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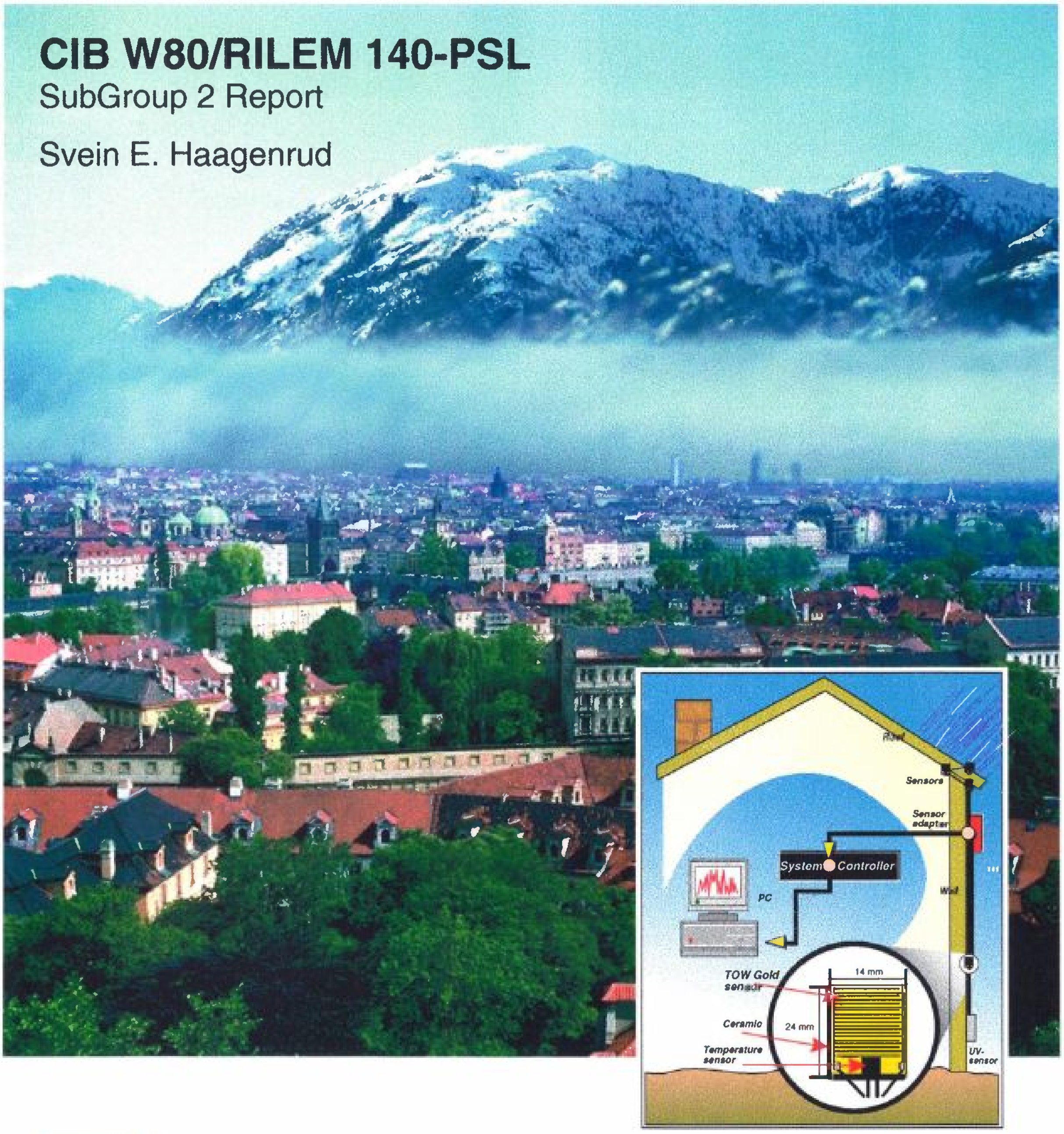
Environmental Characterisation including Equipment for Monitoring

CIB W80/RILEM 140-PSL

SubGroup 2 Report

Svein E. Haagenrud



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Preface

This is the final report from CIB W80/RILEM 140-TSL, Sub-Group 2. The group's task was to produce a report presenting the state of the art and the research needs regarding characterisation of the degradation environment, including methods and equipment for micro-climate monitoring.

A draft report was sent out to members of CIB W80/RILEM 140-TSL and the ISO/TC59/C3/WG9 "Design Life of Buildings" in May 1996 for comments. The plan was to incorporate comments for a second draft in autumn 1996.

Quite a few comments were received. All of them were positive, and some also contained additional material. Due to lack of time it was therefore decided just to incorporate the amendments in a final report, and not to distribute a second draft. The present report is printed in a small number, and it is going to be reedited into the final single volume publication based on the reports also from the four other groups.

The author wishes to thank all who has made contributions, with a special thank to my co-chairman Dr. Jonathan W. Martin from NIST, USA, Dr. Ivan S. Cole and Dr. George King from CSIRO, Australia, Dr. Takashi Tomiita from BRI, Japan, and Dr. Dagmar Knotkova from SVUOM, The Czech Republic, and my colleagues at NILU and at BMG.KTH, Sweden, who all took a lot of effort to make detailed comments and provide additional material.

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Contents

Summary and conclusions

The following summaries and conclusions can be drawn from the 8 Chapters:

Chapter 1 describes the *aim* and the *scope* of this report of sub-group 2 of the CIB W80/RILEM 140-TSL:

- Aim: "present *state of the art* and *research needs* regarding *characterisation* of degradation environment, including *methods* and *equipment* for *micro climate* monitoring";
- Scope: "identify methods for measuring and characterising these primary environmental factors, to demonstrate how these measurements can be related to *laboratory measurements*, and identify areas in which standards are necessary to improve the precision and accuracy of these measurements. It will also discuss availability of methods and data for characterising and classifying ambient exposure environment".

Chapter 2 introduces an overview of contents of the report. A generic model for degradation of materials and the important concepts of *dose response, damage* and *performance over time functions*, and their inter-relationship are presented. Dose response functions become damage functions when the performance requirements or limit states for allowable degradation are implied. The establishment of the limit state is complicated and should involve consideration of both technical, economic and environmental aspects.

Levels of geographical scale are defined, and the systematics for characterisation, classification and mapping of environmental degradation factors are described. The importance of exploitation of information technology in building assessment is emphasized.

In order to be able to characterise and report the right type and form of the environmental degradation factors, they have to be related to the degradation mechanism and dose response functions for the specific materials in question.

Chapter 3 is a review of recommended dose response functions produced in important environmental field studies during the last three decades. These are:

NAPAP Lipfert study, who composed a data base of atmospheric corrosion test results for metals, together with environmental variables published from 8 test programmes at up to 72 test sites in many countries.

Kucera et al. produced dose response functions for carbon steel and zinc via exposure on 32 test sites in Scandinavia.

Feliu and Morcillo in Spain surveyed and compared data from 250 test sites in 28 countries in many parts of the world, and developed dose response functions for carbon steel, zinc and copper.

The *UN ECE ICP on materials*, who are evaluating the effect of airborne acidifying pollutants on corrosion of materials involving exposure at 39 test sites in 12 European countries and in the United States and Canada.

The recommended functions are presented in Table 1.

Chapter 4 provides basic characterisation of the principal agents that affect the durability of building materials, and some knowledge on the degradation mechanism. It follows the systematics in standard ISO 6241-1984E of agents relevant to building performance and requirements. The degradation factors are classified according to *their nature* as *mechanical, electromagnetic, thermal, chemical* and *biological* agents, and to their *origin* (external/internal to the building, atmosphere, ground etc.), and *not to the nature of their action* on the buildings or components. In the report an overall *emphasis is on the outdoor atmospheric exposure environment.*

There is a clear lack of data on quantitative characterisation of degradation factors in their relevant type and form, and in geographical resolution. It will require much more research on quantitative damage functions also incorporating the relevant degradation mechanisms, for the right characteristics to be provided. Another problem is the identification of the right performance characteristics and degradation indicators. Although quite a few good examples on the right approach is shown through work of Tomiita, Martin et al. and a whole lot of good studies on dose response functions exist from the environmental research area, it is a clear lack of relevant functions. This lack of systematic approach is a major barrier for further progress in the area.

Chapter 5 *contains an overview of international programmes for measuring, modelling and mapping environmental degradation factors in the environmental research area of air quality.* Point measurements are very expensive, and for a broader assessment of air quality, needed for policy development and assessment, public information etc., measured data needs to be combined with modelling based on emission inventories, to assess properly the exposure to, and thus the effects of the pollution on public health and on other receptors, such as buildings. In the context of assessing building performance, a huge bulk of data on global, continental (macro) and national (meso) levels are therefore available for exploitation. Respectively, the UN Global Environment Monitoring System (GEMS/AIR), the Transboundary UN EC EMEP Programme, and the tasks organised under the European Environmental Agency in Copenhagen are described, and some data are given.

The European policies and directives on air quality monitoring including a status of the European Air Quality Monitoring Networks and the European Environment Agency is given. On the regional scale about 750 sites are in operation totally in Europe, with very extensive monitoring of sulphur and nitrogen compounds in air and deposition, while ozone data are available from about 500 monitoring sites in 14 member states.

On the local urban scale, monitoring is carried out at a very large number of sites in Europe, totally close to 5,000 sites, where compounds of the EU directives (SO_2, particles, NO_2, ozone, lead) are extensively covered. The *extensive reporting of exceedances of threshold values* should be of extreme importance also for the building society, when threshold values for damage to building materials could be established.

The Chapter further contain overview of ISO standards for air quality, and overview of measuring devices for continuous monitoring of emissions and ambient air quality.

Fully integrated information and management systems for air quality are now rapidly entering the market, and one such system is described. The system also contains *effect modules* allowing for assessment of damages due to population and building *exposure*, and for evaluation of recommended abatement strategies. A module for modelling and calculating buildings degradation, service lives and maintenance costs has been developed and used.

Chapter 6 *describes the principle in the classification and mapping of environmental degradation factors and corrosivity.* Classification as described in the ISO standards ISO 9223-26 “Classification of atmospheric corrosivity for metals” employs two approaches, e.g. classification in terms of the corrosion determining environmental parameters, and/or classification based on corrosion rate measurements of standard samples exposed in the environment concerned. In this report emphasis is put on the first approach. This ISO standard has improved maintenance as their prime objective, and represents a huge step forward as it for the first time in this context describes a system for quantitative characterisation and classification of the important environmental degradation factors. Its standard approach can also be used for other types of materials, and such standards are beginning to emerge.

Examples are given of mapping according to the service life (and ISO 9223) approach from Japan, UK, Spain, US and the world wide ISO CORRAG programme.

In the recent years the environmental concern and the strive for sustainable development have also generated a need for mapping the corrosivity of the exposure environment, in order to provide input to environmental regulations. This is done both by using corrosivity mapping for proper cost benefit analysis of building degradation, and now also mapping according to the critical loads/levels approach being used in environmental research.

The mapping procedure developed in UN ECE and the interesting related Environmental Assessment Level approach in UK are described, and examples of implementation of these approaches are given for the urban area Oslo and for UK, respectively.

The mapping of dose response functions and acceptable corrosion rates would be of extreme value for the building society. Such maps can easily be transformed into maps for service life and maintenance intervals if the performance requirement is defined for the material in question. Input from the building society in this context is a necessity, and could then serve as a tool for maintenance planning for individual users etc. These maps would therefore be of extreme value for standardisation work going on within CEN and ISO TC59 WG9 Design life of buildings. In that respect the question of transformation and validation of the dose response and damage functions to the micro environment on the building surface has to be addressed.

Chapter 7 *overviews some of the monitoring systems available for measurement of important degradation factors in the micro environment on buildings.* Multi-sampling instruments with automatic data handling presentation tools are now available for temperature, wetness and UV, and passive samplers for gases and particles also exist. Other methods are certainly available around the world, and contributions are especially welcome in this context. Examples of results and use are given for described methods.

The air quality and exposure of buildings can also be modelled by available dispersion models for roads and street canyons. In the environmental research are traffic planners are often in need of practical tools for studying the effect of abatement strategies on air quality in streets where people are exposed. A PC based model exists, that calculates total emissions, concentrations along each road segment and the air pollution exposure of the population and buildings along each road.

Chapter 8 lists the proposed needs for R&D and standardisation concerning the issue of characterisation of environmental degradation factors, as follows:

1. There is a *lack of systematic knowledge* on the right type and form of degradation factors to be characterised. In order to produce this knowledge, extensive service life research based on damage functions approach has to be carried out. They should involve models for degradation mechanisms and should be tested out in well monitored relatively short exposures in field and in laboratory.
2. Damage function based research and proper characterisation of degradation factors both in field and laboratory is one absolute criterion for relevant coupling of *field and laboratory tests.*
3. Some *methods* for automatic and continuous monitoring of important degradation factors in the micro environment on buildings exist, but testing and further development of methods are strongly needed.
4. Quite a *few dose response functions* exist today after extensive research in the environmental research area. However, these functions have to be tested and validated in the *micro environment* on buildings. Measuring and modelling methods for micro environmental loading and materials degradation have to be developed and extensive measurements carried out.

5. The dose response functions produced so far often stems from the environmental research area. They are therefore limited in terms of choice of degradation indicators. In addition, they do not contain identified *limit states,* and are therefore not damage- or service life functions.
6. Interdisciplinary co-operation between the building and environmental research community is a must.

Environmental Characterisation including Equipment for Monitoring

CIB W80/RILEM 140-PSL
SubGroup 2

1. Introduction

1.1 General

In the developed countries, the building stock and infrastructure constitute more than 50 per cent of each country's real capital. This built environment is in a bad state. After the "build and let decay" age during the last 30 years, the concern is not only the environmental impact on the cultural heritage. Generally, the damages to building materials and constructions have become an enormous economic, cultural and environmental problem.

The wasteful consumption of energy and materials linked to the degrading built environment makes this a major environmental problem in the context of sustainable development.

To safeguard our built environment, action is urgently needed, see Figure 1. In principle, there are two possibilities – and both should be pursued in parallel. Firstly, society should try to improve the exposure environment surrounding the materials, and secondly, better products, processes, methods and standards should be developed. The first action is being pursued by the environmental research area via cost-benefit analysis for degradation of materials and buildings, while the second issue is the concern of many RTD and standardisation programmes around the world (Haagenrud et al., 1996; AIJ, 1993; CSA, 1995).

An international standard for prediction of service life of building materials/components and buildings is currently in the process of being elaborated within ISO/TC59/SC3/WG9 (ISO, 1995). This group was set up from the joint initiative for standardisation of service life methodologies by the EUREKA umbrella project EUROCARE and CIB/RILEM, towards CEC and CEN in 1991. It was based upon the generic RILEM recommendation for prediction of service life (Masters and Brandt, 1984). In Europe the entry into force of the Construction Products Directive (CPD) also creates an urgent and increased need for standards addressing the issue of durability (Caluwaerts et al., 1996).

The service life prediction models for building materials and components are based upon knowledge of degradation mechanisms and dose-response functions. For industry to respond to the standards and requirements a lot of data and knowledge in this field needs to be compiled or generated. As shown in the following, much of these data could be provided for through extensive co-operation with the meteorological and environmental research community.

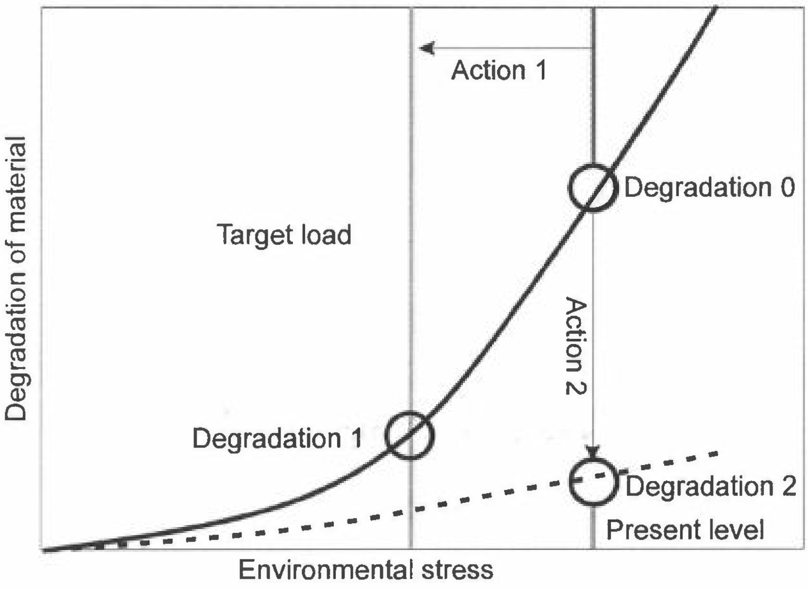


Figure 1: The two principal actions for improving the durability of the built environment.

1.2 Background and aim of work of SG2

This report has its background in long-term CIB and RILEM joint Committees work on methodologies for service life prediction. In 1982 the CIB W80/ RILEM 71-PSL (Prediction of Service Life) was established. This Committee concluded its work in 1986, and proposed a generic methodology for the prediction of service life.

During the period 1987-1990 the RILEM co-operation with CIB W80 continued with the formation of TC 100-TSL, which focused its work on developing methodologies for generating data from long-term ageing studies of materials and components in actual, 'in-use', conditions. The combined work resulted in the publication of a number of reports and papers.

During the period 1991-1996 the third joint Committee, the CIB W80/RILEM 140-TSL, has continued the work aiming at further detailing of the generic methodology established by W80/71-PSL. Christer Sjöström, KTH, Sweden, was elected as chairman of the joint committees. The programme covered five subject areas and was likewise organised into five sub-groups each having their respective sub-group chair to co-ordinate activities within the group. The five groups include:

1. *Data from field exposure testing, in-use testing and experimental buildings in service life prediction* (The chairman of this sub-group has been Mr. Erik Brandt, SBI, Denmark).

2. *Environmental characterisation including equipment for monitoring* (This subgroup has been chaired by Dr. Svein Haagenrud, NILU, Norway and Dr. Jonathan Martin, NIST, USA).

3. *Materials characterisation including monitoring of degradation processed* (The chair in this sub-group has been Dr. Per Jernberg, KTH, Sweden).

4. *Mathematical modelling* (The subgroup has been chaired by Mr. Ton Siemes, TNO, The Netherlands and Dr. Jonathan Martin, NIST, USA).

5. *Design of short-term test methods* (Ms. Lesley Jacques from South Florida Test Service, USA has been the chair for this sub-group).

At the end of the working period it was decided to publish the result of the committee work in a single volume publication. This report covers Sub-group 2, and will only be printed in a small number. Its content will be reedited and rearranged in the final publication.

The *aim* of this report is "presenting *state-of-the-art* and *research needs* regarding *characterisation* of degradation environment, including *methods and equipment for microclimatic monitoring*".

The *scope* is "to identify methods for measuring and characterising these primary environmental factors, to demonstrate how these measurements can be related to laboratory measurements, and identify areas in which standards are necessary to improve the precision and accuracy of these measurements".

Characterisation of environmental degradation factors should be linked to the knowledge of degradation mechanisms and dose response functions. Therefore the report will also review the knowledgebase of such functions.

Further it will discuss what measuring methods and data that are available for characterising the ambient exposure environment, and how these data can be classified. The report will then focus on *micro environmental* measurements and data, which are one of the main barriers for reliable service life predictions of building materials and components.

2. Service Life Prediction Concept – Need of data

2.1 Model for degradation

With reference to the "definition" and "preparation" steps in the generic service life methodology (Masters and Brandt, 1989), data is needed on (see Figure 2):

- the performance over time functions for the materials and products,
- the dose-response or damage functions for the materials,
- the degradation factors at a macro-, meso- and micro-environment level.

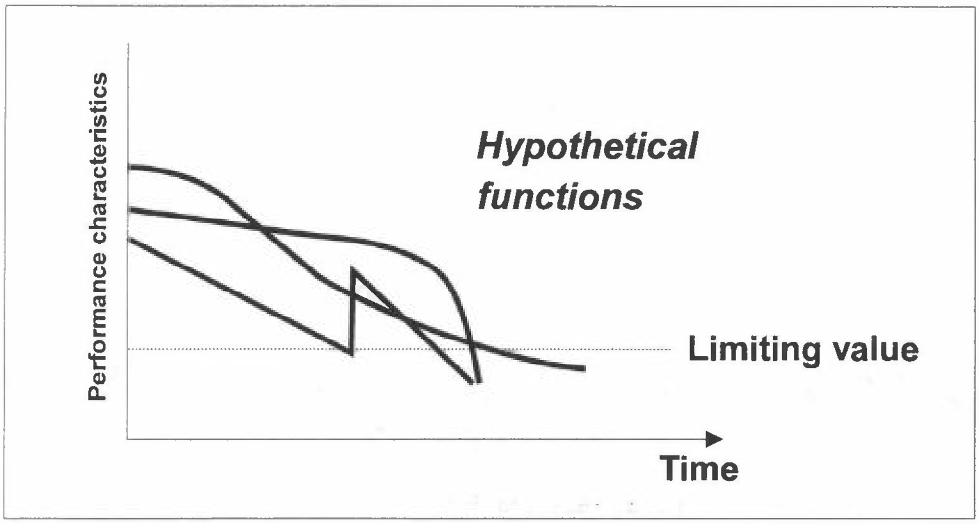


Figure 2: Performance over time functions.

Materials degradation and loss of characteristic properties, as described by performance over time functions (Figure 2), are in most cases due to chemical or physical deterioration or corrosion. The corrosion can be expressed by the mathematical model consisting of a power function of degradation factors and elapsed time:

$$M = a \cdot t^b \qquad (1)$$

where

M = corrosion at time t;
a = rate constant, which can be expressed by the deposition of pollutants or other degradation agents to the surface;
b = power exponent governed by diffusion processes, where b ~ ½ for the case of corrosion products forming a protective layer through which fresh reactants must diffuse (Figure 3).

In the present context the equation (1) will be defined as a **dose-response** function, aiming to describe the physico/chemical connections between the material degradation and the degradation factors of its exposure environment. Although this is not according to a strict definition of dosage (Elandt-Johnson and Johnson, 1980), it is because the generic equation (1) has been used to analyse and reconcile a great number of so-called dose-response functions from the environmental research area. In the environmental area a huge amount of studies have been performed aiming to find the corrosive effect of air pollutants and to establish the relationship between materials decay and the environmental degradation factors. Although generating a lot of useful data and knowledge about the effects, the studies of course lacks a homogeneous approach in terms of measurements, time frames and data-analytical procedures. A survey of many of these studies and their reconciling is given in Chapter 3.

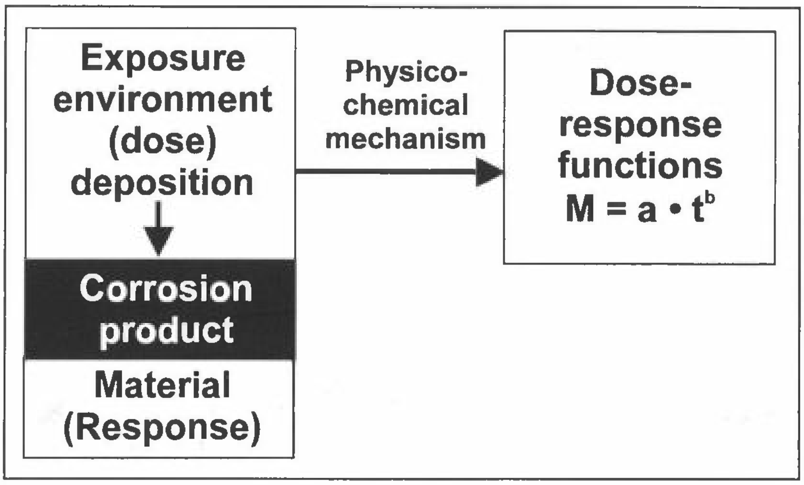


Figure 3: Degradation model.

After having generated experimental data from long-term and or short-term tests (Crewdson and Lewry, 1996) the dose-response functions can be elaborated by regression analysis. This can be done simply by screening the best fitting function, or, even better, adopting the regression analysis to the best available model for the degradation mechanism. Examples of both approaches are shown in Chapter 3.

The dose-response functions are not directly suitable for service life assessments. To transform the degradation into service life terms, performance requirements or **limit states** for allowable degradation before maintenance or complete renewal of material or component, have to be decided. The dose-response function then transforms into **damage function**, which is also a performance over time function, and a service life assessment can be made.

The establishment of the limit state is complicated, and can be discussed both from a technical, economic and environmental point of view. Within the building society the first two aspects have so far been dominating (ISO 6241-1984(E); Caluwaerts, 1996). However, within the environmental area the discussion has started on fixation of the limit state from the "sustainable requirement" point of view (Butlin et al., 1994, see Chapter 6). A convergence of these requirements would have great interest and impact in the building sector (see Chapter 6).

A major barrier for further progress concerning the durability and service life aspects within the building community, is the lack of knowledge of and implementation of the damage function approach. This approach is the basis for the level of knowledge in high-tech industries and in the medical, biological and agricultural community and so on (Martin et al., 1993). Until this approach is taken seriously and adopted by the building community on a broad scale, no substantial improvements in the field of durability of building materials and components can be anticipated. The lack of this systematic approach has become quite evident in writing this report.

Tomiita (1993) has used the mathematical damage function approach (eq. 1), and developed it into a cumulative damage model as a computer software application.

He has thus been able to use the right type and form of the environmental degradation factors, and therefore also to predict and compare degradation rates from long term field exposure and laboratory exposures. These results are convincing and very promising.

The same approach is advocated by Martin et al. (1993) in discussing and proposing methodologies for predicting the service lives of coating systems. They established *a set of criteria* for assessing the adequacy of the current durability methodology and a reliability based methodology, which include the ability to:

1. handle high variability in the time-to-failure data for nominally identical coated panels exposed in the same service environment,
2. analyse multivariate and censored time-to-failure data,
3. establish a connection between laboratory and field exposure results, and
4. quantitatively predict the service life of a coating system exposed in its intended service environment.

They conclude that in order to implement a reliability based methodology *substantial changes* in the current experimental procedures will be required. *These changes result* from the quantitative nature of the service life data, and will include

1. more systematic characterisation of the initial properties of a coating system,
2. *quantitative characterisation of each of the weathering variables comprising the in service environment*,
3. quantification of macroscopic degradation via cumulative damage function models,
4. utilisation of experimental design techniques in planning and executing short term laboratory based experiments, and
5. development of computerised techniques for storing, retrieving and analysing the collected data.

A lot of knowledge can also be transformed from the many studies that have been performed in the environmental research area to establish dose response and damage functions (Haagenrud and Henriksen, 1996). However, it should be pointed out that the dose response functions which are currently available are very limited in terms of *choice of degradation indicators and establishment of performance requirements.*

Another major barrier to reliable predictions of service life and/or maintenance intervals is insufficient knowledge of the relevant exposure environment. However, substantial knowledge and data exist on the environmental exposure conditions on the *macro* and *meso* level. It is a serious problem that these tend to be in a generalised form such as a contour map of average data, for example mean temperature, humidity etc., while researchers and designers need to consider the *specific form*, and also the local- and micro-environmental conditions of the building (see definitions point 2.2).

A *third* barrier is just this adaptation of data and knowledge to the *local* and *micro environmental* conditions. The complexities of a structure can result in very different climatic and environmental conditions on a single structure and greatly affecting damage rates (Vlckova and Knotkova, 1996; Cole et al., 1996; Henriksen and Haagenrud, 1993; Rendahl et al., 1996). A main problem would also be the differences of the standardised surfaces and real surfaces of components connected with the object (Knotkova, 1996). The dose-response functions are primarily established under more or less controlled experimental conditions, and a *major task* would be the transition to real constructions. *The dose-response functions must be validated for micro environmental conditions*, and testing under in-use conditions have to be done. Measuring and modelling methods for *micro environmental* loading and materials degradation have to be developed and extensive measurements carried out.

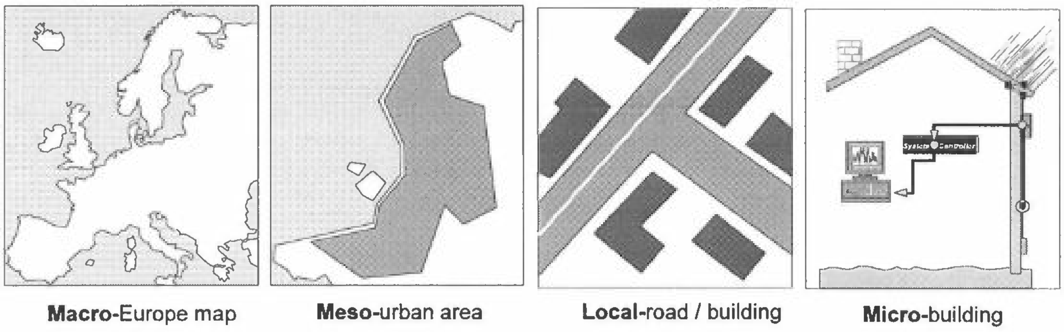
2.2 Characterisation and Mapping of the most important environmental degradation factors

2.2.1 Definition of scale

The proper use of dose-response functions require characterisation and mapping of the relevant degradation factors on the different geographical scales.

One frequently used basis of classification for climate, and environment, is the division into macro, meso, local and micro scales. (Sjöström and Brandt, 1990). This division means a definition of different scales describing the variations in the meteorological variables. There exist no common and exact definitions of the different scales, but in this report will be used the following (Figure 4):

By *macro* is normally meant the gross meteorological conditions described in terms like polar climate, subtropical climate and tropical climate. The descriptions are based on measurement of meteorological factors such as air temperature, precipitation etc.(IEC 721-2-:1982).



Macro-Europe map **Meso**-urban area **Local**-road / building **Micro**-building

Figure 4: Exposure environment on different geographical scales.

When describing *meso* climate, the effects of the terrain and of the built environment are taken into account. The climatological description is still based on the standard meteorological measurements.

In this report we also use the term the *local* scale. By that is meant the local conditions in the building proximity, such as for example in the streets to the building. The ***micro*** climate describes the meteorological variables in the absolute proximity of a material surface. The micro climate or micro environment is crucial to a materials' degradation.

2.2.2 Systematics for describing degradation agents

Various systems have been used to classify the degradation agents. The standard ISO 6241-1984 (E) presents a detailed list of agents relevant to building performance. The degradation factors are classified according to *their nature* as *Mechanical, Electro-magnetic, Thermal, Chemical and Biological agents*, and to *their origin* (external-internal to the building, atmosphere, ground etc.). The same set-up will be used in this report with the overall emphasis on the *outdoor atmospheric exposure environment.*

However, in order to characterise and report the right *type* and *form* of the environmental degradation factors, they have to be related to the degradation mechanism and dose-response functions for the specific materials in question (Tomiita, 1992; Martin et al., 1993). This will facilitate comparisons to be made between field and laboratory measurements.

In their discussion of environmental characterisation, Martin et al. (1993) states: "With respect to statistical characterisation, it is known from laboratory based studies, that weathering factors act *synergisticly* in causing a coating system to degrade, and that often, for values below some threshold, the rate of degradation related to a weathering factor is so low that the degradation at level below this threshold can be neglected for all practical considerations. ...The existence of *synergistic effects*, the effects of *wet-dry cycles*, and the possible *presence of threshold values raise serious questions as to whether characterising weathering factors by their mean value and viewing the degradation effects of these factors as acting independently is meaningful in the context of service life prediction.* As an alternative, it is recommended that until more is known about the effect of the individual weathering factors on the degradation process, *time series* for each of the primary weathering factors be simultaneously monitored and characterised.

The quantitative characterisation of in service environment raises some critical questions including:

1. Can the weathering factors causing the *predominant* degradation of a coating system in a specified in service environment be isolated from the factors which have only a *secondary* effect?
2. Is the *average intensity* of each weathering factor sufficient for characterising the severity of an in service environment, or will a more precise knowledge of each of these factors be necessary?

3. Can the value of weathering factor be converted into some *common metric of degradation* (e.g., total dosage, which is the same for both laboratory and field studies)?

In addition to changing the way weathering factors are *statistically characterised*, it is recommended that changes be made in the way they are *physically characterised.* For the purposes of the service life prediction of coatings, metrics for expressing the *severity* of the outdoor weathering factors of temperature and UV degradation are proposed."

It is interesting to see that the European Organisation for Technical Approval (EOTA), in their Guidance Paper on "Assessment of Working Life of Products" to the Convenors of the Technical Committees has adopted the service life methodology of RILEM, the ISO 6241, the damage function approach and emphasizing the specific need for characterising the exposure environment on the geographic scales of Europe (EOTA, 1996).

2.2.3 Sources of data

The measuring, testing and evaluation of air quality are assuming growing importance in developed countries as elements of a comprehensive clean air policy and geared to sustainable development. A huge bulk of data are therefore generated on the various geographical levels.

In the context of assessing building performance, data on global, continental (macro) and national (meso) levels are available for exploitation. To some extent data are also available for a local scale, while most is lacking for the micro environment on buildings.

Chapter 5 therefore contains an extensive state of the art report on availability of data and methods from the atmospheric environmental research area on the global and the macro and meso scale in Europe. *(The European bias here can be corrected for.)*

Methods for making micro environmental characterisation are also available, as discussed in Chapter 7.

2.2.4 Environmental Classification Concept

Based on knowledge of dose-response functions (see 2.1) the environmental degradation factors can be *characterised* and from this characterisation it should be possible to classify an exposure environment relative to its severity. This can be mapped and exhibited in geographical information systems software applications. Such classification system already exist for some metals (ISO 9223–9226, 1992). They have been developed for the classification of atmospheric corrosivity and employ two approaches. Either environmental classification in terms of the corrosion-determining parameters, Time of Wetness (TOW) and pollution, or classification based on corrosion rate measurements of standard metals exposed in the micro environment concerned.

The above mentioned standard approach for classification can also be used for classification of other materials corrosivity if the dose-response functions/ degradation mechanism are known.

Degradation of non-metals is generally caused by other mechanisms than those responsible for the corrosion of metals, even if oxidation processes are important in most cases. For example, a generic classification of degradation environments for polymeric materials in outdoor use calls among other things for improved knowledge concerning surface temperatures, UV-radiation, moisture periods, and the influence of air pollutants (Tomiita, 1993).

Basically corrosivity mapping and environmental characterisation was undertaken to meet the needs for better maintenance, and design of constructions.

However, in the recent years, the environmental concern have generated a need for mapping the corrosivity of the exposure environment, in order to provide input to environmental regulations.

A review is made of the various classification approaches used today. According to the scope of the report emphasis is on systems for classification of the environmental degradation factors (see Chapter 6).

2.3 Use of Information Technology in Building Assessment

Monitoring and assessing the performance of a building and its components will require extensive amounts of data. The inability to integrate the accumulated information has hitherto been a serious barrier to further development. With the recent leap forward in information technology this delimitation is no longer present. Micro environmental multisampling techniques, user-friendly on-line presentation and complete facility information and management systems are available for managing and integrating geographical information. Examples of the development and use of such systems will be described (see Chapter 5.8 and 6.6).

3. Review of dose-response functions

Many studies have been performed to establish such functions (Haagenrud and Henriksen, 1996; Butlin et al., 1994). Conclusions from some of the most important studies are presented in Table 1.

3.1 NAPAP-Lipfert

In the US National Assessment Program for Acid Precipitation (NAPAP), Lipfert et al. (1986) composed a database of atmospheric corrosion test results for **metals** together with environmental variables published from 8 test programmes taken at up to 72 test sites dating back to the 1960's. A substantial part of this data was obtained from the Scandinavian countries. Statistical regression analysis was used to infer dose-response functions, using several different basic model formulations.

Lipfert concludes that time of wetness is most important for steel and that SO_2 *seems to be the only pollutant that is important for the four metals (see Table 1), on the basis of confidence limits calculated for the various coefficients.*

Critical relative humidities for corrosion to occur differ among the four metals, indicating differing corrosion behaviour. Final conclusion was that large numbers of observations are required in order to generate statistically robust dose-response functions based on essentially uncontrolled field tests. Regression analysis indicate predictability to be only within a factor 2 or more, for any given time period and location, with weight loss of the specimen used as the damage indicator.

Lipfert (1989) has also surveyed corrosion data and environmental data for **calcareous stone** from 9 field tests in USA and other countries. The theoretical dose-response function developed is based on recognition of three basic mechanisms for stone degradation:

1. Normal calcite dissolution in clean rain ($pH < 5.6$)
2. Dry corrosion by deposition of gaseous air pollutants, notably SO_2 and HNO_3
3. Wet corrosion acceleration due to rain acidity.

3.2 Scandinavian studies

In a Nordic field exposure programme sponsored by NORDFORSK from 1975–1984, dose-response functions for carbon steel and zinc were established via exposure at 32 test sites in Scandinavia (Kucera et al., 1986). Dose-response functions were developed for carbon steel and zinc by linear regression analysis.

NILU performed, on contract for the Norwegian Pollution Control Authority, detailed corrosion assessment studies in four areas in Norway. Linear statistical analysis were used to develop the dose-response functions, of which the ones for metals in the urban area Sarpsborg/Fredrikstad are presented in Table 1. In this area the steel corrosion was modelled from the developed dose-response function based on the modelling of SO_2 with NILU's air dispersion model (Haagenrud et al., 1985).

3.3 Feliu and Morcillo

In Spain, Feliu and Morcillo (1993) surveyed and compared data from 250 test sites in 28 countries in many parts of the world. Statistical analysis were performed in developing the dose-response functions for carbon steel, zinc and copper shown in Table 1.

