which the deterioration process can proceed, and primary avoidance strategies. Initial sources for further reading are identified in the right hand column of the tables.

## D2. Additional References

The references in Section G4 of Appendix G provide additional reading on deterioration mechanisms and control strategies for various building materials.

## Table D1
## Deterioration Mechanisms for Building Materials and Their Control

| Material | Mechanism | Failures | Conditions for Process | Avoidance | References |
|---|---|---|---|---|---|
| **Ground-soil** | Frost heave | Damage to building foundation or fabric, floor slope | Fine-grained soils & ground temperature <0°C | Foundation location, type of soil | CBD 182 |
| | Swelling and shrinkage of soils | Damage to building foundation or fabric, floor slope | Expansive clays & changes in soil moisture content | | CBDs 62, 84 |
| **Ground-rock** | Expansion of pyritic shales | Damage to building foundation or fabric, floor slope | | | CBD 152 |
| **Wood**<br>• porous<br>• cracks due to shrinkage<br>• organic | Fungal decay | Loss of material, strength, appearance | Sustained moisture and oxygen with temperature 5–40°C | Drainage (avoid water traps), ventilation, preservatives | USDA *Wood Handbook*<br>CSA O80 Series<br>CWC *Wood Building Technology* |
| | Subterranean Termites | Loss of material, strength | Access from ground, sustained moisture and oxygen, temperature 5°C or more | Preservatives,<br>barriers,<br>bait blocks | CFS *Canadian Woods*,<br>CBDs 111, 112 |
| | Marine Borers | Strength, loss of material | Salt or brackish water (eg, piles) | Preservatives,<br>barriers | BRE 299, 345,<br>CWC *Wood Piles* |
| | Thermal degradation | Strength | Certain fire-retardants, high temperature and moisture (eg, unventilated roof spaces) | Stable fire-retardants, roof ventilation | CSA O80 Series<br>ASTM E520 |
| | UV exposure | Surface degradation, coating breakdown | Exposure to sunlight | Protective coatings and stains | CWC *Wood Reference Handbook* |
| | Drying shrinkage perpendicular to grain | Splitting, damage to other components, floor misalignment, nail popping | High initial moisture content, accumulated thicknesses perpendicular to grain (beams, stringers, plates) | Use dry wood, protective coatings, improved design | Commentary D on NBC Part 4,<br>CBD 244,<br>CWC *Wood Design Manual* |
| | Differential movements due to changes in moisture content | Damage to interior fabric due to outward bowing of wood systems | Seasonal variations in moisture content, type of wood/slope of grain | Use dry wood of good grade, design to allow movements | Commentary D on NBC Part 4 |

*(Continued)*

## Table D1 (Continued)

| Material | Mechanism | Failures | Conditions for Process | Avoidance | References |
|---|---|---|---|---|---|
| **Masonry**, of<br>• stone<br>• clay brick<br>• concrete block | *(See table entries for*<br>*• stone*<br>*• clay brick*<br>*• concrete, concrete block, and mortar*<br>*• steel*<br>*• stainless steel)* | | | | CMCA Maintenance Guide |
| **Stone**<br>• porous to varying degrees<br>• crack susceptible at planes of weakness<br>• inorganic | Acid attack (leaching) | Disintegration, disfigurement | Carbonates in stone (eg, limestone or sandstone), acid rain, drainage, orientation | Choice of stone, pointing of mortar, protective coating | ASTM C97,<br>Amoroso & Fassina (1983),<br>BS 7543 |
| | Salt crystallization | Spalling, occasionally efflorescence | Salts in mortar or adjacent materials (eg, ground) | Drainage details, dampproof course | Kulak & Smith (1993),<br>ISO 6241 |
| | Freeze/thaw | Spalling | Water in pockets, freeze/thaw cycles | Drainage details | |
| | Movements due to moisture change | Bowing of panels | Type of stone (marble), thickness | Use thicker section or stiff backing | ASTM C97 |
| **Clay brick**<br>• porous to varying degrees<br>• crack susceptible<br>• inorganic | Freeze-thaw | Spalling, disintegration | Lack of drainage, high moisture content during freeze-thaw cycles, aggravated by non-breathing surface coatings | Manufacturing process, drainage details, moisture barriers, breathable coatings, good mortar joints | CSA A82 Series |
| | Salt crystallization | Efflorescence, occasionally spalling | High moisture content and presence of salts in brick, mortar, or adjacent materials | Low salts in bricks and mortar, drainage details, good mortar joints | CSA A82 Series,<br>CBD 2,<br>BRE 359 |
| | Moisture expansion | Bowing of walls, cracking | Bricks expand after manufacture | Ageing prior to use, movement joints | |
| | Movements due to moisture or temperature variations | Cracking | Restraints | Movement joints | CSA A371,<br>Commentary D on NBC Part 4,<br>BRE 359 |

*(Continued)*

## Table D1 (Continued)

| Material | Mechanism | Failures | Conditions for Process | Avoidance | References |
|---|---|---|---|---|---|
| **Concrete, Concrete Block, and Mortar**<br>• porous to varying degrees<br>cracks due to shrinkage<br>• inorganic | Freeze-thaw | Disintegration, appearance | High moisture content during freeze-thaw cycles, aggravated by chlorides and lack of drainage | Air entrainment, mix design, choice of aggregates, drainage details | CSA A23.1,<br>CBD 116 |
| | Sulphate attack | Expansion, followed by disintegration | Sulphates in ground water, bricks, coal stockpiles, or sea water | Type of cement, mix design, drainage, low sulphate in brick | CSA A23.1,<br>CBD 136 |
| | Alkali-aggregate reaction | Expansion followed by disintegration | Silica or dolomite aggregates, requires moisture | Type of aggregates or cement additives, control of moisture | CSA A23.1 |
| | Acid attack | Strength, disintegration | Acids in industrial buildings - amount in contact. Permeability | Protective coatings | CEB Bulletin 182 |
| | Leaching of lime | Efflorescence,<br>mortar disintegration | Vapour transfer, permeability | Mix design, drainage details | CSA A179 |
| | Biological attack | Strength, disintegration | Contact with sewage (generation of acids) | Protective coatings | CEB Bulletin 182 |
| | Shrinkage | Cracking, damage of adjacent *components* (eg, brick veneer) | High W/C ratio | Mix design, construction sequence, control joints, reinforcement, curing and moisture control prior to use | CSA A23.1, A371, A165 Series |
| | Creep | Deformation | | Design (greater thickness, pre-stressing) | |
| | Temperature movements | Cracking | Large sections, hot climates | Reinforcement,<br>control joints | CSA A23.1, S304.1, Commentary D on NBC Part 4 |
| | Abrasion | Surface disintegration | Heavy traffic, wind-driven particles | Protective toppings, choice of aggregate, additives | Appendix F of CSA A23.1,<br>CSA S413 |

