FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS
RESEARCH FOR AND APPLICATION TO THE BUILDING DOMAIN

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Failure Modes Effects and Criticality Analysis Research for and Application to the Building Domain

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Preface

This report presents a state-of-the-art regarding FMEA research for and application to the building domain. Beginning by a summary of objectives, approaches and applications of organisations and individuals working on FMEA and FMECA, this report offers a bibliographic list of papers, reports and related work documents. Finally, a selection of published papers and non-published reports that are pertinent to this report have been included in the appendices.

By presenting several research studies and applications to the building domain, this document underscores the evident usefulness of FMEA and FMECA methods and thus helps foster and encourage future developments and new applications of these methods.

Acknowledgements

This report has been compiled over the course of the CIB W080 2002-2005 work programme. The CIB W080 Working commission focuses on research related to the Prediction of Service Life of Building Materials and Components and the authors are indebted to the many within the Task Group who made contributions and to those who assisted in the review of the document. In particular, the efforts of Dr. M. A. Lacasse and Dr. Prof. Christer Sjöström, chairs to the CIB W080, to review and sustain the initiative are gratefully acknowledged.

Contents

1. Introduction

Developed in the sixties for the aeronautical domain, Failure Modes and Effects Analysis (FMEA) or Failure Modes Effects and Criticality Analysis (FMECA) is a risk analysis method that has stood the test of time and is presently used in the space, nuclear, chemical and automobile industries. The aim of this document is to present the manner in which this method can be integrated from research and applied to the building domain.

This document is comprised of five parts:

1. Brief descriptions are provided for each of the organisations and include objectives associated with the integration of FMEA or FMECA in research focused on their respective approaches and related applications.
2. Specific projects dealing with FMEA or FMECA are presented.
3. A bibliographic list of papers, reports and related work documents on FMEA or FMECA that were prepared by the previously listed organisations.
4. A list of research or industrial organisations working on developing the use of FMEA or FMECA in the building domain has been included in the appendices in which are also identified individuals associated with the work.
5. A selection of published papers and non-published reports that are pertinent to this report has been included in the appendices.

2. Objectives, approaches and applications respectively related to organisations working on FMEA or FMECA

2.1 Centre Scientifique et Technique du Bâtiment*

Objectives:

The primary objectives in regards to the integration of FMECA to existing research topics, are:
Evaluate the service life of buildings products;

- Evaluate and forecast failures of building products.

Approach:

The approach is summarized in the following figure:

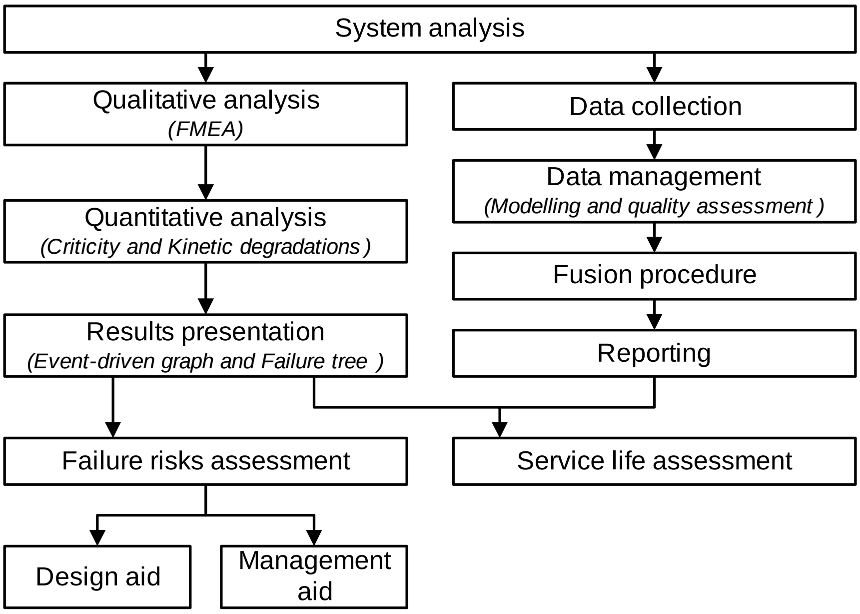

Figure 1: Approach of CSTB regarding the application of FMEA and FMECA to the building domain

The approach is initiated through a system analysis in which both a risk analysis and data fusion process is completed. The risk analysis comprises a combined set of qualitative and quantitative analysis followed by presentation of results. Details regarding this section can be found in [Talon *et al.* 2005], [Talon *et al.* 2004], [Chevalier *et al.*2003], [Lair 2003a], [Lair 2003b], [Talon *et al.* 2003a], [Talon *et al.* 2003b], [Talon *et al.* 2003c], [Talon *et al.* 2003d], [Chevalier *et al.* 2002], [Lair *et al.* 2002a], [Lair *et al.* 2002c], [Talon 2002], [Lair *et al.* 2001].

The qualitative analysis is based on the use of FMEA whereas quantitative analysis incorporates criticality analysis, that is to say the “C” found in FMECA, as well as the quantification of kinetics of degradations of products or components. The results of these combined analyses are presented in an event-driven graph and a failure tree. The event-driven graph is a “schematisation” of the linkages between degradation scenarios among different components over a building products’ service life. This method provides risks assessment of failure of the building product that can be applied either as a design or management aid.

*The complete list of references cited is provided in the bibliography of section 5

The second approach, referred to as data fusion, is composed of data collection, data management, the fusion procedure and reporting the information. Data collection means collection of all relevant available data on the product, or its' parts, in the products' projected in-use environment. Data management includes modelling and quality assessment of the data. The fusion procedure is a statistical technique, based on "evidence theory", that provides a mass belief function in relation to time. Reporting aims to present results in an understandable and easily usable format [Lair 2003a], [Chevalier *et al.* 2002], [Lair *et al.* 2002b], [Lair *et al.* 2001], [Lair 2000a], [Lair 2000b], [Lair 2000c], [Lair *et al.* 2000a], [Lair *et al.* 2000b] and [Lair *et al.* 1999].

When data fusion is combined with risk analysis, an assessment of the building product service life may be obtained.

Applications:

Several applications have been developed within different projects and collaboration, including:

- Roofing system [Lair et al. 2002a], [Lair 2000c];
- Timber window [Lair 2000c];
- Glued stone wall [Lair et al. 2001], [Lair 2000c];
- Double glazing unit [Lair 2003c], [Talon et al. 2003b], [Lair 2002a], [Lair 2002b], [Lair et al. 2002c], [Lair 2001c];
- Insulated glazing [Lair 2003 c], [Platzer 2003], [Lair 2002d], [Lair 2002e], [Lair 2001b];
- Solar panel [Talon 2004], [Lair 2003c], [Lair et al. 2003], [Talon et al. 2003a], [Talon et al. 2003b], [Talon et al. 2003c], [Talon et al. 2003d], [Lair 2002c], [Lair et al. 2002c], [Talon 2002]
- Traditional Italian wall [Iacono 2005]

  This application has been led in the context of a co-operation between the Sustainable Development Department of the CSTB and the Durability of Building and Components Group (DBCG) of the Politecnico di Milano for development of methods for durability evaluation based on FMEA and Performance Limits Methods (PLM) [Daniotti et al. 2003].

2.2 Aspen Research Corporation, Pando Technologies*

Objectives:

The three basic objectives of the Aspen Research Corporation involve the development of:

- A qualitative and quantitative interpretation of a products failure mechanisms;
- Durability models on the basis of the previous mechanistic understanding of failure mechanisms;
- Accelerated test protocols on the basis of durability models and knowledge of failure mechanisms.

Approach:

An outline of the approach is presented in Figure 2:

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*The complete list of references cited is provided in the bibliography of section 5

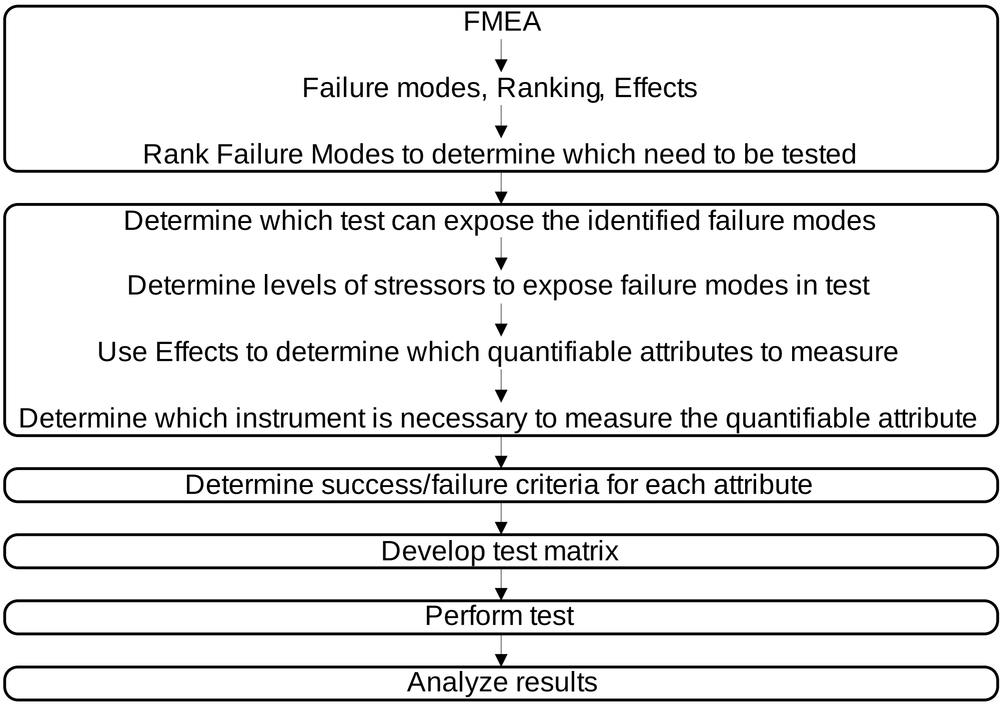

Figure 2: Approach of the Aspen Research Corporation to applying FMEA to the building domain [Aspen Research Corporation 2002]

The initial step to this approach is the need to identify failure modes and the quantification of their effects. Thereafter, relevant tests to measure quantifiable attributes related to the failure mode are determined. The last four steps include: (1) establishing the success or failure criteria for each attribute; (2) the development of a test matrix; (3) the development of a performance test, and; (4) analysis of results.

Details regarding this approach can be found in [Curcija *et al.* 2005], [Aspen Research Corporation 2002], [Hage 2002a], [Hage 2002b], [Hage 2002c] and [Hage *et al.* 2002].

Applications:

The approach has been applied to several examples of insulated glass building products:

- Box spacer system [Curcija et al. 2005], [Aspen Research Corporation 2002], [Hage 2002b], [Hage 2002c];
- U channel spacer system [Aspen Research Corporation 2002], [Hage 2002b], [Hage 2002c];
- Corrugated metal spacer system [Aspen Research Corporation 2002], [Hage 2002b], [Hage 2002c];
- Non-rigid barrier spacer system [Curcija et al. 2005], [Aspen Research Corporation 2002], [Hage 2002b], [Hage 2002c].

2.3 Building Research Establishment*

Objectives:

The prime objective is to adopt a framework that allows the supply chain to consider service life, whole life cost, building component performance and environmental data during procurement and throughout the building's life.

Approach:

Figure 3 provides a schematic of the manner in which FMECA is integrated in the whole Integrated Logistical Support analysis.

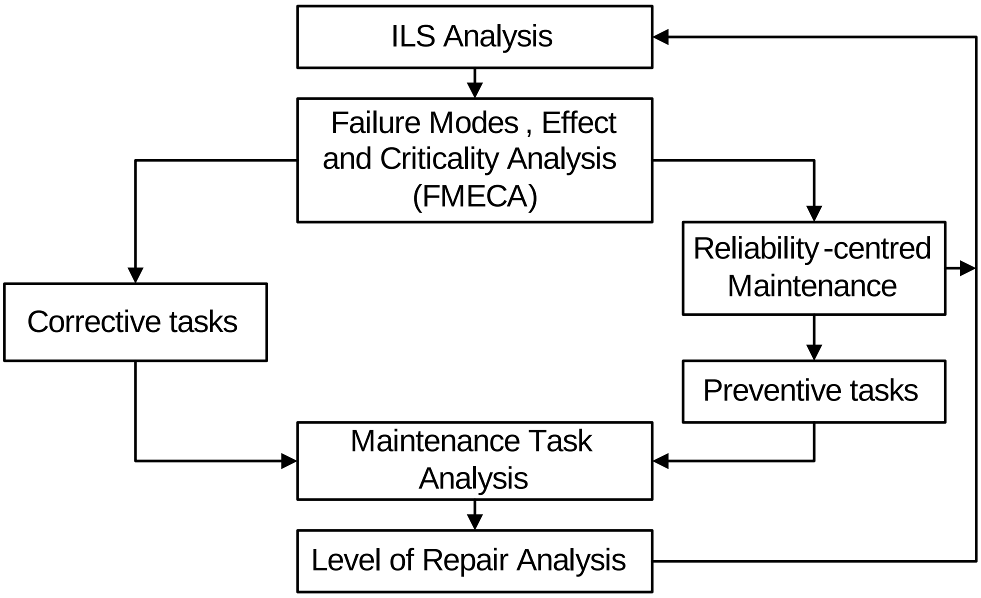

Figure 3: Approach of the Building Research Establishment [Bartlett 1999]

2.4 Centre for Window and Cladding Technology, University of Bath*

Objectives:

The Centre for Window and Cladding Technology, have used FMECA to:

- Prioritise and inform decision-making, and;
- Facilitate site inspection and supervision.

Approach:

A schematic of their approach is given in the following figure 4.

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*The complete list of references cited is provided in the bibliography of section 5

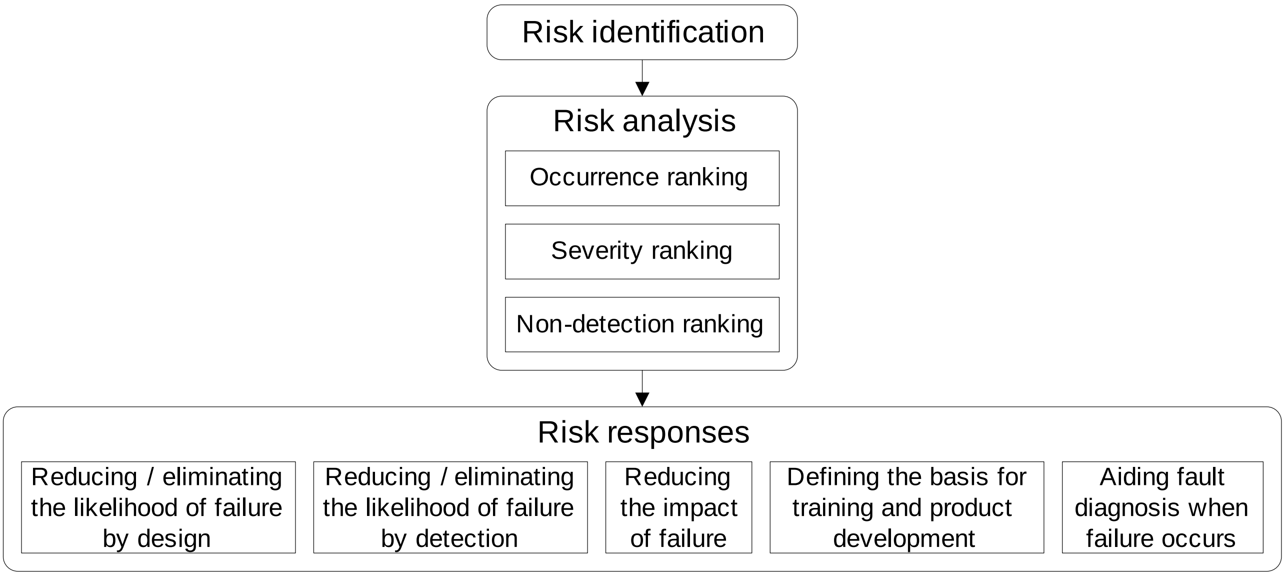

Figure 4: Schematic of Approach adopted by the Centre for Window and Cladding Technology, University of Bath, UK

As suggested in this figure, risks are first identified, thereafter, a risk analysis is undertaken in which three ranking criteria are determined that include: occurrence, severity and non-detection ranking.