3.4 UN ECE ICP

The most extensive and best designed test programme is the International Co-operative Programme (ICP) within the United Nations Economic Commission for Europe (UN ECE). The programme which started in September 1987, aims to evaluate the effect of airborne acidifying pollutants on corrosion of materials, and involves exposure at 39 sites in 12 European countries and in the United States and Canada. (Figure 5).

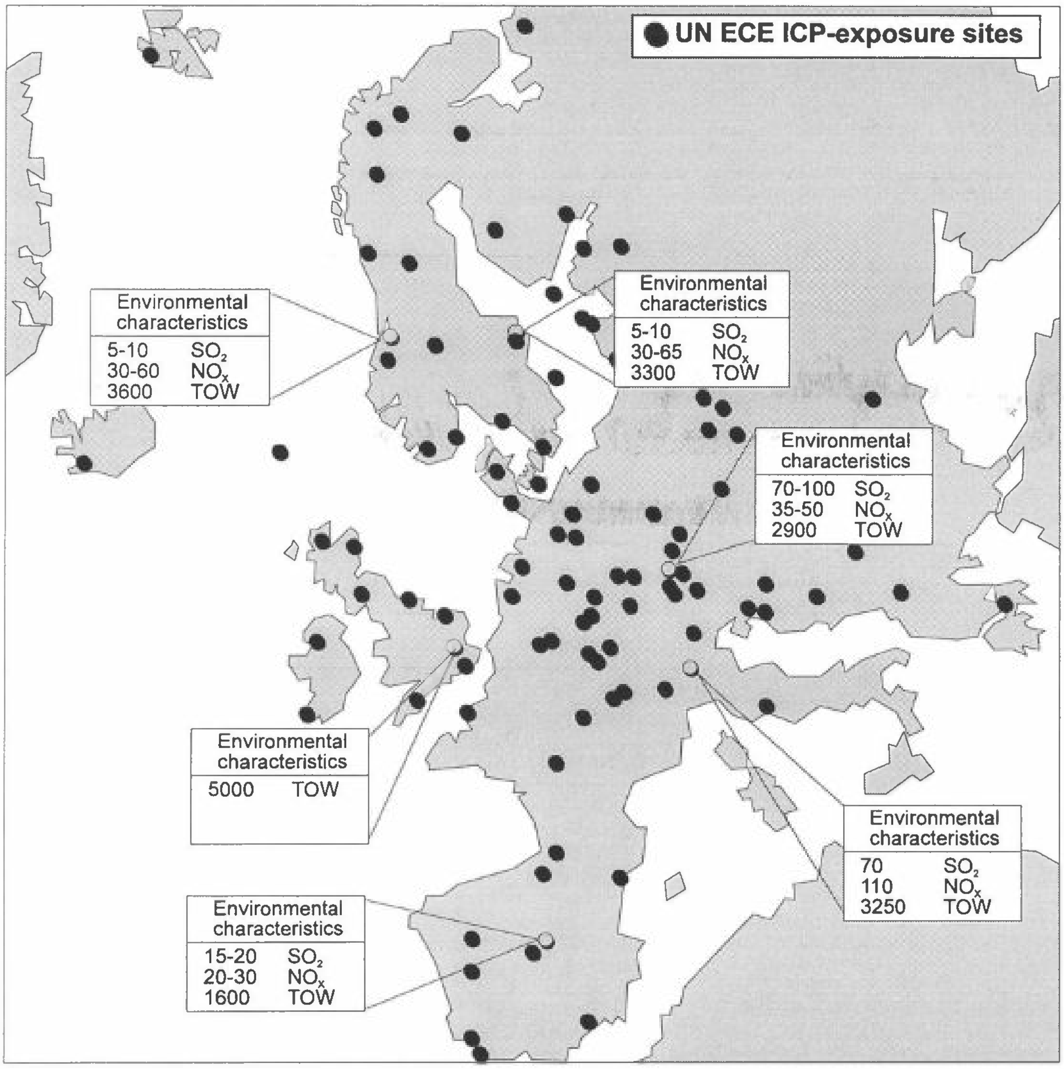


Figure 5: UN ECE ICP sites.
(Units: SO_2 and NO_2 = µg/m^3, TOW = hours/year.)

Samples have been withdrawn after 1, 2 and 4 years exposure and dose-response functions have been developed (Kucera et al., 1995) for carbon steel, zinc, aluminium, copper, bronze and calcareous stone as shown in Table 1. The equations should at present be seen as provisional and may be subject to further elaboration when the results from the 8 year exposure will be available in 1996.

For unsheltered exposure most of the dose-response functions have the same form

$$\text{ML or MI} = a + b\ \text{TOW}\ [SO_2][O_3] + c\ \text{Rain amount}\ [H^+] \qquad (2)$$

This is the first time a synergistic effect of O_3 and SO_2 has been indicated in a field exposure. There is, however, also a very complex interaction between O_3, SO_2 and also NO_x. The mechanisms for chemical interaction and degradation mechanisms for the materials will be dealt with more in detail in Chapter 4.4.2.5.

Table 1: Universal dose-response functions for building materials (Haagenrud and Henriksen, 1996).

Material	Equation	Correlation	Eq. No.
NAPAP			
Lipfert et al. (1986)			
Data from 8 test programmes comprising 72 test sites in many countries. In the dose-response functions recommended for assessment use, $\mathbf{M_{metal}}$ = mass loss (g/m^2), and H^+ = (meq/m^{2}yr) and based on 1 m of precipitation per year, Cl^- = 10 mg/m^{2}d and dustfall = 50 mg/m^{2}d, f = fraction of time above indicated critical relative humidity.			
Zinc (galv. steel)	$M_{Zn} = [t^{0.779} + 0.0456 \ln (H^+)] [4.534 + 0.547 f_{85} \cdot SO_2 + 0.0293 H^+]$		(3)
Copper	$M_{Cu} = 2.23 t^{0.805} (0.492 f_{80} \cdot SO_2 + 0.016 H^+ + 3.04)^{0.641}$		(4)
Aluminium	$M_{Al} = 0.203 t^{0.987} [0.099 + 0.139 f_{90} \cdot SO_2 + 0.0045 H^+]^{0.870}$		(5)
Carbon steel	$M_{Fe} = 300.4(f_{90} t)^{0.541} (f_{90} \cdot SO_2)^{0.257} (H^+)^{0.067}$		(6)
Lipfert (1989)			
Dose-response function for **carbonate stone** developed from experimental data from 9 field tests in USA and sites from other countries, where ER = erosion rate (mass loss/m rain), V_d = deposition velocities (cm/sec), pollutant concentrations (µg/m^3) and rainfall R (m) in metres.			
Carbonate stone	$ER = 18.8 + 0.016 H^+ + 0.18 (V_{dS} \cdot SO_2 + V_{dN} HNO_3)/R$		(7)
Scandinavia			
Kucera et al. (1986)			
8-year exposure of carbon steel and zinc at 32 test sites in rural, urban and marine environments. Dose-response functions developed by linear regression analysis, where M_{metal} = reduction of thickness (µm), SO_2 = µg/m^3, Cl = mg/m^2 · d, t = time.			
Carbon steel	$M_{Fe} = (0.77 SO_2 + 0.42 Cl + 14) t^{0,59}$	R = 0.94	(8)
Zinc	$M_{Zn} = (0.023 SO_2 + 0.011 Cl + 0,53) t$	R = 0.89	(9)
Haagenrud et al. (1985)			
The corrosion in urban Sarpsborg/Fredrikstad area (Norway) was modelled and mapped in a 4 year exposure programme on 13 sites with specimen withdrawal monthly, quarterly, yearly and after 2 and 4 years. Dose-response functions for yearly corrosion developed by linear regression analysis, where K_{metal} (g/m^2/yr) TOW (h/y) is time of wetness (hours per year with T > 0°C, RH ≥ 80%).			
Carbon steel	$K_{Fe} = 7.6 SO_2 + 172.0$	R = 0.93	(10)
Zinc	$K_{Zn} = 0.35 SO_2 + 0.01 TOW - 21.8$	R = 0.94	(11)
Copper	$K_{Cu} = 0.14 SO_2 + 0.007 TOW - 16.9$	R = 0.91	(12)
Aluminium	$K_{Al} = 0.01 SO_2 + 0.00053 TOW - 1.2$		(13)

Table 1 contd.

Material	Equation	Correlation	Eq. No.
Feliu and Morcillo (1993)			
Data from 28 countries comprising 250 test fields in various parts of the world. C = corrosion (µm), t = time (years), Cl = yearly average concentration (mg/dm^2/d), S = yearly average concentration (mg/dm^2 /d), T = yearly average temperature (ºC), D = number of days/nights of precipitation, RH = yearly average relative humidity (%), R = multiple correlation coefficient.			
Carbon steel	$C_{Fe} = At^n$, where		(14)
	$A = 33.0 + 57.4\ Cl + 26.6\ S$	R = 0.73	
	$n = 0.57 + 0.0057\ Cl\ T + 7.7 \times 10^{-4}\ D - 1.7 \times 10^{-3} = 0.40$	R = 0.40,	
Zinc	$C_{Zn} = At^n$, where		(15)
	$A = 0.785 + 5.01\ Cl + 2.26\ S$	R = 0.73	
	$n = 0.53 + 0.55\ S\ (1-0.068\ T) + 0.025\ T$	R = 0.062	
Copper	$C_{Cu} = At^n$, where		(16)
	$A = 1.03 + 1.45\ Cl + 2.00\ S$	R = 0.60	
	$n = 0.82 - 0.068\ T\ (1-0.011\ RH)$	R = 0.47	
UN ECE ICP **Kucera et al.** (1995)			
Exposures at 39 sites in 12 countries in Europe, USA and Canada. 4-year dose-response functions below, where ML, and MI are respectively mass loss and mass increase after 4 year exposure (g/m^2), TOW = time of wetness (RH>80%, T>0°), as time fraction of a year (8760 hours), $[SO_2]$ and $[O_3]$ = concentration (µg/m^3), rain = precipitation per year (m/year), $[H^+]$ = concentration (g/l).			
METALS			
Weathering steel			
Unsheltered	${}^4ML = 85 + 0.26\ TOW\ (SO_2)\ (O_3) + 432\ TOW$	R = 0.67	(17)
Sheltered	${}^4ML = 106 + 0{,}54\ TOW\ (SO_2)\ (O_3)$	R = 0.59	(18)
Zinc			
Unsheltered	${}^4ML = 14.5 + 0.043\ TOW\ (SO_2)\ (O_3) + 80\ Rain\ (H^+)$	R = 0.83	(19)
Sheltered	${}^4ML = 5.5 + 0.013\ TOW\ (SO_2)\ (O_3)$	R = 0.72	(20)
Aluminium			
Unsheltered	${}^4ML = 0.85 + 0.028\ TOW\ (SO_2)\ (O_3)$	R = 0.49	(21)
Sheltered	${}^4ML = -0.03 + 0.053\ TOW\ (SO_2)\ (O_3) + 74(Cl^-)$	R = 0.47	(22)
Copper			
Unsheltered	${}^4ML = 19.3 + 0.011\ (SO_2)\ (O_3) + 162\ Rain\ (H^+)$	R = 0.49	(23)
Bronze			
Unsheltered	${}^4ML = 11.8 + 0.047\ TOW\ (SO_2)\ (O_3)$	R = 0.59	(24)
Sheltered	${}^4ML = 5.3 + 0.024\ TOW\ (SO_2)\ (O_3)$	R = 0.52	(25)
STONE			
Limestone			
Unsheltered	${}^4ML = 34.4 + 5.96\ TOW\ (SO_2) + 338\ Rain(H^+)$	R = 0.66	(26)
Sheltered	${}^4MI = 2.536 + 0.80\ TOW\ (SO_2)\ (O_3)$	R = 0.40	(27)
Sandstone			
Unsheltered	${}^4ML = 29.2 + 6.24\ TOW\ (SO_2) + 480\ Rain\ (H^+)$	R = 0.63	(28)
Sheltered	${}^4MI = +2.84 + 0.88\ TOW\ (SO_2))$	R = 0.69	(29)
Painted coatings	${}^4CD = -6.1 + 0.18\ (SO_2) + 0.18\ (O_3)$, where ${}^4CD$ = Spread of damage from scratch in coating.	R = 0.35	(30)

3.5 Comparison of a range of dose-response functions reported for zinc

A comparison of the different published dose-response functions for each type of material will determine the reliability of the functions and the calculated rates of decay. However, comparison of dose response functions is not straightforward as the units and forms of the variables and therefore the functions are different.

Table 2 shows a set of recommended functions for zinc, mostly taken from Table 1.

To allow a useful comparison we have calculated Zn-losses using Oslo as an example with the following set of environmental variables: Cl dep. = 10 mg/m^2/day; dust dep. = 50 mg/m^2/day; prec. = 0.6 m/year; H^+ = 0.025 mg/l = 15 meqv/m^2 · year; pH = 4.5; f_{85} = 0.23 (2000h/year); TOW = 2785 h = 0.32; T_{year} = 8 °C; and the three SO_2-values of SO_2 = 0-,10- and 100 µg/m^3 = 12.5 mg/m^2/day and 125 mg/m^2/day, respectively.

Table 2: Comparison of a range of dose-response functions reported for zinc.

Study	Zinc Loss equation
1) Benarie & Lipfert (1986)	$M_{Zn} = [t^{0.779} + 0.0456 \ln (H^+)] [4.534 + 0.547 f_{85} \cdot SO_2 + 0.0293 H^+]$
2) Saunders (1983) (from Shaw Data for Average UK conditions)	$1.806 + 0.022 (SO_2)$
3) Haynie (1980)	$2.36 + 0.022 (SO_2)$
4) Atteraas & Haagenrud (1982)	$1.58 + 0.078 (SO_2)$
5) Mikailovskii (1982) (assuming a temperature of 15°C)	$3.92 + 0.067 (SO_2)$
6) Kucera et al. (1986)	$M_{Zn} = (0.023 SO_2 + 0.011 Cl + 0{,}53)t$
7) UN ECE (1995)	$^4ML = 14.5 + 0.043 TOW (SO_2) (O_3) + 80 Rain (H^+)$
8) Feliu & Morcillo	$C_{Zn} = At^n$, where $A = 0.785 + 5.01 Cl + 2.26 S$ $n = 0.53 + 0.55 S (1-0.068 T) + 0.025 T$

Figure 6 shows the results, where also the average dose-response function values are shown.

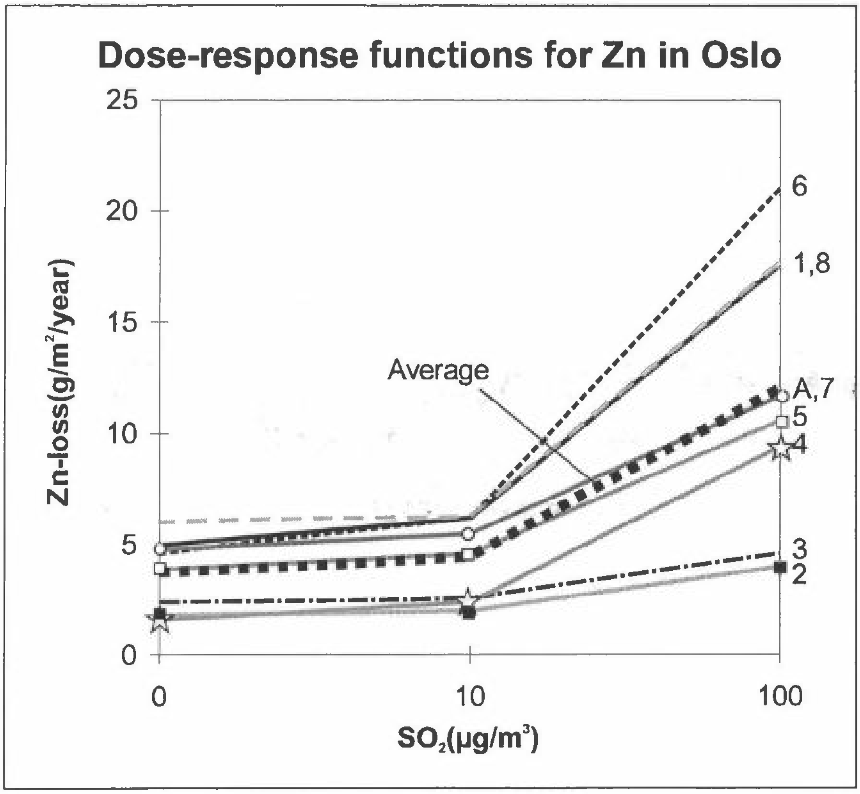


Figure 6: Comparison of different dose-response functions published for zinc.

4. Characterisation of Key Environmental Degradation Factors

4.1 Introduction

This Chapter provides *basic knowledge and characterisation* of principal agents affecting the durability of building materials. In principle it follows the detailed systematisation in standard ISO 6241–1984 (E) of agents relevant to building performance and requirements. The degradation factors are classified according to *their nature* as *Mechanical, Electro-magnetic, Thermal, Chemical and Biological agents*, and to *their origin* (external-internal to the building, atmosphere, ground etc.). The same classification is used in this report for *outdoor atmospheric exposure environments.*

This systematisation implies that the agents are *listed according to their own nature* and **not** *to the nature of their action* on the buildings or components; for example, a thermal agent may have a physical action (for example thermal expansion) or a chemical action (for example catalysis); a chemical agent like water may have a physical action (for example swelling) or a chemical action (for example hydration dissolution); moreover the agents in combination may have additional physical actions (for example wetting followed by freeze-thaw cycles), chemical actions (for example photo-oxidation by atmospheric oxygen and solar radiation) or biological actions (for example spread of roots).

The set-up in the standard lists the agents to be taken into account when defining performance and specifying requirements. The agents that apply in any particular situation, and their magnitudes, will depend on the building's situation, form, intended use and the way it is designed to perform.

In other words, in order to be able to characterise and report the right *type* and *form* of the environmental degradation factors, they have to be related to the degradation mechanism and dose-response functions for the specific material and material characteristic in question.

Reference is made to the survey in Chapter 3, and where possible there is an explanation of the process that takes place and examples to illustrate the data needed.

4.2 Mechanical agents

4.2.1 Snow loads, rain and water loads

The most significant action on buildings of water in solid form, i.e. snow (or ice), is structural loading on horizontal surfaces. The effect of snow on walls is minimal unless at drifting takes place. Problems can sometimes occur when snow is blown into buildings, particularly into roofspaces, through small holes. The **availability** of data on snow is sparse since snowfall is normally measured as equivalent rainfall (BRE Digest 332, 1988).

Precipitation in the form of hail is seldom in most parts of the world and, apart from the rare instances of impact damage from exceptionally large hailstones, may be regarded in the same category as rain. In the US, however, hail damage is a major source of damage to asphalt shingled roofs. The annual damage to these shingles is approximately a billion dollars per year (Martin, 1996).

Publications are available that contain data on creep and fatigue factors for most traditional building materials under loading. However, for many plastics and other modern composite materials manufacturers may need to carry out tests on specific building components. When considering these factors the expected design life for the structure must be taken into account. Tall reinforced concrete structures are particularly subject to contraction in height during their early life, not only from shrinkage but also from creep under self loading. Sufficient forces may consequently develop in infill clay brickwork or cladding, or rendering applied to them, eventually causing cracking or loss of adhesion. Other examples of long term movements that may lead to damage to adjacent construction are the expansion of clay bricks and butted floor and wall tiles due to absorption of moisture.

4.2.2 Ice formation pressure, thermal and moisture expansion

4.2.2.1 Daily temperature difference

All external construction materials experience both diurnal, seasonal and annual temperature fluctuations (Keeble, 1986; Martin et al., 1993; Cole, 1994). Building materials are heated by sunshine in the daytime and are cooled by thermal emission from the material at night. The fluctuations of temperature induce movements in the joints between building elements or cracks in concrete. Sealants and exterior finishing materials suffer from repeating tensile and compressive and shear stresses and are fatigued sufficiently as to deteriorate.

One special temperature variation that may greatly affect, for example, the micro cracking of coatings is rapid drop in surface temperature. A dark coating on an insulated sheet metal facade with a surface temperature of approximately 70 °C, when exposed to cold heavy rainfall may lose 50–60 °C in temperature in a few minutes.

The majority of available temperature data originate from measurements of the ambient atmospheric temperature. From measurements at meteorological stations, data are readily available on mean temperatures, temperature extremes and differences between maximum and minimum temperatures for specified periods of time. However, the relations between data on ambient temperature, surface temperature and temperature in the bulk of materials are very complex.

The *daily temperature difference* of building elements can be treated as a *mechanical deterioration index.* Tomiita (1992) collected daily maximum/minimum BPTS (Black Panel Temperature Surface), T_{Pmax}/T_{Pmin} (°C), and expressed them as functions of climatic data:

$$T_{P\,max} = 1.143T_{max} - 2.244W_{12} + 0.928S_v + 5.214 \tag{31}$$

$$T_{P\,min} = 1.049\,T_{min} + 0.022W_N - 2.389C_l - 3.056 \tag{32}$$

where T_{max} is the daily maximum ambient temperature (°C), W_{12} the wind velocity at 12.00 hours (m/s), $S_D{}^e$ daily total solar energy (MJ/m2/day), T_{min} the daily minimum ambient temperature (°C), W_N the daily average wind speed at night (m/s)

$$W_N = (W_3 + W_6/2 + W_{18}/2 + W_{21} + W_{24})/4$$

and C_l the clearness index, the ratio of total daily solar radiation to extra terrestrial solar radiation.

By inserting the meteorological data observed at 66 points during 1976-1985 into Equations (31) and (32), the daily maximum/minimum BPT was estimated. The yearly averages of the daily differences of BPT are then classified and mapped for Japan (Chapter 6.4.1). By multiplying the length of a building element by its thermal expansion rate, the daily movement in the joint or crack can be calculated.

4.2.2.1.1 Freeze/thaw

When water freezes it expands, and when it thaws the effects of this expansion can become apparent in the form of frost damage.

Frost damage occurs when there is sufficient water entrapped in the pores of the material to freeze and cause damage. The necessary conditions therefore include wetting (tending towards saturation) and freezing.

The wetting may be due to rainfall, but melt-water from a partial thaw of snow or ice is a common precursor to damage as it is likely to saturate the pore structure of the material and to start freezing. The air temperature at which frost damage occurs can be substantially below freezing, since temperatures just below zero might not freeze water in small spaces, and the temperature of material is often higher than the surrounding air. For this reason the number of *zero transitions (air temperature passing through 0°C) is not likely to give an accurate indication of the number of freeze thaw cycles in the material.* Zero transitions may, however, provide a useful means of ranking the frost resistance of porous materials.

Recent research on the risk of frost damage to exposed concrete has found the following were more critical than either the air temperature at the time of thawing, or the duration of the frost:

(a) severity of frost (lowest air temperature);
(b) speed for freezing (rate of fall of air temperature, and therefore rate of thermal change in the material);
(c) change of air temperature during periods of frost;
(d) numbers of frost cycles (i.e. daytime thaw after frost at night).

Data on freeze-thaw cycles may be used as indicators of the risk of frost damage to porous materials. Organic coatings may also be affected through movements in ice layers on the coating surface and by water freezing in cracks. As the thermal expansion coefficient of most polymeric systems is 10 fold greater than that of most metals the volumetric contraction of a coating would greatly increase the tensile load within the coating, thereby fostering cracking (Martin, 1996)

In the UK there are at present *two approaches* to identifying sites susceptible to frost damage.

One approach classifies a site as severely exposed to frost when all of the following factors apply (London Brick Company, 1988):

(a) The average annual frost incidence is in excess of 60 days.
(b) The average annual rainfall is in excess of 1000 mm.
(c) The altitude of the site is in excess of 91 m above sea level. *(This factor is likely to reflect the greater liability to wind driven rain on higher ground).*

The other approach is based on driving rain only. It recommends that suitable grades of mortar, and of bricks or blocks, should be used in areas subject to severe driving rain as defined in the map of the all direction driving rain index drawn from BS 7543: 1992 (see Figure 7).

In both approaches the saturation of material by rain is an important factor. Frost damage can be reduced by protecting a structure from saturation by detailing projecting eaves, cappings etc.

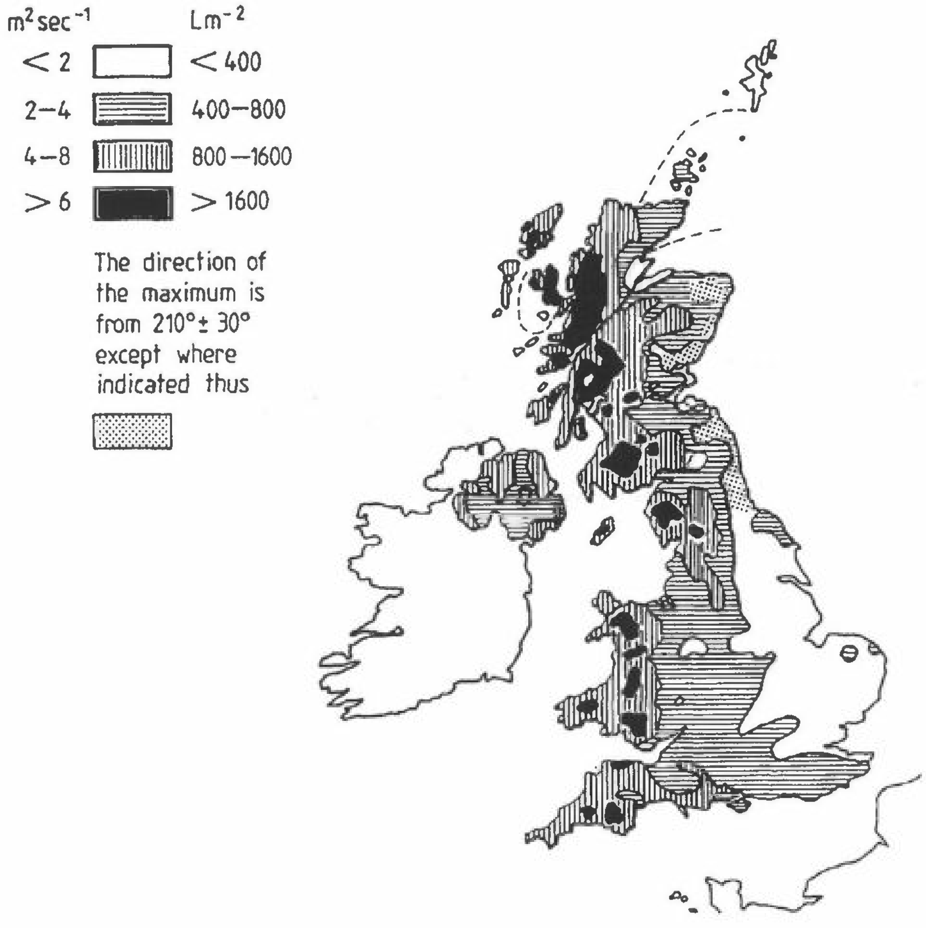


Figure 7: Maximum directional annual driving rain index map for UK.

4.2.2.2 Moisture

The presence of moisture is likely to enable physical, chemical or biological degrading reactions to take place. Moisture therefore acts as a mechanical, thermal (frost) and chemical agent. Different processes occur:

4.2.2.2.1 Driving rain

The quantity of water falling on the vertical faces of buildings is related to the combined effects of wind and rainfall (see Figure 7) (Lacy, 1976).

Most organic materials and many inorganic materials absorb moisture to varying degrees. The direct effect of water alone on a material item can be as follows:

(a) a volumetric expansion;
(b) a change in mechanical properties (e.g. strength);
(c) the development of bending and twisting forces;
(d) a change in electrical properties;
(e) a change in thermal properties;
(f) a change in appearance.

Quantitative dose-response functions exist between driving rain and some of these functional characteristics. In Germany 140 l/m^2 is given as the maximum amount of driving rain that a timber-framed houses can withstand without special protection being necessary for sealants (Eckermann and Veit, 1996).

4.2.2.2.2 Differential wetting or drying

Internal forces may be generated within a construction as a result of differential wetting or drying or from variations in moisture characteristics of the ingoing materials. Consideration should be given to dimensional tolerances to avoid such developments.

Examples of the weight absorptivity of water by weight of a material are (% (m/m):

(a) *Bricks* can absorb up to 30 % (m/m). (However, it should be noted that there is **no** direct relationship between water absorptivity of a brick and its durability.) (BRE CP 16/73 and BRE CP 92/74).
(b) *Natural stone and dense concrete* can absorb up to 10 % (m/m).
(c) *Nylon* can absorb from 2 % to 10 % (m/m).
(d) *Glass reinforced plastic* can absorb approximately 0.5 % (m/m).
(e) *Wood* – the maximum amount of moisture absorbed by wood varies according to species. However, in general terms wood swells as it takes up moisture to it's maximum content. This maximum is the content beyond which any additional moisture is accumulated in the cell lumina as free water. Maximum moisture content is highly dependent on the specific gravity of the wood. After it has reached it's maximum water content, more moisture will still be absorbed but the wood will remain dimensionally stable. Sapwood can absorb its own weight in water (see Chapter 4.5.1.2).

As for quantitative dose-response functions reference is made to Chapter 3, where time of wetness variable is shown to be a significant variable in the degradation of many materials. In 4.4.1.1. this very important variable is defined and discussed in detail.

On the macro and meso scale general meteorological data on the various forms of water are available from national meteorological institutes.

4.2.3 Wind

The major considerations relating to wind loads and durability include:

(a) the effects of the driving of rain and of particulate solid matter;
(b) the effect of differential pressures that may be developed in localised positions on a structure;
(c) catastrophic failure

The former is a major cause of erosion and rain penetration into the vertical structures.

Differential pressures may be built up in large areas such as roof coverings, cladding panels and glazing. These may cause deflections or loosening from fixings. They can also affect flashing, joints and seals.

Only generalised data relating to wind loads can be obtained. Local topography, including the influences of nearby structures, especially tall buildings, considerably affects the direction of the local air flow, and there are wide variations in wind speed over periods of time. Generalised data are available from the meteorological community.

BRE Digest 346 (BRE, 1989) which is in seven parts deals with different aspects of wind loads including, in Part 7, fatigue loadings caused by oscillation of a structure by the wind and fatigue due to the repeated gusts.

Examples of other intermittent stresses include earthquakes and man-made vibrations such as those due to road traffic, trains, music, dancing, and machine induced vibrations.

4.2.4 Use factors (wear and tear, abuse)

W*ear and tear* is abrasion results from traffic, the action of detritus, and contact with moving parts.

The severity of abrasive action is dependent on the nature of the abrasive material, its quantity and the influence exerted by the agency bringing it into contact with the building. The cleanliness of the environment also has an important effect. Abrasion caused by the combined action of traffic and detritus is considerably greater than that of traffic alone.

What is considered normal wear and tear for one type of building may be seen as untypical or excessive for another. For wall and flooring materials there are recognised grades that will withstand the expected levels of use, washing down etc. that are likely to occur in particular situations. For example, The British Carpet Manufacturers' Association use a six level classification from "extra heavy wear" to "light wear" and the UPEC classification used by the British Board of Agreement for thin plastics floorings identifies four separate properties: resistance to wear, to indentation, to water and to chemicals.

The frequency and nature of *cleaning and maintenance* needs to be assessed in relation to the likely consequence on the length of life of a component, particularly in cases such as:

(a) masonry where the actual cleaning procedure may lead to deterioration
(b) plastics surfaces that can be scratched by abrasive cleaning materials, e.g. unsuitable graffiti-removal processes and solvents;
(c) porous masonry when a coating of impermeable paint can lead to increased moisture contents and consequently to frost damage.

Uninformed and uncaring use of a building can accelerate its deterioration. An example is condensation caused by the combination of blocking of ventilation grilles and the excessive quantities of water vapour produced by the heavy use of liquid petroleum gas (LPG) room heaters, cooking and washing equipment.

With some components in certain types of buildings (e.g. school windows) breakages have to be considered as part of normal wear and tear. BS 6262 gives the extra precautions to be taken in areas where there are added risks to children, whose more active behaviour is likely to lead to more frequent accidents.

4.3 Electromagnetic agents

4.3.1 Solar radiation

The energy that reach the earth's surface from solar radiation is concentrated in certain wavebands. Figure 8 shows the variation in the energy received at different wavebands from direct sunlight. A portion of solar radiation is absorbed or reflected by the earth's atmosphere. This portion varies from one waveband to another and is affected by cloud cover. The degree of shading from direct sunlight also affects the quantity of the radiation received in each waveband.

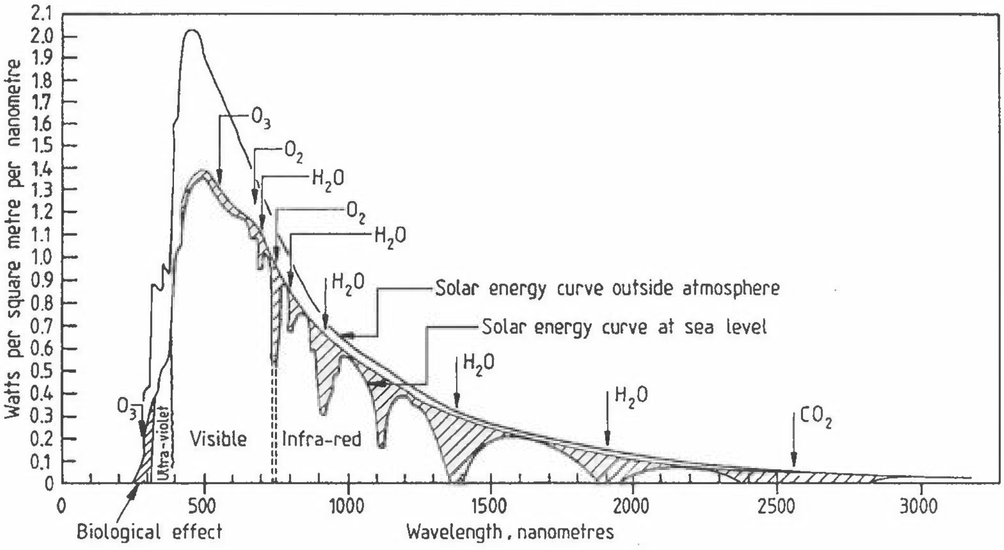


Figure 8: Curves showing the distribution of energy in the solar spectrum outside the atmosphere and at sea level (from BS 7543:1992).

4.3.1.1 Infra-red radiation (approximately 700 nm to 3000 nm)

Infra-red radiation is absorbed to some extent by all forms of matter and this causes an increase in temperature, thus creating surface temperatures greater than that of the surrounding air (in some cases markedly so). The opacity, texture and colour of a surface involved have considerable effect on the amount of radiation absorbed. The absorbed radiation will raise the temperature of a material by an amount dependent upon the specific heat and thermal conductivity of the material and the structure behind (see 4.2.2.1.1).

For given surface texture the colour of a surface considerably affects the absorption of solar radiation. Assuming a perfectly black surface has an absorptivity of 100%, the absorptivities for the following colours are (BS 7543: 1992):

a)	ordinary black	80%
b)	dark green or grey	70%
c)	light green or grey	40%
d)	white	12% to 20%

4.3.1.2 The visible waveband (400 nm to 700 nm)

There is no distinction made in most published data about the spectral absorption of visible light. The majority of published information concerns solar radiation measured either as bright sunshine or as total radiation. For most purposes the intensity of solar radiation on clear cloudless days is taken as the significant design value but it should be remembered that there will be considerable variation in the total radiation received at a given place on the ground depending upon:

(a) the cloud cover both in type and quantity;
(b) the season of the year;
(c) the local topography.

Peak solar radiation is likely to occur around noon inland, and during the late morning on the coast. Surfaces normal to midday summer sun, or those receiving substantial reflected radiation from adjacent surfaces, experience the highest temperatures. A value of 1.36 kW/m^2 ± 3.5% can be taken as the total radiation intensity at the mean distance of the earth normal to the sun, the variations being due to seasonal distance variation factors. This value ignores losses due to scattering by dust and water vapour particles and by the earth's atmosphere which will significantly reduce the value for a large proportion of time. In approximate terms, the radiation received on an overcast day is about one third of that received if it had been cloudless. On very dull days the proportion would be very much less.

4.3.1.3 Ultraviolet radiation (290 nm to 400 nm)

A large proportion of the ultraviolet (UV) waveband is scattered by the atmosphere, the remainder reaching the earth's surface has no adverse effect on inorganic materials. It is however, very important in its potential for deterioration of some organic materials. Although UVR (adiation) constitutes no more than 1–7% of the total solar radiation intensity, in practice it decides the service life of polymeric materials in outdoor use. The penetrating power of the UV - radiation is not great, and the action is consequently confined to surface layers exposed to radiation (Janson and Sjöström, 1979).

Measurements of total UV radiation over the spectral range are of limited value because of the sensitivity of materials to specific wavebands. For example polystyrene shows a maximum sensitivity at about 318 nm whereas polypropylene peaks about 370 nm. As a general rule it has been found that radiation shorter than about 360 nm tends to cause yellowing and embrittlement. Radiation of a longer wavelength tends to cause fading (Yamasaki, 1983).

Many organic dyestuffs are degraded by UV radiation, which may affect appearance.

Bituminous materials and some synthetic polymers are also degraded by UV radiation, and the changes to surface properties may alter the performance of the material.

UV radiation can also play an important role in initiating a degradation reaction which is then propagated under suitable conditions of moisture and temperature, e.g. the yellowing and surface denudation of glass fibre reinforced polyester roofing sheets caused by the combined actions of UV radiation and moisture.