*(Continued)*

## Table D1 (Continued)

| Material | Mechanism | Failures | Conditions for Process | Avoidance | References |
|---|---|---|---|---|---|
| **Metals (all)** | Galvanic corrosion | Many | Electrolyte (moisture-filled porous material), metals electrically connected | Choice of materials, electrical disconnection of adjoining metals | Appendix F of this Guideline |
| | Differential thermal movements | Cladding damage | Metals of different thermal coefficients connected to produce constraint stresses | Design to allow movements, choice of metals | Commentary D on NBC Part 4 |
| **Steel**<br>• non-porous<br>• inorganic | Corrosion: atmospheric *environment* | Connector *failures*, appearance, damage due to rust expansion | Sustained moisture, oxygen, aggravated by acids and hygroscopic impurities | Drainage (avoid water traps), ventilation, protective coatings | BS 5493,<br>DIN 55928,<br>CBD 170 |
| | Corrosion: marine *environment* | Corrosion of piles in splash zone | Sustained moisture, oxygen, aggravated by chlorides | | BS 5493 |
| | Corrosion: soil *environment* | Pile *failures*,<br>pipe *failures* | Sustained moisture, oxygen or anaerobic bacteria, aggravated by soluble salts, stray electric currents | Type of soil (test for resistivity, bacteria etc), protective coating, cathodic protection | ANSI/AWWA C105/A21.5 |
| | Corrosion: concrete *environment* | Failure of reinforcement or delamination of concrete | Sustained moisture, oxygen, chlorides or pH reduced by carbonation | Protective barriers, concrete mix, drainage details | CSA A23.1, S413,<br>CBD 224, 225 |
| | Corrosion: masonry *environment* | Failure of connectors, cracking of masonry | Sustained moisture, oxygen, aggravated by salts | Zinc coatings, stainless steel thickness | CSA A370, A371,<br>Ailor (1982),<br>CIB 127 |
| | Corrosion, timber *environment* | Failure of connectors and surrounding wood | Sustained moisture, oxygen | Drainage (avoid water traps), ventilation, protective coatings | USDA *Wood Handbook*,<br>BRE 301 |
| | Fatigue | Structural *failure* | Cyclic loads | Welding details, structural design | CSA S16.1,<br>Coveney (1992),<br>CIB 128 |

*(Continued)*

## Table D1 (Continued)

| Material | Mechanism | Failures | Conditions for Process | Avoidance | References |
|---|---|---|---|---|---|
| **Weathering steel** | Corrosion: atmospheric environment | Connector *failures*, damage due to rust expansion | Retention of water between surfaces, sea water | Detailing to avoid accumulation of water between surfaces | |
| **Stainless steel** | Pitting or crevice corrosion, intergranular corrosion, stress corosion cracking | Connector *failures* | Type of stainless steel, aggravated by warm chlorinated atmospheres, high stress | Type of stainless steel | BRANZ 230, Blaga (1984) |
| **Aluminum alloys** | Corrosion: (dark pitted appearance) | Downgrading of appearance, connector failures | Type of alloy, surface finish, contact with alkaline solution, contact with copper or copper containing solution, contact with some other metals | Drainage (avoid contact with alkaline solutions or drainage from large dissimilar metal surface area), protective coatings | BRANZ 213, 225, Blaga (1984) |
| **Copper and alloys** | Dezincification of brass | Failure of fasteners by loss of strength or cracking | Type of brass | Material selection (brass with less than 20% zinc) | Blaga (1984) |
| | Stress corrosion cracking (season cracking) | Failure of fasteners, cracking | High humidity composition of brass | Annealing to reduce residual stresses | |
| **Glass** | Weathering | Lowered resistance to lateral pressure - static fatigue | Moisture, surface flaws, stress corrosion; abrasion from windborne particles or unsuitable cleaning agents | Use conservative design, heat strengthen | CGSB 12.20 |
| | Impact | Lowered resistance to breakage | Accidental contact during *maintenance*; windborne debris, eg, roof gravel | Design for post-breakage *performance* - laminates, structural films | Appendix C of CGSB 12.20 |
| | Thermal stress | Cracks starting at edge | Unequal solar heating (centre hot, edges cold); shadows, heat-absorbent glass, indoor heat | Avoid heat traps and strong shading; produce clean-cut edges or finish them well; heat strengthen | Appendix D of CGSB 12.20 |

*(Continued)*

## Table D1 (Continued)

| Material | Mechanism | Failures | Conditions for Process | Avoidance | References |
|---|---|---|---|---|---|
| **Glass** *(cont'd)* | Etching, leaching | Hazy appearance, milky or scummy deposit, darkening | Alkaline runoff from masonry or concrete; acid rain or water that leaches alkalis | Drain contaminated runoff away from glass | McLellan & Shand (1984),<br>BRANZ 236 |
| | Expansion of inclusions (eg, nickel sulphide) | Sudden dicing of tempered glass | Tempered glass, inclusions made unstable by tempering | Use heat strengthened rather than tempered glass | |
| | Corrosion | Staining and etching | Presence of water | Drain water away from glass | BRANZ 236 |
| | IG Units: seal breakdown | Fogging, condensation inside space on cooler pane | Water in glazing pockets, flexing under load, incompatible materials | Limit deflections; exclude standing water from sill; change materials | |
| | IG Units: atmospheric pressure/temperature | Breakage in high stress region parallel to edge | Small, rigid units plus changes in pressure and temperature since sealing (including altitude changes during transport) | Avoid excessively stiff small units;<br>use breather tubes, especially during transportation to site | |
| **Polymers** (natural & synthetic rubbers; sealants; roof membranes) | Chemical degradation, oxidation, ozonation | Loss of strength, cracking | Contact with oils and the atmosphere | Avoid contact with oils, selection of suitable synthetic rubber | Coveney (1992),<br>ASTM D4637,<br>BRE 372 |
| **Plastics,**<br>**GRP** (glass-fibre reinforced polyester) | Moisture absorption | Fibre "pop-out",<br>loss of toughness | Presence of moisture | Drainage, cut edges should be sealed | |