On the basis of their study they identified five advantages from the use of FMECA that includes the:

- Reduction or elimination of the likelihood of failure by design;
- Reduction or elimination of the likelihood of failure by detection;
- Reduction of the impact of failure;
- Defining the basis for training and product development;
- Aiding fault diagnosis when failure occurs.

Applications:

FMECA has been applied to the study of glass-metal curtain wall cladding systems [Layzell 1998].

2.5 SP Swedish National Testing and Research Institute*

The approach adopted by the SP Swedish National Testing and Research Institute approach is quite different from what has up to now been presented in this report. Indeed, they do not carry out FMECA but an Initial Risk Analysis (IRA) for determining potential failure modes of products. However, this approach is presented in this document because the process for determining potential failure modes by conducting an Initial Risk Analysis, as described by this organisation [Carlsson 2002], [Carlsson *et al.* 2002] and [Carlsson *et al.* 2001] is quite similar to FMECA.

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*The complete list of references cited is provided in the bibliography of section 5

Objectives:

The primary objective of carrying out an IRA is to develop a qualification test from which accelerated life tests can thereafter be developed. The secondary objective is to predict the service life of the building product.

Approach:

Figure 5 presents the manner in which the IRA of potential failure modes is integrated to the qualification test and the service life prediction procedure.

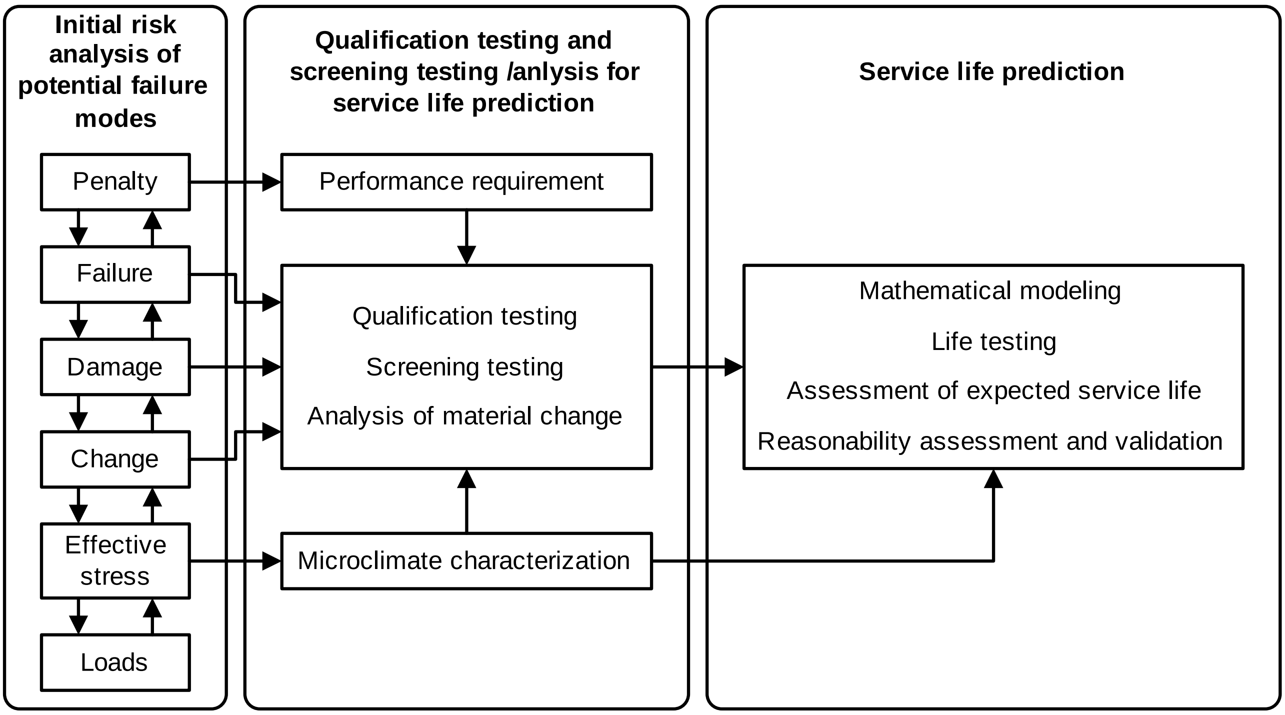

Figure 5: Approach of the SP Swedish National Testing and Research Institute [Carlsson *et al.* 2002]

The first step of this approach allows determining performance requirement and microclimate characterization. Consequently, on this basis, qualification and screening test can be defined and the analysis of material degradation can also be determined. Prediction of building product service life is established on mathematical modelling and life testing from which an assessment of the expected service life is achieved. The prediction is based on further assessment and validation of the results through a process of determining the degree to which the service life estimate is a reasonable reflection of expectations for its' in-use conditions.

Applications:

The IRA process has been applied to two products:

- A selective solar absorber coating of electrochemically produced anodised aluminium doped with metallic nickel;
- Polymeric solar collector glazings.

2.6 Polytechnic of Turin*

Objectives:

The goal is to stimulate, at the design stage, the action of degradation factors on the building sub-systems performances and operating costs.

Approach:

The approach is summarized in Figure 6:

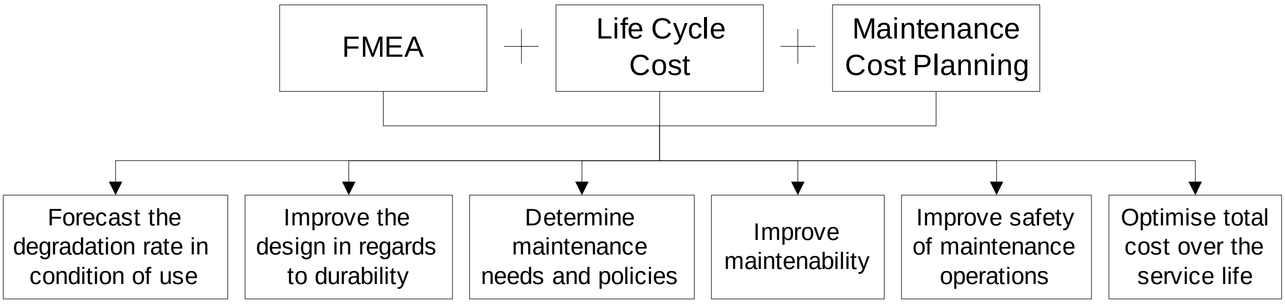

Figure 6: Approach of the Polytechnic of Turin

This approach consists in combining three methods: FMEA, Life Cycle Cost and Maintenance Cost Planning in order to:

- Forecast degradation rates for in-use conditions;
- Improve design in regards to durability;
- Determine maintenance needs and policies;
- Improve maintainability;
- Improve safety of maintenance operations;
- Optimise total cost over the service life.

Applications:

This approach has been applied to a metal frame door [Pollo 2003].

2.7 Technical Consultant D. Wyatt*

Objectives:

The prime objective of D. Wyatt is to best evaluate the service life design of constructed assets by integrating the FMEA and FTA (Fault Tree Analysis) into a performance review and performance audit process.

Approach:

Figure 7 provides a schematic of the manner in which FMEA is integrated in the whole performance review and performance audit process.

*The complete list of references cited is provided in the bibliography of section 5

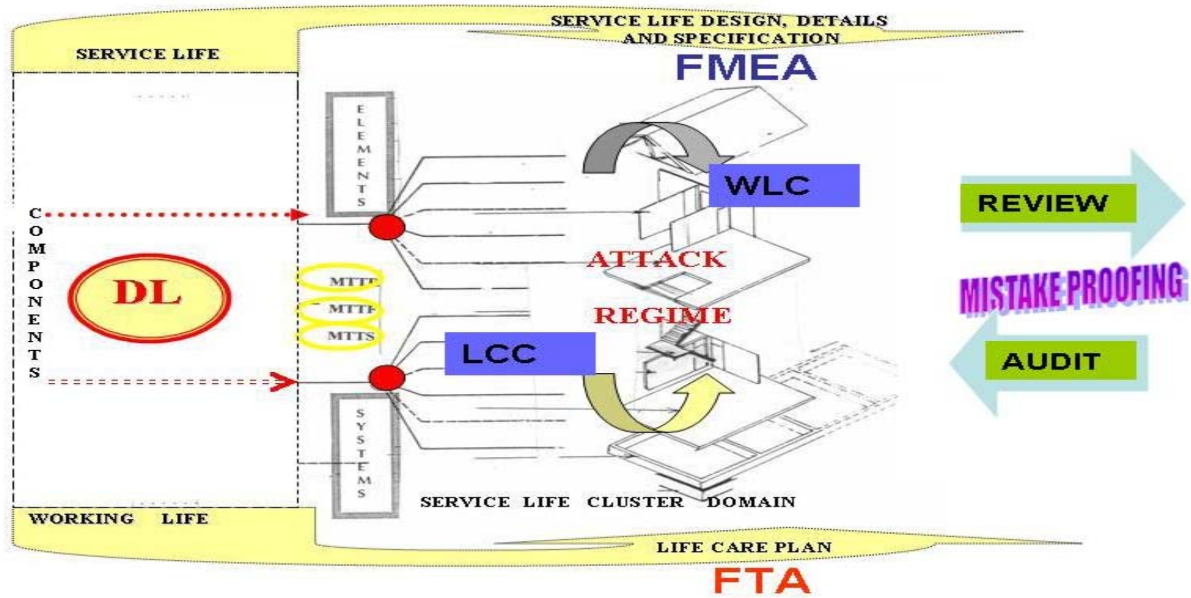

Figure 7: Approach of the Technical Consultant D. Wyatt [Wyatt 2005]

Where:

- DL is the Design Life;
- FTA is the Failure Tree Analysis;
- LCC is the Life Cycle Costs;
- MTTF is Mean Time to Failure;
- MTTR is Mean Time to Repair or Replacement;
- MTTF is Mean Time to Servicing;
- WLC is the Whole Life Costs.

Details regarding this approach can be found in [Wyatt 2005], [Wyatt 2004], [Wyatt 2003], [Wyatt *et al.* 2001], [Wyatt 2000a] and [Wyatt 2000b].

3. Projects dealing with FMEA or FMECA

The projects dealing with FMEA or FMECA, in which organisations mentioned in the first part, are or have been implicated, are the following:

- SWIFT (Switchable Façade Technology) Work package 2: Durability and Reliability;
  References: [Platzer 2003], [Lair 2002e], [Lair 2001a], [Lair 2001b].

- IEA (International Energy Agency) Task 27 Project C2: Failure Mode Analysis;
  References: [Lair 2003c], [Talon *et al.* 2003b], [Lair 2002a], [Lair 2002a], [Lair 2002b], [Lair 2002c], [Lair 2002d], [Lair *et al.* 2002c], [Lair 2001c].

- IEA Task 27 Project B1: Durability assessment methodology development;
  References: [Carlsson 2002], [Carlsson *et al.* 2001].

- Convention ADEME (Agence De l'Environnement et de la Maîtrise de l'Énergie): Durabilité et fiabilité des capteurs solaires;
  References: [Lair *et al.* 2003]

- DOE (Department Of Energy) project : An Insulating Glass Knowledge
  References: [Aspen Research Corporation 2002], [Hage 2002a], [Hage 2002b], [Hage 2002c], [Hage *et al.* 2002].

4. Summary

This document offers a summary of research and applications related to Failure Modes and Effects Analysis (FMEA) or the Failure Modes Effects and Criticality Analysis (FMECA) in the building (i.e. construction) domain. In this document are presented, the organisations and individuals working on FMEA or FMECA, their objectives, approaches and applications and descriptions of projects focusing on the development, use and application of these methods. A bibliography has been compiled that includes papers, reports and presentations completed by these different organisations. Additionally, selected papers and project report extracts that further help understand the research being carried out at these organisations are offered in the appendices.

This document underscores the evident usefulness of FMEA or FMECA methods and illustrates that such methods can, through the research process, readily be integrated to different applications. It would, at this stage, be useful to identify the manner in which the different approaches complement one another. This would in turn permit determining the approach that might be adopted for incorporating FMEA or FMECA to other areas of the building (construction) domain. Consequently, it is expected that the use of the information provided in this document will help foster and encourage future developments and new applications of these methods.

5. Bibliography

Published papers:

Curcija, C., Dukovski, I., Velthius, H., Fairman, J. and Doll, M. (2005) *Real-Time Simulations of the Durability of Insulating Glass Units*, Proceedings of the 10th Durability of Building Materials and Components (10DBMC), Lyon, France, 17-20 April 2005.

Talon, A., Boissier, D., Chevalier, J.-L. and Hans, J. (2005) *Temporal Quantification Method of Degradation Scenarios Based on FMEA*, Proceedings of the 10th Durability of Building Materials and Components (10DBMC), Lyon, France, 17-20 April 2005.

Wyatt, D. P. (2005) *The Contribution of FMEA and FTA to Performance Review and Auditing of Service Life Design Constructed Assets*, Proceedings of the 10th Durability of Building Materials and Components (10DBMC), Lyon, France, 17-20 April 2005.

Talon, A., Boissier, D., Chevalier, J-L. and Hans, J. (2004) *A Methodological and Graphical Decision Tool for Evaluating Building Component Failure,* Proceedings of the CIB World Building Congress (CIB WBC 2004), Toronto, Canada, 2-7 May 2004.

Wyatt, D. P. (2004) *Referenced Service Life Based Constructed Works,* Proceedings of the CIB World Building Congress (CIB WBC 2004), Toronto, Canada, 2-7 May 2004.

Chevalier, J-L., Lair, J., Talon, A. and Boissier, D. (2003) *Failure Mode Effect and Criticality Analysis for Decision Aid at Design and Exploitation Stages*, Proceedings of Integrated Lifetime Engineering of Buildings and Civil Infrastructures (ILCDES 2003), Kuopio, Finland, 1-3 December 2003.

Daniotti, B. and Iacono, P. (2003), *Long-Term Degradation Under Outdoor Exposure Conditions,* International Workshop on Management of Durability in the Building Process (MDBP 2003), Politecnico di Milano, Milan, Italy, 25-26 June 2003.

Lair, J. (2003a) *Méthodes Opérationnelles pour la Prise en Compte de la Durabilité dans la Norme ISO 15686 « Service Life Planning »,* Proceedings of the XXIèmes Rencontres Universitaires de Génie Civil (AUGC 2003), La Rochelle, France, 2-3 June 2003, pp.381 - 388.

Pollo, R. (2003) *Service Life and LCC Assessment. The Use Of FMEA As Design Tool*, International Workshop on Management of Durability in the Building Process (MDBP 2003), Politecnico di Milano, Milan, Italy, 25-26 June 2003.

Talon, A., Boissier, D. and Chevalier, J-L. (2003a) *Failure Modes, Effects and Criticality Analysis: Risk Analysis Methodology for Capitalization and Use of Experience and Knowledge on Building Products Degradations,* 2nd International Symposium on Building Pathology, Durability and Rehabilitation (BPDR 2003), Lisbonne, Portugal, 6-8 November 2003, pp.597 - 606.