The UVR-intensity varies with the atmosphere, local weather, air pollution, time of day etc. Due to the environmental ozone-UV problem there is now extensive intensity measurements being carried out on a global scale (see 5.2.4).

Estimates of the UVR environment for a certain geographic location can be made from meteorological data on global solar radiation or number of sunshine hours.

Tomiita (1992) has used a photodiode sensor (range 305–390nm), to measure the hourly solar UV energy on a horizontal plane in outdoor exposure in Japan for a year, and expressed it as a function of the entire range of solar radiation, observed by a pyranometer, and solar altitude as follows:

$$U_{hour} = -0.894 \quad Z^{-0.229}\ S_{hour} + 0.796\ Z^{-0.165}\ S_{hour}^{0.968} \tag{33}$$

Here U_{hour} = hourly solar UV energy (MJ/m²/h)
Z = solar altitude (degrees)
S_{hour} = hourly entire range of solar radiation (MJ/m² /h)

By applying this equation to the hourly solar energy calculated from the percentage of sunshine at 141 points in Japan, the hourly solar UV energy was estimated, and the yearly solar UV energy integrated. The results were classified and mapped, as shown in Ch. 6.4.1.

Tomiita has also produced quantitative dose-response functions for some polymeric materials, using the service life methodology with short- and long-term exposures to estimate the constants in the functions. *This would be a very valuable approach on a broad basis, but at present there is a considerable gap of knowledge concerning quantitative dose-response functions for solar radiation influences on the various types of materials/components performance characteristics.*

Martin et al. (1993) propose in a similar way the following metric for UV dosage, quoting: "Ultraviolet radiation is deleterious to most organic materials. The medical, biological, and agricultural communities characterise the degradative effects of ultraviolet radiation using a different approach from the one used in the coatings community. They relate the degradative effects directly to total effective UV dosage, D_{tot}, whereas the coatings' community tends to use total UV irradiance. The total effective UV dosage is defined by:

$$D_{tot}\,(t) = \int_{o}^{t} \int_{\lambda_{min}}^{\lambda_{max}} E_o\,(\lambda, t)\left(1 - e^{-A(\lambda)}\right)\left[\phi(\lambda)\right] d\lambda\, dt \tag{34}$$

where λ_{min} and λ_{max}	are the minimum and maximum photolytically effective wavelengths, respectively;
$E_o(\lambda,t)$	is the UV spectral irradiance to which the material is exposed at time t ($W\ m^{-2}\ nm^{-1}$);
$(1-e^{-A(\lambda)})$	is the spectral absorption of a material (dimensionless); and
$\phi(\lambda)$	is the spectral quantum yield of the material (dimensionless).

Thus, the total effective UV-dosage is computed by integrating the product of the spectral irradiance, $E_o(\lambda,t)$, the spectral absorption coefficient, $(1-e^{-A(\lambda)})$, and the UV solar spectral efficiency of the absorbed radiation, $\phi(\lambda)$, over both the range of photolytically effective wavelengths and the duration of the exposure. Experimentally, the spectral absorption and the spectral quantum yield coefficients are determined from laboratory-based experiments. The spectral irradiance measurements are monitored in both the laboratory and field. The total effective dosage, D_{tot}, can then be related to biological damage using a damage function. The possible application of this approach to coatings has been discussed by Martin (1993) and some preliminary analyses of spectral UV irradiance measurements have been performed."

4.3.2 Thermal radiation

Heat accelerates the degradation of materials. By using the service-life approach Tomiita (1993) has expressed the change in property of a building material as a function of temperature based on Arrhenius equation, using the following dose-response function

$$\ln (P/P_0) = C_H \exp(- E_H/RT)t \tag{35}$$

where P is the property of the material, P_0 the initial property of the material, C_H the thermal deterioration constant of the material, E_H the activation energy of thermal deterioration (kJ/mol), R the gas constant (8.314×10^{-3} kJ/ mol/K), T the absolute temperature of the material (K), and t the elapsed time.

By various assumptions Tomiita has been able to calculate the degradation curve as a function of solar radiation energy, S_D, daily average wind speed, W_D, average daily temperature in the daytime, T_D, and -in night-time, T_N, and the daily equivalent black panel temperature, BPT. The percentage degradation for a 10-year period has been mapped for the various parts of Japan (see Chapter 6.4.1).

Quoting Martin et al. (1993), who proposed to compute the panel temperature for coated panels: "In laboratory experiments, the temperature of the coated panels can be monitored directly by outfitting each panel with a thermocouple or indirectly by controlling the exposure conditions. Obviously, such methods would be expensive if the number of specimens was large, as at many commercial outdoor exposure sites. A more economical and practical approach to monitoring panel temperature, but one that is dependent on the availability of adequate models, would be to determine the thermal properties of a coating system before its exposure in its expected in-service environment. Additionally, common meteorological variables like ambient temperature, sky temperature, background temperature, wind speed, and total solar radiation during its exposure need to be monitored. Then the panel temperature for all the coated panels at an exposure site can be computed by solving for T_p for each panel using the following energy balance equation:

$$AH_t\alpha = 2hA\left(T_p - T_a\right) - \varepsilon A\sigma\left(T_s^4 - T_p^4\right) - \varepsilon A\sigma\left(T_b^4 - T_p^4\right) \tag{36}$$

where A is the surface area of a panel (m^2);
H_t is the total solar radiation ($W\ m^{-2}$);
α is the absorptivity of the coating;
h is the convection coefficient ($W\ m^{-2}\ K^{-1}$), which is a function of wind speed;
σ is the Stefan-Boltzmann constant which is $5.67 \times 10^{-8}\ W\ m^{-2}\ K^{-4}$;
T_a is the ambient temperature (°K);
T_b is the background temperature (°K);
T_p is the panel temperature (°K);
T_s is the sky temperature (°K); and
ε is the panel emissivity.

The feasibility of this approach has been demonstrated by Saunders et al. (1990)."

Ganther et al (1996) have developed accurate techniques to measure surface temperature on exposed plates. Although detailed analysis is not yet complete preliminary results indicate that the surface temperature of plates are not in general in equilibrium with the environment and depending on the material and the climatic conditions can be appreciable cooler during the night and the early morning and appreciably hotter during the day. The implication of these results is that the state of wetness on the plates is as much controlled by the surface temperature as by ambient conditions. Deposition of sea salts on surfaces may increase the importance of surface temperature in controlling surface wetness. A salt contaminated surface at a lower temperature than ambient will absorb moisture when the ambient RH is below the salt/air equilibrium. Thus in marine environments a prime factor controlling surface wetness may be surface temperature.

4.4 Chemical agents

4.4.1 Water and temperature -humidity, condensation, precipitation.

4.4.1.1 Time of wetness or critical wetness for deterioration

The term Time-of-wetness (TOW) is very much used, and often misleadingly so. To avoid misunderstanding the original definition which originates from the field of atmospheric metal corrosion should be remembered. Here TOW is defined as the *period of time* during which the material surface is subjected to *enough moisture for the corrosion rate to be significant.* This lead to the concept of a *time above a critical wetness, i.e. that both the level and duration of wetness is important.*

Therefore, to avoid misconception, the term should generally include the word "critical", to be called something like "the time of critical wetness" (TOWCrit), and should be defined as a material specific property.

The total time of wetness, TOW, was described (Lala et al., 1989) as the time during which the surface is covered with a *thin adsorbed* moisture layer, T_{ads}, and/or the time during which there is (several) monolayers *of water* on the surface, T_{pha}.

$$TOW = T_{ads} + T_{pha} \qquad (37)$$

Table 3 shows the relationship between the occurrence of various humidity events in ambient air and the thickness of the wetness film on the material surface.

Table 3: Various humidity conditions and resulting wetness film thickness on the material surface.

humidity events	70%RH	85%RH	100%RH	dew	rain
wet.film thick. (µm)	0.01	0.1	1	10	100

Now, depending upon the material critical wetness properties, the TOWCrit may contain only the T_{pha} term if pronounced wetness is needed, and so on. It also implies that a material can have different TOWCrit – values, depending upon the performance characteristic and degradation indicator in question (see also Chapter 2.1).

For metals the corrosion is caused by electrochemical reactions on the surface where the formation of an electrolyte is essential. The formation of the electrolyte depends on humidity and the pollutants available, as illustrated in Figure 9 for carbon steel. In extreme clean laboratory conditions, 100% relative humidity (RH) and dew are needed to start the corrosion. In practice the electrolyte will be formed at lower RH due to pollutants. In areas where gas pollutants like SO_2 are present, a critical humidity level of 80% for corrosion is observed, and in areas with sea-salt aerosols the critical humidity level will be even lower.

From this figure it is also obvious why Lipfert in his reconciliation process found best correlation with various expressions of the time of wetness (see Chapter 3.1) Practically all dose-response functions contain a term expressing the time of wetness or more precisely, the *time above critical wetness.*

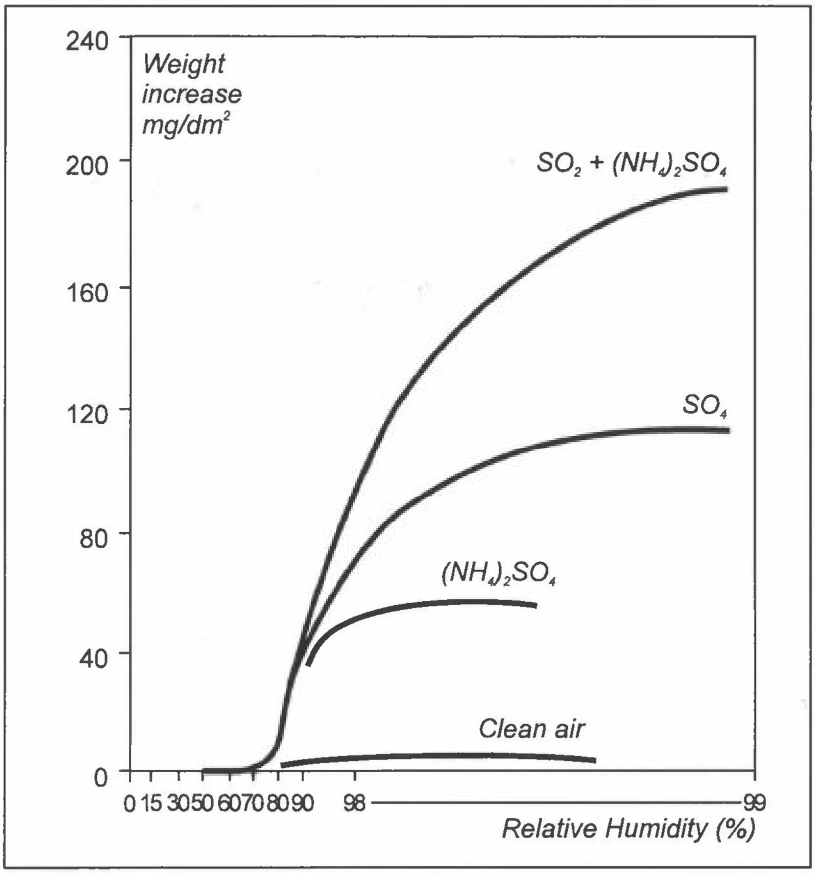


Figure 9: Corrosion attack on carbon steel at increasing relative humidity, based on work by W.H. Vernon (1931).

From empirical observations, the term TOW for metals is defined as the time when the relative humidity is greater than 80% at temperature above 0°C. This definition is used in ISO standard 9223 "Corrosion of metals and alloys – corrosivity of atmosphere – classification", where the TOW is calculated together with selected climatological characteristics of the macroclimatic zones of the world. This classification is extracted from the standard IEC 721-2-1:1982 (see 6.2).

The level and duration of moisture in the immediate vicinity of the material surface is also crucial to the degradation of *non-metallic materials*, if they are prone to deteriorate under the influence of moisture. Condensed moisture on coating surfaces during longer periods of time is, for example, considered to have a more deteriorating effect than shorter periods of rain (Stoll, 1977; Jansson and Sjöström, 1979).

The humidity impact is also observed for *porous materials* like wood, stone, rendering and concrete, underlining the extreme importance of the fact that the concept also accounts for the *wetness inside* porous materials. For example, for wood the degradation process of rottening takes place after prolonged period of time above a moisture content of 15–20 weight% (Mattson, 1995; Cole, 1994) has made an extensive study of temperature and humidities in wall cavities of houses in Australia. Calculations of existing equilibrium moisture contents (EMC), and comparison with required EMC levels for growth of wood decay fungi were used to assess probable differences in material durability in the micro environment.

4.4.1.2 Data on "time of critical wetness" – TOWcrit

Monitoring methods and data for TOWcrit is very important and should be the subject of extensive R&D.

Data can be established *indirectly* from measurements of air temperature and relative humidity, or directly through measurements with electrochemical cells.

With the indirect method, TOWcrit is calculated as the time when RH exceeds a certain level, normally 80%, during periods when the temperature is 0°C or higher. The data on temperature and RH may originate from daily measurements, or even be monthly mean values.

Haagenrud (1985); Tomiita (1992); Morcillo and Feliu (1993) has calculated the TOWcrit according to the ISO criterion from available meteorological data. Tomiita and Kashino (1989) calculated also the number of wet-dry cycles causing condensation. These values have been classified and mapped for Japan (see Chapter 6.4.1).

In direct measurements electro-chemical cells are used, attached to the material surface. Also in direct measurements, the TOWcrit depends on the predefined level of wetness, expressed as a critical current in the cell (Haagenrud and Henriksen, 1994).

4.4.1.3 Factors influencing TOW in the building envelop

In the actual micro environment for constructions TOWCrit will differ enormously. Consequently there is a great need for developing monitoring methods for mapping the level and duration of wetness in the micro environment for the various constructions and materials in use. The WETCORR instrument can be used for such applications (Svennerstedt, 1989; Cole and Ganther, 1996) (see 7.1.1).

In the Australian context Cole (1994) has investigated the conditions in a number of wall cavities in the different climatic zones in Australia. These studies indicated that high humidities could occur in wall cavities particularly in tropical and sub-tropical Australia and that these high humidities gave rise to relatively high time of wetness values which have the potential to promote corrosion. In further work Cole et al (1996b) completed a more extensive study of the factors controlling building envelope microclimate in houses sited in tropical and sub-tropical Australia. It was found that in non-marine locations wetness within the building envelope was primarily controlled by condensation cycles. These cycles were promoted by temperature differences between different building spaces and by differences between exterior surfaces and building envelope air spaces. The surface wetness (on sensors) within the building envelope of buildings sited in areas of high airborne salinity was controlled by deposition of hygroscopic salts .

In an early work Cole et al (1995) derived a model of the mass transfer from a metal plate to air. The application of this model to conditions in the building envelope and on the exterior demonstrated that while the time taken for a surface to dry following wetting was likely to be minimal in the open it could be significantly longer within the building envelope and thus the total TOW in the building envelope should be considered as the time of active wetting and the time of drying with these two components of similar magnitude.

4.4.2 Oxidizing agents

4.4.2.1 Oxygen

Photochemical oxidation of organic materials, such as coatings, mostly takes place with oxygen molecules in excited state as the active chemical constituent.

When an oxygen molecule in the ground state absorbs radiation quanta with high enough energy it may transfer to an excited state having a new electron configuration. The effects of oxygen in different states (molecular oxygen, atomic oxygen and singlet oxygen) and ozone on the photochemical degradation of polymers have been studied in several investigations. The following is a brief summary of the dominating photochemical degradation mechanisms (Henriksen and Sjöström, 1987), involving oxygen in different states and ozone, of common polymers such as polystyrene, polyvinylchloride, polyethene, etc.

4.4.2.1.1 Molecular, singlet and atomic oxygen

In atmospheres of *molecular oxygen* photochemical oxidation of polymers occurs through absorption of UVR quanta, double bonds are excited and free radicals, hydroxy, hydroperoxy, ketone and aldehyde groups are formed. The reactions lead to chain scission and a molecular weight decrease affecting the technical and aesthetical properties of the polymer.

Singlet oxygen is present in the atmosphere through a number of processes: direct absorption in molecular oxygen of sun light quanta, photolysis of ozone under elevated pressure, photolysis of air pollutants combined with an energy transfer between the pollutants and molecular oxygen.

The mechanism for photo-oxidation of polymers with singlet oxygen as the reactive constituent is comparable with that involving molecular oxygen, the formation of free radicals, hydroxy and peroxy groups, and chain scission of the polymer molecules.

Atomic oxygen forms naturally through photolysis of ozone. Photo-oxidation with atomic oxygen occurs by the formation of alkyl radicals, unsaturated chain ends and, finally, chain scission.

4.4.2.2 Ozone

Ozone is one of the most important oxidising constituents and reacts with many polymers such as polyethene, polybutadiene, polystyrene etc. The effects are normally discoloration and embrittlement. Ozone attacks double bonds in the polymer, causing chain scission and crosslinking reactions. The degradation reactions occur via the formation of peroxy radicals, which photochemically may be excited to other free radicals. The reactions take place on the material surface.

There are great variations in the occurrence of ozone in the atmosphere. At high altitudes, more than 20 km above earth level, the amount is more than one thousand times higher than at earth level.

Ozone may exist in nature as an effect of solar radiation on oxygen in the presence of air pollutants. This has caused major concern in the last few years, and evidence for damages to health and vegetation has triggered off a European Council Directive (92/72/EEC) for monitoring and warning of ozone. This is dealt with more closely in Chapter 5.4.

4.4.2.3 Carbon dioxide

In the presence of moisture carbon dioxide will attack susceptible inorganic materials since it forms a slightly acidic solution.

Atmospheric carbon dioxide is a major cause of deterioration in exposed reinforced concrete structures. The penetration of the concrete by carbon dioxide from the atmosphere neutralises the alkaline calcareous materials that inhibit corrosion of the steel reinforcement. The process is called carbonation. Rate of carbonisation depends on the quality and type of concrete, the level of humidity in the concrete cover, the content of CO_2 in the ambient air, and so on (Tutti, 1982). When it has reached the depth of the embedded steel, moisture can cause corrosion with severe expansion disruption of the concrete.

As for the CO_2, the rate of carbonation increases rapidly with increased CO_2 content, as shown in Figure 10. It is therefore substantially faster in industrial than in rural atmosphere. The average global CO_2 concentration for 1994 was 358 ppm (= 0.0358 %), undergoing a yearly average increase in the last decade of 1.5 ppm/year (Stordal, 1996).

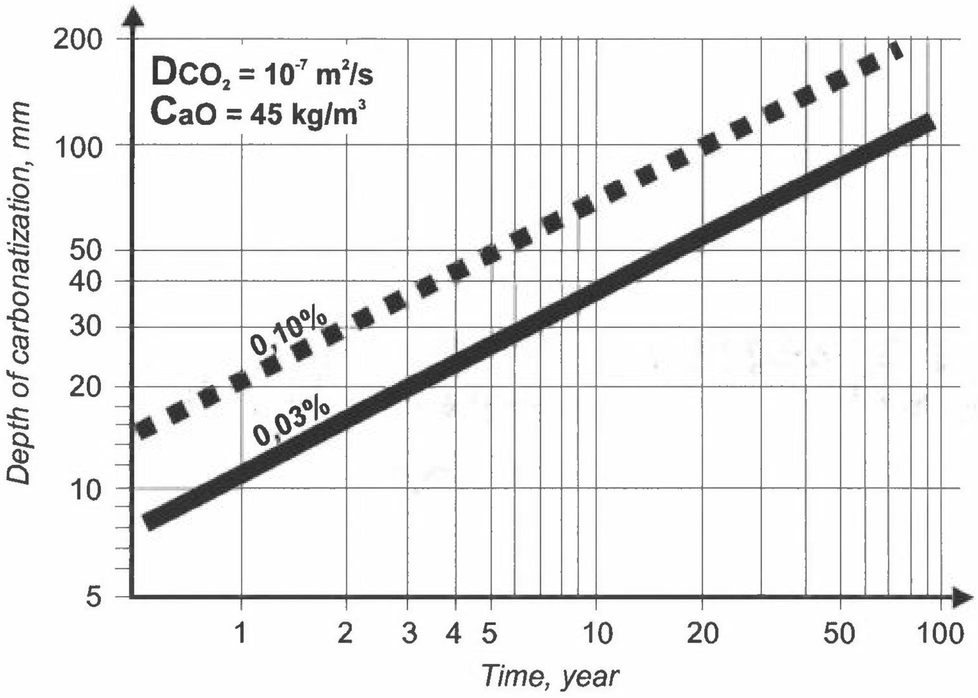


Figure 10: Effect of ambient CO_2 concentration on rate of carbonation of concrete. Normal background CO_2 value =0.03% (Tutti, 1982).

4.4.2.4 Sulphur dioxide

Sulphur dioxide is, in connection with atmospheric corrosion, the most studied air pollutant. SO_2 is considered a major contributor to acid rain and environmental acidification. Local concentrations of SO_2 show considerable variations. During recent years SO_2 concentrations have declined in most countries, due to the combined effects of growing environmental awareness and improvements to industrial processes and combustion techniques (Chapter 5).

SO_2 is easily adsorbed on material surfaces, and the deposition may be wet or dry. The concentration, or deposition rate, of SO_2 is a parameter in the classification of atmospheric corrosivity according to the ISO/DIS standard 9223 (see Chapter 6).

SO_2 transforms in the atmosphere to SO_3, which may also be both wet and dry deposited. The transformation reactions may take place both in gas phase or in aerosol phase, e.g. in cloud droplets.

SO_2 degrades materials that are susceptible to acid attack. Moisture conditions are of vital importance. As shown in Chapter 3 relatively good quantitative dose-response functions exist for quite a few materials.

4.4.2.5 Effects of nitrogen pollutants, SO_2, and ozone on materials

The most important sources of NO_x are vehicular traffic and combustion of petroleum products. Increased traffic intensity has led to high concentrations of many oxidised forms of nitrogen, such as NO, NO_2, HNO_2, and HNO_3. Whereas concentrations of SO_2 have generally decreased during recent years, NO_x pollution has increased.

From a recent publication of V. Kucera, Swedish Corrosion Institute, and project-leader of the UN ECE ICP on materials (1996), the following is quoted:

"In contrast to SO_2 the effects of NO_x and O_3 are not well documented. Some reviews in this area have been published usually focusing on the effects of either NO_2 (Arroyave and Morcillo, 1995) or O_3 (Lanting, 1984; Lee et al., 1994) on metallic or organic materials and surfaces. The increased interest in the effects of nitrogen pollutants and VOC within the Convention on LRTAP has evoked systematic investigations also in the field of materials. In the 1980´s the effect of NO_x attained increasing interest. In recent years finally the effect of O_3 in combination with S- and N-pollutants has been subject to systematic investigations which have revealed synergistic corrosive effects. Consequently the effect of acidifying air pollutants is now considered as a combined effect in the multipollutant complex situation (Tidblad and Kucera, 1996). To treat this field exhaustively is beyond the scope of this presentation. In the sequel a brief description of the mechanisms of main corrosive effects involving NO_x and O_3 will be given including examples on effects on different inorganic materials. The effect of ozone on organic materials will be treated in the following presentation (Holland et al., 1996).

4.4.2.5.1 Effect of NO_X

In the combustion of fossil fuels nitrogen oxides are emitted largely in the form of NO which is subsequently oxidised to NO_2 in the air, the most rapid being the reaction with O_3 and nitrate radical (NO_3).

$$NO + O_3 \rightarrow NO_2 + O_2 \qquad (38)$$

$$NO + NO_3 \rightarrow 2NO_2 \qquad (39)$$

The deposition rate of NO_2 on material surfaces is much lower than that of SO_2 and this is certainly one of the reasons that low contents of nitrates compared to sulphates are usually found in corrosion products also in rain protected areas. The direct corrosive effect of NO_2 is low except, as far as known, for some organic materials like polymers and textiles.

In the complex pollution situation, however, also further oxidation of nitrogen oxides resulting in gaseous HNO_3, should be considered by the following sequence of reactions

$$NO + O_3 \rightarrow NO_3 + O_2 \qquad (40)$$

$$NO_2 + NO_3 + M \rightarrow N_2O_5 + M \qquad (41)$$

$$N_2O_5 + H_2O \rightarrow 2HNO_3 \qquad (42)$$

or by photolytic oxidation of HNO_2.

Since HNO_3 is a strong acid with a high deposition rate, it is of principal interest for corrosion. HNO_3 concentrations have been supposed to be low in urban areas close to emission sources due to the slow reaction rate. During the last years daily mean values of HNO_3, between 4 and 28 mg/m^3 have been reported in Rome (Brocco et al., 1988). The corrosive action of HNO_3 on calcareous stones has been demonstrated to occur under natural conditions in Athens and in the laboratory (Sikiotis and Kirkitsos, 1994). HNO_3 exerts its corrosive effect also at low relative humidities which is important in warm, dry climates like in California or in southern Europe which can give rise to a summer peak of atmospheric corrosion. It can be noted that in Athens the highest values of HNO_3 were found in the summer period.

4.4.2.5.2 Synergistic effect of SO_2 and NO_2

In the 1980´s, a strong synergistic effect of NO_2 and SO_2 has been found in several laboratory investigations. The mechanism may be either a direct oxidation according to

$$SO_2 + NO_2 + H_2O \rightarrow SO_4^{2-} + 2H^+ + NO \qquad (43)$$

which has been found on gold and lead, while the oxidation of sulphite to sulphate, on e.g. zinc or calcareous stones, can be accelerated with NO_2 acting as catalyst. It may be emphasized that in both of the synergistic mechanisms involving NO_2 , no solid nitrogen containing corrosion products are created.

4.4.2.5.3 Effects of ozone

The principal mechanism of formation of ozone in the troposphere is by reduction of NO_2 to NO due to photolysis

$$NO_2 + hv \rightarrow NO + O \qquad (44)$$
$$O + O_2 + M \rightarrow O_3 + M \qquad (45)$$

where M denotes a third body molecule.

Ozone levels are controlled by the emissions of NO_x and volatile organic compounds (VOC) which is illustrated in Figure 11.

The ambient levels of tropospheric ozone have almost doubled in the last 50 years. The use of catalytic converters on motor vehicles is expected to reduce O_3 concentrations in the long term. *However, as NO emitted by motor vehicles is a major sink for O_3, decreased NO concentrations will probably increase O_3 levels in urban areas where most of materials are located (PORG 3, 1993).*

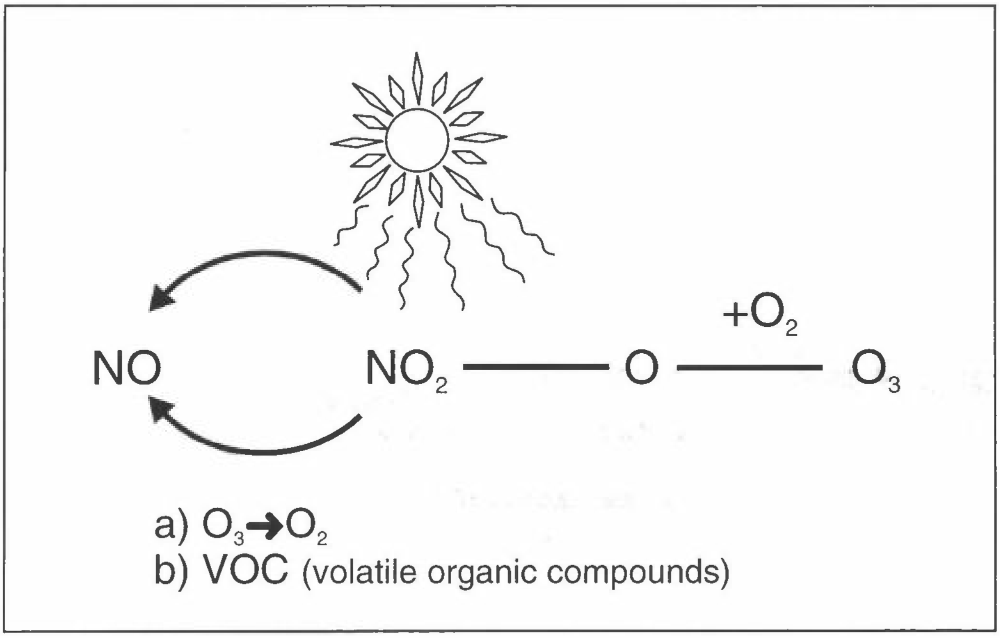


Figure 11: Ozone created from NO_2 *under the influence of UV radiation.* NO_2 *then regenerates from NO.*
a) by reaction with ozone;
b) by a reaction including VOC.

This may be illustrated by the strong negative correlation between NO_2 and O_3 which has been found on the UN ECE ICP Materials test sites, described by the relation

$$[O_3] = 60.5 \text{ exp.}^{-0.014 \, NO_2} \tag{46}$$

For this reason, O_3 levels are usually lower than in areas with heavy traffic as in town centres outside city areas. Ozone in contrast to NO_x can thus create both a local and a more regional problem.

Ozone exerts a direct corrosive effect on natural rubber, on some plastic materials, textiles and on paint and surface coatings (Lee et al., 1994; Holland et al., 1996).

4.4.2.5.4 Synergistic effect of SO_2 *and* O_3

Recently, as mentioned above, a synergistic effect of SO_2 and O_3 has been disclosed in laboratory exposure of zinc, copper, nickel and calcareous stone materials. The following mechanism is proposed for O_3

$$SO_2 + O_3 + H_2O \rightarrow SO_4^{2-} + O_2 + 2H^+ \tag{47}$$

When comparison is possible the synergistic effect of $SO_2 + O_3$ is stronger than for $SO_2 + NO_2$, see Figure 12 (Svensson and Johansson, 1993).

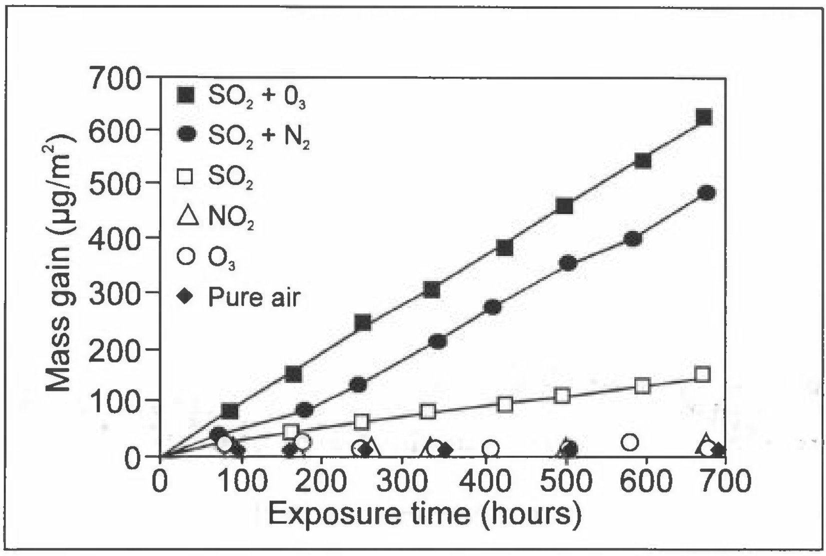


Figure 12: Mass gain of zinc exposed at 95% RH; influence of SO_2 (225 ppb), NO_2 (400 ppb), and O_3 (400 ppb) (Svensson and Johansson, 1993).

4.4.2.5.5 Effects on materials

In the following the individual materials are treated separately:

4.4.2.5.5.1 Steel

Only a few field exposures have been performed and the results are inconclusive. A Japanese investigation has shown a positive but not significant correlation between corrosion rate and NO_2 concentration, while another study has shown that SO_2 increased, NO_2 decreased and O_3 had no affect the corrosion rate. In the UN ECE exposure programme a dose-response function was presented for weathering steel after 4-year exposure involving both SO_2 and O_3 as explanatory variables, Table 1, Chapter 3.4. This is the first time a synergistic effect of O_3 and SO_2 has been indicated in a field exposure. The role of NO_2 has not been clarified in the UN ECE exposure. In laboratory studies both inhibitive effects of NO_2 and a synergistic corrosive effect in combination with SO_2 have been reported (Svensson and Johansson, 1993).

4.4.2.5.5.2 Zinc

Field studies in the United States have indicated that dry deposition of HNO_3 can be an important parameter. In a statistical analysis of the degradation rate measured as Zn^{2+} run-off, NO_3^- significantly improved the fit compared to an equation with only SO_4^{2-}. Also in a California study corrosion rates for galvanised steel were higher in the summer than in the winter, which is the opposite to the seasonal dependence observed at most other locations. This could be due to HNO_3 produced by photochemical oxidation in the summer.

In the UN ECE exposure programme a dose-response relation has been presented for zinc involving both SO_2 and O_3 as explanatory variables, Table 1, Chapter 3.4.

4.4.2.5.5.3 Copper materials

In the UN ECE exposure programme copper and bronze are exposed as a construction material and copper also more sheltered as an electric contact material. The statistical evaluation of structural metals after 4-year exposure produced damage functions for copper and bronze involving both SO_2 and O_3 as explanatory variables, Table 1, Chapter 3.4. In the evaluation of electric contact materials it was concluded that both O_3 and NO_2 accelerate the deposition of SO_2 on copper. High weight increases were observed both at sites with high SO_2 concentrations and at sites with low SO_2 concentrations where O_3 reached high levels.

In laboratory exposure the combination of NO_2 and SO_2 exerts a synergistic corrosive effect but only at high relative humidities. The SO_2 deposition rate on copper was seven times higher when O_3 instead of NO_2 was added to SO_2 at 90% relative humidity.

4.4.2.5.5.4 Nickel

In field exposures conducted at indoor sites nitrates were not found in the corrosion products. In the UN ECE exposure programme nickel is the metal which correlates most strongly with the SO_2 concentration. No effect of the NO_2 or O_3 concentrations could be proved by statistical methods although nitrate as well as chloride were detected on the surface together with sulphate, which was the main constituent.

4.4.2.5.5.5 Calcareous building materials

Attack on either $Ca(OH)_2$ or $CaCO_3$ by sulphuric acid generally leads to the formation of gypsum, $CaSO_4.2H_2O$, while nitric acid gives calcium nitrate, $Ca(NO_3)_2.4H_2O$. The nitrate is more soluble than the sulphate.

In a UK study of limestone decay nitrate levels were often lower than the detection limit and none of the weathering indices correlated with NO_x (Butlin et al., 1992a and b). Also in other field exposures it was not possible to correlate high NO_x concentrations to the low nitrate content of the stone samples. It should, however, be pointed out that calcium nitrate is deliquescent and readily absorbs water from air at relative humidities higher than 50%. One can then find nitrates on a greater depth in stones than sulphates, which accumulates as $CaSO_4$ in the surface layer.

In the UN ECE exposure of limestone and dolomitic sandstone as well as in the UK national exposure programme the dose-response relations obtained contain only a SO_2 term, characterising dry, and a term describing the effect of wet deposition. The statistical analysis has not shown any effect of O_3 as for the metals.

Limestone, marble and travertine show at laboratory exposure to NO_2 and SO_2 in humid air a drastical synergistic effect when introducing NO_2 in combination with SO_2. The SO_2 deposition on marble is also strongly enhanced by the presence of O_3. Recent laboratory exposure confirmed that similar to the case of zinc, NO_2

catalyses sulphate formation, while O_3 acts by direct oxidation. The catalytic effect of NO_2 is only efficient at high humidities, whereas the direct O_3 effect is efficient at both dry and humid conditions (Elfving et al., 1994).

4.4.2.5.6 Conclusions

- There are considerable gaps of knowledge concerning atmospheric corrosion effects of NO_x and O_3. Traditionally scientists working with inorganic materials have focused on SO_2 as the primary pollutant while those working with organic materials have dealt primarily with O_3. In this way the synergistic effects of SO_2 with O_3 and NO_2 have not been subject of any systematic investigations until recently.

- Laboratory and field investigations performed in the last decade have contributed to the understanding of the interrelated role of SO_2, NO_x and O_3 and underlined the necessity to treat the deterioration of materials as a multipollutant situation which may increase the degradation importance of pollutants in less polluted areas and in indoor locations.

- A warning should be issued for the corrosive action of HNO_3. Its importance for atmospheric corrosion, especially in warm regions, should be clarified.

- Reliable dose-response functions are needed in order to be able to calculate acceptable levels of pollutants and for calculations of economic impact.

4.4.3 Acids

The acids most important to the deterioration of materials through atmospheric corrosion are sulphuric acid (H_2SO_4), nitric acid (HNO_3), and hydrochloric acid (HCl) (Butlin et al., 1994, see Chapter 3.6).

Sulphuric and sulphurous acid are used in many industrial processes and local pollution may occur around certain industrial facilities. The acids are easily deposited on exterior materials. The pH-values on surfaces close to major pollution sources may be very low, promoting corrosion attack on the materials. The transformation of SO_2 to sulphuric acid in the atmosphere has been mentioned earlier. Sulphuric acid may be transported over long distances and be a major cause of acid precipitation (see Chapter 5.3).

Nitric acid is used in many industrial processes. As HNO_3 is very volatile, local pollution may easily occur around industrial facilities. Quantitative data on nitric acid concentrations in the atmosphere are scarce. The acid is easily deposited, both wet and dry, and if deposited on material surfaces it is very aggressive and attacks both native and synthetic polymers (see 4.4.2.5).

Hydrochloric acid too is also used in industrial processes, and is often detected around many industrial facilities. Combustion of coal and wood is a known source of HCl-formation, and a very important and much discussed source is the combustion of waste materials (Sjöström and Henriksen, 1987); Hydrochloric acid is especially aggressive to metals, concrete, rendering materials (Butlin et al., 1994).