*(Continued)*

## Table D1 (Concluded)

| Material | Mechanism | Failures | Conditions for Process | Avoidance | References |
|---|---|---|---|---|---|
| GRP, other plastics, other FRP (fibre reinforced plastic) | Chemical attack under tensile stress | Crazing and possible fracture | Exposure to solvents or contact with some sealants, tensile stresses | Avoid use of solvents, select compatible sealant | CBD 122,<br>BRANZ 241,<br>Blaga (1984) |
| | Fatigue induced by temperature and moisture fluctuation | Surface cracking, degradation of mechanical properties | Exposure to temperature and humidity fluctuation, U.V. light | Surface protection from U.V. exposure | BRE 69 |
| | Oxidation and photo-oxidation | Degradation of mechanical properties, discolouration, hazing, dullness | Exposure to U.V. light | Use of surface coating and/or U.V. absorber | |

**Complete designations of referenced documents are listed in Section G4 of Appendix G. Acronyms for referenced documents are as listed below.*
*ANSI/AWWA = American National Standards Institute/American Water Works Association*
*ASTM = American Society for Testing and Materials*
*RANZ = Building Research Association of New Zealand, Porirua NZ*
*RE = Building Research Establishment Digest (U.K.)*
*BS = British Standard (British Standards Institute)*
*CBD = Canadian Building Digest (National Research Council of Canada)*
*CEB = Comité Euro-International du Béton*
*CFS = Canadian Forestry Service*
*CGSB = Canadian General Standards Board*
*CIB = Conseil Internationale du Bâtiment (International Council for Building Research Studies and Documentation)*
*CMCA = Canadian Masonry Contractors' Association (of British Columbia and The Yukon)*
*CSA = Canadian Standards Association*
*CWC = Canadian Wood Council*
*DIN = Deutsches Institut fur Normung (Germany)*
*NBC = National Building Code (of Canada)*
*USDA = United States Department of Agriculture (Forest Products Laboratory, Madison)*

# Appendix E
# The Corrosion of Metals in Building Environments

**Note:** *This Appendix is included for information purposes only.*

## E1. The Effects of Corrosion

The corrosion of metals exposed to *environments* outside and within buildings and within building *assemblies* and materials is the most costly unforeseen problem in buildings today and the problem least addressed by current building codes and standards. The two primary manifestations of the problem are *failure* of building *components* due to the expansion caused by the formation of corrosion products and the fracture of prestressing wires or ties due to stress corrosion cracking or pitting. Another is unsightliness due to the formation of rust products. This Appendix contains a short review of corrosion of metal *components* and should lead to a better ability to predict where *failures* may occur.

Corrosion can lead to critical *durability* problems with building *components* or *assemblies. Failure* of metal ties due to corrosion can cause *premature failure* of cladding panels. Falling cladding panels present a risk to human life and may cause damage to other parts of the building or to adjacent buildings. Spalling of concrete cover and delamination due to expansive pressure from rebar corrosion is a major problem with parking structures and coastal structures. Staining on surfaces of *components* due to leaching of corrosion products is also considered an important *durability* problem which can lead to costly *maintenance* and *repairs.*

## E2. The Corrosion Process

Metal corrosion of building *components* is an electrochemical process which involves the transfer of electrons between two distinct metallic sites: the anode (where the metal is corroding) and the cathode (the noncorroding metal). The essential elements of the electrochemical process involved in corrosion of metals are illustrated in Figure E1.

The chemical reaction taking place at the anode is called oxidation, or anodic, reaction. During the oxidation process metals lose electrons, $e^-$, and become positively charged ions, $M^+$, which react chemically with the adjacent *environment* as discussed later. The electrons generated by the oxidation process travel through an electrical conductor to the cathode. Those electrons are consumed at the cathode in a cathodic, or reduction, reaction. The nature of the reduction process depends on the nature of the *environment* in which corrosion takes place. In acidic *environments* two processes can take place: hydrogen evolution and/or oxygen reduction. In the hydrogen evolution reaction, the hydrogen ions, $H^+$, present in acids react with the electrons on the cathode surface to form hydrogen atoms and hydrogen gas ($H_2$). When oxygen is dissolved in acid, electrons are also consumed when oxygen and hydrogen ions react together to form water. In neutral or alkaline *environments* in the presence of water, oxygen reduction results in the formation of hydroxyl ions ($OH^-$). Oxygen reduction in neutral or alkaline *environments* is a very common cathodic reaction in building *environments* because of the widespread occurrence of air and water in close proximity. Hydrogen evolution is less common in building *environments,* but can occur when pollutants such as carbon dioxide and sulphur dioxide acidify the *environment.* Other cathodic reactions are also encountered but are less common and are most frequently found in the chemical process industry.

The oxidation reaction and the reduction reaction are partial reactions — both must occur simultaneously and at the same rate on the metal surface. If this were not the case, the metal would spontaneously become electrically charged, which is impossible. This leads to one of the most important principles of corrosion: *during metallic corrosion, the rate of oxidation equals the rate of reduction.*

The principal driving force for corrosion is the electrical potential difference existing between the anode and the cathode (the common battery is a corrosion cell which makes use of this potential difference to generate electricity). The potential difference results from local variations within the *environment* to which a metal *component* is exposed and/or variations within the metal itself. These variations create a chemical imbalance which will provide the driving force for the current flow taking place during corrosion. Some of the most common variations are: variation in metal composition; variation of the concentration of dissolved elements in the electrolyte; and variation of temperature.