Talon, A., Chevalier, J-L., Hage, R. and Fairman, J. E. (2003b), *FMEA as a Risk Analysis Decision Aid Tool for Design and Maintenance Planning: Application to Windows and Solar Collectors*, IEA SHC Task 27 Dissemination Workshop, Fraunhofer ISE, Freiburg, Germany, October 2003.

Talon, A., Lair, J. and Boissier, D. (2003c) *Analyse des Modes de Défaillances et de leurs Effets Appliquée à l'Analyse de Risques et la Planification de la Maintenance***,** Proceedings of the: Performance et Nouvelles Technologies en Maintenance (PENTOM 2003), Valenciennes, France, 26-28 March 2003, pp. 291 – 302.

Talon, A., Lair, J. and Boissier, D. (2003d), *Failure Mode Effet and Criticality Analysis to Improve the Quality of Building Products and Processes,* International Workshop on Management of Durability in the Building Process (MDBP 2003), Politecnico di Milano, Milan, Italy, 25-26 June 2003.

Wyatt, D. P. (2003), *Sustaining the Future through Durability and Service Life Planning,* International Workshop on Management of Durability in the Building Process (MDBP 2003), Politecnico di Milano, Milan, Italy, 25-26 June 2003.

Carlsson, Bo. (2002) *IEA SHC Task 27: Durability Assessment of Solar Energy Materials Based on General Methodology of Accelerated Life Testing: Introduction*. Workshop "Recent Research Activities in IEA T27" – Ottawa, Canada, October 2002.

Carlsson, Bo., Möller, K., Marechal, J-Ch., Köhl, M., Heck, M., Brunold, S. and Jorgensen, G. (2002) *General Methodology Of Test Procedures For Assessment Of Durability And Service Life,* Proceedings of the 9th Durability of Building Materials and Components (9DBMC), Brisbane, Australia, 17-21 March 2002, paper n° 212.

Chevalier, J., Lair, J. and Rubaud, M. (2002) *Pour une Approche Intégrée des Travaux de Maintenance et de Réhabilitation,* Revue Travaux (Fédération Nationale des Travaux Publics), n°791, Novembre 2002, pp. 60-66.

Hage, R. (2002a) *A Methodology for Ensuring Durability of New Product Offerings*, IGMA Technical Division Meeting, August 2002.

Hage, R. (2002b) *Capturing Insulating Glass Failure Events Using Failure Modes and Effects Analysis and Event Trees*, IGMA Technical Division Meeting, August 2002.

Hage, R. and Eastep, M. (2002) *Methodology for Top Level Durability Assessment of Existing Insulating Glass Units*, IGMA Technical Division Meeting, August 2002.

Lair, J. and Chevalier, J-L. (2002a) *Failure Mode Effect and Criticality Analysis for Risk Analysis (Design) and Maintenance Planning (Exploitation),* 9th Durability of Building Materials and Components (9DBMC), Brisbane, Australia, 17-21 March 2002, paper n° 32.

Lair, J. and Chevalier, J-L. (2002b) *Service Life Assessment of Building Products with Data Fusion,* Revue Française de Génie Civil "Fiabilité des ouvrages de Génie Civil – Conception et maintenance". Volume 6, n°3 (2002), pp. 421-431.

Lair, J. and Hage, R. (2002c) *Failure Mode Effect and Criticality Analysis – Application to Windows and Solar Components,* Workshop "Recent Research Activities in IEA T27" – Ottawa, Canada, October 2002.

Lair, J., Chevalier, J-L. and Rilling, J. (2001) *Operational Methods for Implementing Durability in Service Life Planning Framework,* CIB World Building Congress (CIB WBC 2001), Wellington, New Zealand, April 2001, paper n° INF 11.

Wyatt, D. P. and Lucchini, A. (2001) *Validating Design Life Trough Performance Reviews,* CIB World Building Congress (CIB WBC 2001), Wellington, New Zealand, April 2001, paper n° CL1 29.

Lair, J. (2000a) *Evaluation de la Durabilité des Produits du Bâtiment,* Concours Jeunes chercheurs Prix René Houpert, La communauté du Génie Civil et urbain au service de la qualité de la vie et de l'environnement, Lyon, France, 2000 (AFGC – AUGC – IREX).

Lair, J. (2000b) *La Qualité dans la Durée : une Méthode pour Innover en Toute Sécurité,* Lettre d'information CSTB RECHERCHE n°42 Juillet-Août 2000.

Lair, J., Le Teno, J-F. and Boissier, D. (2000a) *Durability Assessment of Building Products,* Integrated Life Cycle Design of Materials and Structures (ILCDES 2000), A, Sarja, Ed., Helsinki, Finland, pp. 393 - 397.

Lair, J., Le Teno, J-F., Chevalier, J-L. and Boissier, D. (2000b) *Service Life Prediction Under Uncertainty as a Criteria for Decision-Making,* 2nd Conference on Decision Making in Urban and Civil Engineering, J.C. Mangin and M. Miramond, Eds., Lyon, France, 20-22 November 2000, pp. 1015 - 1026.

Wyatt, D. P. (2000a) *A Service Life Design for Life Care,* Integrated Life Cycle Design of Materials and Structures (ILCDES 2000), A, Sarja, Ed., Helsinki, Finland, pp. 80 - 85.

Wyatt, D. P. (2000b) *The Service Life Design Review and Performance Audit Approach for Sustainable Construction,* Integrated Life Cycle Design of Materials and Structures (ILCDES 2000), A, Sarja, Ed., Helsinki, Finland, pp. 74 - 79.

Bartlett, E. V. and Clift, M. (1999) *Reliability and Whole Life Performance : Integrating the Supply Chain*, Durability of Building Materials and Components 8 (8DBMC), Vancouver, Canada, May 30 - June 3, pp. 1916 - 1923.

Lair, J., Chevalier, J-L., Le Teno, J-F. and Boissier, D. (1999) *Durability Assessment of Building Systems,* Durability of Building Materials and Components 8 (8DBMC), Vancouver, Canada, May 30 - 3 June 1999, pp.1299 - 1308.

Layzell, J. and Ledbetter, S. (1998) *FMEA Applied to Cladding Systems – Reducing the Risk of Failure*, Building Research and Information: 26(6), pp. 351-357.

Restricted-published papers, reports and presentations:

Iacono, P. (2005). *Proposizione di un Percorso Metodologico Applicabile alla Valutazione della Durabilità di Elementi Tecnici Edilizi e degli Elementi Funzionali Costituenti***.** Thesis prepared at the Polytechnic of Milan – Building Environment Science & Technology.

Lair, J. (2003b) *Failure Modes Effects and Criticality Analysis – A Tool for Risk Analysis (Design) and Maintenance Planning (Exploitation),* Working document, CIB W 80 / RILEM 175 – SLM: Service Life Methodologies – Prediction of Service Life for Buildings and Components, February 2003, 15p.

Lair, J. (2003c) *Failure Modes and Effect Analysis, Service Life Prediction,* Intermediary report (D4-C2-jl-01 Draft 2), IEA Task 27 (Project C2 : Failure Mode Analysis), February 2003, 47p.

Lair, J., Talon, A. and Laporthe, S. (2003) *Fiabilité et Durabilité des Systèmes Solaires Thermiques,* (ACTION 3 OF THE CONVENTION ADEME N° 01.05.128 – 2ND REPORT).

Platzer, W. J. (2003) *Switchable Facade Technology – Final Technical Report (36 month)*, swift-pr-coord-030730, SWIFT project, 30th July 2003.

Aspen Research Corporation (2002) *"Deliverables for Phase I of the DOE Project – An Insulating Glass Knowledge Base"***,** Presentation, IGMA Technical Division Meeting, August 2002.

Hage, R. (2002c) *An Insulating Glass Knowledge Base*, DOE Annual Report – Phase I, DE-FC26-01NT41258, 310p.

Lair, J. (2002a) *Failure Modes and Effect Analysis – Double Glazing Unit,* Intermediary report, IEA Task 27 (Project C2 : Failure Mode Analysis), February 2002, 5p.

Lair, J. (2002b) *Failure Modes and Effect Analysis – Influence of the Frames on the Glazing,* Intermediary report, IEA Task 27 (Project C2 : Failure Mode Analysis), April 2002, 5p.

Lair, J. (2002c) *Failure Modes and Effect Analysis – Solar Panels,* Intermediary report, IEA Task 27 (Project C2 : Failure Mode Analysis), June 2002, 8p.

Lair, J. (2002d) *Failure Modes and Effect Analysis – Argon Gas Filled / Low-e Coating Window,* Intermediary report, IEA Task 27 (Project C2 : Failure Mode Analysis), October 2002, 7p.

Lair, J. (2002e) *Failure Modes and Effects Analysis for Electrochromic and Gasochromic Glazings*, SWIFT project, WP2 Task 3: Reliability assessment, 33p

Talon, A. **(2002)** *Développement d'une Méthode d'Analyse de Risques des Produits de Construction Basée sur l'AMDEC*, Stage double cursus Projet de Recherche et Développement Ingénieur CUST / Stage de recherche DEA, préparé au Centre Scientifique et Technique du Bâtiment / DDD-ED, July 2002.

Carlsson, Bo., Möller, K., Marechal, J-C., Köhl, M., Heck, M., Brunold, S. and Jorgensen, G. (2001) *General Methodology of Accelerated Testing for Assessment of Service Life of Materials*, Working document, IEA Task 27 (Project B1: durability assessment methodology development), May 2001.

Lair, J. (2001a) *FME(C)A Methodology – Failure Modes, Effects (and Criticality) Analysis*, D2.9a Deliverable, SWIFT project – 4th Experts meeting, Roma, Italy, 4-5 October 2001.

Lair, J. (2001b) *Failure Modes and Effects Analysis – EC and GC Glazing*, D2.9b Deliverable, SWIFT project – 4th Expert meeting, Roma, Italy, 4-5 October 2001.

Lair, J. (2001c) *Failure Modes and Effect Analysis, Service Life Prediction,* Intermediary report (D1-C2-jl-01 Draft 1), IEA Task 27 (Project C2 : Failure Mode Analysis), September 2001, 23p.

Lair, J. (2000c). *Evaluation de la Durabilité des Systèmes Constructifs du Bâtiment***.** Thesis prepared at the CSTB – Service matériaux and at the LERMES.

6. Appendices

There are three appendices:

Appendix 1 – Provides a list of the seven known organisations working on FMEA or FMECA.

Appendix 2 – A selection of papers that offer a useful overview of the work carried out by the different organisations involved in the study of FMEA and FMECA as applied to the building (i.e. construction) domain. Some of this information has not yet been published.

Appendix 3 – Additional information has been provided that includes non-published reports generally accessible to those working in research committees and that would not be commonly available from the usual library sources. These additional items add to the depth of information available on the topic and serve to augment published material given in the bibliography.

Appendix 1: Organisations working on FMEA or FMECA

The seven organisations listed below are those that are or have worked on FMEA or FMECA and related individuals associated with the work:

- The Centre Scientifique et Technique du Bâtiment (CSTB) – Fr:
    - J.-L. CHEVALIER;
    - J. HANS;
    - A. TALON.

- The Aspen Research Corporation, Pando Technologies – USA:
    - R. HAGE;
    - J.E. FAIRMAN.

- The Building Research Establishment – UK:
    - E.V. BARTLETT;
    - M.R. CLIFT.

- The Centre for Window and Cladding Technology, University of Bath – UK:
    - J. LAYZELL;
    - S. LEDBETTER.

- The SP Swedish National Testing and Research Institute – Se:
    - Bo. CARLSSON;
    - K. MÖLLER.

- The Polytechnic of Turin – It:
    - R. Pollo.

- The Technical Consultant D. Wyatt – UK

Appendix 2: Selection of published papers

Selected contributions from the CSTB, Fr:

1. **Talon, A., Boissier, D., Chevalier, J-L. and Hans, J. (2005)** *Temporal Quantification Method of Degradation Scenarios Based on FMEA*, Proceedings of the 10th Durability of Building Materials and Components (10DBMC), Lyon, France, 17-20 April 2005.
2. **Talon, A., Boissier, D., Chevalier, J-L. and Hans, J. (2004)** *A Methodological and Graphical Decision Tool for Evaluating Building Component Failure,* Proceedings of the CIB World Building Congress (CIB WBC 2004), Toronto, Canada, 2-7 May 2004.
3. **Lair, J., Chevalier, J-L. and Rilling, J. (2001)** *Operational Methods for Implementing Durability in Service Life Planning Framework,* CIB World Building Congress (CIB WBC 2001), Wellington, New Zealand, April 2001, paper n° INF 11.

Selected contributions from the Aspen Research Corporation, Pando Technologies, USA:

1. **Curcija, C., Dukovski, I., Velthius, H., Fairman, J., Doll, M. (2005)** *Real-Time Simulations of the Durability of Insulating Glass Units*, Proceedings of the 10th Durability of Building Materials and Components (10DBMC), Lyon, France, 17-20 April 2005.
2. **Hage, R. (2002a)** *A Methodology for Ensuring Durability of New Product Offerings*, IGMA Technical Division Meeting, August 2002.
3. **Hage, R. (2002b)** *Capturing Insulating Glass Failure Events Using Failure Modes and Effects Analysis and Event Trees*, IGMA Technical Division Meeting, August 2002.
4. **Hage, R. and Eastep, M. (2002)** *Methodology for Top Level Durability Assessment of Existing Insulating Glass Units*, IGMA Technical Division Meeting, August 2002.

Selected contribution from the Building Research Establishment, UK:

Bartlett, E.V. and Clift, M. (1999) *Reliability and Whole Life Performance : Integrating the Supply Chain*, Durability of Building Materials and Components 8 (8DBMC), Vancouver, Canada, May 30 - June 3, pp. 1916 - 1923.

Selected contribution from the Centre for Window and Cladding Technology, University of Bath, UK:

Layzell, J. and Ledbetter, S. (1998) *FMEA Applied to Cladding Systems –Reducing the Risk of Failure*, Building Research and Information: 26(6), pp. 351-357.

Selected contribution from the SP Swedish National Testing and Research Institute, SE:

Carlsson, Bo., Möller, K., Marechal, J-Ch., Köhl, M., Heck, M., Brunold, S. and Jorgensen, G. (2002) *General Methodology Of Test Procedures For Assessment Of Durability And Service Life,* Proceedings of the 9th Durability of Building Materials and Components (9DBMC), Brisbane, Australia, 17-21 March 2002, paper n° 212.

Selected contribution from the Polytechnic of Turin, IT:

Pollo, R. (2003) *Service Life and LCC Assessment. The Use Of FMEA As Design Tool*, International Workshop on Management of Durability in the building Process (MDBP 2003), Politecnico di milano, Milan, Italy, 25-26 June 2003.

Selected contribution from the Technical Consultant D. Wyatt, UK:

Wyatt, D. (2005) *The Contribution of FMEA and FTA to Performance Review and Auditing of Service Life Design Constructed Assets*, Proceedings of the 10th Durability of Building Materials and Components (10DBMC), Lyon, France, 17-20 April 2005.

Contribution from the CSTB

A. Talon, D. Boissier, J-L. Chevalier, J. Hans

Temporal Quantification Method of Degradation Scenarios Based on FMEA

2005

Original publication:

Proceedings of the 10th Durability of Building Materials and Components
Lyon, France, 17-20 April 2005

10DBMC International Conference On Durability of Building Materials and Components
LYON [France] 17-20 April 2005

Temporal Quantification Method of Degradation Scenarios Based on FMEA

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TT4-139

ABSTRACT

The introduction of sustainable development principles in the construction field and the wish to optimize the functioning of buildings lead us to develop methods that allow to design and manage buildings, during their whole life cycle, by taking into account the objectives of the users. Those methods are mainly based on the apprehension of degradations and failures of the building products. However there is no global capitalization and management method of degradation kinetics of building products.
In this context, we develop a method that allows us to identify and capitalize all the degradation scenarios of a building product and then to quantify their degradation kinetic. Finally, we can generate its multi-performance profiles.