4.4.4 Salts/aerosols

An important effect of salts is that, due to their hygroscopicity, they may, if deposited on material surfaces, increase the moisture content and prolong the wetness periods of the materials. Besides that, salts are more or less aggressive. Recrystallisation of salts in micro-pores of porous materials such as rendering and many stone materials, may cause enough tensions for the material to decompose.

The air content of chlorides is of great importance for metal corrosion, which of course also affects building materials such as factory-coated sheet metal, especially at cut edges, holes in the sheet, fasteners, pores and cracks in the coating etc.

Current levels for wet deposition of chlorides, sulphates and nitrates can be found (see Chapter 5.5).

4.4.4.1 Sea spray

The sea is a major source of salts. The effect of sea-salt on the durability of construction materials are together with SO_2 the most studied environmental variable (Refsnes, King etc.). Sea spray may be regarded as a form of particulate pollution which can travel under the influence of wind for several miles inland from coastal areas. The air content of salts decreases rapidly with distance from the coast (Anda and Refsnes, 1987). Salt spray from the atmosphere can adversely affect the durability of stone as well as accelerating the corrosion of metals, particularly ferrous metals and aluminium.

In Australia King(1993) and co-workers at CSIRO have developed a hyperbolic function of the corrosivity as function of distance from sea, using standard corrosivity specimens of mild steel and copper steel being exposed at numerous sites at various distances from the sea. The hyperbolic function had the following form:

$$log_e\ (corrosivity) = A + \frac{B}{1 + (C\ x\ distance\ from\ ocean)} \qquad (48)$$

The model describing the variation in one-year corrosivity of mild steel with distance from the ocean are shown in Figure 13 for three regions: Newcastle; south-east Melbourne; and Victor Harbour.

The very sharp fall-off in corrosivity with distance inland is evident in all three cases, as are the increasing levels of corrosivity in the order Melbourne, Victor Harbour, Newcastle (King, 1993). *It should, however, be remembered that the primary variable is the salt and not the distance* (Anda and Refsnes, 1987). For Newcastle, corrosivity was found to vary by more than an order of magnitude across the area surveyed. The rates at the beach-front were the highest ever measured in Australia, and the marine environment represents a major corrosion hazard.

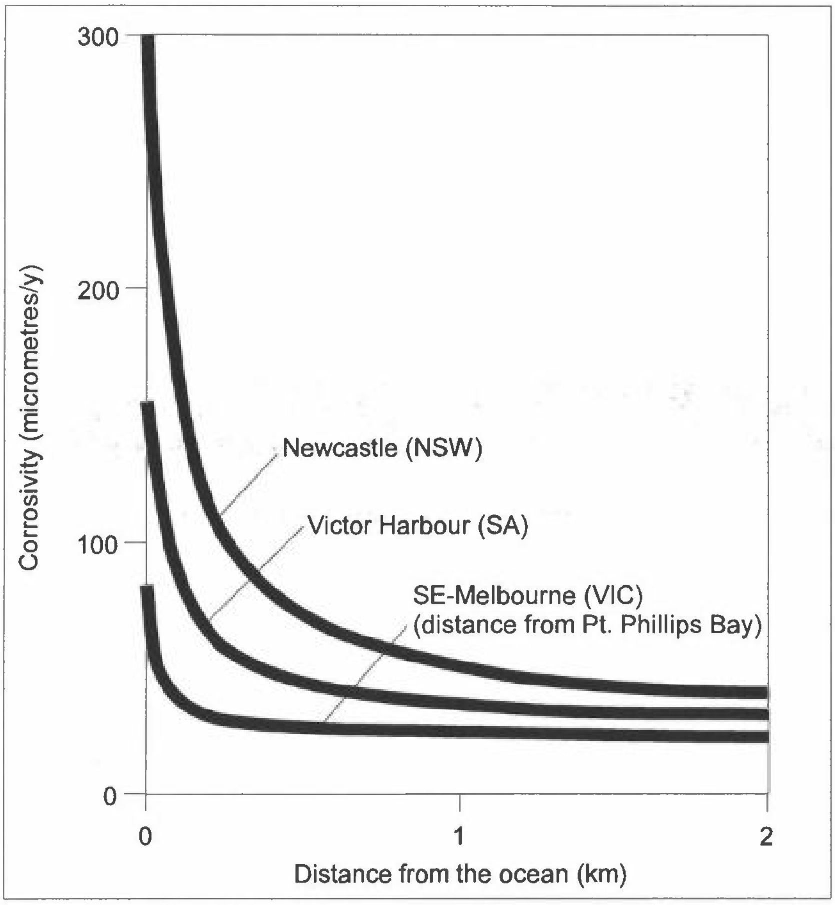


Figure 13: Models showing the variation in the corrosivity of mild steel exposed for one year with distance from the ocean, for three regions in Australia.

Quantitative dose-response functions and classification systems exist (see Chapter 6).

As for dose-response functions Cole et al (1996a) have partially completed a matrix of dose tests in which a range of materials are subjected to well defined(constant) doses of humidity and airborne salinity for short to medium term exposures. In these exposure RH was held constant at values from 60 to 100% while salt doses equivalent to 0 to 120 mg/m^2·day were applied once a week. For tests without salt had duration from 6 to 38 weeks whilst tests with salt had duration from 6 to 12 weeks. The materials tested included Cu-steel, galvanised steel, solid zinc and aluminium-zinc coated steel.

The data indicates that a number of different patterns in terms of dependence corrosion rate on RH and airborne salinity occur. Galvanised and solid zinc show a strong dependence on salinity levels but a weak dependence on RH while Al-Zn shows a marked dependence on RH and a weaker dependence on salinity. It is notable that the corrosion rate of the galvanised and the solid zinc plates subjected to a high natural sea salt dosage(120 mg/m^2·day) did not decrease when RH was decreased from 90 to 60% RH. The implication from this result is that the use of approximation of TOW as time when RH>80% is not appropriate when there is significant natural sea salt deposition.

Although the data was not primarily designed for the development of dose function type expressions such expressions can be derived for the data at 90% RH. As sea salt and NaCl will wet at 90% the TOW can be regarded as 100% as long as salt is present. Units of airborne salinity are $mg/m^2 \cdot day$, The data was all derived at a constant temperature of 30°C. The most appropriate formulation is then.

$$C= a+b*salinity$$

If the galvanised data is analysed and the TOW factor is explicitly included (adding in data at 100% RH and thus 100% TOW but zero salinity) then the following form can be derived.

$$Cgal= a+(TOW)*(b+c*salinity)$$

Cole and Ganther (1996c) studied the airborne salinity on the facade and within building envelopes. This study indicated that there was a significant reduction of salinity levels on the facades and a further reduction within the building envelope. However while the salinity levels within the building envelope were considerably reduced they were not negligible and thus these levels in combination with the relatively high TOW values indicated that low but significant corrosion rates could occur in wall cavities.

4.4.4.2 Soot and particles

During recent years the air content of particles has increased by approximately 4% per year. Traffic is a main contributor in urban areas. A major effect of soot and particles is that they, if deposited on surfaces, may prolong wetness periods.

Further, soot and particles may contain corrosive compounds, may affect surface properties such as light reflection and lead to mechanical damage to surfaces due to the need of cleaning.

More detailed descriptions and classifications of soot and particles and their occurrence in different atmospheres are presented by *Sjöström and Henriksen (1987); Verhoef-RILEM Technical Committee 62 SCF – Soiling and Cleaning of Building Facades (1988), Hamilton and Mansfield (1992).*

4.4.5 Chemical incompability factors

When different materials are used in conjunction, due consideration should be given to the possible interactions which may occur between them and which may lead to deterioration.

Specific chemical attack of one material on another can occur with many materials. Not all such interactions are documented. Often the effect will be dependent on the environmental circumstances and, in particular, the presence or absence of moisture.

With materials in contact or even adjacent to each other, action may be direct or indirect because one material influences the response of another to the environment. It may even be because a material itself degrades and affects neighbouring materials.

4.4.5.1 Leaching/leachates

Certain materials react slowly with water or contain substances soluble in water or are extractable in water. Other materials, whilst not themselves a source of harmful leachates, may be capable of transporting leachates over quite long distances. The solvent action of water for these constituents may cause changes in the properties of the material itself. Alternatively or additionally the leachate solutions formed can constitute reactive agencies towards adjacent materials which of themselves would not be attacked by water alone.

4.4.5.2 Solvents

Other interactions can occur when migrating solvents and solvent vapours cause the plasticizers in certain thermoplastics to migrate, and bituminous compounds to soften.

4.4.5.3 Contaminated land

Any building material placed in contaminated soil an groundwater needs special attention as the performance of the materials may be seriously affected by the contaminants. The effect of soil contaminants depends on their combination, on the concentration and on the soil type etc. Examples of causes and effects are:

(a) soil containing solvents which can attack plastics pipes, causing swelling or salvation leading to loss of mechanical properties;

(b) surface active substances, e.g. alcohol, soap and other wetting agents, in combination with a stress may cause environmental stress cracking o rigid building products;

(c) many chemicals, typically strong oxidizing agents, can chemically attack and degrade plastic and rubber;

(d) land containing explosive gas (e.g. methane) can not only destroy buildings if the gas becomes concentrated in a confined space and is ignited, but the gas can also create voids below ground that lead to gradual subsidence;

(e) bacterial activity, particularly sulphate reducing bacteria affecting corrosion of metals;

(f) sulphate and acid attack on concrete.

4.5 Biological agents

4.5.1.1 Fungi and bacteria

Living organisms such as fungi and bacteria are important environmental degradation agents of organic building materials, but they may also affect inorganic materials such as calcareous stones, sandstone and even metals (*Sjöström and Henriksen, 1987*). While biological factors are not weathering factors, biological attack of exterior building materials depends highly on weather conditions.

Fungi attack on facade materials often appears as mould growth on organic surface treatments or as wood rot. Mould growth on a coating normally causes a darkening of the colour. Linseed oil coatings are regarded to be more affected by mildew attack, than coatings based on synthetic resins. However, extenders, stabilisers and plasticisers in synthetic coatings may provide the necessary conditions for biological attack. Modern coatings are normally protected by specific additives, like fungicides and insecticides

Both aerobic and anaerobic bacteria may participate in the deterioration of exterior building materials. Products emanating from the life processes of the bacteria often cause the attack on materials, e.g. bacteria that live of sulphides may produce sulphuric acid.

Bacterial activity can induce corrosion in metals when suitable nutrients are available. Concrete structures can be attacked by sulphuric acid produced by bacteria which use hydrogen sulphide derived from the breakdown of putrescible materials as an energy source.

4.5.1.2 Fungal and insect attack in timber

Fungi causing wood decay, and wood boring insects are found more or less everywhere, and they can cause damage in most parts of a building.

Mattson (1995) has given a systematic survey of microbiological attack and its causes on timber (Figure 14). *Temperature, moisture content of timber* and *nutrients* are the predominant factors when considering its susceptibility to both fungal and insect attack. The *duration of time* for their impact are also of great importance.

For fungi to grow on wood a moisture content of 28% or more is necessary. If growth has started, it can continue at lower moisture levels. A typical activity curve for fungi as function of temperature is also shown in Figure 14, while Table 4 show moisture-temperature requirements for some typical damaging fungi in Norway (Mattson, 1995).

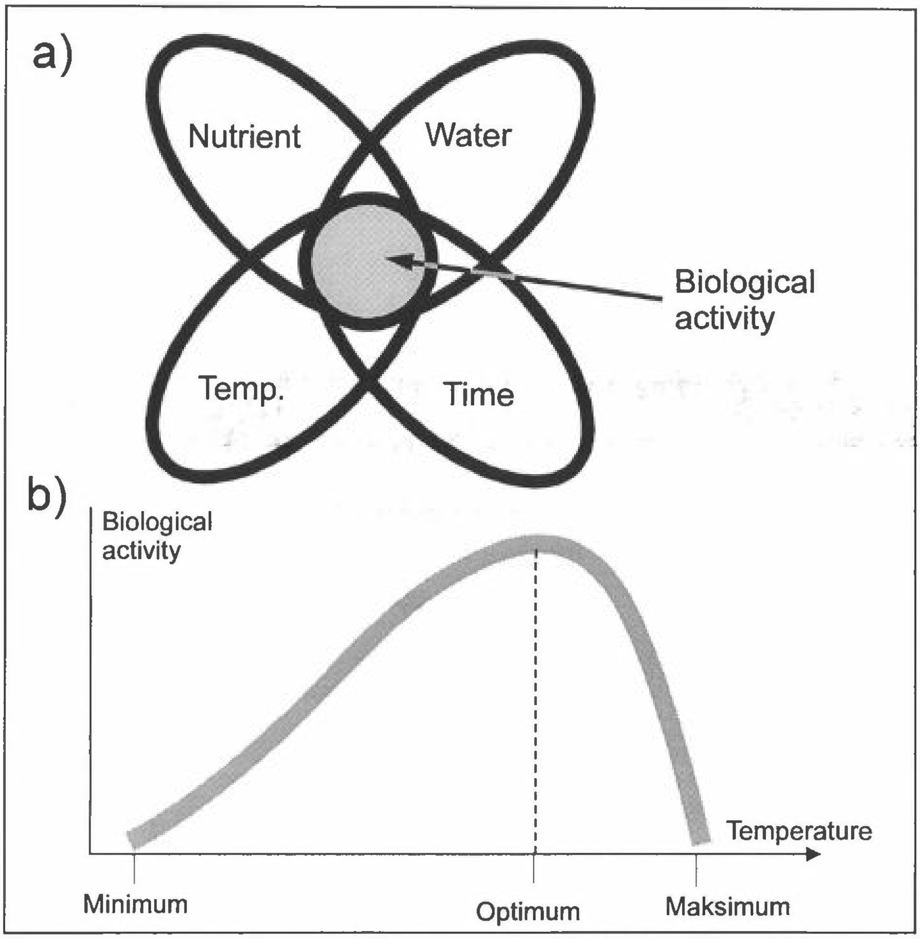


Figure 14: Determining environmental degradation factors for micro-biological attack on wood, and b. Typical temperature dependent activity curve for fungi on wood (from Mattson, 1995).

Table 4: Moisture temperature regimes for typical damaging fungi in Norway (Mattson, 1995).

Type of Fungi	Moisture in Wood	Temperature Optimal	Lethal
Corticiacea spp.	50-70%	ca. 30 °C	ca. 50 °C
Blue stain fungi	> 30%	ca. 25 °C	ca. 45 °C
Dry rot fungus(Serpula lacrymans	20-55%	ca. 23 °C	ca. 35 °C
"Poria" fungi, white pore fungus (Antrodia serialis, A, sinuosa, A, xantha, Fibroporia waillantii)	35-55%	ca. 28 °C	ca. 45 °C
Cellar fungi	30-50%	ca. 23 °C	ca. 40 °C
Mould fungi	20-150%	ca. 20-45 °C	ca. 55 °C
Dacrymytces stillatus	20-150%	ca. 23 °C	ca. 35 °C
Gloeophyllum sepiarium	30-50%	ca. 35 °C	ca. 75 °C

The location of the most frequent rot spots on a timber building (from Mattson, 1995) is likely to depend on moisture content (Figure 15):

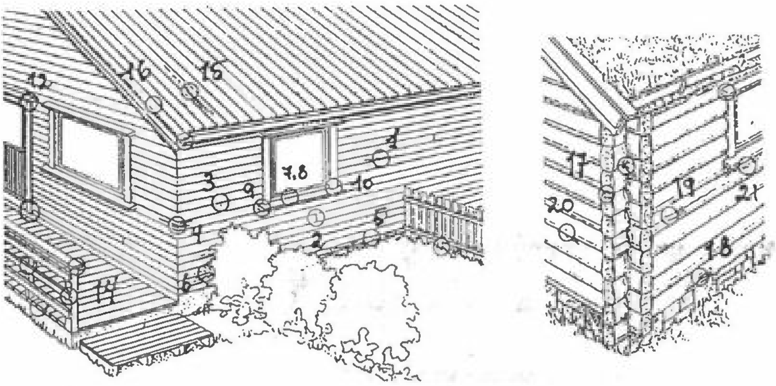


Figure 15: Location of most frequent rottening spots on a timber building (from Mattson, 1994).

The information above on fungus activity fits very well with the climatic index developed by Scheffer for the U S(1970), as follows:

$$\text{Climate index} = \frac{\sum_{Jan.}^{Dec.}[(T-2)\ (D-3)]}{17} \tag{49}$$

where T is the mean monthly temperature in °C and D is the mean number of days in the month with 0.25 mm or more precipitation.

This climatic index, which is also a damage function, for decay of wood is based on US public bodies requirements for estimation of needs for wood protective measures. The index was developed from 10 years exposure of samples of various types of wood and correlating their decay rate with existing meteorological monthly data for temperature and duration of precipitation. The derivation of this index is therefore based on the *assumption, which was shown to be highly valid,* that *precipitation and temperature* by far overshadow other elements of climate that might influence attack by wood destroying fungi.

Scheffer also stated that analysis of typical growth – temperature curves for a few commonly occurring decay fungi indicated that the suitable temperature factor for the climate index would be the mean monthly temperature minus 2°C, taking into account that most of the fungi's become active a couple of degrees above 0°C. It is also assumed that for practical requirements relation of fungi growth rate, and presumable also rate of decay to temperature can be considered linear from 0°C to the actual active temperature area. This is not strictly true for all fungi's, but fits very well with Figure 14.

The *duration of rain* was considered more significant for the total wetting of wood, and gave better correlation, than the total rainfall. The factor "-3" in the formula is added just to keep the index in the range of 0–100 for most part of the US.

Insect attack is possible at 12% (m/m) moisture content and above, which often applies' to roof and ground floor timbers, and sometimes to mid-floor timbers.

4.5.1.3 Rodents and birds

The pests most likely to cause damage or deterioration to building materials are mice and rats. They can cause considerable damage by gnawing timber, other organic substances and PVC casings to electric cables.

Birds can damage fragile roofs by pecking and are sometimes responsible for damage resulting from the debris that they collect or drop. Woodpeckers sometimes attack external timber claddings.

Animal waste matter is a source of nutrient for plants, insects and bacteria that may cause damage.

4.5.1.4 Plants and trees

A major cause of damage to buildings from plants and trees is due to roots disrupting foundations or penetrating underground drains and to new tree planting in clay subsoils.

Serious damage has occurred where buildings with shallow foundations or with faulty infilling of the oversite have been built on sites of shrinkable clay, especially if there are trees or large shrubs nearby. If the trees or other large plants die or are cut down, water will no longer be extracted from the surrounding soil and the clay will swell. Damage to adjacent buildings will occur unless the foundations have been designed to take account of the swelling (BRE Digest 251).

Plants can also cause damage by growing in gutters and blocking them, and by developing roots in the joints and cracks of masonry walls or in drains.

5. Measurements, Modelling and Mapping of Air Quality

5.1 Introduction

The measuring, testing and evaluation of air quality are assuming growing importance in developed countries as elements of a comprehensive clean air policy geared to the objective of sustainable development. A huge bulk of data are therefore generated on the various geographical levels. This concerns point measurements of both emissions and ambient air concentration, and as well emission surveys of almost every type of sources.

Point measurements are very expensive, and for a broader assessment of air quality, needed for policy development and assessment, public information etc., measured data needs to be combined with modelling based on emissions inventories, to assess properly the exposure to, and thus the effects of the pollution on public health or on buildings. Such air dispersion models exist, and the results can be mapped and exhibited by modern information technology (GIS).

During the last decades it has become evident that air pollution is not only a problem of densely populated and industrialised areas, but pollutants may be transported over long distances and affect the environment far beyond the source regions. This implies that monitoring and control of air pollution on a local or national scale is not sufficient to solve environmental problems, and that international co-operation is a necessity.

In the context of assessing building performance, the bulk of data on global, continental (Macro) and national (meso) levels are therefore available for exploitation. To some extent data are also available for the local scale, while most is lacking for the micro-environment on buildings. This should then be a subject for concentrated R&D effort. Some methods are available from the environmental area for such an effort. This will be dealt with in Chapter 7.

The following is a state of the art report on availability of data and methods from the atmospheric environmental area on the *global*, and then the *macro* and *meso* scale in Europe. Respectively, the UN Global Environment Monitoring System (GEMS/AIR), the transboundary UN ECE EMEP-programme and the tasks organised under the European Environment Agency in Copenhagen are described, and some data are given.

5.2 Global Environmental Monitoring

5.2.1 UN Global Environment Monitoring System (GEMS/AIR) – 1973-1992

GEMS/AIR is an urban air pollution monitoring and assessment programme, which evolved from a World Health Organisation (WHO) urban air quality monitoring pilot project, that started in 1973. Since 1975, WHO and the United Nations Environment Programme (UNEP) have jointly operated the programme as a component of the United Nations systemwide Global Environment Monitoring System (GEMS). GEMS is a component of the UN Earthwatch system.

The original objectives of GEMS/AIR were:

- to strengthen urban air pollution monitoring and assessment capabilities in participating countries;
- to improve the validity and comparability of data amongst cities;
- to provide global assessments on levels and trends of urban air pollutants, and their effect on human and ecosystem health.

5.2.2 The GEMS/AIR Achievements and Network

Since its beginning in 1973, the GEMS/AIR network has included some 270 monitoring sites in 86 cities in 45 countries. Monitoring stations are run by the national or city authorities who voluntarily contribute their data to the GEMS/AIR global data base. The cities represent a wide range of climatic and socio-economic conditions, as well as different levels of development and air pollution control capabilities. GEMS/AIR is the only global programme which provides long-term air pollution monitoring data for cities in industrialised as well as in developing countries. Thus the programme enables the production of assessments on the levels and trends of urban air pollution world-wide.

5.2.3 GEMS/AIR Phase 2 (1993–2000) – Perspective and Programme Activities

In recognition of the increasing challenges faced by the escalating urbanisation all over the world, an outline for an expanded GEMS/AIR programme (GEMS/AIR Phase 2) was prepared for the period 1993-2000. The overall *objective* of the programme is to provide the comprehensive information needed for rational air quality management.

Within this objective, the following sub-objectives were defined:

- provide an international framework for co-ordinated and valid monitoring of urban air quality, effective data management, and reliable information dissemination;
- develop methodologies, adapted to the specific needs of the participating countries, required for the comprehensive monitoring and assessment of urban air quality;
- produce comprehensive assessments which include levels and trends of urban air quality, pollution sources, and options for abatement, as well as of potential health and environmental effects;
- strengthen urban air quality monitoring networks and assessment capabilities in developing countries.

5.2.4 The GRID – Arendal Solar UV Radiation Information Service

Ozone depletion leads to increased ultraviolet radiation reaching the earth surface. Excessive exposure to UV rays from the sun leads to sunburn, and, in some cases, also to skin cancer. If people continue their sunbathing habits the health implications could be serious.

UV-intensity maps are being produced by GRID-Arendal in co-operation with NILU. Sun-angle and satellite measurements of stratospheric ozone are entered into a model to calculate UV-intensity at noon for the whole earth. Maps are then produced indicating this intensity for selected areas.

Institutions, media and private persons can now order a UV-intensity information package from GRID-Arendal, with colour maps and graphics showing the UV and ozone situation over a selected period of time.

At an additional cost – based on production time – custom made UV-intensity maps for selected areas can also be ordered.

The unit used on the UV-intensity maps produced is the UV-index developed by Environment Canada. The UV-index runs on a scale from 0 to 10, with 10 being a typical mid-summer day in the tropics. A relative scale from low to extreme is also applied. In extreme conditions, with a UV-index higher than 9, light and untanned skin will burn in less than 15 minutes.

Three main trends in UV-intensity level disparity are easily seen on the UV-intensity maps from GRID-Arendal. These are the variation between north and south, the influence of stratospheric ozone, and the annual fluctuations.

There is now also information on UV monitoring around the world on home pages on the World Wide Web. The address is:

`http:// www.srrb.noaa.gov/UV`

This information show that quite a few countries now also perform spectral measurements which is of course even more interesting from the materials durability point of view, see Ch. 4.3. A newly developed cheap instrument that can be used for measurements on buildings are described in Chapter 7.2.

5.3 UN ECE European Monitoring and Evaluation Programme (EMEP)

5.3.1 Background

In Europe, most of the research and monitoring activities related to long range transport of air pollutants have been connected to the "acid rain" issue. Towards the end of the 1960s, Nordic scientists presented data which strongly indicated that acidification of rivers and lakes in southern Scandinavia was having a severe impact on aquatic life This data led to a discussion on whether air pollutants emitted in industrialised areas of central Europe and United Kingdom could cause acidification of precipitation in Scandinavia. To study this, the Organisation for Economic Co-operation and Development (OECD) in 1972 launched a co-operative programme with the objective "to determine the relative importance of local and distant sources of sulphur compounds in terms of their contribution to the air pollution over a region, special attention being paid to the question of acidity in atmospheric precipitation." The programme, which ended in 1977, provided the first comprehensive insight into the transport of air pollutants on a continental scale. It showed that "air quality in any one European country is measurably affected by emissions from other European countries" (OECD, 1977). Mathematical models developed within the programme made it possible for the first time to quantify the depositions within one country due to emissions in any other country.

During the OECD programme, which had included 11 Western European countries, it became evident that future studies ought to include all European countries. After a period of discussions at a political level, such an all European programme was launched in late 1977: The Co-operative programme for the monitoring and evaluation of long-range transmission of air pollutants in Europe (EMEP). It was organised under the auspices of the United Nations Economic Commission for Europe (ECE), in co-operation with the United Nations Environment Programme (UNEP) and the World Meteorological Organisation

(WMO). Today EMEP is an integral part of the co-operation under the 1979 Geneva Convention on Long-range Transboundary Air Pollution (Dovland, 1993).

5.3.2 Objective and organisation

The main objective of EMEP is to provide governments with information on deposition and concentration of air pollutants, as well as on the quantity and significance of long-range transmission of air pollutants and transboundary fluxes. To achieve its objective, EMEP is based on three main elements:

- emission data,
- measurements of air and precipitation quality,
- atmospheric dispersion models that, by using emission data, meteorological data and parameters describing transformation and removal processes, provide concentration and deposition fields for relevant pollutants.

A Steering Body for EMEP, where all participating countries are represented, has been established to supervise its work. Canada and United States are also participating in the Steering Body, inter alia to ensure proper liaison with related activities in North-America. The final decisions on work programme and budgetary matters are taken by the Executive Body for the Convention on Long-range Transboundary Air Pollution.

The EMEP-activities are divided into two main parts: chemical and meteorological. A Chemical Co-ordinating Centre (CCC), located at the Norwegian Institute for Air Research (NILU), is responsible for the chemical part of the programme. The main tasks are to collect, check and store data from national measurement programmes in the participating countries and to organise and co-ordinate quality assurance procedures. The meteorological part of EMEP is being undertaken at two Meteorological Synthesizing Centres, an eastern centre (MSC-E) in Moscow, and a western centre (MSC-W) at the Norwegian Meteorological Institute in Oslo. Their main task is to design, operate and verify atmospheric dispersion models. The work at the EMEP centres is funded by the participating countries according to a protocol to the Convention, while measurement activities are funded through national monitoring programmes in the participating countries. The participating countries also contribute by organising workshops and expert meetings on selected topics.

Working Groups on effects are also established within the context of EMEP, under which the WG on materials exist, and which has established the UN ECE ICP on materials Exposure program (see Chapter 3.4).

5.3.3 EMEP's work programme

During its first years of operation, only sulphur compounds were included in EMEP. The work programme has been gradually expanded to include also nitrogen compounds, volatile organic compounds and ozone.

5.3.3.1 Emission data

Emission data are essential input data for model calculations, and are also needed for other purposes in the co-operation under Convention. The EMEP models have so far been using a grid size of 150 km × 150 km, but new models under development will be based on a 50 km × 50 km grid. Emission data are to be provided by the participating countries and they are at present working on annual emission data for 1990 in the 50 km × 50 km grid. This closely linked to the EU project CORINAIR '90 which now forms part of the working programme of the Copenhagen based European Environment Agency (EEA) (see Chapter 5.4).

For the model calculations, a best as possible time resolution of the emission data are needed. This has so far been solved by specifying seasonal variations based on information on heating demand, etc.

The collection of reliable emission data with the required spatial resolution has been a difficult task within EMEP. Workshops and expert meetings have been used to elaborate guidelines to harmonise the methods used for emission estimates. The present guidelines include SO_2, NO_x, NH_3, CO and VOC. A Task Force was established to strengthen the co-operation between the large number of countries, and to further develop the common methodologies and a guidebook with detailed descriptions of emission inventories, including recommended default emission factors, was issued in 1995. The efforts on improving the quality of European emission data is of vital importance not only for EMEP but also for efforts related to monitoring of compliance with the various commitments European countries have made by signing agreements on emission reductions.

5.3.3.2 Measurements of air and precipitation quality

EMEP monitoring sites should be located in rural areas to be representative for large areas and should not be unduly influenced by local sources. However, emission densities vary much over Europe and it has therefore not been possible to define strict siting criteria. The present station network includes about 100 sites in about 30 countries (Schaug et al., 1993), Figure 16.

The present measurement programme includes the components shown in Table 5.

For nitrate and ammonium, impregnated filters have been used to measure the sum of these compounds in gaseous and particulate form. This is not a satisfactory solution and is changed so that gaseous and particulate species are determined separately by using denuder techniques.

Measurements of light hydrocarbons were initiated in late summer 1992 at five EMEP sites. Samples are collected in electropolished stainless steel canisters at noon twice per week and are sent to the CCC for chemical analysis. In addition, aldehydes and ketones (8-hour samples), were included from spring 1993. One of the objectives is to establish a data base for VOC concentrations to be used for comparison with results from photochemical model calculations.

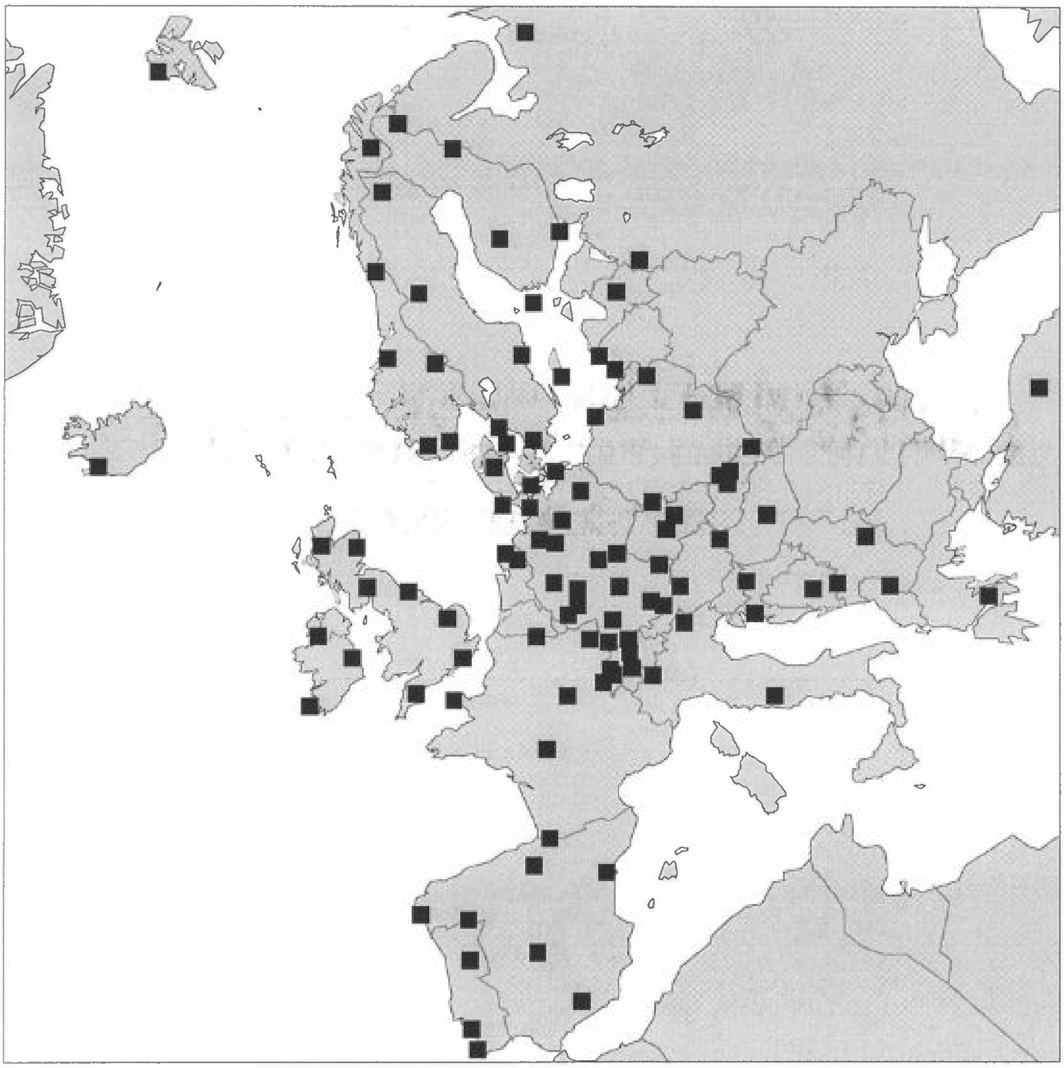


Figure 16: EMEP sampling network in 1993.

It has not been possible to standardise methods for sampling and chemical analysis within EMEP, but a manual with recommended methods has been issued. Most EMEP stations use either a low volume sampler where an air sample is drawn through a filter for collection of particles and then through a solution for absorption of the relevant gases, or a medium volume sampler with impregnated filters instead of a bubbler. The samples are analysed at a national laboratory and data reported to the CCC. For precipitation, both wet-only and bulk sampling are accepted. Several chemical methods are being used, but ion chromatography is being used by an increasing number of laboratories.

The large number of laboratories participating in EMEP and the lack of standardisation of methods imply that various intercomparisons play an important role in the quality assurance activities:

- Interlaboratory tests of chemical analyses.
- To compare the performance of different air samplers, field intercomparisons have been undertaken.

Table 5: EMEP's measurement programme.

	Components	Measurement period	Measurement frequency
Gas	SO_2, NO_2 O_3 Light hydrocarbons C_2-C_7* ketones and aldehydes (VOC)	24 hours Hourly means stored 10 - 15 minutes 8 hours	Daily Continuously Twice weekly Twice weekly
Particles	SO_4^{2-}	24 hours	Daily
Gas + particles	HNO_3 (g) + NO_3^- (p) NH_3 (g) + NH_4^+ (p)	24 hours	Daily
Precipitation	Amount of precipitation, SO_4^{2-}, NO_3^-, Cl^-, pH/H^+ NH_4^+, Na^+ Mg^{2+}, Ca^{2+}, K^+, conductivity	24 hours	Daily

* Measurements are made at a small number of sites only.

Additional quality assurance elements are:

- Regular questionnaires to collect detailed information on monitoring sites, sampling equipment, methods for chemical analysis, as well as on local quality assurance procedures. This information is stored and regularly updated by the CCC.
- Expert consultations, which include visits of a representative from the CCC to participating laboratories, site inspections, as well as visits from the participating countries to the CCC.
- All data received by the CCC are run through a quality control check, e.g. by checking the ionic balance of precipitation analysis.
- The QA elements have been collected in a QA plan.

After completion of quality checks, summaries of the data submitted are presented in annual reports, which will normally be printed 1–2 years after the end of the measurement period (e.g. the 1993-report was issued in July 1995).

Some results of EMEP-measurements of relevance for materials degradation are given in Figures 17 and 18, showing respectively, sulphur dioxide and pH in precipitation in rural areas in 1993. Further information on EMEP measurements are given by Hanssen et al. (1990); Schaug et al. (1993); UN (1991).

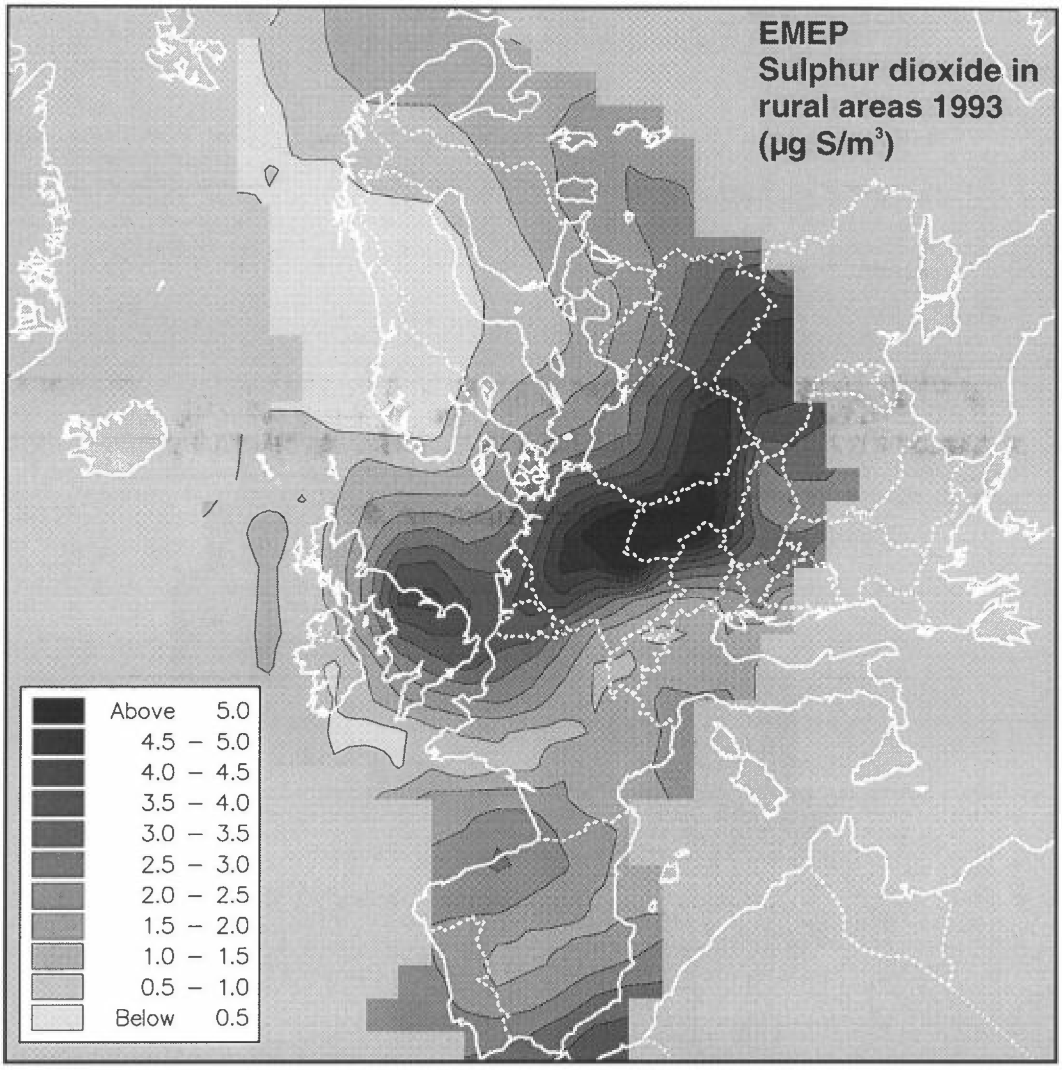


Figure 17: Isoplots of annual average SO_2 concentrations (krieged from measurements in rural areas), for 1993. Reference: EMEP/CCC.