## E2.1 Variation in Metal Composition

This type of variation gives rise to dissimilar electrode, two-metal, or **galvanic cells.** A metal containing electrically conducting impurities on the surface as a separate phase, steel cladding fastened with copper fasteners, or steel coated with zinc are examples of this type of corrosion cell. Galvanic cells also include cold worked metal in contact with the same metal in its annealed condition or a stressed metal in contact with unstressed metal of the same composition. Some metals (eg, magnesium and zinc) or some phases of a given metal (eg, the ferrite phase in steel) have a greater potential to react with their *environment* than others (eg, copper and gold or the cementite phase in steel). If two metals or two metal phases in an electrolyte are connected together, a potential difference exists between the two metals. This potential difference produces electron flow between the two metals. The metal with greater potential to react (the more active metal) will become the anode and corrode while the other metal becomes the cathode. In the case of galvanized steel, for example, the zinc becomes the anode (which gradually corrodes but with little visible change) and the steel will act as the cathode and is therefore not affected until all the zinc is dissolved.

### E2.2 Variation in the Concentration of Dissolved Elements in the Electrolyte

This type of variation gives rise to concentration cells. These are cells having two electrodes of identical metal, each in contact with a solution of differing composition. The most important kind of concentration cell is called the differential **aeration cell.** The difference in oxygen concentration between two metal surfaces produces a potential difference and causes current to flow. The surfaces in contact with the solution containing the higher concentration of dissolved oxygen will become cathodic to the surfaces in contact with the solution containing the lower concentration of dissolved oxygen. The tendency of the corrosion process will be toward a reduction in oxygen concentration where it is highest.

### E2.3 Variation in Temperature

This results in the formation of differential temperature cells. *Components* of this type of corrosion cell are electrodes of the same metal, each at a different temperature, in an electrolyte of uniform composition. This type of cell is of little practical implication for civil engineering structures. They are found in heat exchangers, boilers, and similar equipment.

## E3. Factors Affecting Corrosion

The major factors affecting metal corrosion encountered in building *environments* are passivation, solution acidity, dissolved oxygen, chlorides, and electrolyte resistivity.

### E3.1 Passivation

Passivation can be defined as the loss of chemical reactivity experienced by certain metals and alloys under specific environmental conditions. Certain metals and alloys become essentially inert under particular conditions and behave like the noble metals, eg, gold or platinum. The metals most subject to this kind of behaviour are the common engineering metals such as iron, aluminum, nickel, silicon, chromium, and alloys containing these metals. Although the phenomenon of passivation is complex in nature and not yet completely understood, it is generally agreed that it results from the formation of a protective oxide film which acts as a barrier between the corrosive *environment* and the metal. It is this passive film which prevents many of the common metals such as stainless steel and aluminum from corroding rapidly in ordinary air. Some metals such as stainless steel and aluminum form their protective passive film in mildly corrosive *environments* such as the ambient air. However, other metals form their protective passive film only in more corrosive *environments*. This is the case for iron which corrodes quite easily in moist air. When immersed in a highly concentrated nitric acid, a protective passive film is formed which protects the iron from further corrosion even in air. However, if the protective film is damaged, corrosion of the passivated iron would resume when exposed to moist air. As discussed later (see Clause E4.3), the corrosion of metals with a damaged passive layer may be more serious than without a passive layer. Steel also forms a protective passive film when exposed to an alkaline *environment* such as the one provided by cement paste. Metals not protected by a passive film are said to be active.

## E3.2 Solution Acidity

Solution acidity is a major factor affecting passivation and corrosion. Solution acidity is measured in terms of pH (negative logarithm of the concentration of $H^+$ ions), where a pH of 0 is very acidic and a pH of 14 is very alkaline (high in $OH^-$ ions), with a pH of 7 being neutral (pure water). Rain is mildly acidic (pH 5.6), but $SO_2$ and $CO_2$ in the air can increase its acidity, especially in industrial areas (pH 3.5 to 4.5). Wet cementitious materials are strongly alkaline with pH greater than 12. Carbon dioxide in the air, however, can penetrate cementitious materials to react with $Ca(OH)_2$ to remove the $OH^-$ ions (carbonation) thereby reducing the pH. With this variation in mind, aluminum passivates for pH between 4 and 8.5 and therefore corrodes in cementitious materials. Steel passivates for pH greater than approximately 10, and therefore does not corrode in concrete, except for porous concrete with little cover (eg, mortar) because of carbonation. Zinc passivates for pH between 8.5 and 12. Stainless steel passivates for pH between 3 and 14.

Solution acidity also is a major factor affecting cathodic reaction. Hydrogen evolution is an important cathodic process in acidic *environments*. As the solution acidity decreases, the amount of hydrogen available for the cathodic process decreases until, in a neutral or alkaline *environment*, hydrogen evolution is not a contributing factor in corrosion. In solutions with a pH greater than 7, oxygen becomes essential in the corrosion process as discussed in the next section.

The effect of pH on corrosion of steel and zinc is shown in Figure E2.

## E3.3 Dissolved Oxygen

Oxygen reduction is the most common cathodic reaction. In acidic solutions the presence of oxygen increases the cathodic activity and, hence, the corrosion rate of non-passivated metals. For present building *environments*, dissolved oxygen from air (or from anaerobic bacteria in organic soils) is generally required for corrosion to occur. This is well illustrated by offshore structures where the greatest corrosion attack occurs at the water line where water, as an electrolyte, and oxygen are both abundant, while there is little corrosion in deep water because of the lack of oxygen. This is not always the case, however, since acidic conditions can occur in heavy industrial areas and corrosion can take place without dissolved oxygen.

## E3.4 Chlorides

Chlorides have the ability to create *defects* in the passive layer (not yet clearly understood) which become anodic, the passive layer becoming the cathode. This is called depassivation and occurs for reinforcing steel in concrete (alkaline solution) and for stainless steel. Corrosion of metals in the presence of chloride often takes the form of pitting which can lead to *premature failure* of structures subjected to cyclic loading or to leakage of containment structures. *Failure* of concrete parking structures due to chloride-induced corrosion (the rust expansion forces break the concrete cover) is one of the most expensive problems today.

## E3.5 Electrolyte Resistivity

Since the flow of electrons from the anode to the cathode in an electric circuit is directly proportional to the potential difference between the anodic and cathodic sites, and inversely proportional to the resistance of the electric circuit, the resistance of the electrolyte, which forms part of the electric circuit, is of prime importance. Pure water has a high resistance to flow of electricity whereas sea water has low resistance (due to $Cl^-$). In porous materials, particularly soils, the resistivity varies considerably and is therefore a major factor affecting corrosion susceptibility.