Firstly, the system analysis provides us with a functional model of the building product. Then the Failure Modes and Effects Analysis (FMEA) allows us to determine and capitalize its whole potential degradation scenarios.
The second step is the quantification of the degradation kinetic, i.e. the research of degradation dates and scenario times. First of all, we capitalize all available information on degradation state curves. Then we select and unify a part of this information from various sources, for each degradation phenomenon of the studied building product. After that, we determine the degradation scenario times, from the degradation phenomenon times.
Thirdly, we evaluate the functionnal performances of the building product. We start on the degradation scenarios related to the considered use function. Then, the correlation between the degradation states and the performance levels leads us to evaluate the multi-performance profiles of a building product during its exploitation stage.

The temporal quantification and the multi-performance profile evaluation both provide us with the service life of building products. On the one hand, it corresponds to the quickest degradation scenario, on the other hand it corresponds with the time until the first performance threshold is reached.
Lastly, we present the main forecasted developments and perspectives of this method.

KEYWORDS

Degradation kinetic, degradation scenario, FMEA, multi-performance profile, service life.

1 INTRODUCTION

Since twenty years, the building field tries to integrate sustainable development principles, in order to improve the welfare of present and future generations. Those principles influence on the building design and management, notably the inspection - maintenance - repair, that are expressed as the will to hold the functional performances of buildings. As a matter of fact, to improve the design and the management of buildings, one has to know “how” and “when” buildings and their components (building products) will be degradated or will fail, in order to know “how”, “when” and “on which” one should intervene. Without this information, the design and the management are not optimum and generate significant exploitation costs that could be reduced.
In the industry field, a lot of failure analysis methods has been developed; their description can be found in [Desroches *et al.* 2003] and [Zwingelstein 1996]. Jérôme Lair [Lair 2000] selected one of those methods, the Failure Modes and Effects Analysis (FMEA), and adapted it to the building field specificities. We have completed his research ([Talon *et al.* 2003], [Talon *et al.* 2004]) so as to have a progressive view of failure by introducing the notion of degradation and to automate this analysis. Indeed, this method allows us to be exhaustive in the search of degradations and degradation scenarios, but its use application needs a quite long time.
Moreover, there is a significant knowledge of states and kinetics of degradations of the materials used in the building sector. We can extract from a lot of studies the ones on the concrete degradations ([Vu & Stewart 2002], [Taylor 1997] and [Crane 1983]). However, those specific studies are relevant to a material and not to a building product that is generally composed of several materials.
The performance evaluation is a significant thematic of the building field, as the PeBBu (Performance Based Building) network proves it. On the same topic, we can notably notice the Performance Limits Method [Re Cecconi & Iacono 2003] that allows estimating the service life of a component by definition of the limits of its performance characteristics. However, this method is interested in the performance characteristics of a specific function of the building product and consequently not in all the functions of the studied building product.
That are the reasons why we propose a temporal quantification method of degradation scenarios that allows us to evaluate the multi-performance profiles of building products during their exploitation stage, and consequently to determine their service life. We aim this method to be applicable to all building products.

2 IDENTIFICATION AND CHARACTERIZATION OF DEGRADATION SCENARIOS

The aim of this phase is to obtain the degradation chainings that could damage the studied building product during its exploitation stage. The system analysis and next the Failure Modes and Effects Analysis (FMEA) provide us with the list of the degradation scenarios.

2.1 System analysis

The system analysis consists in modelizing the building product behaviour submitted to stresses that could undergo during its exploitation stage.
The first step of this analyis is to build up the structural model. It needs the determination of mecano-physico-chemical and geometrical characteristics of the components that constitute the studied building product, and the determination of links between all those components.
Then we characterize the stresses. This step including the determination of the building product media (for example the inside and the outside media for a front wall) and the identification of their environmental agents (for example: the snow, the wind, the solvent...).
The final step is the functional model building, based on the identification of the functions that are ensured by the building product and its components. It allows us to know the building product behaviour submitted to the previously defined stresses.

In order to aid the user in that phase, we developed both a database of environmental agents and a database of the functions that are ensured by building products.
The functional model is the starting point of the Failure Modes and Effects Analysis.

2.2 Failure Modes and Effects Analysis

The interest of the Failure Modes and Effects Analysis (FMEA) is to obtain the more complete as possible list of degradations and degradation chainings that could damage the building product during its exploitation stage. The FMEA is a risk analysis method, developed during the 1970's and still used in industrial fields, such as spatial, nuclear, medical,...The application of this method to the building field was initiated by Jérôme Lair [Lair 2000] who modified the table format that allows to capitalize the FMEA results.
First of all, the FMEA principle consists in defining the potential degradation modes, the causes (stresses, incompatibilities between materials) and the consequences for each function/component pair. It is to be noticed that all the function/component pairs and the stresses had been identified during the system analysis.
The second step consists in determining the degradation scenarios in an iterative way. The iterative principle, from a step i (step i=0: beginning of the exploitation stage) to a step $i+1$, is to determine if the degradation consequences of the step i could be the origin, that is to say the causes, of the degradations at the step $i+1$.
As far as the capitalization of the results and the automation of the FMEA are concerned, we created databases of material/stress pairs and incompatibilities between materials. Moreover we are developing a database of degradation phenomena.
For more information about the identification and the characterization of degradation scenarios, one can refer to the papers [Talon *et al.* 2003] and [Talon *et al.* 2004] that especially detail and illustrate this step within our global methodology.

3 TEMPORAL QUANTIFICATION OF DEGRADATION SCENARIOS

This paragraph presents the method that gives us the time evaluation of all the degradation scenarios of the studied building product, and then the evaluation of its service life from the knowledge of degradation states. We aim this method to be applicable to all the building products. As a matter of consequences, we present how we capitalize data about the states of degradation, relevant to all the potential degradations of building products. Then the way to exploit this data is exposed, in order to obtain the evaluations of degration scenario times and the service life of building products.

3.1 Capitalization of degradation state data

From the system analysis and the FMEA, the material and stresses associated to each degradation scenario are notably identified.
Consequently, we need to capitalize all the available information relative to the degradation states, for all the building products and for all the potential stresses that we defined in the database of environmental agents (cf. Paragraph 2.1).
The degradation state data may proceed from several origins (fundamental study, ageing testing, feedback, expert judgement,...), so the data may be heterogeneous, imprecise, uncertain and incomplete. That are the reasons why we evaluate the quality of each of the degradation state data.
In order to exploit this rough data, we have to define a common format. In this context, we propose the use of the Weibull laws (presented in [Murthy *et al.* 2004]). The obtained degradation state data are then named formalized data.
The following Fig. 1 schematizes the main stages of capitalization of degradation state data.

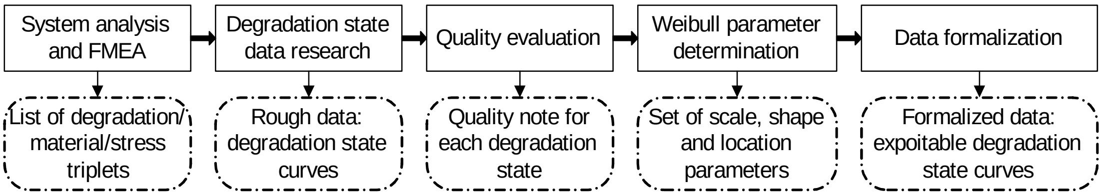


Figure 1. Capitalization principle of degradation state data.

3.2 Exploitation of degradation state data for a specific building product

The exploitation of degradation state data for a specific building product includes the selection and the unification of the formalized data as shown on paragraph 3.1.

The selection of data consists in drawing out all the formalized data that refers to the constitutive materials of the studied building product. For each triplet material/degradation/stresses, all the data could differ, owing to the fact that they come from different origins and that they are not wholly relevant to the product. Indeed, included into two different products the same material should not ensured the same functions. However, it could be damaged by the same degradation, but its kinetics should be different. As a matter of fact, the data will be all the more relevant as they will be associated to the same quadruplet material/degradation/stresses/function(s).

For all the potential degradations, the unification of data aims to provide us one degradation state, from all the available and selected formalized data. The unification of data (detailed in [Lair 2000]) allows us to take into account the quality of the data (with reference to the origin) and the relevance of the data to the studied case.

3.3 Evaluation of degradation scenario times

This phase consists in evaluating the degradation scenario times from the degradation states that have been previously determined. The principle of this evaluation is illustrated on Fig. 2.

One degradation scenario is a succession of degradations. Moreover, we can measure the degradation state - $E_i(t)$ - of a degradation *i* by its degradation rate, τ_i. Consequently, for a given degradation scenario S_j, the transition time $t_{i+1}^{S_j}$ from a degradation *i* to a degradation *i+1* is achieved when the degradation rate associated to the degradation *i+1* is reached.

As a consequence, the degradation scenario time Ts_j is the sum of times separating the degradations of this scenario. This can be formalized as follows :

$Ts_j = \sum_{i=0}^{n-1} t_{i+1}^{S_j}$ where *n* corresponds to the number of degradations of the *j* scenario.

Remark: *this result is applicable under the hypothesis that degradation states do not have mutual influence.*

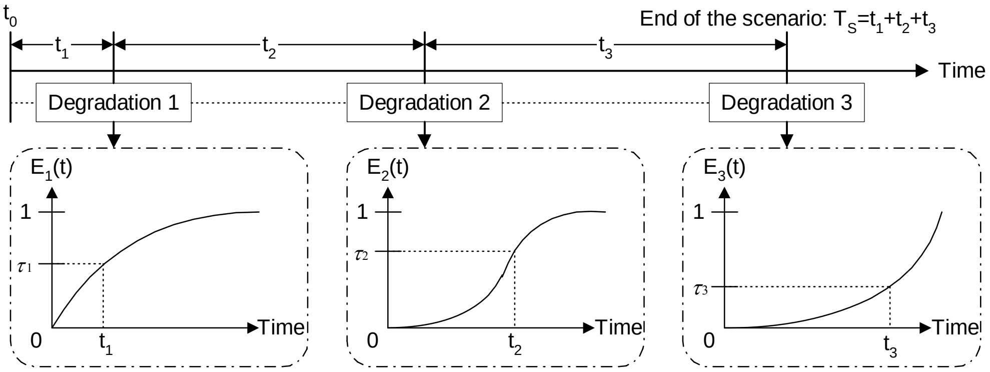


Figure 2. Evaluation principle of degradation scenario times.

3.4 Evaluation of building product service life

The building product service life, here named RSL as defined in the ISO 15686 Standard, can be considered as the time of the quickest degradation scenario. Consequently it is the minimum of the duration of all the determined degradation scenarios as presented in the paragraph 3.3. That can be formalized as follows :

$RSL = \min\limits_{j \in [1 \ldots m]} (Ts_j)$ where m corresponds to the number of degradation scenarios.

Remark: *this result is applicable only if one considers that each degradation has the same coming out possibility and that the performance thresholds of the use functions are zero (cf. paragraph 4.4).*
It is to be noticed that the determination of the service life of building products, when the degadations coming out possibilities differ ones from the others, is another part of the research – the criticity analysis – not presented in this paper.

The building product service life, as presented in this paragraph, does not take into account the users' waits. Indeed the performance thresholds of the use functions are zero. Consequentlythe way to evaluate the performance levels of the use functions will be presented in the following paragraphs. As a matter of fact, it will be then possible to evaluate a more relevant service life, i.e. when the performance thresholds are not zero.

4 EVALUATION OF MULTI-PERFORMANCE PROFILES

At a specific exploitation stage date, a multi-performance profile of a building product, is the representation of the performance state of all its use functions. The performance level of a use function corresponds to the capacity of the components to ensure this use function. The multi-performance profiles are evaluated from the knowledge of the degradations and of the correlation between degradation states and functional performance levels.

4.1 Selection of degradations

The system analysis and the FMEA provide us with the triplet material/stresses/functions for each degradation. Consequently, one scenario may be associated to several use functions (responding to the needs of the user) or to technical functions (allowing the building product to achieve the use functions). As a matter of consequences, one needs to select the degradations associated to each use function in order to evaluate the functional performance of this use function.

4.2 Relation between degradation states and functional performance levels

The aim of this step, as illustrated on Fig. 3, is to determine the correspondence between the use function' performance levels and the degradation states, for all the use function/degradation pairs previously selected.

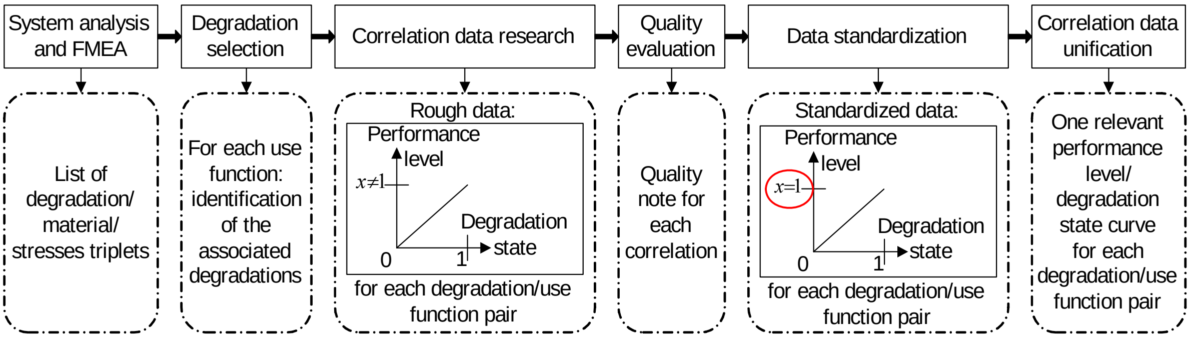


Figure 3. Relation principle between degradation states and functional performance levels.

We aim to capitalize the correlation data in order to facilitate the evaluations of the multi-performance profiles. This correlation data, as well as the degradation state data, may proceed from several origins. The performance levels could notably be evaluated according to different scales. That are the reasons why we evaluate the quality of rough data and standardize it, i.e. we represent them whith the same format in order to facilitate their exploitation.

The exploitation principle of correlation data is based on the unification of all the available data; it is the same as the exploitation principle of degradation state data that is detailed in paragraph 3.1.

4.3 Evaluation of the performance level of a use function at a specific exploitation stage date

The principle of evaluation of the performance level of a use function at a specific exploitation stage date is illustrated on Fig. 4.

The degradation times of the studied building product can be ranged on a time axis. The rectangles on the Fig. 4 represent the degradations and the arrows correspond to their chainings. The grey rectangles schematize the degradations relevant to the studied use function, here named F_1. At a T date, we have to consider the selected degradations that are anterior to T to evaluate the performance level of the F_1 function, here named $\mu^{F_1}(T)$. In the example of the Fig. 4, the degradations D_1 and D_5 are to be taken into account.

The degradation state curves of each degradation are supposed to be known; consequently one can determine their degradation rates, corresponding to this T date ($\tau_{D_1}(T)$ and $\tau_{D_5}(T)$ rates in our example).

Next, the performance levels corresponding to each of those degradation rates can be evaluated. Indeed, the way to correlate the performance levels and the degradation states of each degradation/use function pair has been detailed in paragraph 4.2.

The performance level of the considered use function, at a T date, is the minimum of the performance levels ($\mu^{F_1}_{D_1}(T)$ and $\mu^{F_1}_{D_5}(T)$ performance levels in our example) evaluated for all the considered degradations. That can be formalized as follows :

$$\mu^{F_1}(T) = \min_{i\in[1\ldots r]}(\mu^{F_1}_{D_i}(T))$$ where r corresponds to the number of degradations to be considered.