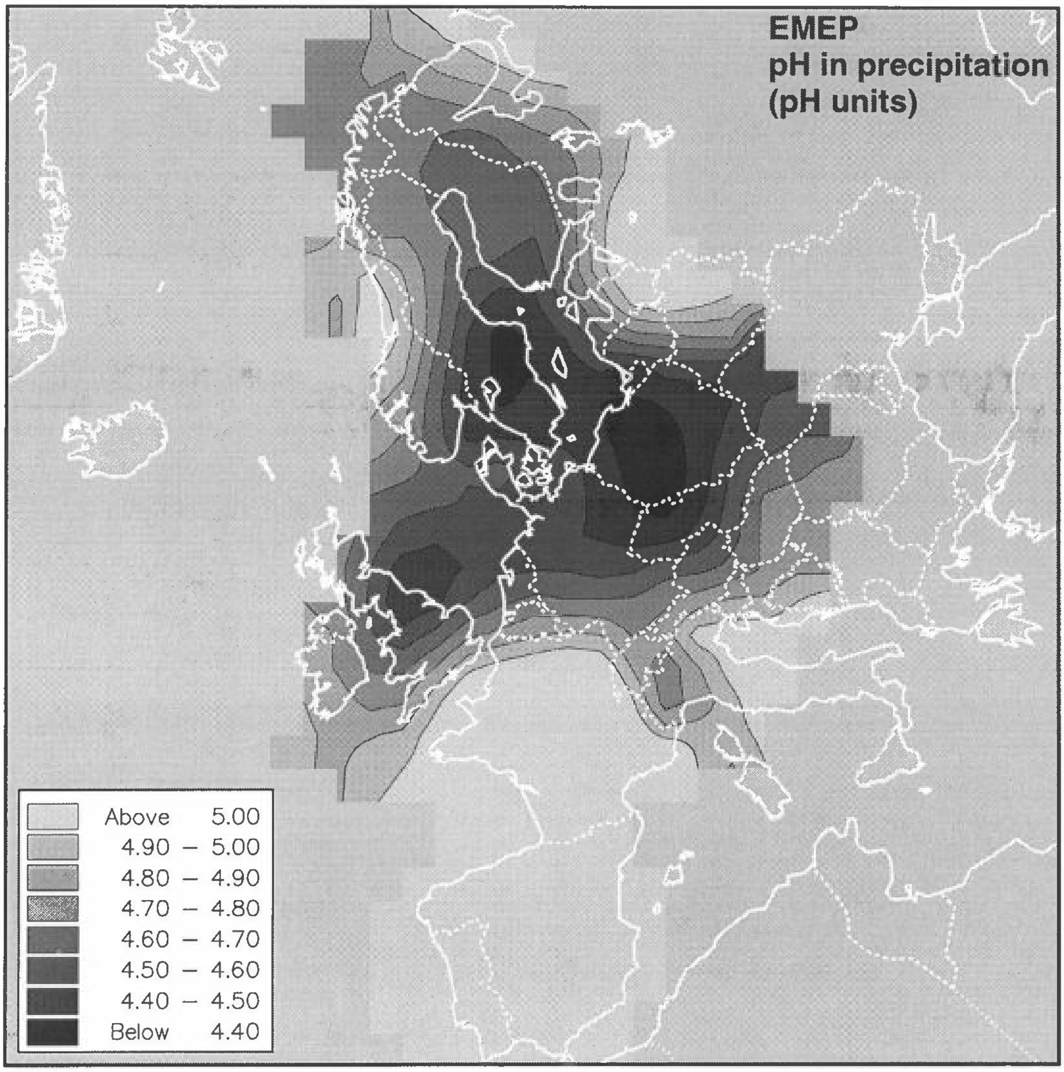


Figure 18: Isoplots of annual average NO_2 *concentrations (krieged from measurements in rural areas), for 1993.*
Reference: EMEP/CCC.

5.3.3.3 Modelling activities

The meteorological dispersion models employed by EMEP's Meteorological Synthesizing Centres are similar in their basic approach. The one-layer Lagrangian models being used calculate concentrations of pollutants in air parcels following air trajectories from a balance of sources and sinks. For primary pollutants (e.g. SO_2) the emission inventory provides the source term. Chemical transformation may act as a sink (e.g. for SO_2) or a source for secondary pollutants (e.g. sulphate). All pollutants are removed by dry and wet deposition. Model calculations are regularly made for sulphur and nitrogen compounds, and some model estimates for large-scale formation and transport of ozone are also available. The most important basic meteorological data needed are wind fields (925 mb) and precipitation fields given every six hours. For further information on the models used, including comparisons between model results and measurements, reference is made to reports prepared by the EMEP-centres, e.g. (UN, 1991; Sandnes, 1992; MSC-E,1993; Simpson, 1993). Work has been initiated by MSC-W on multi-layer Eulerian models. However, it is a clear goal for EMEP to keep the models simple enough to allow calculations over long time periods (several years).

The most widely used results from EMEP are the model estimates of sulphur deposition in each European country caused by emissions in other countries. Annual country-to-country emitter-receiver matrices for sulphur and nitrogen compounds are regularly provided by EMEP and forms a valuable input to the work under the Convention. The model results have been a prerequisite for the negotiations on emission reductions based on the critical loads approach[1] Table 6 show some results from MSC-W for sulphur.

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[1] The "critical loads approach" takes the level of deposition or concentration that an ecosystem can tolerate without negative effects as a starting point. Based on the "critical loads", which often will vary geographically, an optimal strategy for reduction of emissions can be elaborated using the following information: Inventories of current emissions and projections of future emissions; estimates of potential for and costs of emission reductions; long-range transport models describing emitter-receiver matrices; maps of critical loads; and integrated assessment models in which the above elements are combined to assess alternative reduction strategies.

Table 6: *Sulphur deposition in some European countries in 1991 from sulphur emissions in Germany (Sandnes, 1992). Unit: 1000 tons of sulphur. German SO_2-emissions in 1991: 2870 ktons.*

Austria	50
Belgium	10
Belarus	31
Czechoslovakia	123
Denmark	14
Finland	17
France	58
Germany	899
Hungary	21
Italy	33
Netherlands	20
Norway	20
Poland	252
Romania	23
Russia	71
Sweden	29
Switzerland	13
Ukraine	46
United Kingdom	18
(Remaining area inside EMEP-grid)	448

Table 7: *Sulphur deposition in Germany in 1991 originating from emissions in various European countries (Sandnes, 1992). Unit: 1000 tons of sulphur. Total deposition: 1261 ktons.*

Austria	2
Belgium	27
Czechoslovakia	87
Denmark	5
France	51
Germany	899
Hungary	7
Italy	8
Netherlands	12
Poland	38
United Kingdom	47
(Remaining countries and seas)	(26)
(Indeterminate origin)	(51)

5.3.4 Further development and concluding remarks

Taking into account the large number of countries participating in EMEP and the quite significant differences in availability of technical resources in the various countries, EMEP has been reasonably successful in achieving its objectives.

An important issue for EMEP in the coming years will be to monitor changes in air and precipitation quality in Europe as a result of emission reduction commitments laid down in the various protocols to the Convention on Long-range Transboundary Air Pollution. High priority will therefore be given to maintaining and improving the quality of the activities related to sulphur and nitrogen oxides, as well as VOC (and photochemical oxidants). Efforts to improve the quality of the emission data are of particular importance. The measurement strategy will be evaluated, aiming at a more equal distribution of stations over the region and also considering issues such as whether all stations should have identical measurement programmes. Efforts to improve harmonisation and standardisation of methods will also have to be addressed. The modelling work will be improved by better spatial resolution and possibly also by using multilayer models.

5.4 Air quality information dissemination at European Environment Agency (EEA)

5.4.1 Objective and organisation

After years of preparation the European Environment Agency (EEA) was established in Copenhagen in December 1994. The main objective of EEA is laid down in the EEA Regulation (No. 121/90, EEC 1990), where EEA's main task (Article 1) is to provide the European Community and its Member States with

objective, reliable, and comparable information at a European level enabling the Member States to take the requisite measures to protect the environment, to assess the results of such measures and to ensure that the public is properly informed about the State of the environment

With regard to monitoring and information gathering Article 2 lists the Agency's tasks to be:

- to establish, in co-operation with the Member States, and co-ordinate the network referred to in Article 4 (EIONET). In this context, the Agency shall be responsible for the collection, processing and analysis of data, in particular in the fields referred to in Article 3, among them: ambient air quality.

The development of the EIONET technical infrastructure is of special importance. This will support its *decentralised* and *distributed organisation*, emphasising *interconnecting existing systems* so that they can exchange information and operations. The focus on interconnecting existing systems, implies neither a "central information system" nor the implementation of the same system in all nodes, but the creation of a distributed information machine. A layered approach is needed to accommodate the requirements and needs, as illustrated in Figure 19.

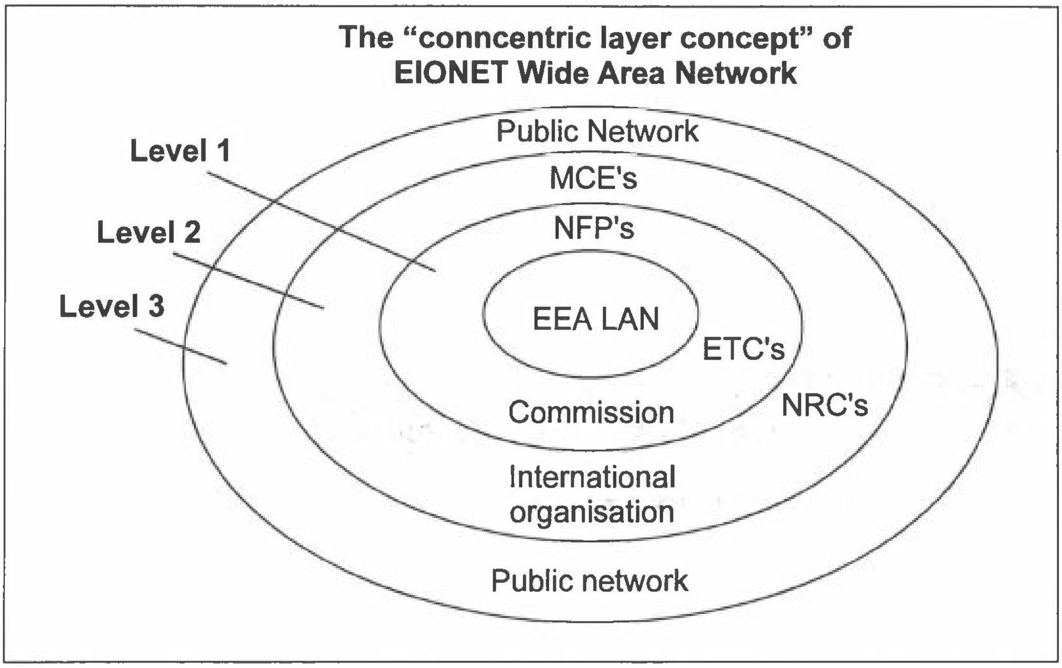


Figure 19: The European Information and Observation Network (EIONET).

Level 1 is composed of EEA, National Focal Points, European Topic Centres and the Commission. This shell comprises the highest operating level and is intended to:

- support efficient communication,
- enable inter-organisational co-operation and planning,
- provide capabilities to track the flow of documents,
- offer "conference" facilities,
- enable reporting and data flows, and
- provide access to relevant EEA data.

So far 8 of 12 Topic Centres Consortia have been established. For air pollution two Topic Centres were established in December 1994, the ETC.-Air Quality (AQ) and ETC.-Air Emissions (AEM). The ETC.-AQ is lead by the National Institute of Public Health and Environment (RIVM) in the Netherlands, and the other members of the Consortium are Norwegian Institute for Air Research (NILU), Norway, National Observatory of Athens (NOA), Greece, Norwegian Meteorological Institute (DNMI), Norway.

Other main tasks of EEA are:

- to provide the Community and the Member States with objective information necessary for framing and implementing sound and effective environmental policies; in particular to provide the Commission with the information that it needs to carry out successfully its tasks of identifying, preparing and evaluating measures and legislation in the field of the environment;

- to record, collate and assess data on the state of the environment, to draw up expert reports on the quality, sensitivity and pressures on the environment within the territory of the Community, to provide uniform assessment criteria for environmental data to be applied in all Member States. The Commission shall use this information in its task of ensuring the implementation of Community legislation on the environment;
- to help ensure that environmental data at a European level are comparable and, if necessary, to encourage by appropriate means improved harmonisation of methods of measurement;
- to promote the incorporation of European environmental information into international environment monitoring programmes such as those established by the United Nations and its specialised agencies;
- to ensure the broad dissemination of reliable environmental information. In addition, the Agency shall publish a report on the state of the environment every three years;
- to stimulate the development and application of environmental forecasting techniques so that adequate preventive measures can be taken in good time;
- to stimulate the development of methods of assessing the cost of damage to the environment and the costs of environmental preventive, protection and restoration policies;
- to stimulate the exchange of information on the best technologies available for preventing or reducing damage to the environment;
- to co-operate with the bodies and programmes referred to in Article 15;

5.4.2 European Policies on Air Quality Monitoring

Current European directives and conventions requiring monitoring of air quality and deposition is mentioned below. In addition comes national requirements in each state.

The current set of air quality directives in the European Union comprise the compound-specific directives for SO_2, particulate matter/black smoke, NO_2, lead and ozone, of which lead was the first (1982) and ozone the last (1992). These directives require in principle that all exceedances are detected, and thus that monitoring is carried out in all areas where exceedance of the limit values are expected.

The Exchange of Information (EoI) decisions (1982 and 1994) provide the framework for making monitoring data from selected sites regularly (annually) available to the Commission.

Under the new directive on Ambient Air Quality Management (the “Framework” directive, Council Directive 95/9514/EC) new air quality target values are being developed by the Daughter Directives Working Groups for SO_2, NO_2, lead and particulate matter (PM), and new requirements to air quality assessment and monitoring are being developed concurrently. Also here, full monitoring/

assessment coverage of areas of exceedances of target values or areas where those values are approached, is required.

These directives and EoI decision will set the stage for European air quality monitoring and assessment, and reporting in the years to come.

The monitoring requirements under these directives will mainly relate to urban areas or industrial hot spot areas where concentrations may be high enough to affect human health. In other (rural, regional) areas monitoring is required mainly due to effects of deposition of acidic compounds (see below).

5.4.3 Present status of European Air Quality Monitoring

The first State of the Environment report for Europe, initiated by the pan-European Conference of Environment Ministers, at the Dobris Castle of the Czech Republic in 1991 and published by the EEA in 1995, took a pan-European approach. It is likely that the area of interest of the Agency will be extended to cover those countries covered by the Dobris assessment, and thus have a pan-European outlook.

On the *local/urban scale*, the Dobris report provided information on air quality in more than 100 European cities, mainly for the years 1985 and 1990. The assessment covered SO_2 and particles ("winter smog compounds"), NO_2 and O_3 ("summer smog compounds"), and also to some extent CO and lead. The data coverage was good for SO_2 and particles (mainly black smoke), less extensive for the other compounds. Data were collected and presented both for high short-term concentrations, and long-term averages. As example Figure 20 shows a summary of the state for SO_2.

The 6 page summary of the local/urban air pollution in the Dobris report was followed up by a 2-volume Scientific Background Document for local/urban air pollution, presenting extensive summaries, and a 2-5 page city report for each one of the cities (Sluyter, 1995).

The ETC.-AQ produced in 1995 also a status description on *air quality in Europe in 1993*. This was produced under the MA 2 project of the Agency's work programme (sub project MA 2-4) (Larssen et al., 1995).

Data were thus made available from 91 monitoring sites (in 49 cities) from 9 EU Member States. In order to extend this fairly limited data base, national reports on 1993 air quality which were available, were also used. This extended the data base to 6 more European countries. As example Figure 21 shows SO_2.

One of the problems encountered when using data from such varied sources, was that data presentations and statistics parameters in the data sources were not harmonised. The status description was based on presenting averaging times and percentiles of concentrations as they appear in EU Directives and WHO Air Quality Guidelines. These parameters were not, in general, available from the national reports.

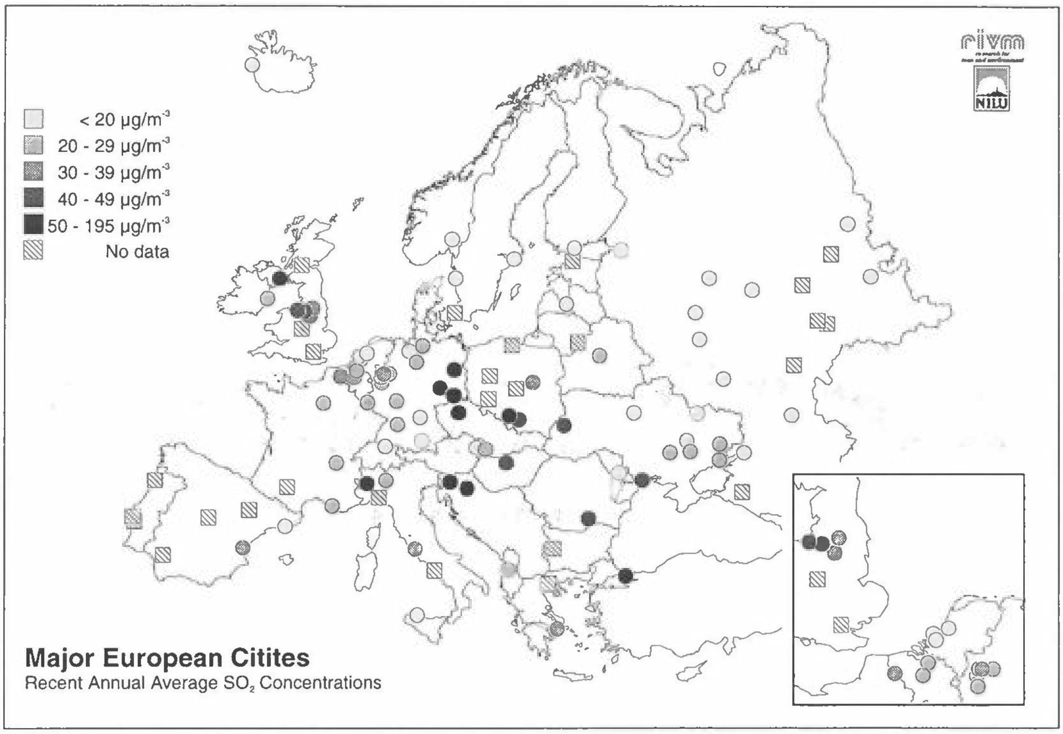
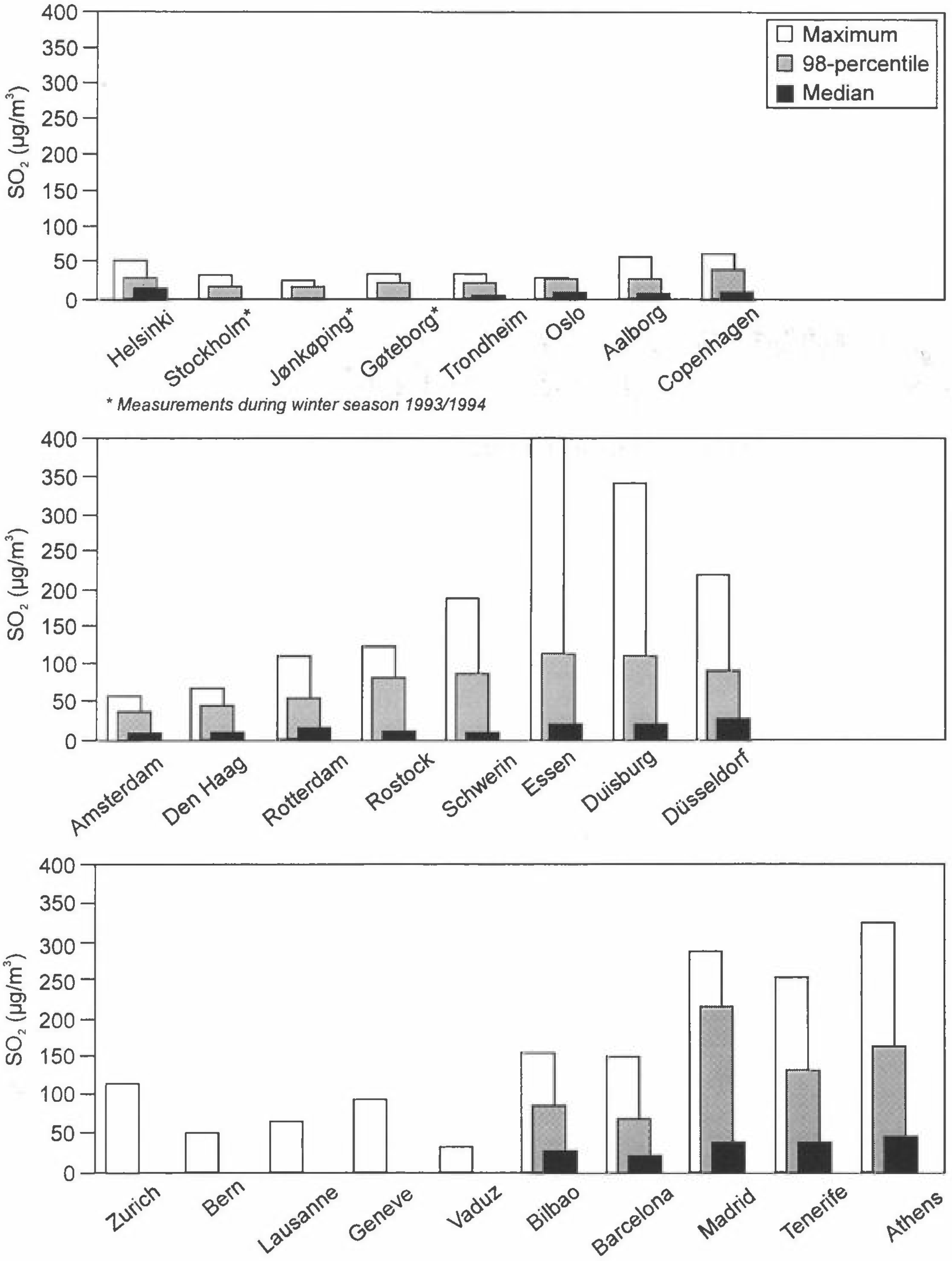


Figure 20: SO_2 concentrations (annual average) in European cities, recent years (mostly 1985).
Reference: R. Sluyter (ed.) (1995).

For *ozone* specifically, the ETC.-AQ in 1995 produced for the European Commission a report summarising the 1994 pollution situation regarding ozone in the EU Member States (de Leeuw et al., 1995). The report was produced to summarise the state of the ozone situation relative to the EU Ozone Directive. Ozone data were collected through a dedicated procedure, where Member States transferred the data to the Commission according to the requirements of the Directive, from which they were made available to the ETC.-AQ. *Data were thus made available from 461 monitoring sites in 14 Member States, for 1994.*

The various ozone threshold values as defined in the Directive are shown in the Table 8.



** Measurements during winter season 1993/1994*

Figure 21: 24 h maximum, 98 percentile and median SO_2 values for 1993 for selected stations and cities (µg/m^3).

Table 8: Thresholds for ozone concentrations in air.

Thresholds	Values
Health protection threshold	110 μg/m^3 for 8-hours mean
Vegetation protection threshold	200 μg/m^3 for 1-hours mean 65 μg/m^3 for 24-hours mean
Population information threshold	180 μg/m^3 for 1-hours mean
Population warning threshold	360 μg/m^3 for 1-hours mean

As an example, Figure 22 shows, for hourly values, the number of days with exceedance of the 180 μg/m^3 threshold value.

If ozone threshold values for damage to building materials could be established, which seem likely from the UN ECE dose-response functions (see Chapter 3.4), the necessary data will be easily accessible from these public sources. In this context it is quoted from Kucera (1996):

"For the purpose of the mapping manual an acceptable level of ozone of 20 ppb (24 μg/m^3) as an annual mean has been chosen for direct effects on organic materials. The value which is based on a few available damage functions for organic materials has to be considered as very provisional."

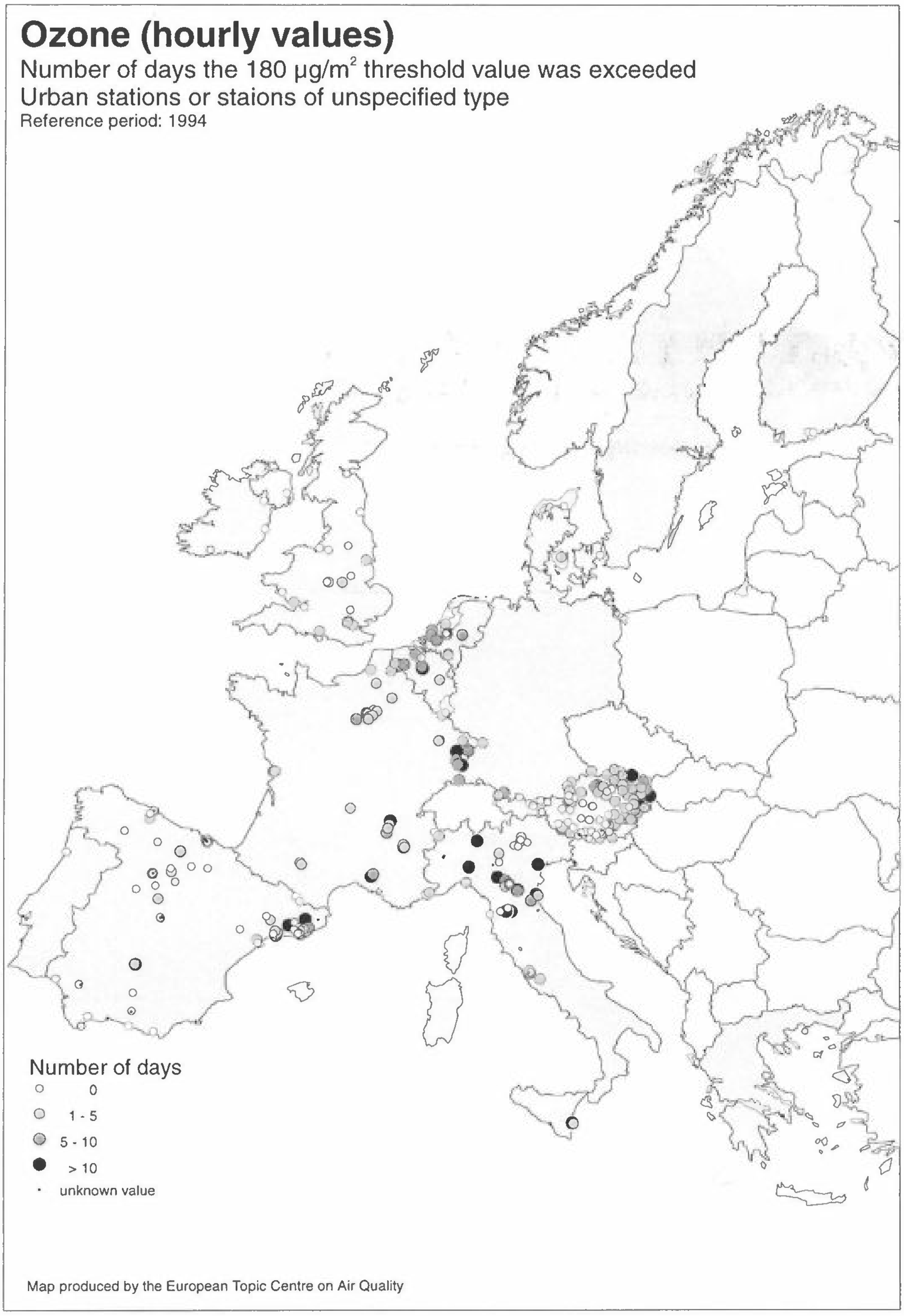


Figure 22: Number of days the 180 µg/m³ ozone threshold value was exceeded in 1994 (ETC.-AQ).

5.4.4 European air quality monitoring networks

As part of the MA 1 project of the Agency's work programme, the ETC.-AQ in 1995 summarised the state of the air pollution monitoring situation in Europe (the MA 1-2 sub project). The information on monitoring networks and sites was collected through a questionnaire, and additional information was provided through a similar activity carried out by the WHO collaborating centre on Air Quality Management and Air Pollution Control, the Institute for Water, Soil and Air Hygiene (WABOLU) in Berlin.

The MA 1-2 report provides detailed country-wise tables on networks, sites, compounds, reporting etc., summarised into country reports, and again summarised into summary tables covering all the 29 countries from which data were available.

On the *regional scale*, the MA 1-2 activity revealed that there is extensive monitoring in addition to the EMEP network, and that about 750 sites are in operation totally in Europe. This monitoring is very extensive for S- and N-compounds in air (gases and particles) and deposition, and also for ozone, while monitoring of ozone precursors is so far limited to 7 countries.

On the *local/urban scale*, monitoring is carried out at a very large number of sites in Europe, totalling close to 5,000 sites according to the information made available to the Topic Centre (see Figure 23). Most of these sites seem to be general urban background sites, while hot-spot sites (traffic, industry) are less well represented. Re. compounds, the compounds of the EU Directives (SO_2, particles, NO_2, ozone, lead) are extensively covered.

These 5,000 local/urban monitoring sites are contained in a large number of networks operated by local, regional or national authorities. We can only assume that operating practices, quality control procedures, data availability and reporting vary considerably from network to network.

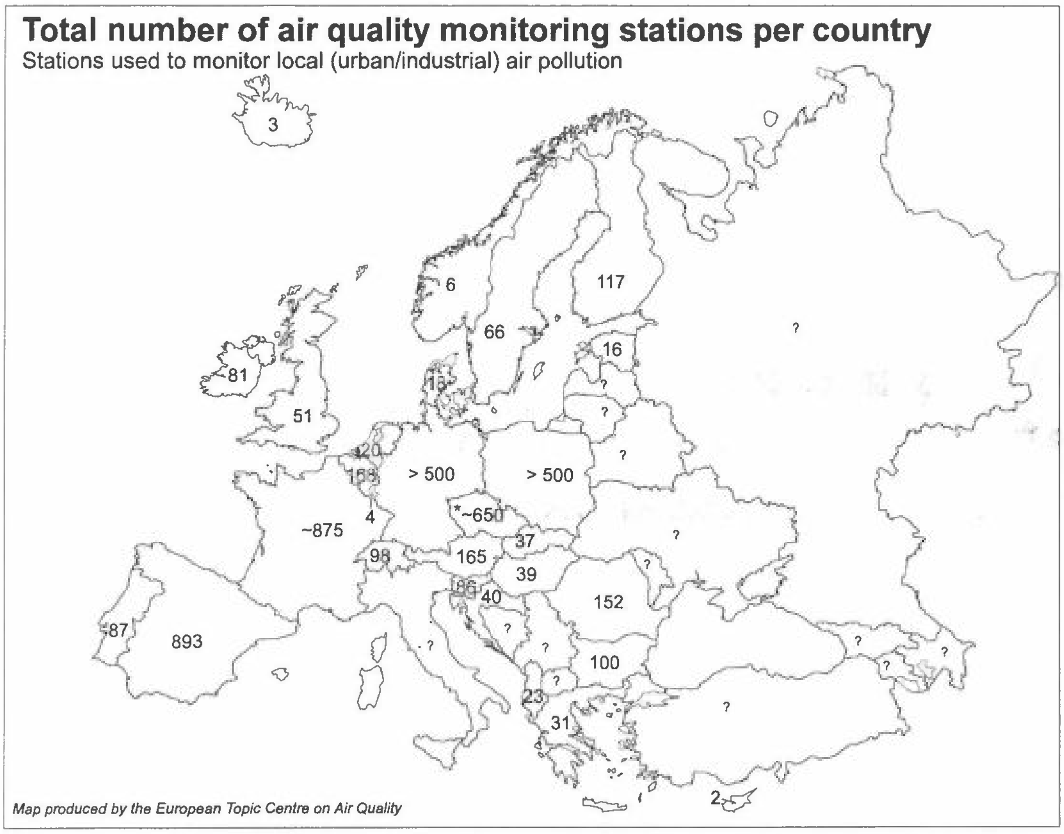


Figure 23: Number of sites per country for the monitoring of urban/local industrial air pollution.

5.5 International Standards for Air Quality

The European Committee for Standardisation (CEN) has assumed responsibility to its technical committee TC 264 Air Quality for working out European standards for the monitoring of emissions, loads and levels. This work was started in 1991, and no standards are yet published (March 1996). However, many standards have been elaborated within the ISO/TC 146 "AIR QUALITY", as follows from Table 9.

Table 9: *ISO/TC 146 "Air quality".*

ISO/TC 146 "AIR QUALITY"		
ISO 7708:1995		
SC 1 "Stationary source emissions"	**SC 2 "Workplace atmospheres"**	**SC 3 "Ambient atmospheres"**
ISO 7934:1989 Stationary source emissions - Determination of the mass concentration of sulphur dioxide - Hydrogen peroxide/barium perchlorate/Thorin method	ISO 8518:1990 Workplace air - Determination of particulate lead and lead compounds - Flame atomic absorption spectrometric method	ISO 4219-1979 Qualité de l'air - Détermination des composés soufrés gazeux dans l'air ambiant - Appareillage d'échantillonnage
ISO 7935:1992 Stationary source emissions - Determination of the mass concentration of sulphur dioxide - Performance characteristics of automated measuring methods	ISO 8672:1993 Qualité de l'air - Détermination de la concentration en nombre de fibres inorganiques en suspension dans l'air par microscopie optique en contraste de phase - Méthode du filtre à membrane	ISO 4220-1983 Ambiant air - Determination of a gaseous acid air pollution index - Titrimetric method with indicator or potentiometric end-point detection
ISO 9096:1992 Stationary source emissions - Determination of concentration and mass flow rate of particulate material in gas-carrying ducts - Manual gravimetric method	ISO 8760:1990 Workplace air - Determination of mass concentration of carbon monoxide - Method using detector tubes for short-term sampling with direct indication	ISO 4221-1980 Air quality - Determination of mass concentration of sulphur dioxide in ambient air - Thorin spectrophotometric method
ISO 10155:1995 Stationary source emissions - Automated monitoring of mass concentrations of particles - Performance characteristics, test methods and specifications	ISO 8761:1989 Workplace air - Determination of mass concentration of nitrogen dioxide - Method using detector tubes for short-term sampling with direct indication	ISO/DIS 4222.2: 1980 Air quality - Measurement of atmospheric dustfall - Horixontal deposit gauge method
ISO 10396:1993 Stationary source emissions - Sampling for the automated determination of gas concentrations	ISO 8762:1988 Workplace air - Determination of vinyl chloride - Charcoal tube/gas chromatographic method	ISO 6767:1990 Ambient air - Determination of the mass concentration of sulphur dioxide - Tetrachloromercurate (TCM)/pararosaniline method
ISO 10397:1993 Stationary source emissions - Determination of asbestos plant emissions - Method by fibre count measurement	ISO 9486:1991 Workplace air - Determination of vaporous chlorinated hydrocarbons - Charcoal tube/solvent description/gas chromatographic method	ISO 6768-1985 Ambient air - Determination of the mass concentration of nitrogen dioxide - Modified Griess-Saltzman method
ISO 10780:1994 Stationary source emissions - Measurement of velocity and volume flowrate of gas streams in ducts	ISO 9487:1991 Workplace air - Determination of vaporous aromatic hydrocarbons - Charcoal tube/solvent desorption/gas chromatographic method	ISO/DIS 6769:1983 Ambient air - Determination of the mass concentration of hydrogen sulphide in ambient air - Methylene blue spectrometric method

Table 9 cont.:

ISO/TC 146 "AIR QUALITY"		
ISO 7708:1995		
SC 1 "Stationary source emissions"	**SC 2 "Workplace atmospheres"**	**SC 3 "Ambient atmospheres"**
ISO/DIS 10849.2:1994 Stationary source emissions - Determination of the mass concentration of nitrogen oxides - Performance characteristics of automated measuring systems	ISO/DIS 9976:1994 Workplace air - Determination of concentrations of C_3 to C_{10} hydrocarbons - Sorbent tube/thermal desorption/capillary gas chromatographic method	ISO 7996-1985 Ambient air - Determination of the mass concentration of nitrogen oxides - Chemiluminescence method
	ISO/DIS 9977:1994 Workplace air - Determination of acrylonitrile - Pumped sorbent tube/thermal desorption/gas chromatographic method	ISO 8186:1989 Ambient air - Determination of the mass concentration of carbon monoxide - Gas chromatographic method
	ISO/DIS 11041:1994 Workplace air - Determination of particulate arsenic, arsenic compounds and arsenic trioxide vapour - Method by hydride generation and atomic absorption spectrometry	ISO 9835:1993 Ambient air - Determination of a black smoke index
		ISO 10313:1993 Ambient air - Determination of the mass concentration of ozone - Chemiluminescence method
		ISO/DIS 10529:1993 Ambient air - Determination of the mass concentration of gaseous and soluble particulate fluorine-containing compounds - Method by filter sampling and ion-selective electrode analysis
	ISO/DIS 11174:1994 Workplace air - Determination of particulate cadmium and cadmium compounds - Flame and electrothermal atomic absorption spectrometric method	ISO 9855:1993 Ambient air - Determination of the particulate lead content of aerosols collected on filters - Atomic absorption spectrometric method
		ISO 10312:1995 Ambient air - Determination of asbestos fibres - Direct-transfer transmission electron microscopy method

Table 9 cont.:

SO/TC 146 "AIR QUALITY"		
ISO 7708:1995		
SC 4 "General aspects"	**SC 5 "Meteorology"**	**SC 6 "Indoor air"**
ISO 4225:1994 Air quality - General aspects - Vocabulary		
ISO 4226:1993 Air quality - General aspects - Units of measurement		
ISO/TR 4227:1989 Planning of ambient air quality monitoring		
ISO 6879-1983 Air quality - Performance characteristics and related concepts for air quality measuring methods		
ISO/DIS 6879.2:1994 Air quality - Performance characteristics and related concepts for air quality measuring methods		
ISO 7168-1985 Air quality - Presentation of ambient air quality data in alphanumerical form		
ISO 8756:1994 Air quality - Handling of temperature, pressure and humidity data		
ISO 9169:1994 Air quality - Determination of performance characteristics of measurement methods		
ISO 9359:1989 Air quality - Stratified sampling method for assessment of ambient air quality		

5.6 Measuring Devices for Continuous Emission Monitoring

Continuous monitoring of emissions from plant requiring an operating licence is increasingly being entrusted to systems which can measure concentrations of several substances successively. This represents a major saving in investment and operating costs on devices which measure concentrations of only one substance.