# E4. Forms of Corrosion

In practice, there are a number of characteristic forms of corrosion that occur, involving the factors discussed above.

## E4.1 Uniform Corrosion

Atmospheric corrosion of steel and iron surfaces is generally uniform. The rate of corrosion is determined principally by the time of wetting. The main *components* of the atmosphere affecting corrosion are oxygen, water, and carbon dioxide but pollutants such as sulphur dioxide, soot, hydrogen sulphide, sodium chloride, nitrogen dioxides, etc (acid rain) increase corrosion rates. Weathering steel provides a dense rust layer with good adhesion to the steel surface which retards corrosion, but only under conditions of cyclic wetting and drying. Consequently, design details which allow prolonged retention of water, eg, flat surfaces, will promote rapid corrosion. Also, staining of adjacent *components* can occur due to run-off formation of the rust layer.

## E4.2 Pitting and Crevice Corrosion

Mill scale, protective coatings such as paint, corrosion products, and particularly passive oxide layers, may create a situation where small anodes are formed where the solution has low oxygen concentration (aeration cell) and where active corrosion takes place. Chlorides often play an active role in this, by creating small anodic *defects* in the passive layers. Crevice corrosion occurs in narrow crevices or overlaps (eg, adjoining metals) or under deposits as a result of differences in oxygen concentration. The surface where the supply of oxygen is lower (in the crevice) will act as the anode whereas the surface where the oxygen supply is greater acts as the cathode. The *environment* in the crevice or pit becomes more corrosive as corrosion progresses because hydrolysis of metal salts ($MCl + H_2O \rightarrow MOH + HCl$) decreases the pH of the solution in the crevice or pit. Pitting corrosion occurs, for example, in concrete reinforcement depassivated by chlorides or in stainless steel exposed to chloride solutions. To avoid chloride depassivation of stainless steel, Type 316, containing molybdenum should be used. Even Type 316 can depassivate when exposed to warm indoor temperatures and acidic moisture containing chlorides (indoor swimming pools).

## E4.3 Galvanic Corrosion

The importance of the galvanic cell in corrosion of engineering metals was discussed earlier. When two dissimilar metals are immersed in an electrolyte, corrosion of the less corrosion-resistant metal is usually increased and attack of the more resistant metal is decreased, as compared to the behaviour of these metals when they are not in contact. The less resistant metal becomes the site of the anodic reaction while the more resistant metal becomes the site of cathodic reactions. Table E1, known as a galvanic series, lists common construction metals in terms of potential to react in unpolluted sea water. If any two of these metals are electrically connected in the presence of a corrosive *environment*, the more active metal will act as the anode and will corrode at a faster rate while the more noble metal will be protected. The galvanic series given in Table E1 takes passivity of stainless steel into account. The information presented in Table E1 is based on galvanic corrosion tests in natural fresh or sea water. Although the galvanic series presented in Table E1 applies for most situations encountered in civil engineering structures, the relative position of metals in the galvanic series may change if the *environment* deviates significantly from natural water.

An important factor in a galvanic cell is the area effect. Because the rate of oxidation equals the rate of reduction in a corrosion cell, a small anode connected to a large cathode will corrode rapidly to provide the relatively large quantity of electrons that can be consumed in the reduction reaction taking place on the large cathode. In contrast, when a large anode is connected to a small cathode, the corrosion rate at the anode is relatively small because the amount of electrons that can be consumed at a small cathode is relatively small. In galvanized steel the zinc anode is large relative to the cathode (steel exposed by *defects* in the coating) and therefore corrodes slowly. A galvanized bolt connecting plain steel *components*, on the other hand, will lose its protective zinc coating rapidly. Similarly, a metal with a passive layer containing small *defects* or holes will corrode rapidly at the *defects* which are anodic to the cathodic passive layer.

The distance between the anodic and cathodic areas also has an important effect on galvanic corrosion. Accelerated corrosion due to galvanic effects is usually greatest near the junction, with attack decreasing with increasing distance from that point. The distance affected depends on the conductivity of the electrolyte.

### E4.4 Intergranular Corrosion

Intergranular corrosion occurs in stainless steels as a result of sensitization. Sensitization is a decrease of chromium content close to grain boundaries due to the precipitation of chromium carbides at the grain boundaries during heat treatment or welding. The precipitation of chromium rich carbides at grain boundaries sets up an intense galvanic reaction wherein the chromium depleted grain boundary acts as the anode and the chromium rich carbides act as the cathode. The methods used to control intergranular corrosion of stainless steels relate to the composition and heat treatment of the steel to minimize carbide precipitation. Certain aluminum-copper alloys may also show this type of corrosion.

### E4.5 Stress Corrosion Cracking

Stress corrosion cracking of metals is defined as a cracking process resulting from the simultaneous action of a corrosive *environment* and a sustained tensile stress. Steels with a tensile yield strength greater than 620 MPa are generally susceptible to stress corrosion cracking. Steels used in prestressing tendons and bridge cables are in this category. For the most part, the *environments* which are of major concern to the cracking of high strength steels are natural waters — rain water, sea water, and atmospheric moisture. Contamination with $H_2S$ (hydrogen sulphide) or nitrates following thunderstorms greatly increases susceptibility to stress corrosion cracking. Corrosion fatigue, which occurs under cyclic loading, is similar but occurs under a wider range of solution *environments*. Corrosion fatigue is generally not a problem in building *environments*.

### E4.6 Hydrogen Embrittlement

This is the only type of corrosion-related *failure* that occurs at the cathode. The processes involved in hydrogen embrittlement are not well understood One theory is that under certain conditions, atomic hydrogen, which forms at the cathode due to reactions involving $H^+$ ions, penetrates the steel and later combines as molecular hydrogen ($H_2$) which expansively cracks the steel. Hydrogen embrittlement by itself is not often the cause of *failures*. However, since the source of atomic hydrogen is often corrosion, hydrogen embrittlement is often a contributing factor to stress corrosion cracking, as can occur in galvanized prestressing.