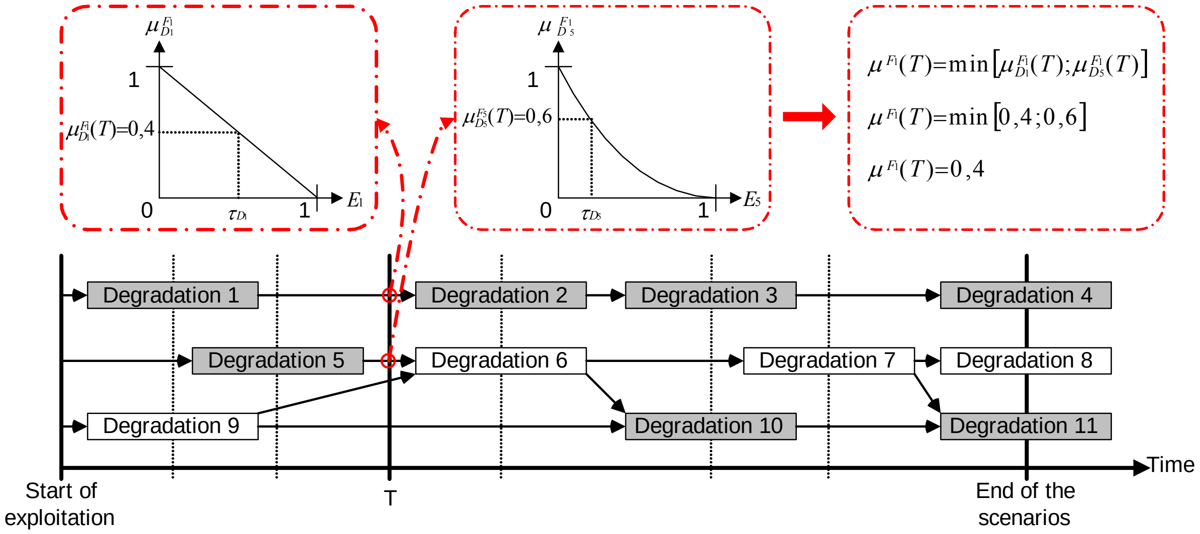


Figure 4. Evaluation principle of the performance level of one use function at a specific exploitation stage date. Grey degradations are the ones relevant to the F_1 use function.

4.4. Evaluation of multi-performance profile at a specific exploitation stage date

The evaluation of a multi-performance profile of a building product at a specific exploitation date, consists in determining the performance levels of all its use functions, at this date. Consequently, it corresponds to the realization of the step described in the paragraph 4.3 for each use function.
Two kinds of building product failures can be distinguished.
On the one hand, a building product fails when one of its use functions is no more ensured. The failure occurs when the performance threshold associated to this use function is reached. For a F_i use function, at a T date, that can be formalized as follows:

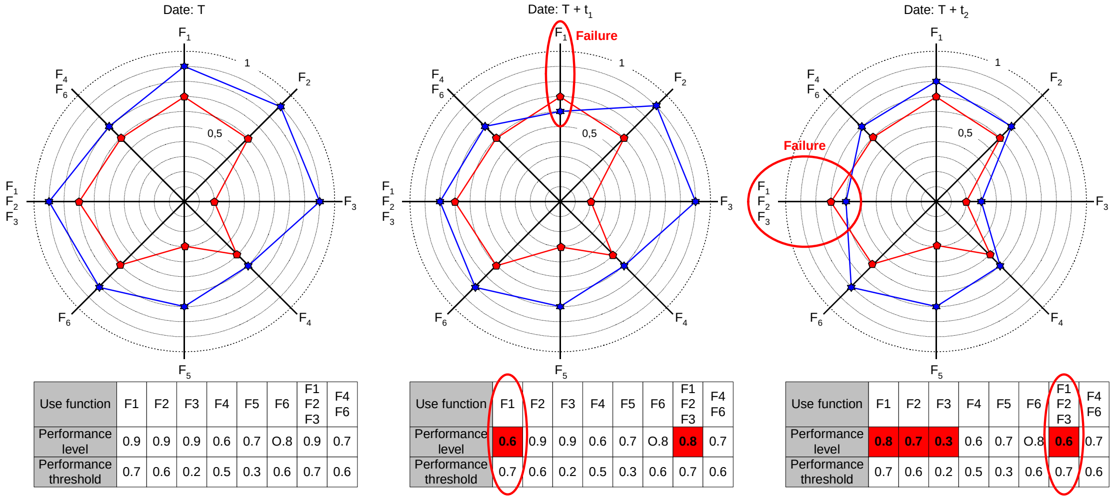
If $\mu^{F_i}(T) > \mu^{F_i}_{seuil}$ **then** there is no failure **otherwise** building product fails.

On the other hand, a building product fails when the performance level of a combination of its use functions (one global performance) is above the global performance threshold of this combination, even if all its use functions are individually ensured. For three F_i, F_j and F_k use functions, at a T date, that can be formalized as follows:

If $f(\mu^{F_i}(T), \mu^{F_j}(T), \mu^{F_k}(T)) > \mu^{[F_i, F_j, F_k]}_{seuil}$ **then** there is no failure **otherwise** building product fails.

Where $f(\mu^{F_i}(T), \mu^{F_j}(T), \mu^{F_k}(T))$ is a standardized function corresponding to the global performance of the F_i, F_j and F_k use functions. It is a combination of their performance levels.

As we have standardized the performance level data of all the use functions (cf. paragraph 4.2), we can have a global vision of the multi-performances of a building product at a specific exploitation stage date, by representing it with a multi-performance rosace. Examples of multi-performance rosaces are presented on Fig. 5.



Use function	F1	F2	F3	F4	F5	F6	F1 F2 F3	F4 F6
Performance level	0.9	0.9	0.9	0.6	0.7	O.8	0.9	0.7
Performance threshold	0.7	0.6	0.2	0.5	0.3	0.6	0.7	0.6

Use function	F1	F2	F3	F4	F5	F6	F1 F2 F3	F4 F6
Performance level	0.6	0.9	0.9	0.6	0.7	O.8	0.8	0.7
Performance threshold	0.7	0.6	0.2	0.5	0.3	0.6	0.7	0.6

Use function	F1	F2	F3	F4	F5	F6	F1 F2 F3	F4 F6
Performance level	0.8	0.7	0.3	0.6	0.7	O.8	0.6	0.7
Performance threshold	0.7	0.6	0.2	0.5	0.3	0.6	0.7	0.6

Figure 5. Multi-performance rosace examples. Red curves represent the performance thresholds, when blue ones are the performance levels. On the left rosace there is no failure, on both the middle and the right ones the building product fails.

4.5 Building product service life taking into account performance levels

In this context of multi-performance profile evaluation, the building product service life may be either the first time one use function performance threshold is reached, or the first time one global performance threshold – relative to a combination of use functions – is reached.

5 DEVELOPMENTS AND PERSPECTIVES

Our contributions on system analysis, on FMEA and on databases facilitate each step from the description of the building product to the more complete as possible FMEA. Nevertheless, it still takes a long-time for manually carrying out them.

That is the reason why the FMEA generation is being automated. We aim this software to be an FMEA realization aid, during the achievement of a "classical" FMEA by the experts of the building product field.

Moreover, this paper was focused on the temporal quantification of degradation scenarios of building products, but we are also extending this analysis to the building scale.

A main perspective is to propose a method to manage the muli-performance profiles of the building products. Indeed, at the present time, we are able to evaluate a multi-performance profile at a specific exploitation stage date. The aim of this management method would be to evaluate the influence of the change of use function performance thresholds on the service life of building products.

6 CONCLUSION

We proposed a temporal quantification method of degradation scenarios, applicable to building products, during their exploitation stage. This method provides us with the degradation scenario times, the multi-performance profiles of the building products at each date of their exploitation stage and their service life.

Firstly, the temporal quantification method is based on the identification and characterization of degradation scenarios, which are obtained by a system analysis and a FMEA.

Then, the capitalization, the formalization and the unification of degradation state data allow us to evaluate degradation scenario times and service life of building products. This service life corresponds to the quickest degradation scenario without taking into account the performance thresholds of use functions.

Finally, we are able to evaluate multi-performance profiles by correlating degradation states to functional performance levels and product service life including users' waits on performance levels.

This method provides the building actors with a precious help for building product design, by identifying the causes and the consequences of potential degradations, and building product management, by knowing "when" and "how" the building products could fail.

7 REFERENCES

Crane, A.A. 1983, *Corrosion of reinforcement in concrete construction*, Ellis Horwood, London.

Desroches, A. Leroy, A. Vallée, F. 2003, *La gestion des risques – principes et pratiques*, Lavoisier, Paris.

Lair, J. 2000, *Evaluation de la durabilité des systèmes constructifs du bâtiment*, thèse préparée au CSTB et au LERMES.

Murthy, D.N.P. Xie, M. Jiang, R. 2004, *Weibull Models*, Wiley Interscience, U.S.A.

Re Cecconi, F. Iacono, P. 2003, ' "Performance Limits Method" (PLM) A New Way To Service Life Prediction', Proc. International Workshop on Management of Durability in the Building Process, Milano, Italy, 25 26 June 2003.

Talon, A. Boissier, D. Chevalier, J.-L. Hans, J. 2004, 'A methodological and graphical decision tool for evaluating building component failure', Proc. CIB World Building Congress 2004, Toronto, Canada, 2 7 may 2004.

Talon, A. Boissier, D. Chevalier, J.-L. 2003, 'Failure Mode, Effects and Criticality Analysis: risk analysis methodology for capitalization and use of experience and knowledge on building products degradations', Proc. 2nd International Symposium on Building Pathology, Durability and Rehabilitation, Lisboa, Portugal, 6 8 november 2003.

Taylor, H.F.W. 1997, *Cement chemistry*, Thomas Telford, London.

Vu, K.A.T. Stewart, M.G. 2002, 'Service Life Prediction Of Reinforced Concrete Structures Exposed To Aggressive Environments', Proc. 9th International Conference on Durability of Building Materials and Components, Brisbane, Australia, 17th 21st March 2002.

Zwingelstein, G. 1996, *La maintenance basée sur la fiabilité*, Hermès, Paris.

Contribution from the CSTB

A. Talon, D. Boissier, J-L. Chevalier, J. Hans

A Methodological and Graphical Decision Tool for Evaluating Building Component Failure

2004

Original publication:

Proceedings of the CIB World Building Congress (CIB WBC 2004)
Toronto, Canada, 2-7 May 2004

A Methodological and Graphical Decision Tool for Evaluating Building Component Failure

CIB T2S5 Facilities management and maintenance

A. Talon (Ph-D student), D. Boissier (Prof.), J-L. Chevalier (Dr. Eng.)
J. Hans (Dr. Eng.)

The goal to improve the quality and the maintenance of building products, and the will to integrate the sustainable development objectives led us to propose an original method based on the use and adaptation of the Failure Modes Effects and Criticality Analysis.

This tool aims to improve the reliability and quality of innovative products by developing preventive actions of risk analysis and quality management at design and installation stages. We try to facilitate the operational follow up of existing products by creating maintenance plans and Inspection Maintenance Repair procedures. These corrective actions are realized during the exploitation stage. This tool also allows us to capitalize on the expert's experience and knowledge. We wish to computerize this method in order to offer a useful tool to the building actors.

The first steps of the method include a structural analysis (definition of the product, its components and environment), a functional analysis (identification of functions ensured by the product and its components), and a process analysis (study of the process stages).

Then a Failure Modes and Effects Analysis (FMEA) is led in order to identify failure modes (research of degradations and failures of components), their causes and effects, taking into account the potential problems and errors, which could occur during the construction process.

A quantitative analysis will allow us to represent the temporal evolution of degradations, the intensity of the involved phenomenon and the geometrical density of degradations. Moreover, a critical analysis will provide us to select the more pertinent failure modes.

We will develop a graphical representation tool simplifying each step of the approach, based on the automation of the approach, the use of databases (list of climatic factors, functions, service life …) and the use of graphical tools.

We apply this approach on several building products, notably a panel solar system.

KEYWORDS

Durability, FMEA, failure modes, risk analysis, maintenance

A Methodological and Graphical Decision Tool for Evaluating Building Component Failure

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1. ABSTRACT

The goal to improve the quality and the maintenance of building products, and the will to integrate the sustainable development objectives led us to propose an original method based on the use and adaptation of the Failure Modes Effects and Criticality Analysis.

This tool aims to improve the reliability and quality of innovative products by developing preventive actions of risk analysis and quality management at design and installation stages. We try to facilitate the operational follow up of existing products creating maintenance plans and Inspection Maintenance Repair procedures. These corrective actions are realized during the exploitation stage. This tool also allows us to capitalize on the expert's experience and knowledge. We wish to computerize this method in order to offer a useful tool to the building actors.

The first steps of the method include a structural analysis (definition of the product, its components and environment), a functional analysis (identification of functions ensured by the product and its components), and a process analysis (study of the process stages).

Then a Failure Modes and Effects Analysis (FMEA) is led in order to identify failure modes (research of degradations and failures of components), their causes and effects, taking into account the potential problems and errors, which could occur during the construction process.

A quantitative analysis will allow us to represent the temporal evolution of degradations, the intensity of the involved phenomenon and the geometrical density of degradations. Moreover, a critical analysis will provide us to select the more pertinent failure modes.

We will develop a graphical representation tool simplifying each step of the approach, based on the automation of the approach, the use of databases (list of climatic factors, functions, service life …) and the use of graphical tools.

We apply this approach on several building products, notably a panel solar system.

2. INTRODUCTION

The building vision had been modified by the new objectives of sustainable development: “a development which answers the needs of the present generation without compromising the ability of future generations to answers theirs” (Charlot-Valdieu and Outrequin 1999). A building has not only to satisfy technical and economical criteria. Nowadays, we must increase its quality (improvement of occupiers comfort, long-terms use …) and its maintenance (improvement of maintenance procedures efficiency and maintenance planning, reduction of maintenance costs, respect of the environment …).

This paper is a presentation of a particular functional approach of the durability, as it has been defined in the (Afnor 1988): “aptitude of one entity for fulfilling a required function in given conditions of use and maintenance, until a limit state has been reached”. We propose a methodological and graphical tool for decision aid by risk analysis and maintenance planning at design and exploitation stages. Jérôme Lair involved this research seven years ago (Lair 2002; Lair 2001; Lair 2000; Lair 1999).

This paper is composed of four parts: the presentation of the method, its applications to risk analysis and maintenance planning, the limits of the method and its perspectives.

To facilitate the comprehension, an example of a panel solar system will illustrate the method presentation.

3. METHOD

3.1 Principle

The proposed method is based on a risk analysis tool, the Failure Modes, Effects and Criticality Analysis (FMECA), developed in the sixties for the aeronautic domain and presently used in the space, nuclear, chemical and cars industries (Leroy 1992; Modarres 1993). Jérôme Lair has adapted this tool to the building specificities (Lair 2000).

The originality of this method is fourfold.

Firstly, we intend to take into account all the available knowledge on the studied product: its physico-chemical composition, topology, morphology, functioning, and environment …

Secondly, we search to use, analyze, treat, and capitalize all the information of degradations and failures which could damage the studied product: causes, degradation modes, consequences, risk for the product and its environment, chaining of degradations leading to the failure of the product …

Thirdly, we aim at the method would be easily used by the various building actors as a decision aid. This motivates the use of data bases development and graphical representations.

Our final objective is to develop a software associated to the method. Consequently we want each step to be easily automated.

The proposed method is composed of four parts: the system analysis (definition of the product, its components, its environment, its functioning), the qualitative analysis (determination of all the degradations and failure which damage the product), the quantitative analysis (research state) and the graphical representation results of the quantitative analysis (Event-driven graph and failures tree).