The list of suitable devices currently available (Table 10) shows that they mostly depend on optical measuring principles spread across the entire spectrum from infrared to ultraviolet.

Table 10: Multicomponent measuring systems used for continuous emission monitoring.

Measuring principle	Substances	Instrument type	Method
NDIR non-dispersive infrared absorption	CO, NO, SO_2, O_2 CO, NO, SO_2	URAS 10 E URAS 10 P	Electrochemical cell
	CO, NO, O_2 CO, NO, SO_2, O_2	ENDA 1000 ENDA 1000	O_2 magnetopneumatic
	HCl, H_2O	MCS 100 HW	Single-beam bifrequency
VIS-FIR visible spectrum absorption	NH_3, CO_2 HCl, CO, NO, NO_2	MCS 100 HW	Gas correlation Single-beam bifrequency
	SO_2 , H_2O CO, NO, NO_2, SO_2	MCS 100 HD	Gas filter correlation
NDUV non-dispersive ultraviolet absorption	NO, SO_2 NO, SO_2 , dust concentration	RADAS 2 GM 30	
	NO, SO_2	GM 30-2	
DOAS differential absorption spectroscopy	SO_2, NO, NO_2 SO_2, NO, NO_2 NH_3, H_2O Phenols, formaldehyd, Hg(O)	OPSIS	
Electrical conductivity	HCl, SO_2	Mikrogas, HCl/SO_2 Air TI	
Pressure loss/ differential pressure	Dust concentration, exhaust gas volume	LPS-E	
Electrochemical monitoring points	CO, NO, O_2	MSI 5600 heating oil EL F	

The most frequent techniques are non-dispersive infrared absorption (NDIR), visible spectrum absorption (VIS), non-dispersive ultraviolet absorption (NDUV) and differential absorption spectroscopy (DOAS) in the UV to IR range, while electrical conductivity and electrochemical cells are used only sporadically.

The DOAS principle has proved particularly versatile, since it is able to measure both classical components such as sulphur dioxide, nitrogen monoxide, nitrogen dioxide, carbon monoxide and ammonia in the exhaust gas of plants fitted with catalytic denitrification devices, and metallic mercury in the cleaned gas from waste incineration plant. The DOAS system is also suitable for measuring phenol and formaldehyde emissions in the manufacture of rock wool.

5.7 Measuring Devices for Continuous monitoring of ambient air quality

The levels of air pollutants can nowadays be monitored with automatic instruments which allow continuous recording and the identification of peak loads. Table 11 gives an overview of parameters and available monitors principles and specifications.

Table 11: Specification of instruments for continuous monitoring of air pollutants.

Parameter	Measuring parameters	Unit	Span	Detection	Accuracy	Frequency
NO	Chemiluminescence	µg/m^3	0-2 ppm	2 ppb	1%	10 sec.
NO_2		µg/m^3	0-2 ppm	2 ppb	1,4%	10 sec.
NO_x		µg/m^3	0-2 ppm	2 ppb	1%	10 sec.
SO_2	UV-fluorescence	µg/m^3	0-0,5 ppm	5 ppb	1%	10 sec.
CO	IR-absorption	mg/m^2	0-100 ppm	100 ppb	1%	10 sec.
O_3	UV-absorption	µg/m^3	0-250 ppb	0,6 ppb	1 ppb	10 sec.
Particles	TEOM resonnance frequency	µg/m^3	0-2 g/m^3	5 µg/m^2	5 µg/m^3	10 sec.
CH_4	Flame Chromatography	ppm	0-10 ppm	0.05 ppm		10 sec.
VOC		ppm	0-10 ppm	0.05 ppm		10 sec.
PAH	Photoionization	ppb	0-2 ppm	1 ppb		10 sec.

Passive samplers are a useful alternative for non-continuous sampling and, more importantly, provide a simple and inexpensive guide to average loads throughout an investigation area. These samplers are also very useful for the mapping of micro-environmental loading, for example on a building. They are therefore described more detailed in Chapter 7.

5.8 Air quality information and management systems

Surveillance and management of air quality can now be facilitated and performed via total information systems. The Air Quality Information System, AirQUIS, represents the air pollution part of a modern Environmental Surveillance and Information System, ENSIS, developed and demonstrated during the Winter Olympic Games, 1994 in Lillehammer (Haagenrud and Sivertsen, 1994).

The AirQUIS system was developed by institutions dealing with air pollution, information technology and geographical information systems (GIS). The combination of on-line data collection, statistical evaluations and numerical modelling enable the user to obtain information, carry out forecasting and future planning of air quality. The system can be used for monitoring and to estimate environmental impacts from planned measures to reduce air pollution.

The AirQUIS system contains the following modules:

- On-line monitoring,
- data handling and quality control,
- modern data bases,
- emission inventories,
- numerical dispersion models
- generation of wind fields
- presentations based upon a geographical information system (GIS)
- exposure models for materials and human health

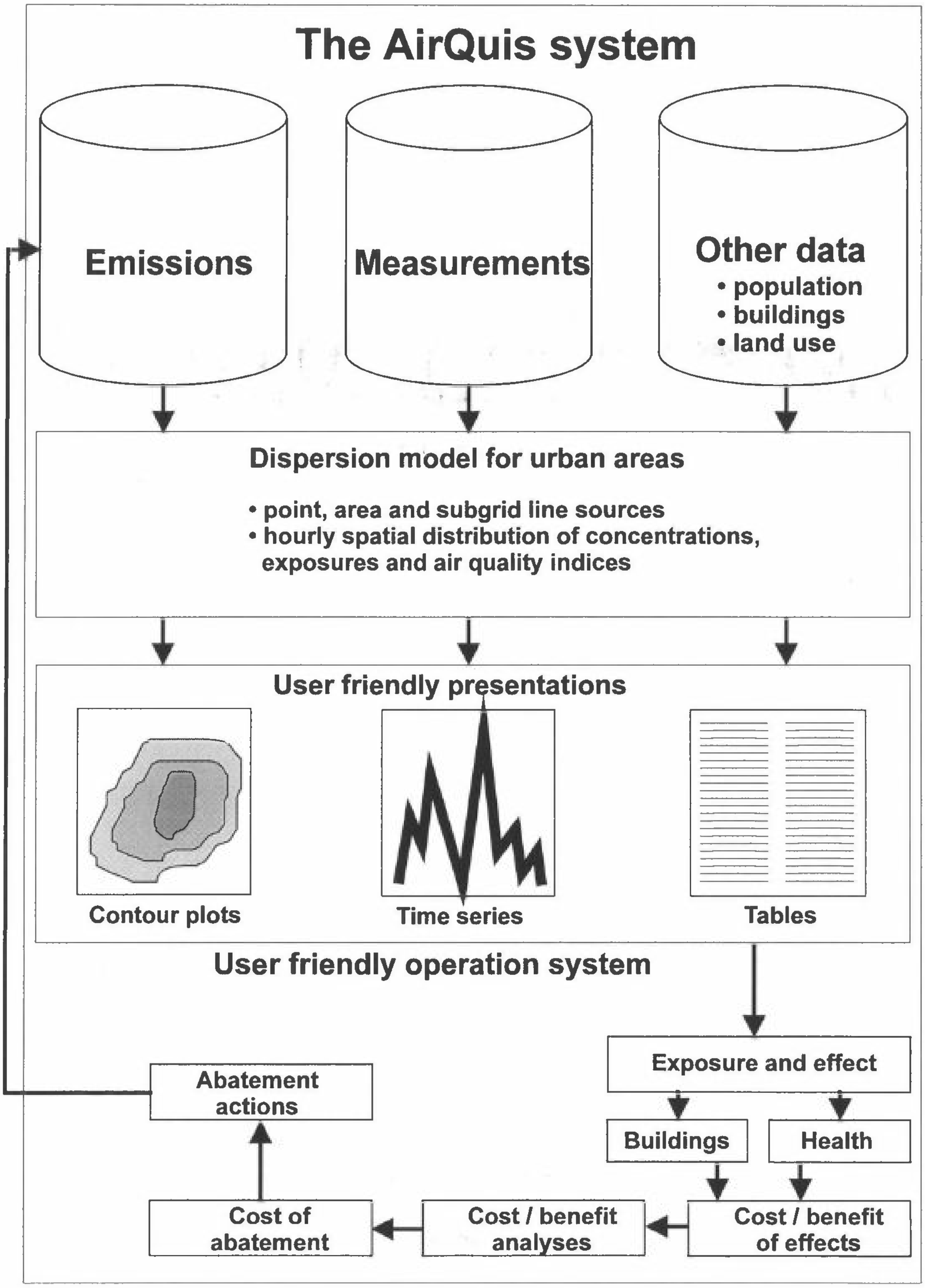


Figure 24: The AirQUIS system.

5.8.1 On-line measurement system

A measurement system of modern on line sensors for selected air pollution indicators can be designed specific for the area concerned. A specially designed data logger for meteorology and air quality is included in the system. The measurements are automatically transferred from the monitoring sites to a central data base for quality control.

Data quality control is performed at different levels throughout the data collection process; and in the approvals of the final storage data base, where simple statistics and data graphics are used to check the validity and representativity of the data.

5.8.2 The emission inventory database

A modern data base for the air pollution emission inventory has been developed. The emission module is a flexible system containing a user friendly map oriented interface to treat the main sources for emission to air such as industry, traffic, energy (consumption of fossil fuels) and emissions related to other mobile sources such as airport and harbour activities.

The industry emission module allows the user to select sources related to specific activities or areas. The time variation of emissions can be entered specific for each source or for groups of sources. Based on emission factors, emissions can be calculated from consumption data.

The traffic module is the most complex part of the emission module, includes road types and facades, vehicle type distribution, traffic time variation and emission factors dependent on parameters such as vehicle type, traffic speed and road type.

The emission inventory database is developed for applications in databases such as Access on PC or Sybase and Oracle on Unix work stations.

5.8.3 Statistical and numerical models

The models included in the AirQUIS system covers air pollution on all scales; traffic in street canyons and along roads, industrial emissions, gridded pollution from household etc. within the urban areas and on a regional scale.

The NILU developed source oriented numerical dispersion model EPISODE calculates spatial distribution of hourly concentrations of SO_2, NO_x, NO_2 and suspended particles. The NILU models ROADAIR and CONTILENK are used to estimate subgrid concentrations close to roads within the square grid. This is of relevance for estimating the micro environment exposure on buildings and it will therefore be described more in dept in Chapter 7. A puff-trajectory model is used to calculate the influence of point sources.

All model results are displayed by using GIS such as ArcInfo/ArcView. The models are running on Unix work station. The presentation of results can be operated both on PC and Unix platforms.

5.8.4 The Geographical Information System

A geographical information system based upon ArcInfo and ArcView are used as a platform for integrating the presentation of measurements, emission inventory and results from model estimates. The geographical information system is directly linked to the data bases, from which statistical evaluations, graphical presentations and spatial distributions of emissions and model results can be presented.

5.8.5 Effect modules and Air Quality Planning

One main application of the AirQUIS system will be as an effective tool for air quality abatement strategy. The contribution of air pollution from different source categories such as traffic, household and industry to the population and building exposure in an urban area can be calculated based upon data on emissions, dispersion and distribution of buildings and population. Different recommended measures to reduce air pollution can be evaluated due to population and building exposure and cost-benefit or cost-efficiency analyses. A priority list of the selected measures can be developed, taking into account air pollution exposure, health aspects and related costs.

The module for modelling and calculating buildings degradation, service lives and maintenance costs is called CorrCost and is further described in an application used in Oslo (Glomsrød et al., 1996) (see Chapter 6.2).

6. Classification and mapping of environmental degradation factors and corrosivity

6.1 Maintenance and Environmental aspects in corrosivity mapping

Classification employs *two* approaches, either classification in terms of the corrosion-determining *environmental* parameters, and/or classification based on *corrosion rate measurements of standard samples* exposed in the environment concerned, see Figure 25.

The *standard specimen* approach were dominant until the last decade due to little available knowledge and data of the dose-response functions and the degradation factors. Originally, this corrosivity mapping was undertaken responding to the needs for better maintenance, and in order to design the best protective systems for constructions. Most of the various national classification and mapping systems served this objective, and used this approach. Because this method is not characterising and mapping the degradation factors this approach is strictly valid only for the time of the measurements, i.e. it is not explanatory and predictatory. The standard specimen approach will therefore only be briefly referred to here.

The ISO 9223 also has improved maintenance as their prime objective. This standard represents a huge step forward as it for the first time in this context describes a system for quantitative characterisation and classification of the important environmental degradation factors. Its standard approach can also be used for other types of materials, and such standards are beginning to emerge.

However, it's practical use has so far been impeded by the lack of data and user-friendly IT tools.

Now that data are becoming more known from the environmental research area, efforts have been undertaken to categorise, classify and map the degradation factors and corrosivity of the exposure environment.

The environmental concern and the strive for sustainable development in the recent years has also generated a need for mapping the corrosivity of the exposure environment, in order to provide input to environmental regulations. This is done in *two* separate ways. The first one uses corrosivity mapping for proper cost benefit analysis of corrosion costs (Haagenrud and Henriksen, 1996), while the other is based on the "critical loads/levels approach" (see 6.4). This methodology, which is elaborated within the UN ECE Working Group on Effects, gives tools for predicting and mapping material degradation rates, and eventually service lives, related to their exposure environment. By co-operation, it could turn out to be extremely useful in converging the needs of the environmental issue and the building society, thereby ensuring a more durable sustainable built environment.

6.2 ISO 9223-26 Classification of atmospheric corrosivity for metals

The standards ISO 9223–9226 *Corrosion of metals and alloys – Corrosivity of atmospheres* have been developed for the classification of atmospheric corrosivity of metals and alloys. The development was based on the Czech classification philosophy, where the approach was used as early as 1975 to map the atmospheric corrosivity for the North Bohemian region (Knotkova, 1996). Based on a huge amount of experimental data for empirical dose-response functions the standards use both the approach of classifying the degradation factors and the corrosion rates, as shown in Figure 25.

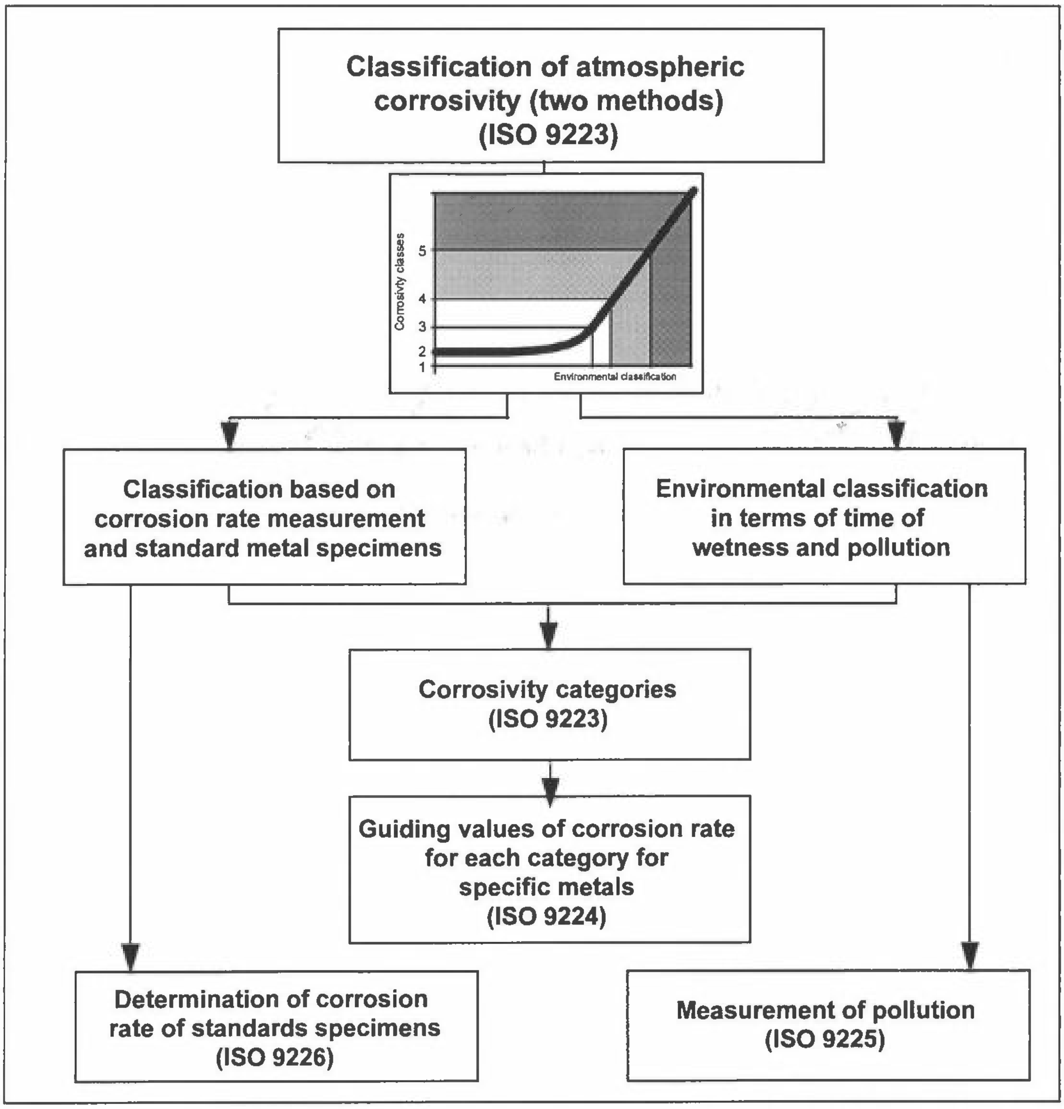


Figure 25: ISO 9223-26-The two ways of classifying atmospheric corrosivity.

The series of standards are:

ISO 9223 – Classification

SCOPE: Specifies the key factors in the atmospheric corrosion of metals and alloys, which are *time-of-wetness (τ), sulphur dioxide (P) and air-borne salinity (S).* Corrosivity categories (C), are defined on basis of these three factors and used for the classification of atmospheres for the metals/alloys-unalloyed steel, zinc and copper, and aluminium. TOW is described in five classes, classification of SO_2 and chloride is done in four classes, and the corrosivity in five classes. The classification can be used directly to evaluate the corrosivity of atmospheres under known conditions of these environmental factors, and for technical and economical analyses of corrosion damage and choice of protection measures.

ISO 9224 – Guiding values for the corrosivity categories

SCOPE: Specifies guiding corrosion values and the characteristics of corrosion for the corrosivity categories defined in ISO 9223. This can be used to predict the service life for metals/alloys in atmospheres corresponding to different corrosivity categories. These values also provides a technical basis for determining the need for protective measures and other engineering purposes. The values are based on experiments obtained from a large number of site exposures and service performances.

ISO 9224 – Measurements of pollution

SCOPE: Specifies three methods for measuring the deposition rates of sulphur dioxide and airborne salinity. It does not cover concentration measurements, as they are covered by ISO 4221:1980. The methods apply for characterisation of the test site, and as such are also suitable for characterisation of the micro environment on buildings, see Chapter 7. The sulphur dioxide methods are lead dioxide(PbO_2) and alkaline surfaces, and for chloride deposition the wet candle method is specified.

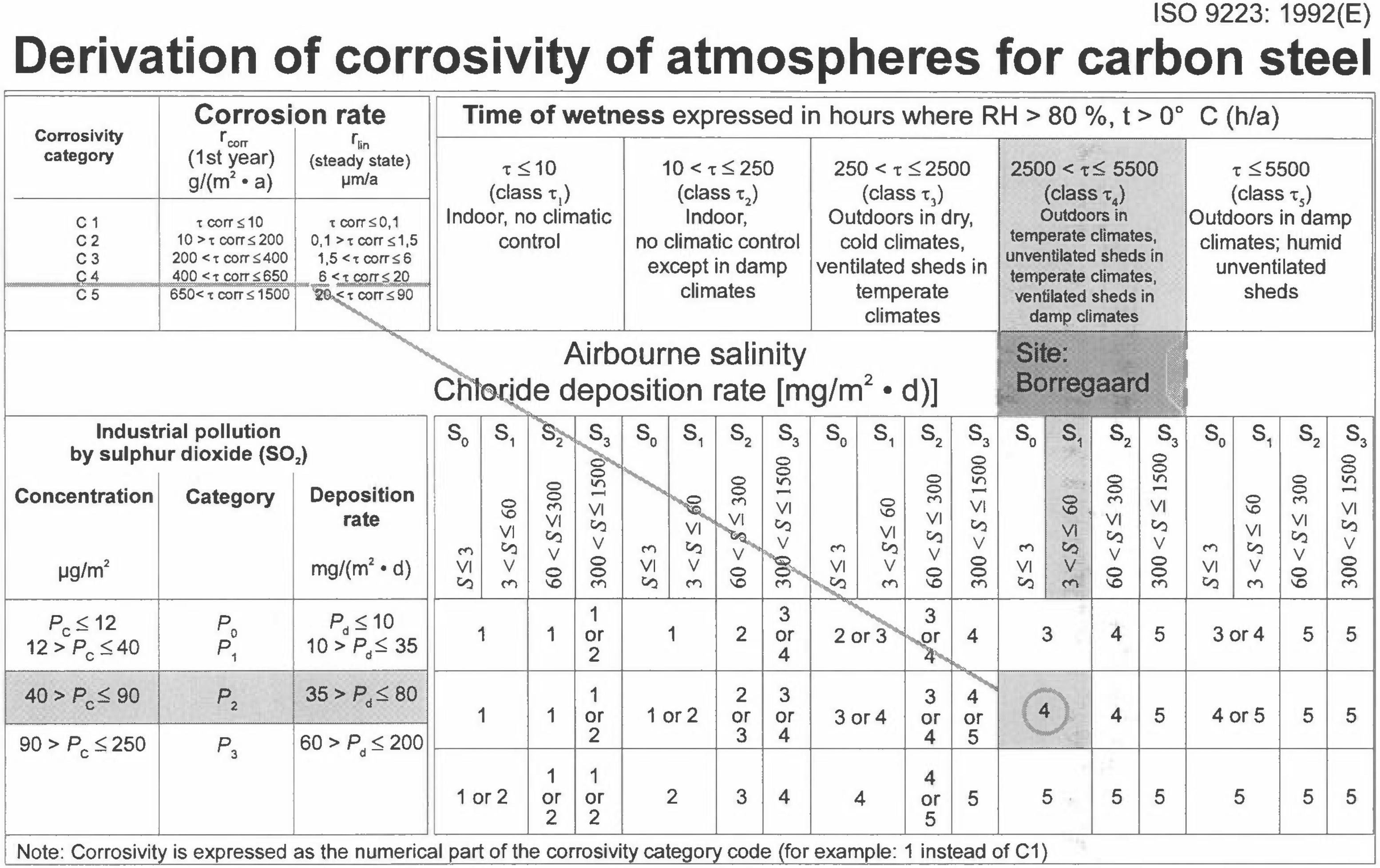
ISO 9224 – Determination of corrosion rate of standard specimens for the evaluation of corrosivity.

SCOPE: Specifies the methods for determination of corrosivity by standard specimens (flat plate or helix) including characterisation of material.

The ISO 9223 approach has since mid 80-ies been used by many researchers to classify and map the atmospheric corrosivity (Haagenrud, 1985; Kucera et al., 1986; Feliu and Morcillo, 1993; Tomiita, 1993).

Table 12 shows an example of practical use of the standard. In this table all the classes/and values for the environmental variables of TOW, SO_2 and Cl, and the corrosivity categories/rates are put together and its use for classifying the corrosion test site Borregaard in Norway by both approaches are shown. This site is one of the most aggressive in the UN ECE ICP network.

Table 12: *Example of the use of ISO 9223-26 to classify the atmospheric corrosion test site Borregaard in Norway.*



ISO 9223: 1992(E)

Derivation of corrosivity of atmospheres for carbon steel

Corrosivity category	Corrosion rate r_{corr} (1st year) g/(m² • a)	Corrosion rate r_{lin} (steady state) μm/a
C 1	τ corr ≤ 10	τ corr $\le 0{,}1$
C 2	$10 > \tau$ corr ≤ 200	$0{,}1 > \tau$ corr $\le 1{,}5$
C 3	$200 < \tau$ corr ≤ 400	$1{,}5 < \tau$ corr ≤ 6
C 4	$400 < \tau$ corr ≤ 650	$6 < \tau$ corr ≤ 20
C 5	$650 < \tau$ corr ≤ 1500	$20 < \tau$ corr ≤ 90

Time of wetness expressed in hours where RH > 80 %, t > 0° C (h/a)

Airbourne salinity

Chloride deposition rate [mg/m² • d)]

Site: Borregaard

Industrial pollution by sulphur dioxide (SO_2): Concentration μg/m²	Category	Deposition rate mg/(m² • d)	$\tau \le 10$ (class τ_1) Indoor, no climatic control				$10 < \tau \le 250$ (class τ_2) Indoor, no climatic control except in damp climates				$250 < \tau \le 2500$ (class τ_3) Outdoors in dry, cold climates, ventilated sheds in temperate climates				$2500 < \tau \le 5500$ (class τ_4) Outdoors in temperate climates, unventilated sheds in temperate climates, ventilated sheds in damp climates				$\tau \le 5500$ (class τ_5) Outdoors in damp climates; humid unventilated sheds			
			S_0 $S \le 3$	S_1 $3 < S \le 60$	S_2 $60 < S \le 300$	S_3 $300 < S \le 1500$	S_0 $S \le 3$	S_1 $3 < S \le 60$	S_2 $60 < S \le 300$	S_3 $300 < S \le 1500$	S_0 $S \le 3$	S_1 $3 < S \le 60$	S_2 $60 < S \le 300$	S_3 $300 < S \le 1500$	S_0 $S \le 3$	S_1 $3 < S \le 60$	S_2 $60 < S \le 300$	S_3 $300 < S \le 1500$	S_0 $S \le 3$	S_1 $3 < S \le 60$	S_2 $60 < S \le 300$	S_3 $300 < S \le 1500$
$P_c \le 12$ $12 > P_c \le 40$	P_0 P_1	$P_d \le 10$ $10 > P_d \le 35$	1		1	1 or 2	1		2	3 or 4	2 or 3		3 or 4	4	3		4	5	3 or 4		5	5
$40 > P_c \le 90$	P_2	$35 > P_d \le 80$	1		1	1 or 2	1 or 2		2 or 3	3 or 4	3 or 4		3 or 4	4 or 5	4		4	5	4 or 5		5	5
$90 > P_c \le 250$	P_3	$60 > P_d \le 200$	1 or 2		1 or 2	1 or 2	2		3	4	4		4 or 5	5	5		5	5	5		5	5

Note: Corrosivity is expressed as the numerical part of the corrosivity category code (for example: 1 instead of C1)

6.3 Other classification standards

The above mentioned standard approach for classification of the atmospheric corrosivity is primarily applicable to the corrosion of metal and alloys and cannot, without complementary amendments, be used for an appropriate description of the degradation environment for non-metals.

The ISO DIS 12944-2 Paints and varnishes. Part 2: Classification of environments deals with the classification of the principal environments to which steel structures are exposed, and the corrosivity of these environments. It defines atmospheric-corrosivity categories, based on ISO 9223 and ISO 9226.

6.4 Mapping according to service life (and ISO 9223) approach

6.4.1 Japan

Solar UV rays, *water* and *heat* are common chemical and mechanical deterioration factors for many building materials used in outdoor environments. Tomiita (1989, 1993) has, as described in Chapter 4, estimated the intensity or index of these factors from meteorological data. He has classified and mapped the following factors:

- Solar UV energy
- Wetness time, Figure 26
- Wet-dry cycle
- Thermal degradation based on BPT
- Daily temperature difference of BPT

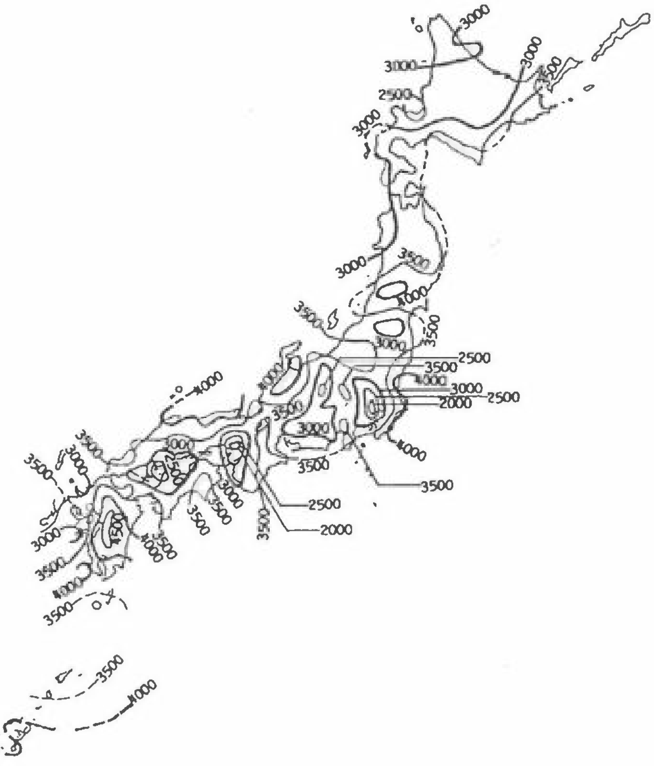


Figure 26: Wetness time (hours/year) according to ISO criterion (from Tomiita, 1992).

The local differences in the ways or rate of the deterioration of building materials can generally be explained by citing the maps presented, of which wetness time is shown in Figure 26.

There are synergistic effects arising from multiple degradation factors. Tomiita and Kashino (1989) have also estimated and mapped the temperature-modified wetness time/wet-dry cycle.

6.4.2 UK – Atmospheric corrosivity values

The Ministry of Agriculture, Fisheries and Food publishes a map every 5 years illustrating the average atmospheric corrosivity rate for 10 km grid squares of the UK (1986). This map is based on a zinc reference data base but corresponding corrosivity rates for other metals (steel, aluminium, copper and brass) can be approximately assessed using dose responsive function relationships. It should also be remembered that the local microclimate can have a greater effect on durability of building materials than the average corrosivity within a section of a 10 km grid.

6.4.3 Spain – Morcillo and Feliu

Probably the most extensive corrosivity classification and mapping for any country has been performed for Spain by Morcillo and Feliu and their co-workers (1993). They have used both ISO classification approaches extensively (Figure 25) and produced detailed classification maps for the whole country and for the various areas and cities. As an example the Time-of - wetness map according to the ISO 9223 criterion is shown in Figure 27.

They have also initiated an extension of the national program to a large program for South- America , called MICAT, starting in 1988, where the total program involves 14 countries, 70 institutions and 71 test sites.

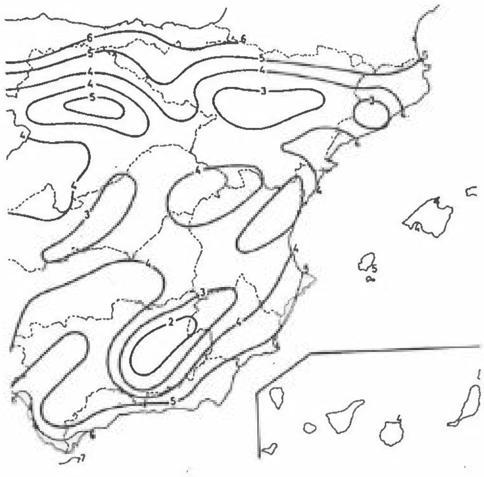


Figure 27: Wetness time (hour/year) for Spain according to ISO criterion (from Morcillo and Feliu, 1993).

6.4.4 The ISO-CORRAG program

The international corrosivity mapping program ISO-CORRAG was prepared in the framework of activity of ISO/TC 156 WG 4" Classification of corrosivity of atmospheres", who elaborated the ISO 9223-26 standards. The programme started in autumn 1986/summer 1987, and the aim is to verify the methodological and technical aspects of the procedures included in ISO 9223-26 (at that time DIS).

The program comprise the same type of materials and environmental variables as in the standard, and involves 46 test sites in 12 countries in Europe, Russia and North America.

Results with regression analyses for period 1987–1992 were recently reported by Knotkova et al. (1995), who also leads the program.

There is a clear connection and co-operation between the three international programmes of UN ECE ICP, MICAT and ISOCORRAG, in the context of both scientific content and scientists involved.

6.4.5 USA – Scheffer's index for wood

There are great differences in temperatures and precipitation regimes on macro scale .This result in equally great differences in potential wood decay rates. A great need exist for mapping these risk factors. Based on Scheffer's climatic index (see Chapter 4.5) the US Weather Bureau developed a climate index map for the US (Figure 28).

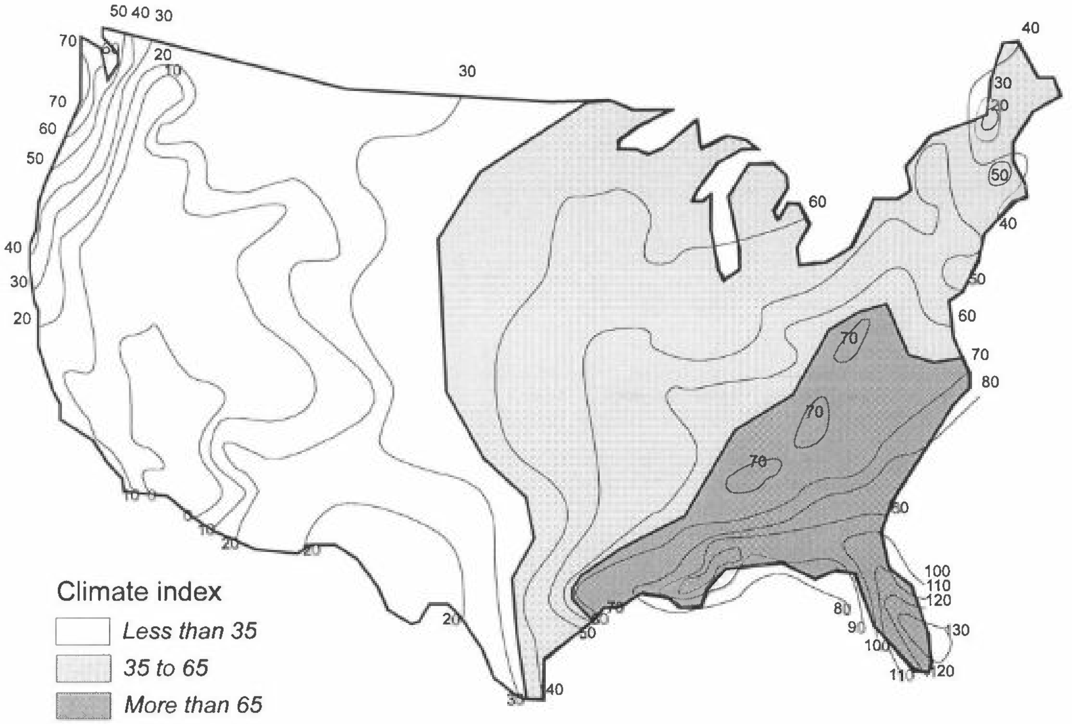


Figure 28: Mapping of Scheffer's climate index for wood decay in US produced from US Weather Bureau data (Scheffer, 1970).