## E5. Prevention of Corrosion

*The prevention of corrosion is achieved by one or more of the following measures:*

(a) micro-environmental protection, including barriers, drainage, and ventilation as described in Clauses 7, 8, 9, and 11 of this Guideline;

(b) choice of materials, for example to avoid galvanic corrosion cells or to resist the attack of corrosive solutions;

(c) protective coatings, including zinc, cadmium, or galvanum metal coatings which provide cathodic protection to steel. There are many other types of non-metallic coatings (see British Standard BS5493); and

(d) methods, including cathodic protection by sacrificial anode or by impressed current using an inert anode, anodic protection for passivating metals, and additives which inhibit a chemical reaction or increase passivation.

## E6. Summary

Corrosion is an electrochemical process involving anodic and cathodic chemical reactions, where corrosion takes place at the anode, and the flow of electricity through the metal, the solution, and across the anodic and cathodic interfaces. The process requires an aqueous solution containing dissolved oxygen (except in the case of acids). The process is retarded or stopped by the formation of a passive metal oxide layer which, however, may break down in the presence of chlorides or other *agents* (eg, $SO_2$, $CO_2$). The two basic types of corrosion cells causing building *failures* are differential aeration cells due to local differences in oxygen concentration in the solution and galvanic cells due to differences in oxidation potential of joined metals.

The prevention of corrosion is achieved by a wide variety of measures involving design to avoid corrosive *environments*, choice of materials and protective coatings, and specialized methods such as cathodic protection.

## E7. References

The references in Section G5 of Appendix G provide a more in-depth understanding of corrosion and corrosion prevention.

### Table E1
### Galvanic Series for Metals and Alloys in Natural Fresh or Sea Water

(See Clause E4.3)

| | |
|---|---|
| Magnesium | Active or anodic |
| Zinc | ⇑ |
| Aluminum (active) | |
| Mild Steel | |
| Cast Iron | |
| Stainless Steel (active) | |
| Lead | |
| Brass | |
| Copper | |
| Monel K | |
| 70 - 30 Cupronickel | ⇓ |
| Stainless Steel (passive) | Noble or cathodic |