3.2 System analysis

The results quality of a study depends on that we try to determine. For instance, it is not necessary to study the whole building if we only want to evaluate the impact of reinforcement corrosion on the concrete for one of the building beams. So, it is essential to define the limits (spacial and temporal) of the studied system and the study scales. We distinguish three scales: the temporal scale, the geographical scale (for instance the four levels scale defined by (Haagenrund 1996): macro environment, meso environment, local environment and micro environment) and the granular scale (structural detail level).

The system analysis is composed of three steps: a structural analysis, a functional analysis and a process analysis.

3.2.1 Structural analysis. The structural analysis firstly consists on the decomposition of the products into components. For each of its components we determine its morphology and physico-chemical composition. The Figure 1 is describing the schematization of the eight components of a solar panel system. The “external components” are outside the spacial limit of the studied product.

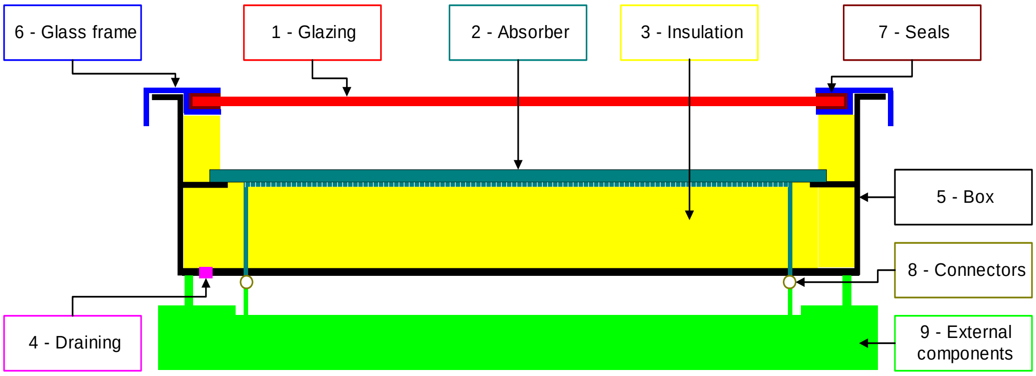


FIGURE 1.
Structural decomposition of a solar panel system

Secondly, we determine the existence and the nature of links between:

- each component of the product (one example for the panel solar system is the link between "glazing" and "seals"),
- the components of the product and the external components of the system (for example: the link between "box" and "external components").

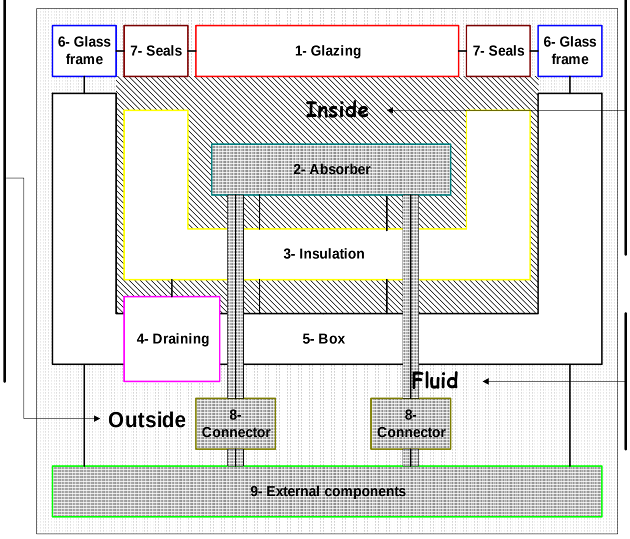
Thirdly, we identify the "mediums" of the product and their environmental composition (a "medium" is composed of several environmental agents). For example, we have to take into account two mediums when we study a window: the external environment (outside the building) and the internal environment.

To facilitate this third step of the structural analysis, we have created a database including all the principal environmental agents that are generally occurred. We have classified the various data, essentially collected in (EOTA 1999; ISO 1997; Lorusso et al. 1999), on eleven categories: liquids, vapors, gas, electricity, radiations, temperatures, animals, vegetables, noises, mechanical actions, precipitations.

Figure 2 regroups the results of the structural analysis of a solar panel system, that is to say the structural representation of components (corresponding to the FIGURE), the schematization of the three mediums that have to be considered (outside environment, inside environment and heat conveying fluid) and the environmental composition of each medium.

Main climatic and use factors for outside environment :

- Temperature (high, low, cyclic, thermal shock),
- Water, vapour, rain, snow, hail, ice,
- Infrared radiation, ultraviolet radiation,
- Loads, pressure, wind, shocks, etc,
- Oxygen, nitrogen,
- Pollutants,
- Vegetation, moss, lichen, etc,
- Vertebrate, etc.



Main climatic and use factors for inside environment :

- Temperature (high, low, cyclic),
- Vapour,
- Infrared radiation, ultraviolet radiation,
- Pressure,
- Oxygen, nitrogen,
- Indoor pollutants.

Main climatic and use factors for heat conveying fluid :

- Water,
- Antifreeze agent.

FIGURE 2.
Structural analysis result representation of the components and links of a solar panel system and environmental composition of the three mediums

<u>3.2.2 Functional analysis</u>. The functional analysis consists on the determination of the functions ensured by the product and each of its components. We distinguish two kinds of functions: the need's functions and the technical and constraint functions.

The need's functions correspond to the essential functions for which the product is realized and fulfill the user's needs. The satisfaction of technical and constraint functions allows the realization of need's functions. This distinction is useful for the quantitative analysis.

At this stage, the functions ensured by each component of the product and the environmental agents in touch with each of those components are known (cf. *Structural analysis*). Consequently we have identified the reactions of the component solicited by environmental agents. For instance, the "glazing" permits the ultraviolet radiation and the "seals" stop the rain. Therefore, we can modelize the evolution of environmental agents through the product.

We use a graphical representation (functional diagram) of this evolution. The arrows correspond to the way of the environmental agents flow. The prohibition roadsign schematize the stopped of this flow. We plot a functional diagram for each category of environmental agents (cf. *Structural analysis*). The Figure 3 displays the functional diagram corresponding to heat flow evolution (geared by solar energy) in the solar panel system. The heat source (solar energy) is symbolized by a sun.

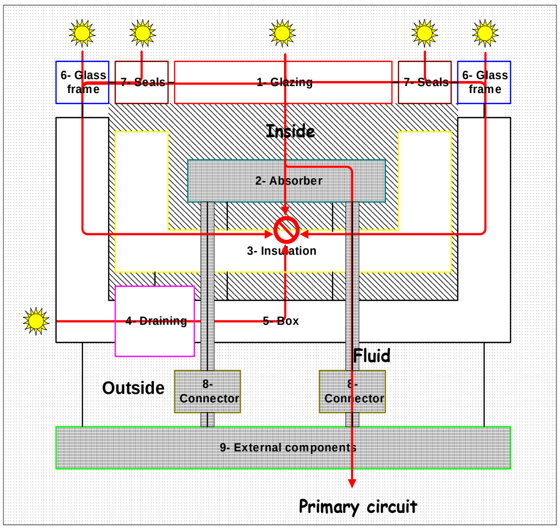


FIGURE 3.
Functional diagram corresponding to the representation of the heat flow evolution through the solar panel system

<u>3.2.3 Process analysis</u>. The aim of the process analysis is to determine all the errors, defects, damages, degradations … that could occur to the product during its construction process (design, manufacturing, packaging, transport, storage, installation …) and could modify the behavior of the product in service.

We are searching a method which allows us to capitalize that information.

3.3 Quantitative analysis

The goal of the quantitative analysis is to determine the behavior of the product in service, knowing its state at the beginning of its exploitation (cf. process analysis), and with information of the system analysis.
We capitalize the results of the qualitative analysis in Failure Mode and Effects Analysis (FMEA) table, presented on Table1.

Functions	Components	Origin stage	End stage	Modes	Causes	Direct effects	Indirect effects

TABLE 1.
Proposed format of a FMEA table – Capitalizing tool of chaining of degradations leading to the product failure: modes, causes and consequences of degradations for each component and each associated function

The first two columns are filled from the information of the system analysis.

We distinguish two types of causes of degradation. The first ones are classical causes as the action of an environmental agent on a component. To facilitate the determination of those causes, we created a database which contains the aggressiveness level of environmental agents on materials. The second type of causes is the unexpected behaviors due to building process (cf. Process analysis).

The determination of causes, modes, direct effects and indirect effects are facilitated by the functional diagram (cf. *functional analysis*). Indeed, these diagrams are a simple and visual representation of the contacts between environmental agent and component and of the reaction of component faced with those solicitations.

The FMEA is based on an iterative principle: the direct or indirect effects can become the cause of other degradations. With this principle we obtain all the failure scenario of the product (chaining of components degradations leading to the product failure). The failure of the product is obtained when one of its principal functions are no more fulfilled.

We consider that the FMEA is finished when all the possible chaining of degradations have led to the components failure or the product failure (when a need's function is at stake).

The columns "origin stage" and "end stage" are useful when the FMEA is finished. Indeed, whatever the considered degradation, we can find the previous degradation.

The following FMEA table (Table 2) is an extract of the FMEA of a solar panel system. This extract aims to illustrate the iterative principle.

Function	Component	Origin stage	End stage	Modes	Causes	Direct effects	Indirect effects
To be tight (liquid, vapour, gas, vegetation, vertebrate)	Seals	a.0	a.1	Surface degradation	Ultraviolet radiation	Surface disintegration	----------
		a.0	a.1	Ozone cracking	Ozone	Holing	----------
		a.1	a.2	Surface disintegration	Ultraviolet radiation	Holing	----------
		a.2	a.3	Holing	- Ozone cracking - Surface disintegration	Failure	Stresses of components in contact with inside environment by outside environmental agents
To be tight (liquid, vapour, gas, vegetation, vertebrate)	Glazing	b.0	b.1	Cracking	- Deviation of temperature between inside and outside environments (low temperature, hail, snow, rain) - Thermal shock - Schocks (vertebrate, hail) - Pressure - Wind	Glazing embrittlement	----------
		b.1	b.2	Breaking	Glazing embrittlement	Failure	Stresses of components in contact with inside environment by outside environmental agents
To absorb infrared radiation	Coating (absorber)	a.3 et b.2	c.4	Corrosion	- Seals : Infiltration of liquid - Seals : Infiltration of pollutants - Glazing : Infiltration of liquid - Glazing : Infiltration of pollutants	Holing	----------
		a.3 et b.2	c.4	Breaking	- Seals : Action of vertebrate - Seals : Action of hail - Glazing : Action of vertebrate - Glazing : Action of hail	Failure	----------
		c.4	c.5	Holing	Corrosion	Failure	----------

TABLE 2.
Extract of an FMEA table of a solar panel system – Illustration of the iterative principle that the direct or indirect effect of degradation can become the cause of an other degradation

3.4 Graphical representations of the quantitative analysis results

The qualitative analysis provides a list of all the potential failure scenario of a product. Those results are identified with difficulty in the FMEA table. That is the reason why we chose to develop clear and synthetic graphical representations of the qualitative analysis results. We develop two types of graph:

- the event-driven graph, which is the representation of the "temporal" evolution of degradations of components leading to the failure of the product;
- the failures tree, which is a deductive method (Hadj-Mabrouk 1997) (from the product failure to the origin causes).

3.4.1 Event-driven graph. The Event-driven graph is composed of three parts: the initial state, the degradations states and the failure state.

The initial state (begin of the graph) represents the state of each component of the product at the beginning of its exploitation stage. This state takes into account all the potential degradations (identified with the process analysis) due to errors, mistakes, damages… on the product occurred during the building process.

The degradations states regroup all the potential successions or concomitances of degradations of components from the initial state to the failure state. We also schematize the causes of degradations due to environmental agent solicitations.

The failure state (end of the graph) contains the various failures of the product, that is to say that the product is no more able to ensure one of the need's functions for which it was designed.

The Figure 4 is an extract of an event-driven graph of a solar panel system. This graph represents the failure scenario defined below (cf. Table 2).

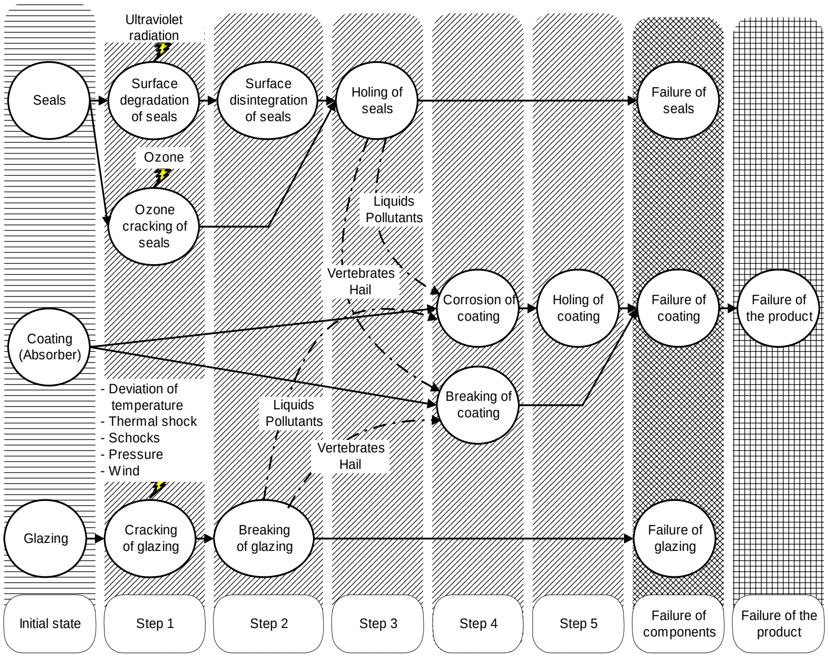


FIGURE 4.
Extract of an event-driven graph of a solar panel system – Representation of the succession or concomitance of degradations of components from the initial state (begin of the exploitation stage) to the failure state

3.4.2 Failure Tree. The failure tree is built from the inverse reading of the FMEA table. We start from the end of the table (which corresponds to the failure state of the event-driven graph) and we search the previous degradations as we find the origin degradation (same as the step 1 of the event-driven graph). The failure tree is a graphical representation of the deduction of the origin degradations from the failures of the product. It is useful when we search the origin of a specific failure or degradation of the product or one of its components.

4. APPLICATIONS

As qualitative analysis provides us a list of failure scenario, and as both event-driven graph and failure tree represent (inductively and deductively) those chaining of degradations, we have defined two ways of applications: design aid and management aid.

The Figure 5 represents the domain of application of both design aid (from design to product failure) and management aid (during the exploitation stage).

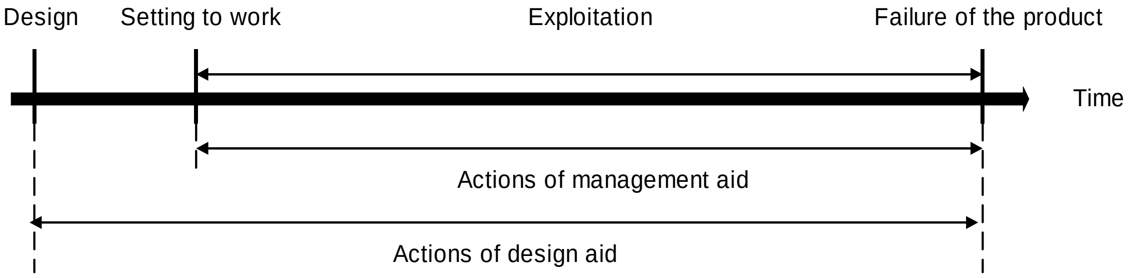


FIGURE 5.
Representation of the domain of application of design aid and management aid during the life of the product

4.1 The method application as design aid

We can use both event-driven graph and failure tree in order to improve the product quality and to plan the maintenance procedures.