6.5 Environmental research mapping approach (UN ECE)

6.5.1 Dose-response functions

To evaluate the effect of airborne acidifying pollutants on corrosion of materials, the Executive Body for Convention on Long-Range Transboundary Air Pollutants decided to launch the UN ECE ICP. The programme and 4-year D-R functions have been described in Chapter 3.4 (Table 1). For unsheltered exposure most of the D/R-functions have the same form

$$\text{ML or MI} = a + b\ \text{TOW}\ [SO_2][O_3] + c\ \text{Rain}\ [H^+] \qquad (2)$$

According to this D-R function the corrosion adds up contributions from natural corrosion (term "a"), dry pollution corrosion (term "b TOW $[SO_2][O_3]$") and from wet pollution corrosion (term "c Rain $[H^+]$").

From these dose-response functions mapping procedures based on the "critical/ acceptable load" concept have been developed.

6.5.2 Mapping procedure

The concept of critical loads or levels has been developed within the convention work in UN ECE and proved to be a useful tool in formulating abatement strategies for natural ecosystems. A critical load has been defined as "the highest deposition of a compound that will not cause chemical changes leading to long-term harmful effects on ecosystems structure and function" (Downing et al., 1993).

As atmospheric corrosion and deterioration of materials is a cumulative, irreversible process which proceeds even in the absence of pollutants this concept has to be modified as even the lowest concentration of pollutants cause an increase in the deterioration rate. This has resulted in the concept of *acceptable rate of deterioration* based on technical and economic considerations. Acceptable levels of atmospheric pollutants can then be defined if dose-response relations are available giving the relationship between the corrosion rate and the levels or loads of pollutants in combination with climatic parameters. The acceptable corrosion rate (K_a) should be related in a simple way to background corrosion (K_b) i.e. corrosion in areas with "background" pollution.

$$K_a = n \cdot K_b \qquad (50)$$

The background corrosion rate has been defined as the lower 10 percentile (K_{10}) of the observed corrosion rate for each material in the ongoing ICP Materials exposure programme.

Table 13: 4-year background corrosion rates for materials in the UN ECE ICP.

Material	4-year background corrosion rate (g/m^2)	Average background corrosion rate (μm/year)
Weathering steel	204	6.5
Zinc	17.1	0.6
Aluminium	0.67	0.06
Copper	14.5	0.4
Bronze	11.6	0.3
Limestone	44.0	3.9
Sandstone	40.0	3.9

The following concepts and maps are defined at

level 1 mapping:

Corrosion rate and acceptable corrosion rate. Corrosion rates are mapped from dose-response functions, and **acceptable corrosion rates** are defined as being a percentage increase in the background corrosion rate. At present it is recommended that values of n between 1.2 and 2.0 are used.

Acceptable exposure load/level is the concentration or load which does not lead to an unacceptable increase in the rate of corrosion. From this definition it is possible to calculate the acceptable pollution level from the acceptable corrosion rate and dose-response functions.

Areas of exceedances where the corrosion rate and the pollution level/ load are unacceptable.

Environmental degradation parameters. In addition to these maps it is also recommended to map the geographical distribution of some of the most important environmental degradation parameters and their combinations.

level 2 mapping is similar to level 1, but includes data on the **stock of material** in each mapping unit and the **economic costs** associated with corrosion of these materials (e.g. replacement or repair costs) (see Examples Oslo).

6.5.3 The Environmental Assessment Level (EALs) approach in UK

Butlin et al. (1994) has on contract for the Department of Environment (DoE) carried out a study fitting in with DoE's aim to establish a methodology by which it can assess the effects of a wide range of emissions on a range of receptors. In the BRE study the receptors were buildings.

The objectives of the programme were:

1. To provide a listing of current dose-response functions for a suite of substances and their relevant interactions with buildings and building components (see also Chapter 3.5);
2. To assess practical options for setting Action Levels (ALs) and Environmental Assessment Level (EALs) based on current definitions of ALs and EALs;
3. To discuss options for further developing EALs;
4. To recommend procedures for further developments necessary in the assessment of the effect of pollutants on buildings.

The critical loads approach needs a practical way to assess the level at which pollutants are considered harmful. In the DoE approach the assessment levels and concepts are defined as shown in Figure 29.

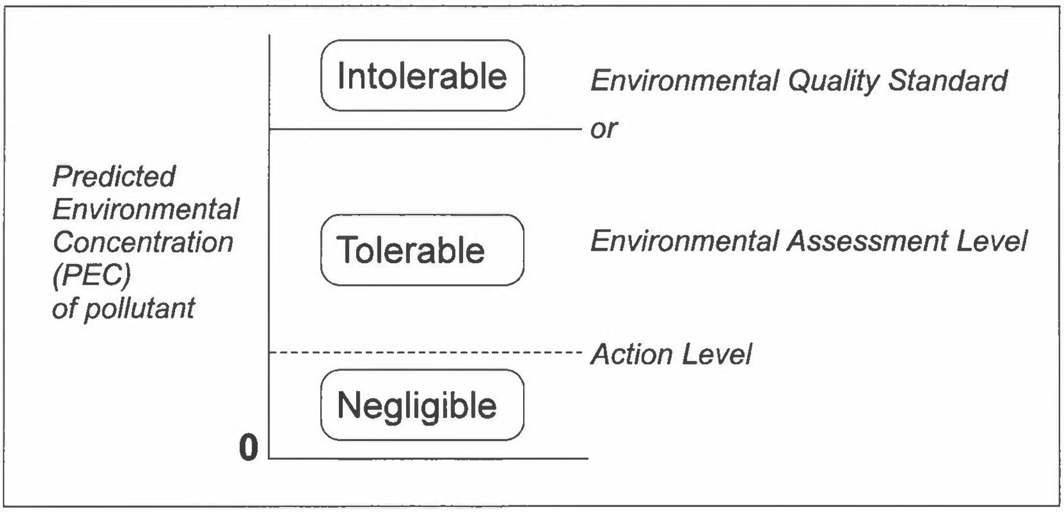


Figure 29: The tolerability of releases (from Butlin et al., 1994).

The dose-response functions surveyed have been combined with the current thinking of this concept to provide provisional values for both ALs and EALs. The final part of the report discusses future options for the further development of the Regulatory Framework, in particular the incorporation of spatial variation and the stock-at-risk into the setting of EALs.

The development of a rational basis for determining the interim EALs should lead eventually to the establishment of "damage functions" which determine the PEC at which harm becomes intolerable.

Quoting from the report: "Five practical indicators have been identified as a basis for determining the EAL and which seek to introduce rational, rather than arbitrary, judgement into the determination:

- **A Threshold Indicator**. The EAL might intuitively be found where damage is measured at the turning point in a dose-response curve that is increasing at an exponential rate.
- **A Catastrophic Indicator**. The EAL might be found where damage clearly becomes catastrophic to property owners; e.g. characterised by building collapse.
- **A Social Indicator**. The EAL should be determined, not on the basis of harm to modern buildings, but on the harm caused by pollution to historic buildings and monuments. Since historic buildings are, by definition, those structures which society judges to be most deserving of protection and preservation, harm to the structure could be deemed intolerable.
- **A Liability Indicator**. The EAL might be based on a risk assessment of damage that reflected standards in liability law and in building regulations. Liability could be assessed by examining the detrimental effects of the pollution on the material itself, and/or by considering the secondary impacts on human health.
- **A Present Worst Case Indicator**. When other indicators can not be applied, the EAL could be determined by the present worst pollutant concentrations, on the basis that regulations do not envisage allowing environmental damage to increase above existing levels."

6.5.4 Implication and use for building society

Maps of the corrosion rates/dose-response functions can easily be transformed into maps for service life and maintenance intervals if the performance requirement is defined for the material in question. In that context the UK DoE project is a very interesting and forward looking approach by the building and environmental society in UK. It should have a huge impact in the process to come.

Such maps could then serve as a tool for maintenance planning for individual users etc. In that respect the question of transformation and validation of these dose-response functions to the micro-environment on the building surface has to be addressed. Such mapping would be of extreme value for standardisation work going on within CEN and ISO/TC59 WG9 "Design life of buildings" on durability of building materials and components.

6.6 Examples of mapping according to environmental research approach

6.6.1 Degradation factors for Europe

Reference is just given to Chapters 5.2 and 5.3 and Figures 17, 18, 20-22.

6.6.2 GIS-based level 1 and 2 mapping for urban Oslo

By using the UN ECE dose-response functions and mapping procedures together with the available air quality data and dispersion models the corrosion is modelled and mapped for Oslo for 1985 and 1993. The corrosion modelling is presented as a new AirQUIS CorrCost module (see Chapter 5.8). Integrated in the AirQUIS CorrCost module is also information from the recently completed digitalized building register GAB, containing all buildings in Norway (Haagenrud and Henriksen, 1996).

For the corrosion and cost assessment mapping of Oslo the following data and models have been used:

For **1985,** modelling has been performed for grid size 1x1 km^2. Calculation of SO_2 and NO_2 concentrations in the grid are based on information of emission sources (industry and heating, traffic in main and local roads) and modelling of the concentration by use of the NILU model system "KILDER" (Gram and Bøhler, 1993). For the corrosion mapping the existing grid winter concentrations were reduced to yearly average values by multiplying the grid values with 0.5 for SO_2 and 0.3 for NO_2, respectively.

The O_3 grid values were formed by using the UN/ECE-ICP established relation between O_3 and NO_2:

$$[O_3]=60.5 \text{ exp. } -0.014[NO_2] \tag{46}$$

For TOW, Rain and the [H$^+$] concentration the yearly values measured at the Oslo UN/ECE-ICP exposure site were used.

The **1993** corrosion mapping was conducted using the 1985 values for TOW, Rain and [H$^+$] and a new inventory for the SO_2 and NO_x emissions. A new model-system "EPISODES" with a grid square of 500 mx500 m was used for calculation of the SO_2 and NO_x concentrations. The values were transformed to yearly average values in the same way as for the 1985 data.

GAB Building register. For cost assessments (level 2) information on the stock of materials and buildings at risk must be included. The Norwegian building register, GAB, with parcels, properties, buildings and addresses, were established in 1978 and completed in 1995 with digitalized information on almost all 4 mill buildings in Norway. Information from GAB is integrated into the AIRQUIS CorrCost module for Oslo.

6.6.2.1 Level 1 mapping

The **environmental degradation factors** NO_2, SO_2, O_3 and the combined factor SO_2 x O_3, have been modelled and mapped for 1985 and 1993, showing the considerable decrease in the SO_2 exposure levels from 1985 to 1993 due to regulations.

corrosion maps have been produced for weathering steel, zinc, aluminium, copper and bronze. As an example Figure 30 shows the map for zinc corrosion year 1985, where the highest 4-year corrosion of zinc in the centre is shown to be >32 g/m^2 (= 4.5 μm).

According to the dose-response relationship the corrosion adds up from contributions from natural-, wet pollution- and dry pollution corrosion. These contributions can be calculated and exhibited for each grid in the GIS-system. As shown the corrosion 23 g/m^2 adds up from 14.5- background (63%), 1.4- wet pollution (6%) and 7.1 g/m^2 dry pollution corrosion (21%), while for corrosion

32 g/m2 the figures are: background 14.5- (45%), wet 1,4- (5%) and dry pollution 16.1 g/m2 (50%).

Figure 31 shows the zinc corrosion mapping for year 1993, showing also results from the UN/ECE ICP test site.

For zinc and the other materials maps are produced showing areas with exceedance of acceptable corrosion rates. Figure 32 shows exceedance areas for acceptable zinc corrosion = 1.3 resp. 1.5* K_{10}, i.e 30% resp. 50% above background corrosion, base year 1985.

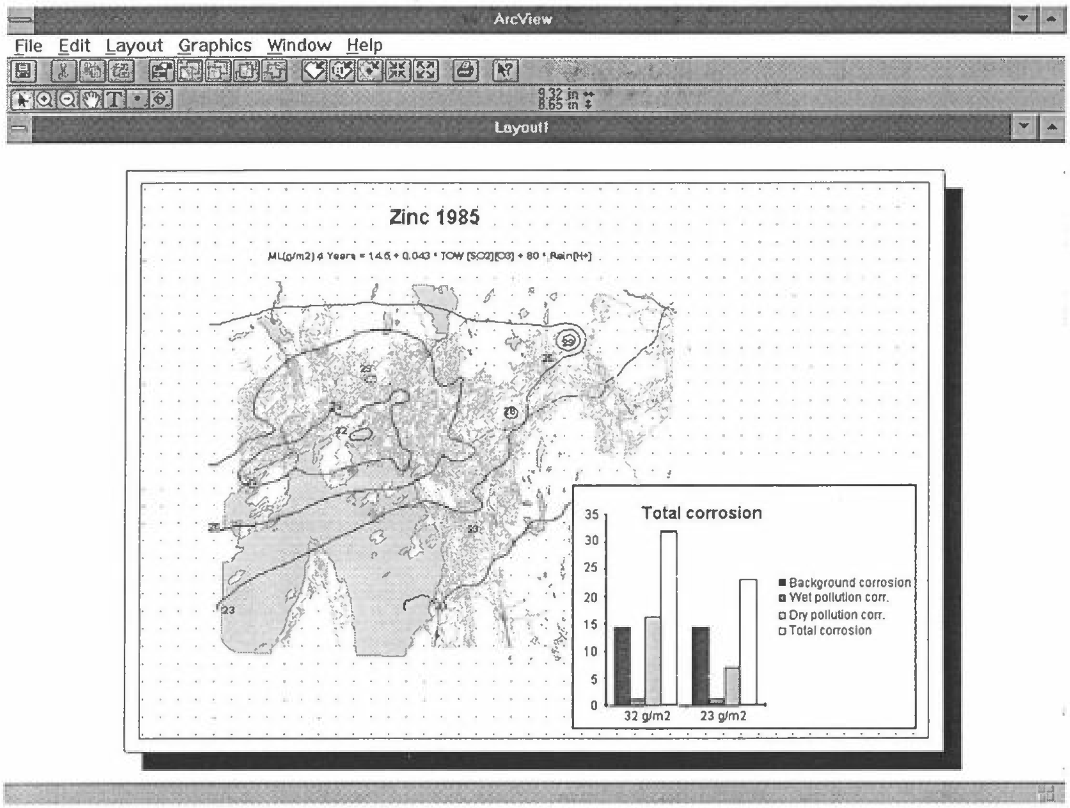
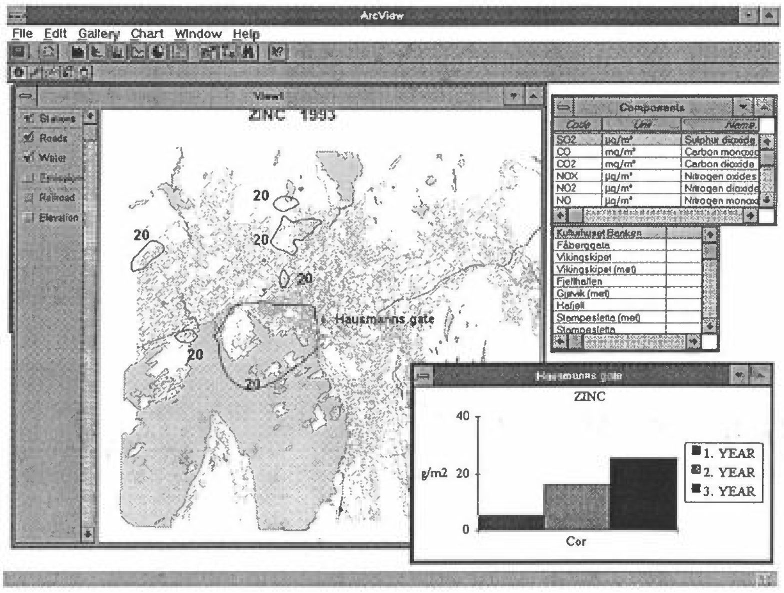


Figure 30: Mapping of zinc corrosion in the Oslo area from UN ECE ICP dose-response function and available data and models for Oslo. Mapping year 1985 and grid size 1kmx1km, where window shows contribution from various terms in the dose-response function at corrosion rates 23 g/m2 and 32 g/m2 respectively.



Code	Unit	Name
SO2	µg/m³	Sulphur dioxide
CO	mg/m³	Carbon monox
CO2	mg/m³	Carbon dioxide
NOX	µg/m³	Nitrogen oxides
NO2	µg/m³	Nitrogen dioxide
NO	µg/m³	Nitrogen monox

Kulturhuset Banken
Fåberggata
Vikingskipet
Vikingskipet (met)
Fjellhallen
Gjøvik (met)
Hafjell
Stampesletta (met)
Stampesletta

Figure 31: Mapping of zinc corrosion in the Oslo area from UN ECE ICP dose-response function and available data and models for Oslo exhibited in the ArcView AIRQUIS CorrCost. Mapping year 1993 and grid size 0.5kmx0.5 km. Windows show components, measuring sites and zinc corrosion results from the UN ECE ICP test site in Oslo.

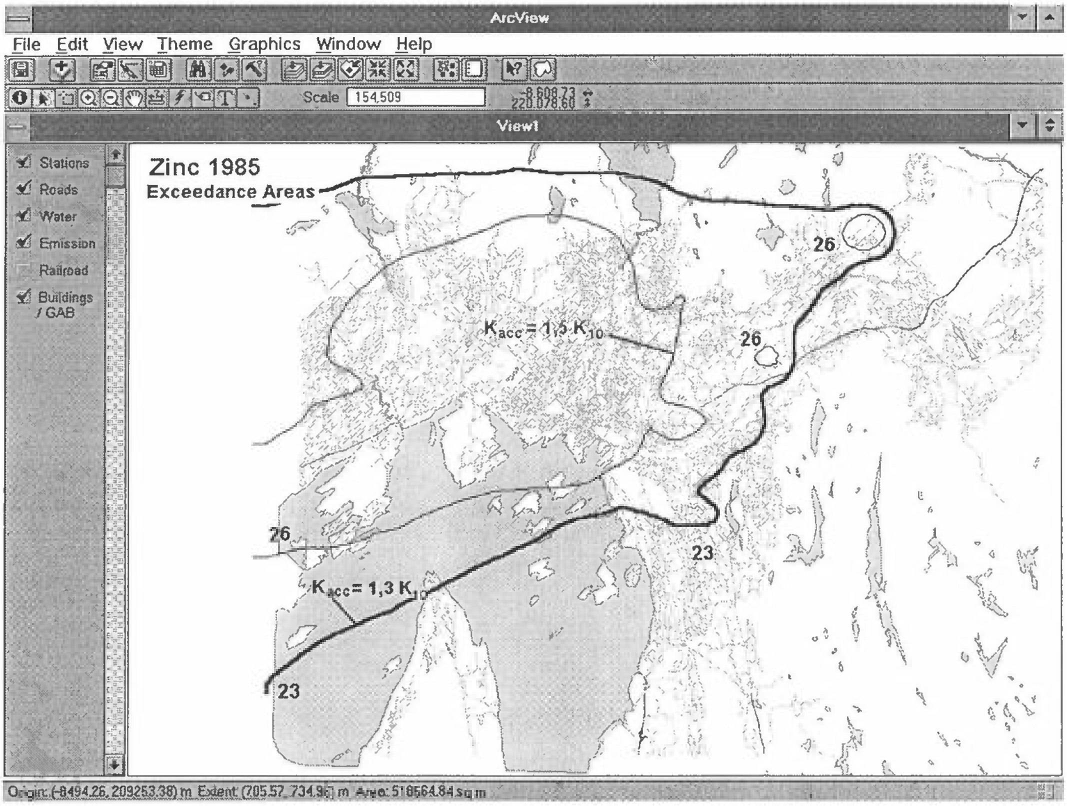


Figure 32: Mapping of exceedance areas for acceptable zinc corrosion = 1.3 resp. 1.5 K_{10},i.e 30% resp. 50% above background corrosion in the Oslo area from ECE ICP dose-response function and available data and models for Oslo. Mapping year 1985 exhibited in the ArcView AIRQUIS CorrCost.*

6.6.2.2 *Level 2 mapping – assessment of corrosion costs*

By use of the tools available in the ArcView AirQUIS CorrCost system a cost assessment study for Norway was done (Glomsrød et al., 1996). It allows counting of different types of buildings and building materials with different economic value to be done for each grid. Maps have been produced showing exposure environment and the stock of materials and buildings at risk by integrating an information layer on the building register GAB. Figure 33 shows the location and number of different types of buildings in grid no. 20-22 (500x500m), together with the environmental characteristics of that grid (Haagenrud and Henriksen, 1996). By use of the materials distribution factors and the environmental dependent service life and maintenance intervals from the MOBAK study the costs can be assessed for each material and building type within each grid. Such calculations have been performed for 1586 grids of the greater Oslo area (Glomsrød et al., 1996).

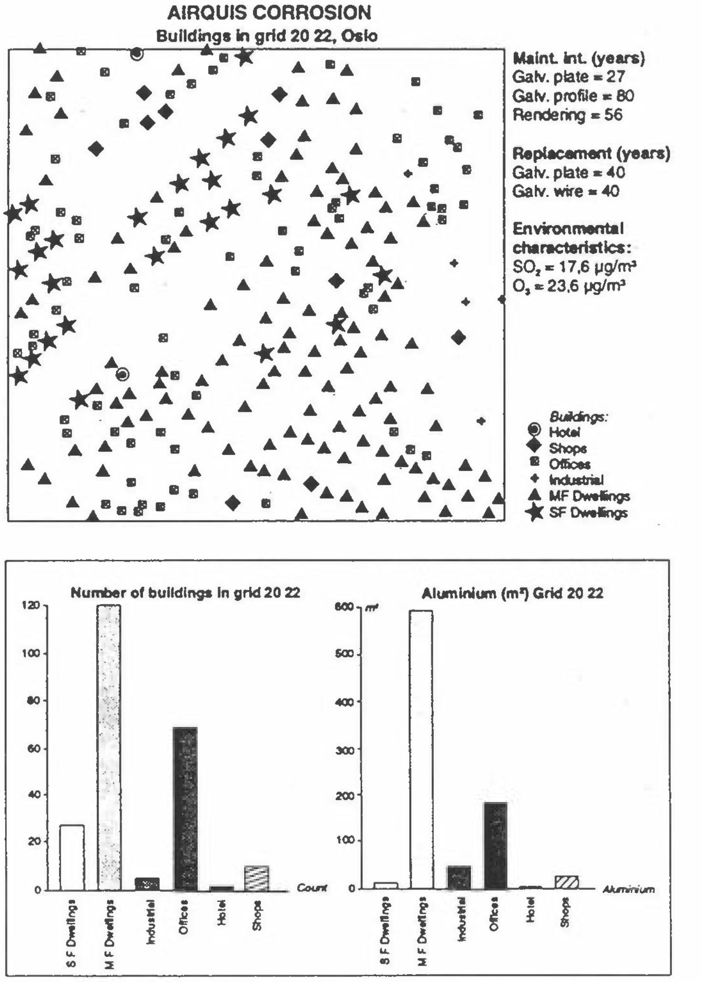


Figure 33: Characteristics of buildings and exposure environment in one of 1584 grids (500x500 m) in Oslo, exhibited in AirQUIS CorrCost (from Haagenrud and Henriksen, 1996).

6.6.3 UK – Mapping of Critical loads/levels to materials damage

From Butlin et al. (1995 the following is quoted: "The United Kingdom National Materials Exposure programme was initiated in 1986 to study the effects of acid deposition on building materials. The output data in the form of empirical dose-response equations (described elsewhere) have been incorporated into a geographical information system (GIS). In addition, data for the stock at risk of building materials has also been used. The dose-response relations indicate a dominance of dry deposition of sulphur dioxide in the decay process. Critical level/load maps have been determined for a number of materials. General pollution and meteorological data sets are also included in the mapping process. Maps give "exceedence squares" on a 20 km square grid basis, indicating the unprotected areas or those still at risk for a given scenario for SO_2 reduction in the context of the UN ECE protocol for sulphur. In order to derive maps of areas sensitive to pollutants in the future a model, HARM 7.2, is used for the prediction of distribution of emissions of pollutants in the UK. A series of maps has now been produced for different materials at 70% and 80% scenarios for the reduction of SO_2. Studies of the sensitivity of the exceedence maps to the accuracy or variation of the components in the dose-response equations have been undertaken. Results from the mapping programme and the sensitivity analysis are presented together with discussion of the concept of critical loads of materials."

7. Micro-environmental characterisation

7.1 Monitoring systems

7.1.1 Temperature and wetness – the WETCORR instrument

The WETCORR instrument is designed for recording of the wetness and temperature condition in the micro environment of constructions, see Figure 34.

The measuring principle makes use of the electrochemical nature of the corrosion processes by measuring the current flow in an electrochemical cell as a function of the thickness of the humidity film bridging the electrodes surface. The principle was proposed by Professor Thomashov as early as in 1950ies and has later been adapted and modified by other research groups (Haagenrud and Henriksen, 1994). By selecting various current levels the time above certain humidity levels can be monitored.

The sensor developed so far consists of a small gold cell for measuring time of wetness, TOW^{100}, defined as the time with 100% RH and/or rain, condensation etc., and a temperature sensor for recording the surface temperature.

To ensure that the temperature sensor follows the surface temperature, the cell backing is made of aluminium oxide with good thermal conductivity.

The gold wetness sensor is made of two gold electrodes arranged in a finger pattern. A fixed voltage usually selected in the range between 100 mV and 200 mV is applied and the current flow is measured. To prevent polarisation of the electrodes the direction of the voltage is changed every 30 sec.

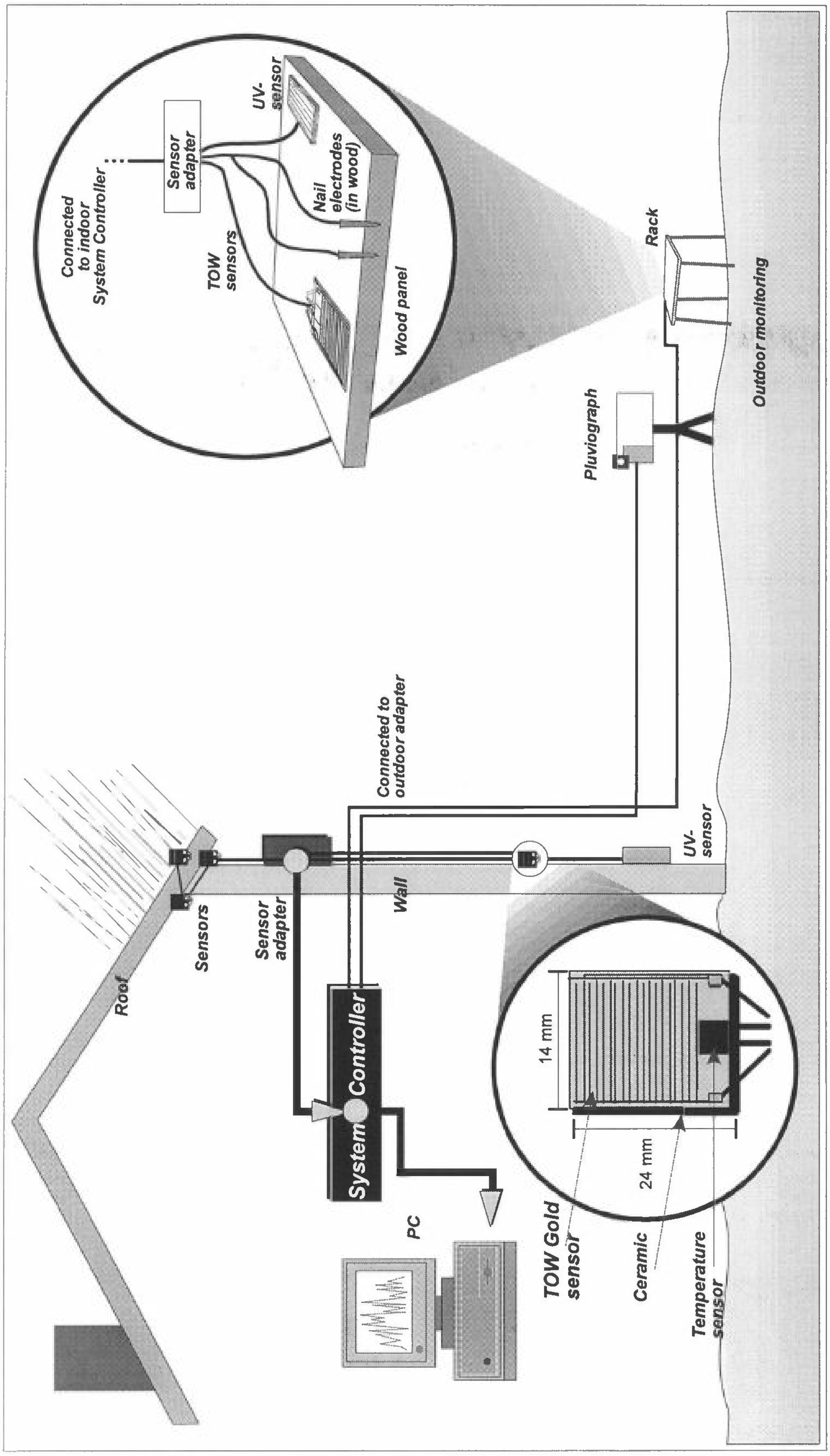


Figure 34: WETCORR measurements on and within building materials.

Work is going on to develop other types of sensors, such as for example sensors for measuring resulting moisture uptake within wood (EU-project ENV-CT95-0110 (DG 12-ESCY)). Figure 34 show the set-up of such measurements, illustrating also the measurement principle.

The instrument consists of the following modules

1 System Controller (SC), which is:
- Control unit for communication with the Sensor Adapters (SA)
- Unit for the external communication with the Sensor Adapters
- Power source for the sensor
- Sampling unit for all data

1-16 Sensor Adapters, each being the control and recording unit for four sensors. The data are recorded as average values over one minute. The SA will convert all data recorded to digital signals before transferring the data to the SC. This is done to reduce the influence of stray currents and radio signals on measured data. The cables between the sensor and the SA are kept short, less than 2 metres, while the cables for the digital signals between SA and SC can still be long, up to 250 meters in two directions. The SA can be placed outdoors in all weather conditions.

1-64 Sensors, the set-up of parameters cell voltage and sampling period must be the same for all 4 sensors connected to one adapter, while each adapter in a system can be configured individually for temperature and humidity.

The amount of data has always been a problem in this type of measurements, and great emphasis is put on solving this problem through user-friendly database design and management, and data presentation tools. The instrument is therefore delivered with one Windows based software package for communication, parameter setting and recording and presentation of data. Presentations within geographical information systems (GIS) is also available.

The following data presentation forms are available:

- Currents and temperatures versus time
- Total current output from the sensors in the period
- Per cent of time with current above the selected TOW crit
- Per cent time with the temperature above or below selected temperatures
- Frequencies for TOW crit and temperature above selected values
- Minimum, maximum and mean values for current and temperature
- Minimum, maximum and mean values for TOW crit.

7.1.2 UV

7.1.2.1 General

There are, in general, three main classes of detectors for measuring UV-radiation: physical, chemical and biological. With *biological methods* one measures e.g. the amount of erythema or pigmentation of the skin in response to UV radiation. *Chemical methods* include the IG Farben dosimeter and Landsberg's glass dosimeter. The *physical methods* are the most common and include the Eppley ultraviolet pyranometer and the CSIRO ultraviolet pyranometer (Lala, 1985).

However, these methods demand an extensive and fairly expensive instrumentation, which is partly why few measurements have been made of the UVR environment on and around buildings. To meet the need for cheap and still reliable UVR measurement techniques, photochemical dosimeters have been developed (Lala, 1989).

Recently NILU has developed a multi-channel UV-system basically for studies of biological effective UV-doses and total ozone abundance (Dahlback, 1995). This UV sensor can be adopted to the WETCORR instrument and used on buildings.

7.1.2.2 Photochemical dosimeters

Results are reported from measurements in Nordic environments using photochemical dosimeters made from thin films of polyphenylene oxide (PPO) (Lala, 1989) The results show, in generalised terms, a certain order of UVR for different facades and shadowed eaves: South > East > West > North > Eaves/ south > Eaves/east. It was found, however, that the difference in values for south and north facades was relatively small, emphasising the fact that the diffuse component of UVR is high. The measurements showed the diffuse component to be between 68% and 88% of the total radiation in the UV band.

7.1.2.3 NILU's UV-radiometer

The solar ultraviolet radiation reaching the ground is controlled by several factors, such as solar elevation, cloud cover, total ozone amount and ground reflection. A decrease in total ozone abundance is expected to lead to an increase in harmful UV radiation if all other factors are kept unchanged.

Cloudiness is among the largest sources of variance in the daily integrated UV irradiance at the surface. Therefore, in order to detect trends in solar UV-B radiation due to trends in total ozone amount a UV monitoring network should measure both UV-radiation, total ozone amount and cloud transmission.

NILU has developed a multi-channel radiometer for measurement of solar ultraviolet radiation. The instrument measures the irradiance (direct plus diffuse radiation) in the UV-B region (280 nm–315 nm) and in the UV-A region (315 nm–400 nm) in 5 channels. The instrument contains a built-in data logger which can store up to 3 weeks of 1 minute average readings from all channels, as well as the temperature, which is measured close to the detectors. The instrument can also be set to store a 1 minute average data every 15 minutes only. In this mode the storage capacity of the data logger is one year.

Changes in the UV radiation due to variations in total ozone abundance and cloud cover can be recorded with the instrument. The UV-B channels are sensitive to variations in total ozone and variations in cloudiness. UV-A channels, however, are sensitive to variations in cloudiness but not sensitive to ozone variations.

Measurements from March 29 and March 30, 1995 at NILU illustrate the sensitivity to ozone variations, Figure 35. The integrated ozone amount was 417 Dobson Units (DU) on March 29 and 329 DU on March 30, i.e. a 20% decrease. The measured increase in UV radiation from March 29 to March 30 was 100%, 50% and 27% in the 305 nm, 308 nm, and 313 nm channels, respectively. No changes were observed in the UV-A channels since the sky was clear on both days and since UV-A wavelengths are known to be insensitive to ozone.

By using a radiative transfer model combined with such irradiance measurements, biologically effective UV-doses, total ozone amount and cloud transmission can be determined.

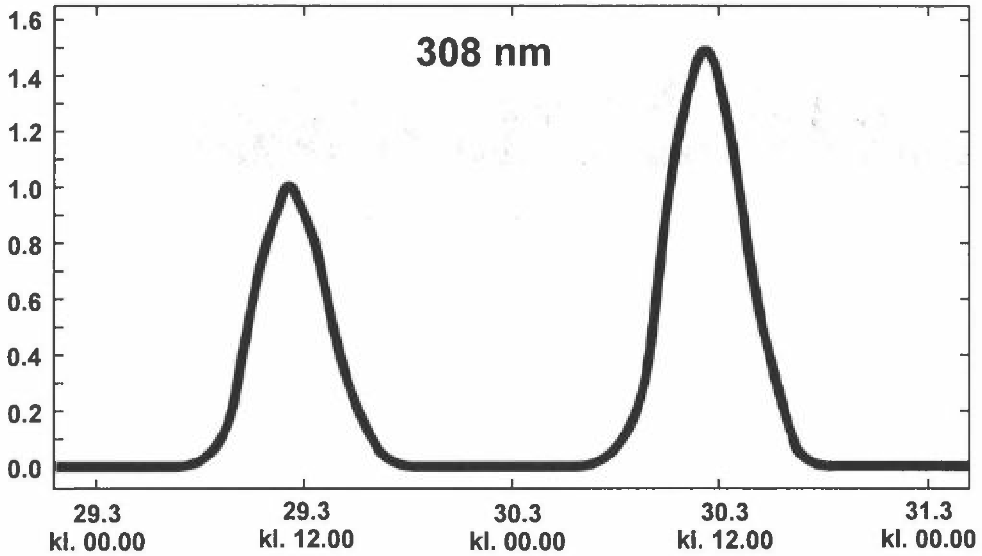


Figure 35: Measurements at NILU show the sensitivity to ozone variations. The 308 nm level (UV-B) increased by 50% from March 29 to March 30 due to a 20% decrease in the total ozone abundance. The sky was clear on both days and no change was observed in the UV-A channels.

7.2 The passive SO_2- and NO_2-samplers

7.2.1 Description

A simple sampler for surveillance of time integrated SO_2 and NO_2 concentration distributions has been developed. The sampler is inexpensive in use, simple to handle and have a good overall precision and accuracy. This method has been used in industrial areas, in urban areas and for studies of indoor/ outdoor exposures.

The sampler was developed by the Swedish Environmental Research Institute (IVL) and has been used in several cases by NILU. The sampler includes an impregnated filter inside a small plastic tube, Figure 36. To avoid turbulent diffusion inside the sampler, the inlet is covered by a thin porous membrane filter. Gases are transported and collected by molecular diffusion. The uptake rate is only dependent upon the diffusion rate of the gas. The collection rate is 31 *l*/24h for SO_2 and 36 *l*/24h for NO_2. Also NH_3 can be collected at a rate of 59 *l*/24h.