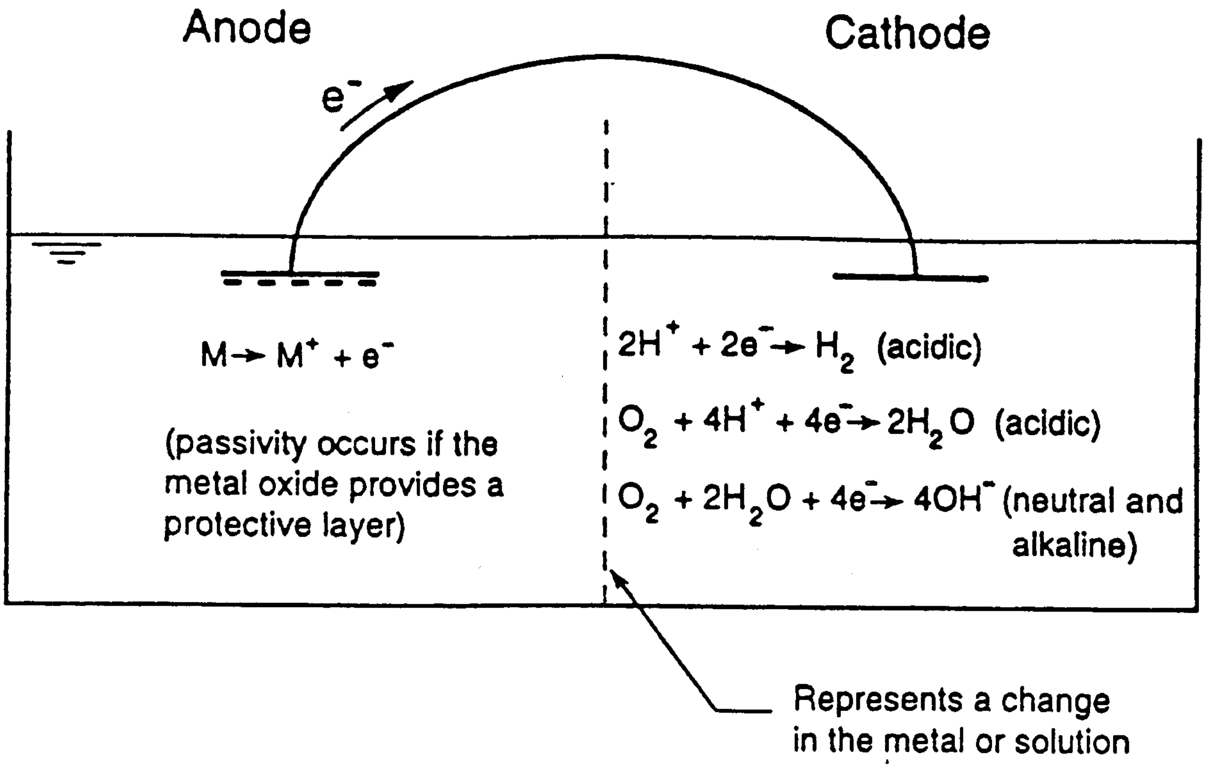


**Figure E1**
**The Corrosion Cell**
(See Clause E2.)

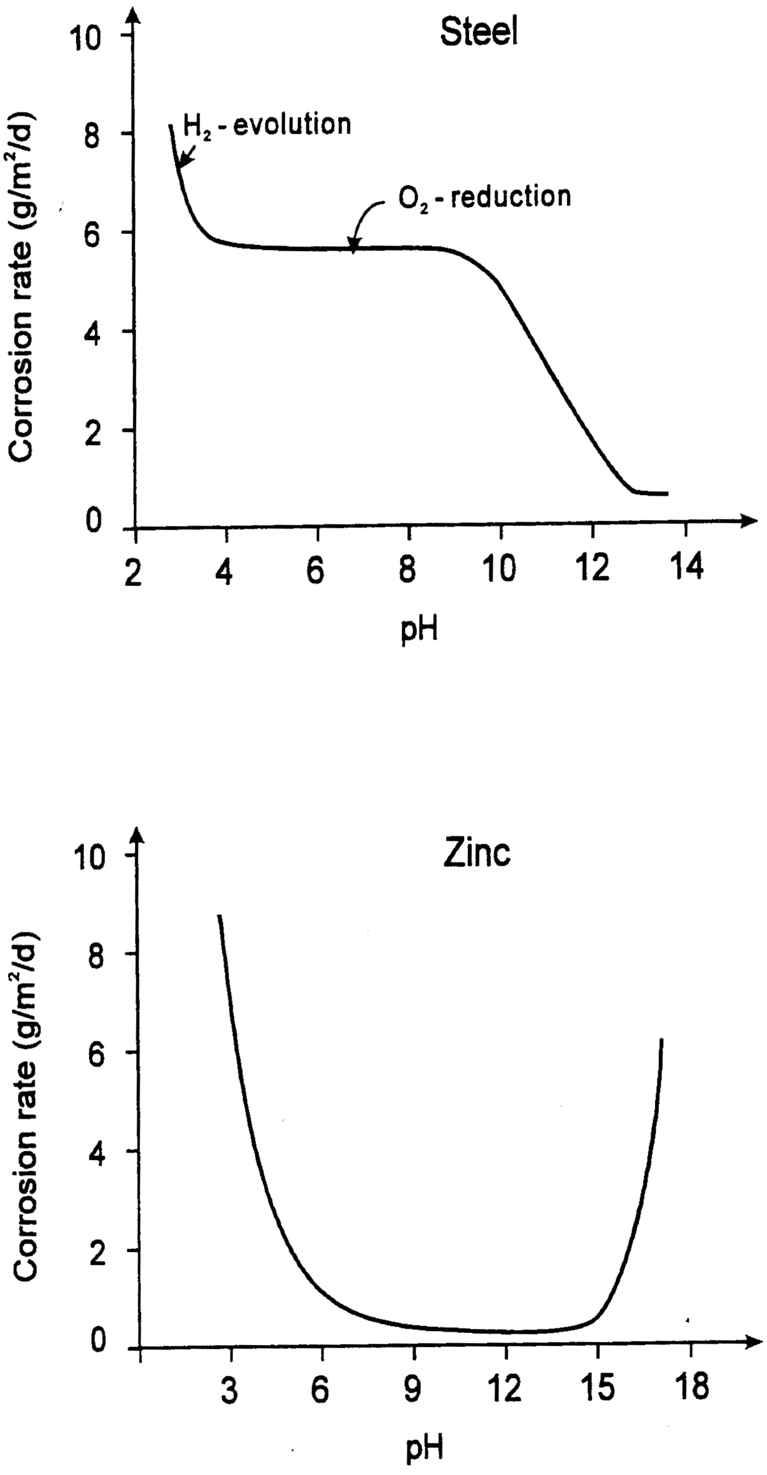


**Figure E2**
**Corrosion Rate of Metals in Aqueous Solutions as a Function of pH**
(See Clause E3.2.)

# *Appendix F*
# *The Building Envelope*

**Note:** ***This Appendix is included for information purposes only.***

## F1. General

The building *envelope* is often the single most expensive *component* of current modern building, ranging from approximately 20% to 40% of the total cost. It also can be extremely difficult and expensive to *repair*. Building *envelope failure* most commonly reveals itself as moisture damaged cladding or roof *components*, condensation on walls and windows, drafts and uneven building temperatures, discolouration, and indoor air quality problems.

The building *envelope* is composed of *components* and *assemblies* that are linked together in a continuous plane to enclose conditioned space and to protect the contents and people within from the forces of the exterior *environment*. The building *envelope* can be divided into several parts, comprising

(a) roofs above ground and their associated openings and penetrations including vents, hatches, and skylights;
(b) exterior walls above ground and associated openings and penetrations including windows, doors, and vents;
(c) soffits and cantilevered floors;
(d) roofs below ground and their associated openings and penetrations including vents, hatches, and skylights;
(e) exterior walls in contact with ground and their associated penetrations including vents;
(f) floors on ground; and
(g) connecting joints and junctions.

None of these parts should be considered in isolation. Rather, an integrated "assembly approach" is necessary to ensure continuity between and among the multiple functions of each part at any location in a building.

The principles for designing functional building *envelopes* were identified by Hutcheon (1963) and are illustrated by Brand (1990). The principles governing *envelope* design also provide the key to identifying and eliminating or controlling the transport mechanisms that allow *agents* of deterioration to reach susceptible *components*.

## F2. Roofs Not in Contact with Ground

A principal function of the roof is to deflect and control moisture (rain, snow, ice).

Sloped roofs offer the easiest approach to handling rainwater and snow meltwater, and they can be easily waterproofed on the exterior with a variety of shingles, shakes, metal claddings, tiles, and slate. Minimizing leakage of moist air into enclosed spaces, eg, attics or interiors of closed roof panels, is critical to longterm *durability*; venting may be necessary to maintain dry conditions.

Flat (very low slope) roofs pose the greatest problems for managing rainwater, snow, and ice. Although flat roofs are the most difficult to waterproof, once provisions for gravity drainage have been provided, there are several waterproofing systems available for the purpose.

A common system is the conventional three- or four-ply asphalt roof membrane. This *assembly* is set over a layer of insulation which is protected from indoor air and moisture below by an effective air and vapour barrier applied over the structural roof deck. This traditional built up roofing system (BUR), has an expected *service life* of 20 years or more if there is a regular program of inspection and *maintenance* in effect.

The protected membrane approach has been applied to many roofing membranes, with a resulting increase in *service life* compared to the conventional BUR technology. In the protected membrane system, the waterproofing and air/vapour barrier may be the same material, placed below the insulation instead of above it. Protected membrane systems are more costly to *repair* than BURs because it is more difficult to trace and correct sources of leakage.

There are several single- or double-ply waterproofing materials, such as PVC, EPDM, Hypolon, and modified asphalt elastomeric membranes available as waterproofing for roofs. The *durability* of these materials has not been sufficiently tested to project *service life* expectancies. It is recommended that the evaluation of the various properties, *performance*, and method of installation of these products be carefully considered by the designer with expert input from the manufacturer.

Building roofs used for vehicle parking, and all parking garage suspended floor slabs, though not part of the building *envelope*, must be protected with traffic coating systems. These systems promote *durability* by waterproofing the deck, to protect against severe damage from corrosion of structural steel resulting from exposure to road salt, and by protecting the traffic surface from physical abrasion. Refer to CSA Standard S413, *Parking Structures*.