4.1.1 Event-driven graph and failure tree for improving the product quality. The end of the event-driven graph and the top of the failure tree represent all the potential failures of a product. To improve the quality of its product (that is to say to avoid a specific failure) the user must know the true and initial causes of this failure.

By coming down the degradations associated to the considered failure from the failure tree, the user can find the initial degradations. By following up the failure scenario (from the considered failure to the real degradations) in the event-driven graph, the user can identify the degradations on which he can intervene if he wants to stop the degradation evolution leading to the considered failure of his product.

4.1.2 Event-driven graph for planning the maintenance procedures. Maintenance influences the durability (in terms of service life) of buildings and the global cost of the construction (Perret 1995). Consequently it is essential to plan the maintenance procedures during the design of the building.

The event-driven graph gives each chaining of events (degradations and / or failures of components) leading to the failure of the product. Consequently, the user knows how the degradations will potentially occur during the exploitation stage. The user can thus choose which degradation he wants to avoid.

One of our perspectives is to integrate the time (within a quantitative analysis approach) in the event-drive graph. Therefore the user will know when the degradations will potentially occur. Finally the user will be able to plan the maintenance procedures from the event-driven graph information.

4.2 The method application as management aid

The third main procedures for building maintenance are:

- the systematic preventive maintenance procedures,
- the conditional maintenance procedures,
- the corrective maintenance procedures.

4.2.1 Event-driven graph as a management aid for establishing systematic preventive maintenance procedures. The principle of the systematic preventive maintenance is to intervene before the apparition of one of the product serious degradations.

For a specific degradation, we can visualize it on the graph and identify all the chaining of degradations (from the initial state) which lead to the considered degradation. In order to avoid this degradation we must stop the evolution of all those chaining of degradations. To stop a chaining of degradations, we have to intervene on one of its degradations. A “minimal cut” is the list of the chosen degradations for all the chaining of degradations leading to the degradation that we want to avoid.

Several “minimal cuts” can be chosen, and the maintenance procedures associated are different. Consequently the user can compare and choose the more appropriate “minimal cut” as regards its economic, social, environmental … obligations.

For example a “minimal cut” at the beginning of the graph (the chosen degradations are at the beginning of the graph) will define cheap but very regular maintenance procedures. On the contrary, a “minimal cut” at the middle of the graph will generate less regular maintenance procedures but also a low performance of the product.

4.2.2 Event-driven graph as a management aid for the establishment of conditional maintenance procedures. The principle of a conditional maintenance is to intervene on the product when symptoms of degradation have been observed during the diagnosis.

The user can locate on the event-driven graph the symptom he has observed during the diagnosis. He can thus identify the evolution of this symptom on the graph by following the failure scenario associated to this symptom. He can also determinate all the potential causes of this degradation by going up the failure scenario linked to this degradation.

4.2.3 Event-driven graph and failure tree as a management aid for establishing corrective maintenance procedures. The principle of the corrective maintenance is to repair the product when he had failed.

The user can identify all the potential causes of an observed failure on his product with help of both the event-driven graph and the failure tree.

With the event-driven graph, the user can locate on the graph the failure he observed on his product during a diagnosis. Then he can visualize on the graph the entire failure scenario which lead to the considered failure. The origin of those failure scenario (begin of the graph) are the initial degradations; and the causes of those degradations are the initial causes of the considered failure.

With the failure tree, the user can identify the observed failure at the top of the tree and come down to the origin degradations and causes.

Finally, the user can choose the appropriate corrective maintenance procedures, which are the ones that remedy to the real causes of the failure.

5. LIMITS AND PERSPECTIVES

Still now, one of the main limits of the method is the non integration of the time scale. Thus we don’t know the temporal evolution of degradations of the product. This integration is crucial, as it can be seen in Figure 4. Indeed, on this extract of an event-driven graph of a solar panel system, we didn’t quantify the time of a glazing cracking with those environmental solicitations, and the time of a surface degradation of seals. Consequently we represent them at the same step that is not realistic.

We are searching to integrate the time within a quantitative analysis and then we have to quantify the kinetic of degradations of product components.

Another aspect is that we don’t evaluate the phenomenon intensity and the spacial repartition of degradations on the product and its components. The development of a criticality analysis will allow us to take into account those aspects and will permit to classify the failure scenario with a criticality scale and to focus on the more serious failure scenario.

6. CONCLUSION

We propose a methodological and its associated graphical tool for decision aid on maintenance planning; at design and exploitation stages; it is based on risk analysis and adaptation of an efficient tool called FMECA to building specificities.

This method is composed of four parts.

A system analysis (structural analysis, functional analysis, process analysis) which allows to collect, capitalize and use the information concerning the structure of the product, its functions and its environment.

A qualitative analysis of risks which aims to describe the degradations and failure of the product (causes, consequences, modes, failure scenario …).

A quantitative analysis: quantification of kinetic of degradations of product components and classification of failure scenario (criticality analysis).

And lastly two graphical representations of the result: the event-driven graph and the failure tree.

We apply those both graphical tools on design aid (improvement of the product quality, planning of the maintenance) and on management aid (establishment of systematic preventive maintenance procedures, conditional and corrective maintenance procedures).

7. REFERENCES

Afnor. 1988. *X60-500 : Terminologie relative à la fiabilité – Maintenance – Disponibilité*.

Charlot-Valdieu,C. and Outrequin, P. 1999. La ville et le développement durable. Cahiers du CSTB, Livraison 397, Cahier 3106.

EOTA. 1999. *Assessment of working life of products*. Guide technique 003.

Haagenrud Svein, E. 1996. Environmental characterization including equipment for monitoring. Norvège : Norsk insitutt for luftforskning.

Hadj-Mabrouk, H. 1997. L'analyse préliminaire de risques. Paris: Editions HERMES.

ISO. 1997. *ISO TC 59 SC 3 : Buildings – Service Life Planning – Part 1 General principles*.

Lair, J. Chevalier, J.-L. 2002. Failure Mode Effect and Criticality Analysis for Risk Analysis (design) and Maintenance Planning (exploitation). Proceedings of the 9th Durability of Building Materials and Components. Brisbane, Australia.

Lair, J. Chevalier, J.-L. Rilling, J. 2001. Operational methods for implementing durability in the service life planning framework. CIB World Building Congress, Wellington, New-Zealand.

Lair, J. 2000. Evaluation de la durabilité des systèmes constructifs du bâtiment. Thèse préparée au CSTB – Service matériaux et au LERMES.

Lair, J. Le Téno, J.-F. Boissier, D. 1999. Durability assessment of building system, Durability of Building Materials & Components 8, Vancouver. ED : NRC-CNRC.

Leroy, A. Signoret, J.-P. 1992. Le risque technologique. Paris : Editions Presses universitaires de France.

Lorusso, S. Marabelli, M. Viviano, G. 1999. Pollution de l'environnement et impact sur les biens culturels. Château-Gontier : EREC.

Modarres, M. 1993. What every engineer should know about reliability and risk analysis. New York: Editor Dekker.

Perret, J. 1995. Guide de la maintenance des bâtiments. Paris : Editions Le moniteur.

Contribution from the CSTB

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OPERATIONAL METHODS FOR IMPLEMENTING DURABILITY IN SERVICE LIFE PLANNING FRAMEWORKS

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ABSTRACT

The ISO 15686 set of standards dealing with service life planning will include an integrated design framework for buildings, incorporating technical, economical and environmental aspects from the very early stages to detailed specification, construction and maintenance.

Durability, that is sustained performance beyond an initial level, is a major parameter to guide that process. From the standard's point of view, it amounts to the determination, based on all of the data available, of a reference service life of the component at hand (RSLC) and of correction factors (A to G) to take into account the effect of process quality aspects (setting up, maintenance, etc.) on this initial estimation of service life.

At its present state of development, this standard does not provide ways to:

1. Make use of all of the service life data which is available in an explicit way, hence making it more open to quality assessment and certification than the current approach which relies solely on professional judgement,
2. Provide a more objective, hence less arbitrary, way to assess the values of the factors.

Therefore complementary methods and tools are needed to help implement the standard's requirements in practice.

By using the case of an innovative cladding product this paper shows that a more explicit and objective method can be achieved by using (a) a data fusion technique and (b) a failure modes and effects analysis (FMEA), respectively. Both methods have been extensively tested and are now routinely used for construction component technical performance assessment within CSTB, particularly for innovative products. The paper also includes examples from other product families.

The evaluation of a component's RSLC goes through the following steps. Firstly the accumulation of existing information on the product as a whole, on its components, and on the deterioration mechanisms leading to a decrease in performance. These data are organised as a function of their granularity and qualified as a function of their source, production mode, and relevance. Secondly they are combined using a statistical technique from Evidence Theory, to provide a service life distribution bracketed by "confidence intervals". Lastly, an additional treatment extracts some characteristic service life value(s) together with a global quality index. The required computations are performed by dedicated software developed by CSTB.

FMEA is a qualitative technique for the evaluation of a system's reliability. Although it was developed in the 1960s in the aeronautical industry, and has been adapted since then to mechanical and electrical engineering, it is seldom used in construction, even though its concepts are generally familiar.

This method can also be used as a basis for the diagnosis of pathologies in audited buildings and for the setting up of an optimised preventive maintenance scheme (Reliability Centred Maintenance). As such, FMEA is a promising method that could be used at various places in the standard, thus providing a uniform concept and increasing the possibility of adoption by practitioners.

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KEYWORDS

Durability, Quality, Data fusion, FMEA, Service life

INTRODUCTION

Currently society thinks about “Sustainable Development” (in terms of avoiding quality problems in building construction, of taking into account social, environmental and economical aspects) encourages us to develop methods and tools for durability assessment of building products (both traditional and innovative products). (see (Jernberg, 1997)).

CONTEXT

The ISO 15686 (ISO, 1998) set of standards “Service life planning” is developing an integrated design framework for buildings, incorporating technical, economical and environmental aspects.

Durability, i.e. “capability of a building or a building part to perform its required function over a specified period of time under the influence of the agents anticipated in service” is a major parameter which guides that process.

Factors method

From the standard’s point of view, durability amounts to the determination, based on every available data of:

- a reference service life of the component (RSLC) defined as “period in years that the component or assembly can normally be expected to last”
- correction factors (A to F) to take into account the quality of the product (materials quality) and the quality of the process (Sitework/execution, Indoor or Outdoor environment, Operating characteristics, Maintenance level).

On one hand, Reference Service Life assessment has to be “based on rigorous scientific prediction” (based on previous experience or observation of similar construction materials, provided by a manufacturer, given in building codes as typical service life for components, …). On the other hand, the assessment of each factor may also be based on previous experience.

We feel that this is still not providing ways:

1. to make use of all service life data in a manner that is explicit, hence more open to quality assessment and certification, than the current usage relying solely on professional and expert judgement,
2. of providing a more objective, hence less arbitrary, way to assess the factors’ values.

As a matter of fact, we need to develop complementary methods and tools to provide information and guidelines in RSLC and factors assessments.

Methods and tools

Two complementary tools have been developed (Lair, 2000):

- a data fusion procedure (left part of Figure 1),
- a Failure Modes and Effects Analysis (right part of Figure 1).

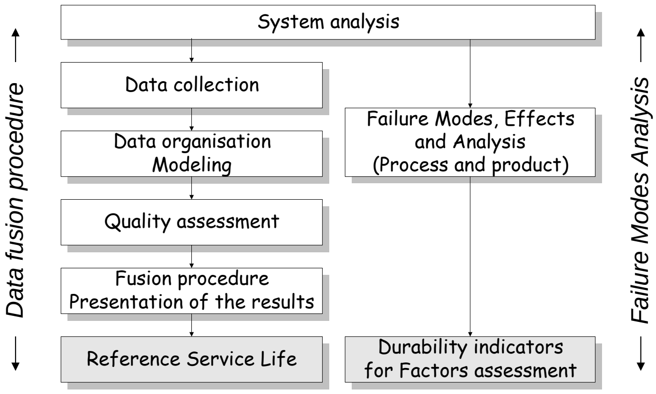


Figure 1 : Durability assessment method and tools

The first step of the approach is a common step called "system analysis" : the structure of the system (elements, materials, geometry …), its environment and the functions it has to fulfil are studied.
In this paper, the next steps of the proposed approach will be detailed, and illustrated with examples.

FUSION PROCEDURE

Data collection

Data collection means collection of all data, available on the product or its part, in its projected environment or one of its parts. We can look at the product, or "zoom in" on each of its parts and have to study the multi-scale aspect of environment (macro, meso, local and micro). (Haagenrud, 1998).
On a basic example: a reinforced concrete wall with external paint, we can collect data on:

- the system in its environment : reinforced concrete (RC) wall,
- the system in a part of its environment : RC wall towards the influence of mechanical loads,
- a part of the system in its environment : concrete in its environment (humidity, CO_2, freezing/thawing cycles, …)
- a part of the system in a part of its environment : concrete facing to carbonation.

Data means either service life data (obtained with field tracking studies, natural or artificial tests, knowledge expert etc) or degradation models (dose response functions, modelling, reliability analysis).

Data organisation and modelling

The following step is the *data organisation*. We want to model the behaviour of a product, but some data are only a partial representation of the real behaviour of the product: partial from a geometrical point of view and/or a phenomenological point of view. Data are more and more accurate in representing degradation phenomena. This accuracy is characterised with a parameter called granularity. Each data is defined by a geometrical granularity (representing : product → components → materials), a phenomenological granularity (taking into account : all phenomena → one phenomenon), and a temporal granularity (Service life → degradation model).Briefly, data organisation consists of grouping data of similar granularities at the same level.

Then, we have to construct various models (one for each level) representing the behaviour in time of the studied product: it is a *modelling* step. From the set of data of a level (partial views of the product), we build a global view of the product (Figure 2).

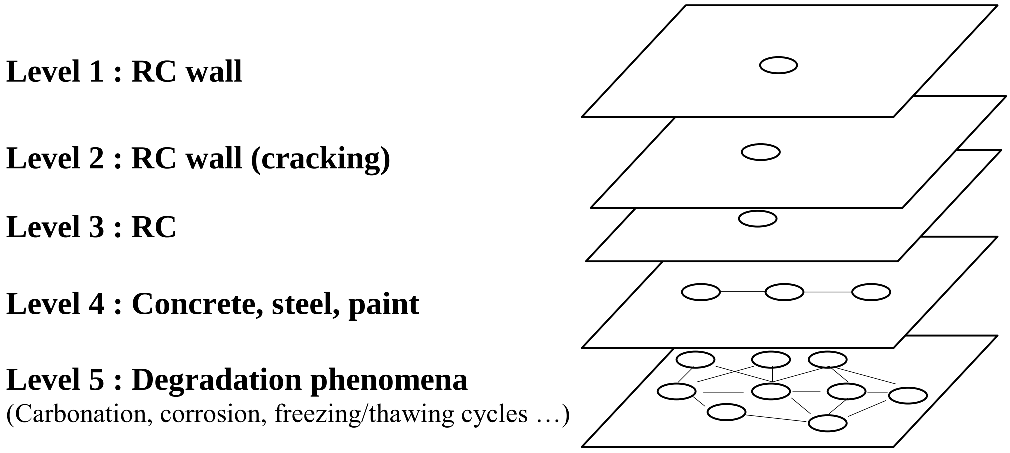


Figure 2: RC wall multi-modelling

For example, the phenomenological aggregation of carbonation, corrosion, freezing/thawing cycles, sulphates etc gives a degradation model of concrete. With geometrical aggregation of the three concrete, steel and paint degradation models, we obtain a degradation model of the system. Each model gives us a service life assessment, under an uncertain formalism : interval, fuzzy sets, probability density functions …

Quality assessment

Before the Fusion procedure is executed, the obtained service lives are qualified, that is to say we assess the "confidence" we have in each service life estimation. It is a *quality assessment* step. In taking into account uncertainty and ignorance (parameters and modelling uncertainties and ignorance), we increase credibility of the results.