For SO_2 the measuring ranges are approximately 0.1–80 ppb (0.3–213 µg/m^3 for a sampling period of one month. The corresponding range for NO_2 is 0.02–40 ppb (0.04–80 µg/m^3). The passive samplers are assembled and made ready for use at

NILU. After exposure the samplers are usually returned to NILU for where concentrations of SO_2 are determined as sulphate by ion chromatography. NO_2 and NH_3 is determined by spectrophotometry.

Some examples of applications are shown in Figures 37–39.

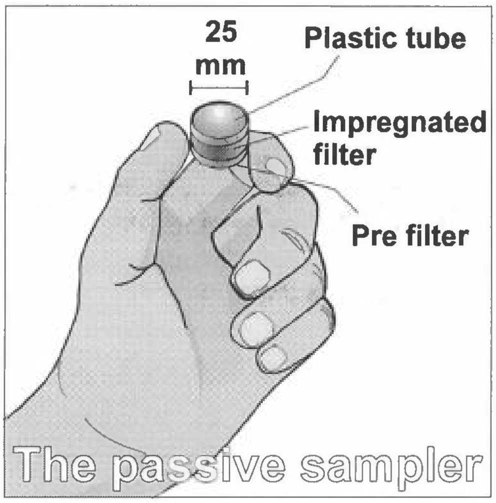


Figure 36: The passive sampler.

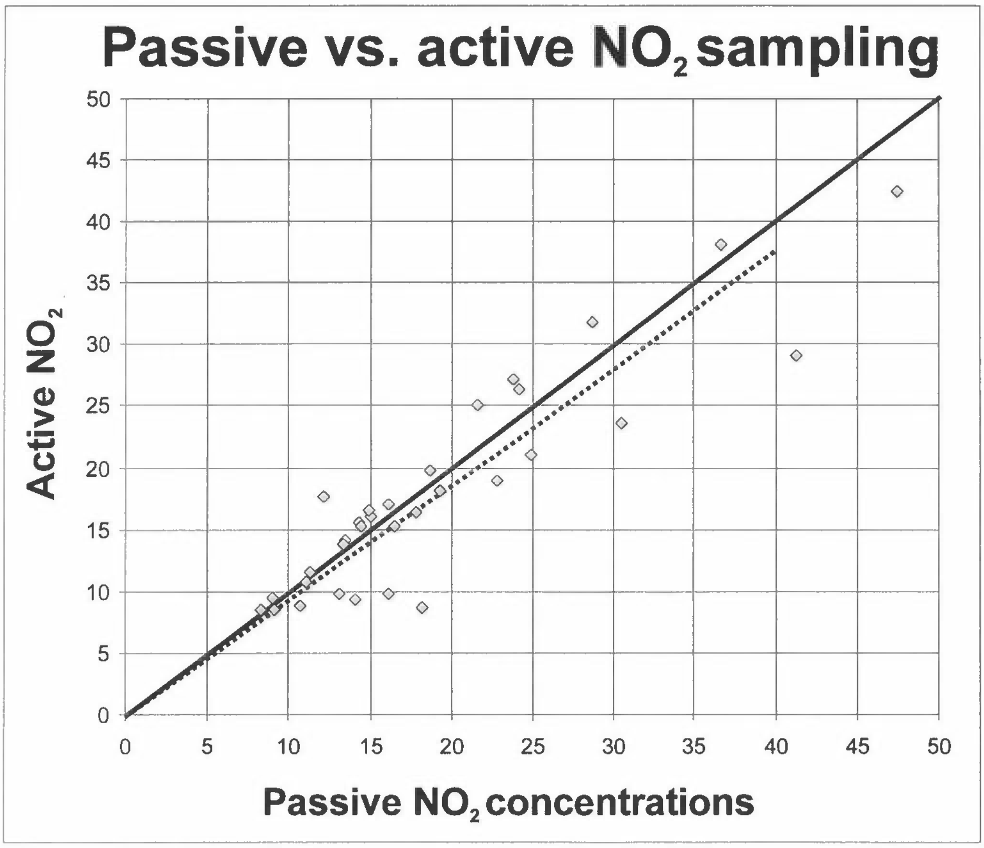


Figure 37: The integrated passive sampling of SO_2 and NO_2 is well correlated to the available active sampling methods.

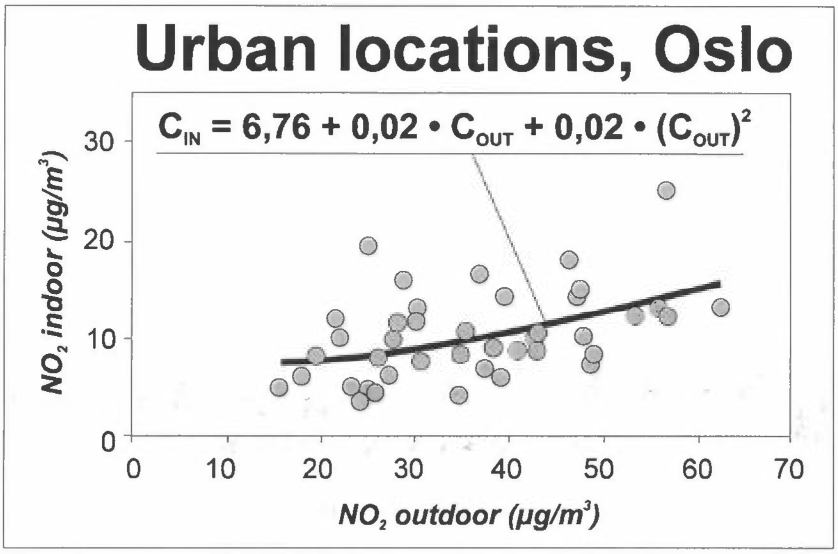


Figure 38: *Several investigations have been performed to study the indoor to outdoor NO_2 pollution levels. In urban locations in Oslo indoor NO_2 concentrations were considerably lower and varied less than outdoor concentrations. At 40 µg/m³ ambient NO_2 the indoor NO_2 concentration was on the average about 10 µg/m³.*

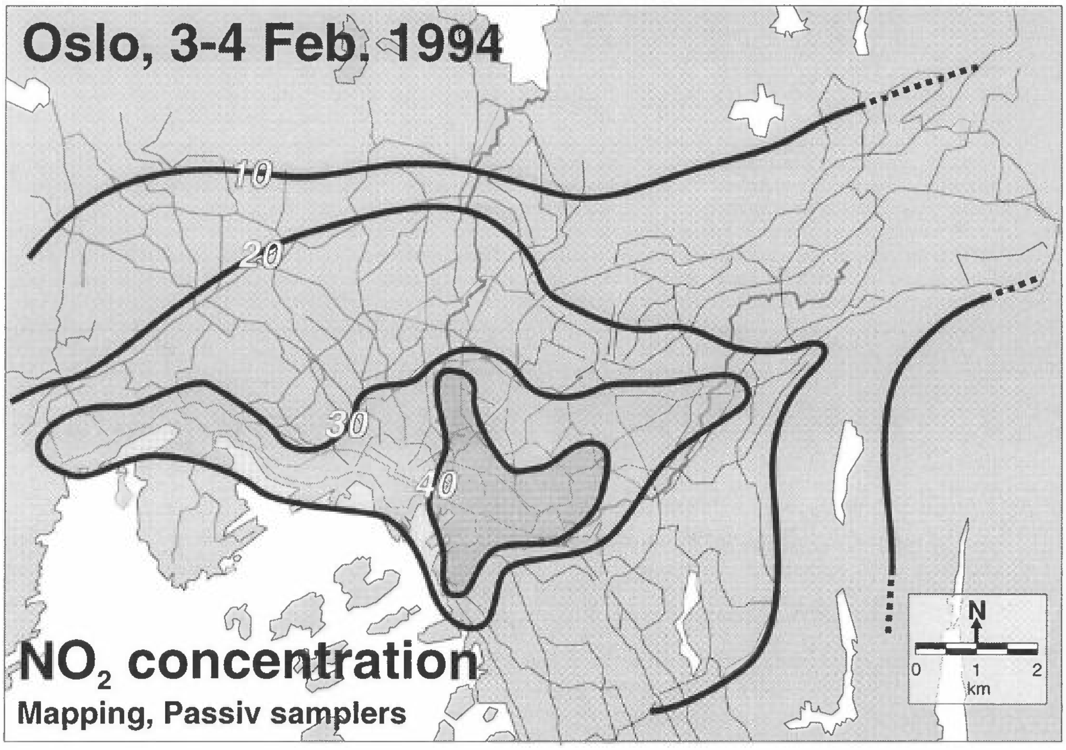


Figure 39: *The 24 h average NO_2 concentration distribution measured in Oslo on 3–4 February 1994 with 20 passive samplers show that the highest concentrations occurred along the main road systems and in central parts of down-town Oslo. This 24 h average distribution may change considerably from one day to the next depending on meteorological conditions in the Oslo airshed.*

7.3 Modelling

7.3.1 Road network emission and dispersion model

The effect of road traffic pollution on urban populations is expected to increase during the next few years. Some measures to reduce this effect are:

- Reducing the total amount of traffic, via economic instruments, town planning, legislation or physical restriction.
- Moving traffic away from residential areas, e.g. by constructing ring roads.
- Improving traffic flow/avoiding congestion, by increasing the capacity of the road network.
- Improving vehicle technology, by applying stricter emission regulations and increasing the renewal rate of the vehicle fleet.

Traffic planners are often in need of practical tools for studying the effect of such measures on the environment. Quite a few air dispersion models exist and can be used for this purpose.

NILU has developed a personal computer-based model *RoadAir*, for quantitative descriptions of air pollution along road networks. RoadAir calculates total emissions, concentrations along each road segment and the air pollution exposure of the population and *buildings* along each road, see Figure 40. Calculations can be carried out for road networks, defined by road and traffic data. The model was primarily developed for conditions in Scandinavia, but can easily be adapted to conditions in other parts of the world. RoadAir is incorporated into the AirQUIS system (see Chapter 5.8).

The pollution concentrations near a road with a given volume of traffic is closely related to the local dispersion conditions. The model calculates maximum concentrations that occur in periods with poor dispersion conditions (e.g. during winter).

The contribution from other pollution sources is accounted for by adding a city background concentration to each road link. Different background concentrations can be added to different parts of the calculation area.

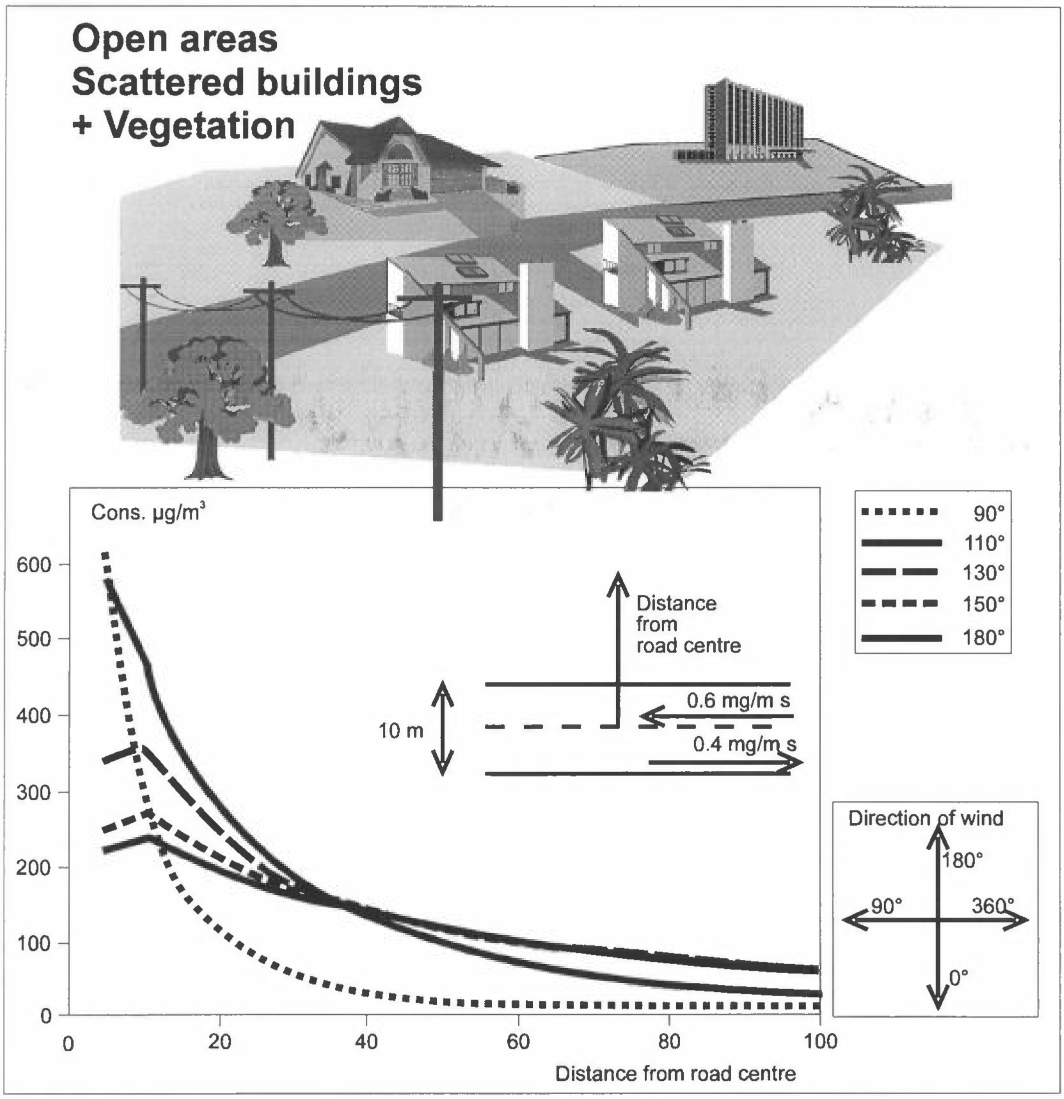


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Figure 40: Dispersion modelling of CO concentration profile across and along roads.

7.3.1.1 Input data

The geometry of each road link must be described by its length, width, steepness and whether it is characterised as a street canyon or an open area.

The traffic data are given on a daily basis for calculation of total emissions, and on an hourly basis for concentration calculation during rush hours. If no rush hour traffic data are available, the model assigns standard values depending on the road type.

The vehicle fleet must be described by fractions of light and heavy duty vehicles on each road. The model assigns standard distributions of technology types within classes of vehicles. The emission calculations take into account vehicular age distribution, effects of cold starts, road steepness and time of observation.

The distribution of population and buildings are described by the position of private homes relative to the road links. An average number of residents per home must be given.

Modelling of the traffic patterns which often represent the input to RoadAir, has to be performed prior to the application of RoadAir.

7.3.1.2 Output data

- Total emissions of NO_x, CO_2 and CO for the road network. Emissions are also specified for each road link.
- Concentrations of NO_2 and CO at a chosen distance from the curb for each road link.
- Tables with number of road links and length of road with concentrations above chosen levels.
- Tables with number of people and *buildings* exposed to various concentration levels of NO_2 and CO for each road link, and in total along the road network.
- Calculations of suspended particle (PM_{10})-concentrations have been included in RoadAir for areas where studded tyres are in use.

8. Needs for R&D and Standards

Concerning the characterisation of environmental degradation factors the following R&D and corresponding standardisation needs are listed:

1. There is a *lack of systematic knowledge* on the right type and form of degradation factors to be characterised. In order to produce this knowledge, extensive service life research based on damage functions approach has to be carried out. They should involve models for degradation mechanisms and should be tested out in well monitored relatively short exposures in field and in laboratory.
2. Damage function based research and proper characterisation of degradation factors both in field and laboratory is one absolute criterion for relevant coupling of *field and laboratory tests*.
3. Some *methods* for automatic and continuous monitoring of important degradation factors in the micro environment on buildings exist, but testing and further development of methods are strongly needed.
4. Quite a *few dose response functions* exist today after extensive research in the environmental research area. However, these functions have to be tested and validated in the *micro environment* on buildings. Measuring and modelling methods for micro environmental loading and materials degradation have to be developed and extensive measurements carried out.
5. The dose response functions produced so far often stems from the environmental research area. They are therefore limited in terms of choice of degradation indicators. In addition, they do not contain identified *limit states,* and are therefore not damage- or service life functions.
6. Interdisciplinary co-operation between the building and environmental research community is a must.

9. References

Architectural Institute of Japan (1993) Principal guide for service life planning of buildings. Tokyo.

Arroyave, C. and Morcillo, M. (1995) The effect of nitrogen oxides in the atmospheric corrosion of metals. *Corrosion Sci., 37,* 293-305.

Berre, B. and Lala, D. (1989) Investigation on photochemical dosimeters for ultraviolet radiation. *Solar Energy*, *42*, 405-416.

Brocco, E. et al. (1988) Air pollution in Rome and its role in the deterioration of porous building materials. In: *Air Pollution and Conservation.* Ed. by J. Rosvall & S. Aleby. Amsterdam, Elsevier. pp. 209-244.

Building Research Establishment (1973) Moisture Expansion of Structural Ceramics: Long Term Unrestrained Expansion of Test Bricks. Watford (BRE Current Paper CP 16/73).

Building Research Establishment (1974) Moisture Expansion of Structural Ceramics: Expansion of Unrestrained Fletton Brickwork. Watford (BRE Current Paper CP 92/74).

Building Research Establishment (1988) Loads of roofs from snow drifting against vertical obstruction and in valleys. Watford (BRE Digest 332).

Building Research Establishment (1989) Assessment of wind loads. Watford (BRE Digest 346).

Building Research Establishment (s.n.) The influence of Trees on House Foundations in Clay soils. (BRE Digest 251).

Building Research Establishment (s.n.) Corrosion of metals by wood. Watford (BRE Digest 301).

Butlin, R.N. et al. (1992) Preliminary results from the analysis of stone tablets from the National Materials Exposure Programme (NMEP). *Atmos. Environ., 26B,* 189-198.

Butlin, R.N. et al. (1992) Preliminary results from the analysis of metal samples from the National Materials Exposure Programme (NMEP). *Atmos. Environ., 26B,* 199-206.

Butlin, R.N. et al. (1994) Effects of pollutants on buildings. BRE final report. May 1994 (DOE report no. DOE/HMIP/RR/94/030).

Butlin, R.N., Yates, T.J.S. and Chakrabarti, B. (1995) Mapping of critical loads and levels for pollution damage to building materials in the United Kingdom. *Water, Air Soil Poll., 85,* 2693-2699.

Butlin, R.N., Yates, T.J.S., Murray, M. and Ashall, G. (1995) The United Kingdom national materials exposure programme. *Water, Air Soil Poll., 85,* 2655-2660.

Caluwaerts, P., Sjöström, C., Haagenrud, S.E. (1996) Service Life Standards - Background and Relation to the European Construction Products Directive. In: *7th International Conference on the durability of building materials and components. Stockholm 1996.* Proceedings. Ed. by C. Sjöström. London, E & FN Spon. pp. 1353-1363.

Cole, I.S. (1994) The implications of the building envelop microclimate to the durability and serviceability of wood and wood products. *24th Forest Products Research Conference, Melbourne, Australia, Nov. 1994.*

Cole, I.S. (1994) An Analysis of the Microclimate of Australian Wall Cavities. *Constr. Building Materials, 8, No. 4,* 1-9.

Cole, I.S. and Holgate, R. (1995) The rate of drying of moisture from a metal surface and its implication for Time of Wetness. *Corrosion Science, 37,* 455-465.

Cole, I.S., Bradbury, A. and Neufeld, A. (1996a) Response of galvanised steel, 55% Al-Zn coated steel and copper steel to well defined salt doses under controlled environments. *Presented at 13th International Corrosion Conference, Melbourne Australia, 1996.*

Cole, I.S. and Ganther G. (1996b) A preliminary investigation into airborne salinity adjacent to and within the envelope of Australian houses. *Constr. Building Materials, 10, No. 3, 203-207.*

Cole, I.S, Norberg, P. and Ganther, G. (1996c) Environmental Factors Promoting Corrosion In Building Microclimates. *Presented at 13th International Corrosion Conference, Melbourne Australia, 1996.*

CSA (1994) Guideline on durability in buildings – Draft 9, September 1994 (CSA-S478-1994).

Dahlback, A. (1996) Measurements of biological effective UV doses – Total ozone abundance and cloud effects with multi-channel moderate band-width filter instruments. *Applied Optics, 35,* 6514-6521.

Dovland, H. (1993) EMEP – The European Monitoring and Evaluation Programme. Presented at the Expert Meeting on Acid Precipitation Monitoring Network in East Asia. Toyama, Japan, 26-28 October 1993. Lillestrøm, Norwegian Institute for Air Research (NILU F 30/93).

Downing, R., Hettelingh, J.P. and de Smet, A.M. (1993) Calculation and Mapping of Critical Loads in Europe. Status Report 1993. Bilthoven (RIVM Report No. 259101003).

Elandt-Johnson, R.C. and Johnson, N.L. (1980) Survival Models and Data Analysis. New York, Wiley. p. 204.

Elfving, P., Panas, L. and Lindqvist, O. (1994) Model study of the first steps in the deterioration of calcareous stone. II. Sulphate formation on calcite. *Applied Surface Science, 78,* 83-92.

European Organisation for Technical Approvals (1996) Assessment of Working Life of Products. Draft (TB 96/23/9.3.1).

Feliu, S., Morcillo, M. and Feliu, Jr. (1993) The prediction of atmospheric corrosion from meteorological and pollution parameters – I (annual corrosion) and II (long term forecast). *Corrosion Science, 34,* 403-422.

Ganther, W., Norberg, P. and Cole, I.S. (1996). Sensors for the measurement of factors promoting corrosion within the building envelope. *Presented at 13th International Corrosion Conference, Melbourne Australia, 1996.*

Glomsrød, S., Godal, O., Henriksen, J.F., Haagenrud, S.E. and Skancke, T. (1996) Corrosion costs in Norway. *Paper presented at the UN ECE Convention on Long-Range Transboundary Air Pollution workshop on Economic evaluation of air pollution abatement and damage to buildings including cultural heritage, Stockholm, January 1996.*

Henriksen, J. F., Haagenrud, S. E., and Støre, M. (1993) Monitoring of the wetness impact on buildings by means of a new instrument for continuous recordings. In: *International RILEM/UNESCO Congress "Conservation of Stone and other materials" Paris, 29 June-1 July 1993.* Proceedings. Ed. by M.J. Thiel. London, Spon. pp. 784-791.

Haagenrud, S.E. and Henriksen, J.F. (1994) Materialkorrosjon forårsaket av luftforurensninger - med vekt på dose-respons-sammenhenger. Kjeller, Norwegian Institute for Air Research (NILU OR 74/94) (in Norwegian).

Haagenrud, S.E. and Henriksen, J.F. (1996) Degradation of built environment – Review of cost assessment model and dose response functions. In: *7th International Conference on the durability of building materials and components. Stockholm 1996.* Proceedings. Ed. by C. Sjöström. London, E & FN Spon. pp. 85-96.

Haagenrud, S.E. and Henriksen, J.F. (1996) Modelling and Mapping of Degradation of Built Environment from available Data and GIS based Information Tools. In: *7th International Conference on the durability of building materials and components. Stockholm 1996.* Proceedings. Ed. by C. Sjöström. London, E & FN Spon. pp. 209-218.

Haagenrud, S.E., Henriksen, J.F. and Gram, F. (1985) Dose-response functions and corrosion mapping of a small geographical area. Electrochemical Society. Symposium on corrosion effects of acid deposition. Las Vegas 14-15 October 1985. Lillestrøm, Norwegian Institute for Air Research (NILU F 53/85).

Hamilton, R.S. and Mansfield, T.A. (1992) The soiling of materials in the ambient atmosphere. *Atmos. Environ., 26A,* 3291-3296.

Hanssen, J.E., Pedersen, U., Schaug, J., Dovland, H., Pacyna, J.M., Semb, A. and Skjelmoen, J.E. (1990) Summary Report from the Chemical Co-ordinating Centre for the Fourth Phase of EMEP. Lillestrøm, Norwegian Institute for Air Research (EMEP/CCC-Report 2/90).

Haynie, F. (1980) Theoretical air pollutant and climate effects on materials confirmed by zinc corrosion data. In: *Durability of Building Materials and Components*. P. J. Seredam and G.G. Litvon, eds. American Society for Testing and Materials. pp. 157-175.

Henriksen, J.F. and Haagenrud, S.E. (1994) The EUREKA project EU 615 EUROCARE WETCORR. Report from the NBS-MK Seminar at ABB Conference Centre, Billingstad, 24 November 1993. Lillestrøm, Norwegian Institute for Air Research (NILU OR 37/94).

Hjellbrekke, A.-G., Lövblad, G., Sjöberg, K., Schaug, J. and Skjelmoen, J.E. (1995) Data report 1993. Part 1: Annual summaries. Kjeller, Norwegian Institute for Air Research (EMEP/CCC-Report 7/95).

Holland, M., Watkiss, P., Cupit, M. and Lee, D. (1996) Economic assessment of ozone effects on rubber goods, textiles and surface coatings in the UK. *Paper presented at the UN ECE Convention on Long-Range Transboundary Air Pollution workshop on Economic evaluation of air pollution abatement and damage to buildings including cultural heritage, Stockholm, January 1996.*

International Council for Building Research Studies and Documentation (CIB) (1990) Feedback from practice of durability data: inspection of buildings. Ed. by C. Sjöström. Rotterdam (CIB Publication 127).

International Organisation for Standardisation (1984) Performance standards in buildings – Principles for their preparation and factors to be considered. Geneve (ISO 6241-1984).

International Organisation for Standardisation (1992) Corrosion on metals and alloys – Corrosivity of atmospheres – Classification. Geneve (ISO 9223:1992).

International Organisation for Standardisation (1995) Design life of buildings, draft 2. Geneve (ISO TC 59/SC 3/WG9).

International Organisation for Standardisation (1996) Paints and varnishes – Corrosion protection of steel structures by protective paint systems, Part 2 – Classification of environments. Geneve (ISO/FDIS 12944-2).

Janson, J. and Sjöström, C. (1979) Fabrikslackerad plåt – åldrande och provningsmetoder. Gävle, Statens institut för byggnadsforskning (Meddelande M79:10) (in Swedish).

Keeble, E.J. (1986) Microclimate data and its interpretation for problems of building deteriology. Paper to SCI/BBA symposium on building deteriology.

King, G.A. (1993) Corrosivity mapping – A sensitive and cost effective means of characterising a region's level of atmospheric corrosion. *NACE Corrosion '93. Dallas, 1993.*

Knotkova, D., Boschek, P. and Kreislova, K. (1995) Effect of acidification on atmospheric corrosion of structural metals in Europe. *Water, Air Soil Poll., 85,* 2661-2666.

Knotkova, D., (1996) Personal communication.

Kucera, V. (1996) Effects of nitrogen pollutants and ozone on damage to materials. *Paper presented at the UN ECE Convention on Long-Range Transboundary Air Pollution workshop on Economic evaluation of air pollution abatement and damage to buildings including cultural heritage, Stockholm, January 1996.*

Kucera, V., Haagenrud, S.E., Atteraas, L. and Gullman, J. (1986) Corrosion of steel and zinc in Scandinavia with respect to the classification of the corrosivity of atmospheres. ASTM Conference, Philadelphia, May 1986. Lillestrøm, Norwegian Institute for Air Research (NILU F 22/86).

Kucera, V., Henriksen, J., Knotkova, D. and Sjöström, Ch. (1993) Model for calculations of corrosion cost caused by air pollution and its application in three cities. In: *Progress in the understanding and prevention of corrosion, 10th European Corrosion Congress, Barcelona, July 1993.* Ed. by J.M. Costa and A.D. Mercer. London, Institute of Materials. Vol. 1, pp. 24-32.

Kucera, V., Tidblad, J., Henriksen, J.H., Bartonova, A. and Mikhailov, A.A. (1995) Statistical analysis of 4-year materials exposure and acceptable deterioration and pollution levels. Convention on long-range transboundary air pollution. Prepared by the main research centre, Swedish Corrosion Institute, Stockholm. (UN ECE ICP on effects on materials including historic and cultural monuments, Report No. 18).

Lacy, R.E. (1976) Driving Rain Index. HMSO (Building Research Establishment, BRE Report).

Lala, D. (1985) Ultraviolet radiation measurements by photochemical methods. Gävle, National Swedish Institute for Building Research (Meddelande M85:12).

Lanting, R W. (1984) Materials damage by photochemical oxidants. In: *Ozones: Proc. of an Internat. Workshop on the evaluation and assessment of the effects of photochemical oxidants on human health, agricultural crops, forestry, materials and visibility.* Ed. by P. Grennfelt. Gothenburg, IVL (IVL-EM 1570). pp. 44-59.

Lee, D.S., Holland, M. and Falla, N. (1994) Assessment of the potential damage to materials in the U.K. from tropospheric ozone. Oxfordshire, UK, AEA Technology, National Environmental Technology Center.

Lewry, A.J. and Crewdson, L.F.E. (1995) Approaches to testing the durability of materials used in the construction and maintenance of buildings. W80 RILEM/140 TSL SubGroup 5 Draft report, May 1995.

Lipfert, F.W. (1989) Atmospheric damage to calcareous stones: Comparison and reconciliation of recent experimental findings. *Atmos. Environ., 23,* 415-429.

Lipfert, F.W., Benarie, M. and Daum, M.L. (1986) Metallic Corrosion Damage Functions for Use in Environmental Assessments. In: *Proceedings of the Symposia on Corrosion Effects of Acid Deposition and Corrosion of Electronic Materials. Las Vegas 1985.* Ed. by Mansfeld, Haagenrud, Kucera, Haynie and Sinclair. Pennington, NJ., The Electrochemical Society. Vol. 86-6, pp. 108-154.

London Brick Company (1988) Climate and brickwork constructional Notes, October 1988.

Martin, J.W., Saunders, S.C., Floyd, F.L. and Weinburg, J.P. (1994) Methodologies for predicting the service lives of coating systems. Gaithersburg, MD., U.S. Department of Commerce, Technology Administration, National Institute of Standards and Technology (NIST building science series, 172).

Martin, J.W., (1996) Personal communication.

Masters, L.W. and Brandt, E. (1984) Systematic Methodology to Service Life Tradiction of Building Materials and Components. *Materials and Structures, 22,* 385-392.

Masters, L.W. and Wolfe, W.C. (1974) The use of weather and climatological data in evaluating the durability of building components and materials. Washington D.C., National Bureau of Standards (NBS Technical Note 883).

Mattson, J. (1995) Damages from rottening and insects. Oslo, Norges forskningsråd (Fuktprogrammets skriftserie nr. 23) (in Norwegian).

Mikailovskii, Yu.N. (1982) Theoretical and engineering principles of atmospheric corrosion of metals. In: *Atmospheric Corrosion*. Ed. by W.H. Ailor. New York, John Wiley and Sons. pp. 85-105.

Morcillo, M. and Feliu, S. (1993) Mapas de España de Corrosividad Atmosferica. Madrid, Spain, Gráficas Salué.

MSC-E (1993) Annual Report September 1992 – August 1993. Moscow, Russia, Meteorological Synthesizing Centre-East.

OECD (1977) The OECD programme on long-range transport of air pollutants; measurements and findings. Paris, OECD.

PORG 3 (1993) Ozone in the United Kingdom. London, Air quality division, Dept. of the Environment.

Refsnæs, S. and Anda, O. (1987) Corrosion in marine atmosphere. Trondheim, Elektrisitetsforsyningens forskningsinstitutt (EFI TR 3408) (in Norwegian).

Rendahl, B., Kucera, V., Knotkova, D., Vlckova, J., Norberg, P. and Sjöström, Ch. (1996) The microenvironment and corrosivity in different positions on the Royal Palace in Stockholm and on Prague castle. In: *7th International Conference on the durability of building materials and components. Stockholm 1996*. Proceedings. Ed. by C. Sjöström. London, E & FN Spon. pp. 219-232.

RILEM (1988) Soiling and cleaning of building facades: report of Technical Committee 62 SCF, RILEM. Ed. by L.G.W. Verhoef. London, Chapman & Hall.

Royal Ministry for Foreign Affairs & Royal Ministry of Agriculture (1971) Air pollution across national boundaries. The impact on the environment of sulphur in air and precipitation. Sweden's case study for the United conference on the human environment. The Ministries, Stockholm.

Sandnes, H. (1992) Calculated budgets for airborne acidifying components in Europe, 1985, 1987, 1988, 1989, 1990, 1991 and 1992. Oslo, The Norwegian Meteorological Institute (EMEP/MSC-W Report 1/93).

Saunders, K.G. (1983) Air pollutant effects on materials. In: *Proceedings of the VIth World Congress on Air Quality*. Paris, IUAPPA. pp. 59-66.

Schaug, J., Pedersen, U., Skjelmoen, J.E. and Kvalvågnes, I. (1993) Data Report 1991, Part 1: Annual Summaries. Lillestrøm, Norwegian Institute for Air Research (EMEP/CCC-Report 4/93).

Scheffer, T.C. (1970) A climate index for estimating potential for decay in wood structures above ground. *Forest products journal, 21*, 10-25.

Sikiotis, D. and Kirkitsos, P. (1994) The adverse effects of gaseous nitric acid on stone monuments. In: *The Conservation of monuments in the Mediterranean Basin*. Proc. 3rd Int. Symposium. Ed. by V. Fassina, H. Ott and F. Zezza. Venezia, Soprintendenza.

Simpson, D. (1993) Photochemical model calculations over Europe for two extended summer periods: 1985 and 1989. Model results and comparisons with observations. *Atmos. Environ., 27A*, 921-943.

Sivertsen, B. and Haagenrud, S.E. (1994) EU 833 ENSIS '94 – An environmental surveillance system for the 1994 Winter Olympic Games. Presented at Vision Eureka Item Conference, Lillehammer, 14–15 June 1994. Lillestrøm, Norwegian Institute for Air Research (NILU F 10/94).

Sjöström, C. and Brandt, E. (1990) Collection of in-service performance data: state of the art and approach by CIB W80/ RILEM 100-TSL. In: *Proceedings of the 5th International Conference on The Durability of Building Materials and Components, Brighton, UK 1990.* Ed. by J.M. Baker et al. London, Spon. pp. 287-298.

Sluyter, R.J.C.F. (1995) Air Quality in Major European Cities. Part I: Scientific Background Document to Europe's Environment. RIVM, Bilthoven (RIVM Report no. 722401004).

Statens institut för byggnadsforskning (1987) Påverkan på fasadytor från yttre miljö. Ed. by C. Sjöström and J. Henriksen. Gävle, Sweden, SIB (Meddelande M:16) (in Swedish).

Stoll, F.K. (1977) Untersuchungen zur Korrosions- und Witterungsbeständigkeit von Coil-Coating Verbundsystemen. Aachen, Germany, Institut für Kunststoffverarbeitung, RWTH (in German).

Svennerstedt, B. (1989) Ytfukt på fasadmaterial. Gävle, Sweden, Statens institut för byggnadsforskning (TN:16) (in Swedish).

Svensson, J.-E. and Johansson, L.-G. (1993) A laboratory study of the effect of ozone, nitrogen dioxide and sulphur dioxide on the atmospheric corrosion of zinc. *J. Electrochem. Soc., 140*, 2210-116.

Tidblad, J. and Kucera, V. (1996) The role of NO_x and O_3 in atmospheric corrosion. Swedish Corrosion Institute/Swedish Board of Environmental Protection. (Report to be published 1996).

Tomiita, T. (1989) Daily range map of black panel temperature. *Transactions of AIJ, 401,* 25-33.

Tomiita, T. (1989) Thermal degradation map based on black panel temperature. *Transactions of AIJ, 395,* 13-20.

Tomiita, T. (1992) Solar UV, wetness and thermal degradation maps of Japan. *Construction and building materials, 6,* 195-199.

Tomiita, T. (1993) Service life prediction system of polymeric materials exposed outdoors. Personal communication.

Tomiita, T. and Kashino, N. (1989) Temperature modified wetness time and wet-dry cycle map in Japan. *Transactions of AIJ, 405,* 1-7.

Tomiita, T. and Kashino, N. (1989) Wetness time and wet-dry cycle map in Japan. *Transactions of AIJ, 395,* 21-27.

Tuuti, K. (1982) Corrosion of steel in concrete. Cement och betonginstitutet (Forskningsrapport 4:1982).

United Kingdom Atmospheric Corrosivity Values 1986. Farm Buildings, Group Ministry of Agriculture Fisheries and Food.

United Nations (1991) Assessment of long-range transboundary air pollution. New York (Air Pollution Studies No. 7) (ECE/EB.AIR/26).

Veit, J. and Eckermann, W. (1996) Schlagregenbeanspruchung von Fachwerkfassaden. Draft Arbeitsblatt Deutsches Zentrum für Handwerk und Denkmalpflege.

Vernon, W.H.J. (1931) A laboratory study of the atmospheric corrosion of metals. *Transactions of the Faraday Society, 27,* 265.

Yamasaki, R.S. (1983) Solar Ultraviolet Radiation on Horizontal South/46° angle and south/vertical surfaces. *Durability of Building Materials, 2,* 17-26.

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ABSTRACT
This is the report of Sub-Group 2 “Environmental Characterisation including Equipment for Monitoring” to the CIB W80/RILEM 140-TSL (Techniques for Service Life Prediction). The report presents the state of the art and the research needs regarding characterisation of the degradation environment related to service life prediction of building materials and components, including methods and equipment for micro-climate monitoring.

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