## F3. Exterior Walls Not in Contact With Ground

The common approach adopted for exterior walls for buildings in cold climates can be summarized as follows:

(a) provide a continuous air barrier, with adequate structural support against wind loads;
(b) ensure that the air/vapour barrier is flexible and allows for movement at joints;
(c) provide continuous insulation, mechanically fastened to the supports and tight to the air barrier, preferably located so that the air barrier is on the warm side;
(d) provide an effective and continuous vapour barrier on the high vapour pressure side;
(e) provide an effective "rainscreen" cladding system to minimize rain penetration, supported in a way that minimizes the piercing of the insulation with thermal bridges; and
(f) provide an air space when possible between the rainscreen and the insulation which is vented, drained, and pressure equalized to the exterior. Include compartmentalization when required.

A typical modern exterior wall system is made up of a cladding and supporting structure, incorporating an insulation system together with vapour barrier and an air barrier system. The control of rain water penetration is achieved by either a rainscreen or a face seal approach.

The traditional rainscreen wall assumes that water occasionally will enter the wall cavity behind the cladding, but that drainage to the exterior will be provided through necessary flashings, drainage holes/gaps, and drips. For masonry cladding, this is still the most common approach used in Canada and abroad. Shiplap and vertical siding panels of several materials perform under the same principles.

The pressure equalized rainscreen approach was developed to control one of the major forces inducing water penetration, air pressure difference across leakage paths in the cladding which drives water into the wall assembly.

The face seal approach is reliant on all holes and joints being completely sealed, and requires frequent inspections and *maintenance* with replacement of defective caulking.

The *durability* of these systems varies according to geographic location and climate characteristics, the indoor *environment* characteristics of humidity, temperature and pressure, materials chosen, and the design approach to obtain required *performance* characteristics, and *quality* of construction. Primary sources of high moisture levels in walls are rain water and snow meltwater that runs off the roof, window sills, or impermeable cladding directly onto the wall, and moisture carried by air leakage from within the building. Cracks in walls also may allow increased water ingress; therefore the design of the wall should incorporate appropriate movement joints to accommodate thermal, moisture, and structural movements.

Unfortunately, the requirement for insulation of exterior walls of new buildings for the purpose of energy conservation has *durability* implications in that claddings that do become wetted may take longer to dry out compared to similar claddings in uninsulated buildings where heat loss can assist the drying process, reducing the time-of-wetness.

Experience has shown that different cladding systems have variable durability attributes and problems. For example:

(a) The *durability* of masonry walls may be affected by high moisture levels, possibly leading to corrosion of metal *components* or to frost damage in masonry units subjected to freeze-thaw cycling while saturated.
(b) The *durability* of precast wall systems requires inspection of anchorages potentially subject to corrosion or to movements related to creep of supporting structure, for extended life periods between 20 to 40 years.
(c) Metal and glass curtain walls and structural glazing have evolved from face sealed systems to rainscreen technology. Well detailed systems may only require significant replacement of glazing after 20 to 25 years.
(d) Metal building technologies are available either as a face sealed approach (traditional warehouse technology) or a structurally supported air barrier system and rainscreen cladding technology. The latter is generally accepted as more durable, but corrosion control of anchorage systems needs to be well considered.
(e) Exterior Insulation and Finish Systems (EIFS) are constructed with a polymer-modified stucco finish over a reinforcing mesh on an insulation board. Their *durability* is reliant on high *quality* workmanship, especially at joints requiring use of site installed sealants to resist rain penetration. The design is essentially a face sealed system, although certain manufacturers have developed pressure equalized systems, and improved fire resistance ratings.

## F4. Windows and Doors

*Durability* is generally related to the individual *components* of frame and glass. Window frames made of aluminum or steel are required by CSA Standard CAN/CSA-A440 to be thermally broken for condensation control and typically have a life expectancy of 25 years or more. The deterioration of seals and gaskets leads to loss of ability of these *assemblies* to resist rain penetration and air leakage.

The *durability* of sealed double glazed units is related to the edge seal and exposure to water, but they can perform satisfactorily for over 20 years.

## F5. Roofs, Walls, and Floors in Contact With the Ground

*Assemblies* in contact with the ground also form part of the protective *envelope*. In addition to their structural functions, they must be designed to manage or to prevent the entry of rain and ground water and control the entry of soil gases, to prevent ground contaminants such as radon gas from entering the building.

Their *durability* is dependent on adequate drainage, well installed waterproofing systems, and special attention to building perimeter tie-in details to prevent water infiltration.

## F6. Soffits and Cantilevered Floors

The common problem of corrosion of suspension systems and deterioration of *components* below cantilevered floors and within soffit spaces usually occurs when low temperatures within a "heated" soffit result in condensation of moisture attempting to exfiltrate the building through the enclosed space. In theory, the "hot soffit" design protects the soffit space *components* by making the enclosed space insulated and air-tight to the exterior (Genge, 1990). In practice, unavoidable air leakage and numerous thermal bridges and penetrations into the space lower its temperature below the dew point of the building's air, leading to condensation and water related deterioration.

The "cold soffit" approach can be a more effective solution to the problem. In this approach, the exterior building wall system is insulated and sealed with an air/vapour barrier floor-to-floor, to minimize leakage into the soffit space, and the lower surface of the slab cantilevering over the soffit is insulated from below, leaving the space unheated. These precautions, plus air/vapour seals installed at wall/floor slab intersections, are more structurally secure and easier to install than in the hot soffit system, and allow venting of the soffit so that *components* can dry out if some condensation does occur.

## F7. Connecting Joints and Junctions

The elements, *components*, and *assemblies* of a protective *envelope* are only as durable as the joints that connect them. Joint design and construction is the most difficult task when assembling a protective *envelope*. The *durability* of joints is highly variable and depends on many factors including design, sequence of assembly, material suitability, and the service and environmental loads imposed.

Connecting joints perform several important functions including the handling of thermal, moisture, and load induced movements. They may, if so designed, facilitate the removal and replacement of deteriorated components or assemblies during maintenance or repair work, and simplify rainscreen detailing. Effective joints can enhance the *durability* of abutting materials and *assemblies*, and should therefore be no less durable than the elements connected.

## F8. References and Recommended Reading

The references in Section G6 of Appendix G provide additional reading on the particular deterioration mechanisms and control strategies particularly associated with the building *envelope*.

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**Note: *This Appendix is included for information purposes only.***

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