Based on the pedigree concept of NUSAP Method (Funtowicz & Ravetz, 1990), the quality assessment method, as a multi criteria analysis, consists of :

- identifying the relevant parameters characterising the quality of the data,
- assessing the parameters,
- aggregating these parameters in order to assess quality.

Six parameters have been defined. They represent the three aspects of data quality : quality of the data production mode, the format of the data, and the relevance of its use in our study. A procedure for the assessment (qualitative or quantitative assessment) and the aggregation (arithmetical mean) have also been defined (see (Lair, 2000) for more details).

We then have a set of couples (Service life, Quality mass) resulting from "multi-modelling" of the product. The quality mass (valued on [0, 1]) is thus defined. It will be used in the Fusion procedure as the weight in a weighted mean.

Figure 3 presents the results of data collection, organisation and modelling steps for the study of a roofing system.

Data n°	**Model (Granularity)**	**Level**	**Service life and Source**		**Quality mass**
1	Service life of roofing system	**1**	25 years	[OFC, 1985]	***0,30***
2			15-20 years	[OPAC, 1993]	***0,36***
3			15-45 years	[EPFL, 1995] (1)	***0,47***
4			15-25 years	[GUMPERTZ, 1996]	***0,39***
5	Degradation of waterproofing layer	**2**	22-32 years	[AMMAR, 1980]	***0,39***
6			20-40 years	[EPFL, 1995] (2)	***0,41***
7			20 years	[PERRET, 1995]	***0,34***
8			{25, 40, 55} years	[PIHLAJAVAARA, 1980]	***0,33***
9			Normal dist. (μ=21,5 ; σ=7)	[KYLE, 1997]	***0,64***
10	Loss of elasticity of waterproofing layer	**3**	24 years	[WYPYCH, 1990]	***0,26***

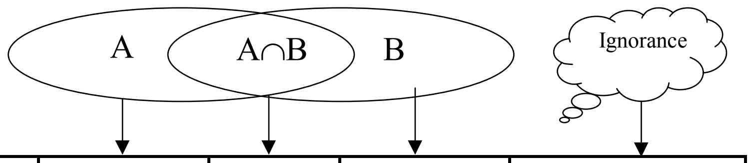
Figure 3 : Data modelling and quality assessment (roofing system example)

Fusion procedure

Fusion procedure is a statistical technique based on "Evidence theory" (Shafer, 1976). From the set of initial service lives, we extract a "consensual service life", that is to say we extract synthetic information of the current knowledge. Each model is called "evidence" (it is a way to assess service life). Each model focuses on a set of service lives. We keep the "right to be wrong", then service life is included in the set "ignorance".

Evidence 1 is translated into a belief function : a mass m_a is associated to A, a mass (1-m_a) is associated to the set "ignorance".
By analogy, evidence 2 is translated.

The consensus is obtained by the product of the masses associated to the considered set : for example, $m(A) = m_a.(1-m_b)$
Data fusion of two evidences (1 and 2 focusing on A and B with respective quality mass m_a and m_b) is illustrated in Figure 4):



Evidence 1	m_a	m_a	$(1 - m_a)$	$(1 - m_a)$	
Evidence 2	$(1 - m_b)$	m_b	m_b	$(1 - m_b)$	
Consensus	$m_a.(1 - m_b)$	$m_a.m_b$	$m_b.(1 - m_a)$	$(1 - m_a) . (1 - m_b)$	$\Sigma = 1$

Figure 4 : Fusion principle

This example is the basic case of the fusion of two "heterogeneous data" (A∩B≠∅).But first, in the building domain, we frequently have conflicting viewpoints (A∩B≠∅) or weakly coherent viewpoints (A∩B nearly ∅). We then propose adaptations to the basic rule. Second, viewpoints could be vague. An expert says "service life is probably [30, 40] but could also be [20, 30] or [40, 50]". This evidence focuses on several service life sets A_i; they are called "separable support functions". The basic rules have to be generalised to this type of evidences (Dempster rule):

$$m(\theta) = k \sum_{\substack{i,j \\ A_i \cap B_j = \theta}} m_1(A_i).m_2(B_j)$$

Third, when we want the fusion of several data, we have to fuse two sets of evidence, then we fuse the result with the third, and so on … Because of problems of conflict and weak coherence, because of the non-associativity of some rules, there is no universal rule allowing the fusion of any set of data. This fact compels us to propose a fusion strategy, intended to choose the most relevant rule for a given set of data. We will not detail further data fusion and fusion strategy. Interested readers could refer to (Lair, 2000).

Presentation of the results

Final results are not exploitable on their own. We have to present them in an understandable and easily usable format. A classical distribution of failure seems to be the best solution. We draw a cumulative probability function. The a-priori probability that product failure occurs in time interval [0, t] is assessed thanks to Smets probability (Dubois, 1990):

$$P([0,t]) = \sum_{x_i < t} \frac{m([x_i, y_i])}{\|[x_i, y_i]\|}$$ $[x_i, y_i]$ are the resulting intervals of fusion

Evidence theory allows us to draw two complementary curves:

- Belief (BEL) is the measure of the belief we have that the failure of the product will occur in [0 ,t].

$$\mathrm{Bel}([0, t]) \;=\; \sum_{[x_i, y_i] \subseteq [0,t]} m([x_i, y_i]),$$

- Plausibility (PL) is the measure of how much we believe that the failure of the product will occur in [0, t] assuming that all unknown parameters are supportive of a failure superior than t.

$$\mathrm{Pl}([0, t]) \;=\; \sum_{[x_i, y_i] \cap [0,t] \neq \phi} m([x_i, y_i])$$

In some way, BEL and PL represent pessimistic and optimistic values of the probability of failure; they draw a zone we call “Uncertainty zone” (grey zone on Figure 5).

We can estimate characteristic service lives. For an acceptable risk k, we assess the characteristic service life SL_k with :

$$DDV_k \;/\; P(DDV \le DDV_k) \le k$$

For example, we could say that $SL_{10\%}$ = 21 years with an uncertainty interval [15, 26] years.

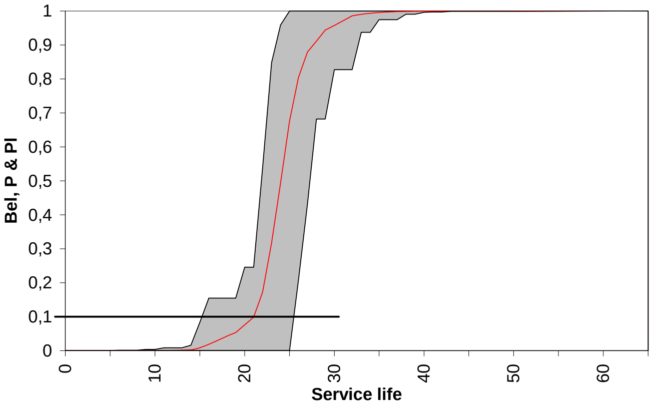


Figure 5 : Failure distributions (Roofing system)

Finally, we want to keep the good sense on what we do.

As Lao Tsu said :

> *“Knowing ignorance is strength,*
> *Ignoring knowledge is sickness”*

Bad input only gives bad results, so we want to “measure” the quality of the approach (quality of the data and results as well as quality of the method).

Additional information are then associated to this assessment. First, we want to qualify the chosen data fusion rule. According to parameters characterising each rules, we assess the quality of the rule with a note between A and F. Second, we want to qualify the informative content of the results (note between A and F) : the wider the uncertainty zone is, the poorer the result.

Interest and perspectives

We propose a procedure for service life assessment. Based on the use of every available information, it is possible to assess the Reference Service Life, required in the Factor Method. Expert judgement, manufacturer judgement, weathering tests, modelling and all other durability sources can be used. The quality assessment principle appears as an essential step, allowing the reduction or increasing of the influence of any data on the result, according to its quality. The existence of “ignorance response” (equivalent to “I don’t know” in an opinion poll) increases the belief in the results.

Currently, we propose an operational method for durability assessment. Tested on some building products (roofing system, wooden window …). It gives interesting results. In the case of innovative products (innovative cladding system), it shows its limits (lack of data). Bad results (in the sense of informative content) are obtained but we point out the studies which are required:

- further thoughts on degradation modelling have to be developed,
- durability and service life data bases have to be developed to make easy the search of information, to capitalise knowledge.

As a start towards these aims:

- the construction of such a database was commenced at CSTB,
- dedicated software was developed by CSTB, to provide guidelines for data quality assessment, make the data fusion and the presentation of results.

FMEA : Failure Modes and Effects Analysis

Generalities

Used from the 1960s in the aeronautical and car industries, FMEA is a convenient tool for the safety studies of industrial systems. FMEA is intended for the verification of the product ability to satisfy client’s needs (reliability, maintenability, disposability, safety). Commonly used in these industrial domains, it targets and checks weak points before mass-production in order to define preventive measures (Modarres, 1993).

Method and originalities

We want to apply a similar approach for building products. With adaptations due to building specificities, we have then developed a “risk assessment” approach currently used in certification procedures.

The proposed approach relies, on one hand, on the precise description of the system, the identification of its functions and the definition of its environment (common part of the method). On the other hand, we also consider the building process of the product (design, manufacturing, transport, storage, setting up …). A *FMEA Process* gives a list of necessary conditions at each step to achieve a good quality product.

We then lead a *FMEA Product* (Figure 6). Briefly, thanks to system analysis, we identify functions ensured by the product, and elements involved in the “success” of each function. FMEA consists of the identification of all failure modes for each function, then the search for causes, and finally the identification of effects. The novelty of the approach concerns the search of causes and effects. The behaviour towards solicitations of an element, its degradation or failure can change the environment of neighbouring elements. For example, dimensional variations of insulation panels of a roofing system under thermal solicitations can involve stresses in the waterproofing layer. We propose to note direct effects (influence of the degradation or failure on the considered element) as well as indirect effects (influence on other elements or on system).

Three types of causes could then be identified:
① a classical cause as the action of an environmental agent on an element,
② an unexpected behaviour due to a defect in building process (potential defects listed in FMEA Process),
③ the influence of a neighbouring element on the considered element (iterative FMEA : a cause could come from the effects of behaviour, degradation or failure of another element).

FUNCTIONS	ELEMENTS	MODES	CAUSES	EFFECTS
Waterproof	Waterproofing layer	Piercing	① Vegetation	Water penetration (→ insulation)
			② Setting-up	
			③ Movements of insulation panels	
			…	
		Tear		
		…		
	Stream breaking membrane			
Thermal insulation				
…				

Figure 6 : FMEA product

We thus have a list of potential failure modes, the causes and effects.

As an example, we propose an abstract of an innovative product FMEA (natural stone facing on aluminium honeycomb structure).

Function	*Element*	*Mode*	*Cause*	*Direct effect*	*Indirect effect*
Watertightness	Natural Stone	Cracking	Shock Prefabrication, transportation, storage Dilatation honeycomb ... Solicitation Freezing Thawing cycles	Water permeability	Solicitation glass/epoxy mesh
		Porosity	Materials selection	Water permeability Freezing sensitivity	Solicitation glass/epoxy mesh -
	Mastic	Cracking	UV Temperature Shock Pollution (atmospherical) Pollution (graffitis) Cleaning products Materials selection Defect of bottom of joint	Water permeability	Solicitation glass/epoxy mesh
		Dissolution	Water and pollutants	Water permeability	Loss of material
		Breaking stone/mastic	Incompatibility (stone/mastic) Defect in gluing (dirt) Shock Retrait (temperature) Weathering (UV, temperature)	Water permeability	Solicitation glass/epoxy mesh
Gluing stone/honeycomb	Natural Stone	Unsticking	Prefabrication (rugosity, dirt) Shock Transportation, storage Dilatation honeycomb ... Solicitation	-	Falls of stone elements

Figure 7 : Stone cladding system FMEA (Abstract)

Interest and perspectives

Though it is seldom used in construction, FMEA is a promising method that could be used in various places in the standard. FMEA is a familiar tool which could be used as a guideline in the assessment of factors. An exhaustive search and knowledge capitalisation are the main interests of such approach. In accordance with occurrence probability, gravity of consequences, detectability …, a criticality indicator is assessed: it allows the ranking and the selection of some “dangerous” failure modes requiring preventive actions. FMEA could give guidelines to improve the reliability and the quality of innovative products. Conclusive FMEA applications on innovative weatherboarding products have revealed the efficiency of this tool. Some failure modes were identified; the designer needed to make adaptations in order to improve the quality of its product, to enrich the certification files.

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CONCLUSION

We propose an operational method intended to qualify product durability:

- On one hand, a tool based on a data analysis and fusion approach which gives a quantitative assessment of service life,
- On the other hand, a second tool, Failure Mode and Effects Analysis (FMEA) which gives qualitative elements for durability assessment.

First, with service life knowledge or assessment, we can design buildings according to a "**service life coherence**" criterion. All the products used in a building should have similar service lives. If a product has a shorter life than others, it should be easily repairable or replaceable (ground coatings, wall coverings,…).

Then, we can use **Global Cost reasoning** (Bourke, 1998) from design stage (Combining economical aspects to durability aspects would allow the management of the different costs of a building: investment, setting up and exploitation) and **a Life Cycle approach** (service life is a major parameter in the assessment of environmental impacts) (Soronis, 1998).

In addition to the benefit of early **risk consideration** (from the design stage), FMEA supplies information about existing products for Inspection/Maintenance/Reparation (IMR) procedure. It could be used as a basis for the **quality assurance** and **diagnosis of pathologies** in auditing buildings, as a basis for consideration of the most relevant corrective actions with which to proceeded.

References

Bourke, K and Davies H. (1998). *Estimating service lives using the factor method for use in whole life costing.* Durability of Building Materials & Components 8, Vancouver, Ed.: NRC - CNRC.

Dubois, D. and Prade H. (1990). *Consonant approximations of Belief Functions*. in International Journal of Approximate Reasoning. 4 : 419-449 (Ed : J.C. Bezdek). Elsevier Science Publishing.

Funtowicz, S. O. and Ravetz J.R. (1990). *Uncertainty and Quality in Science for Policy*. Dordrecht (The Netherlands). Ed.: Kluwer Academic Publishers. 229 pages.

Haagenrud, S. E. (1998). *Environmental Characterization including Equipment for Monitoring*. Institut for Luftforskning (NILU) – Ref. O-90043. CIB W80 / RILEM 140-PSL.

ISO TC59/SC14 (1998) *Buildings – Service life planning*. ISO/DIS 15686.

Jernberg, P., Sjöström, C and Lacasse M.A. (1997). *TC 140-TSL: Prediction of service life of building materials and components (Joint with CIB W80). State-of-the-art-report.* Materials and Structures, supplement March 1997, pp 22-25.

Lair, J. Le Téno, J.F. Boissier D. (1999). *Durability assessment of building systems.* Durability of Building Materials & Components 8, Vancouver, Ed.: NRC - CNRC.

Lair, J. (2000). *"Evaluation de la durabilité des systèmes constructifs du bâtiment"* Thesis. Speciality : Civil engineering. Université Blaise Pascal Clermont-Ferrand II (France). 246 pages.

Modarres, M. (1993). *What every engineer should know about reliability and risk analysis*. New York. Ed.: Dekker. 350 pages.

Shafer, G. (1976). *A mathematical Theory of evidence*. Chichester (West Sussex). Ed.: Princeton University Press. 297 pages.

Soronis, G. Makenya, A. (1998). *Towards a new integrated ISO-standard for sustainable building.* Proceedings of CIB World Building Congress 1998, Vol.1, Gävle, SWEDEN.

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Real-Time Simulations of the Durability of Insulating Glass Units

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ABSTRACT

The current methodology of reliability modeling and simulations is dominated by qualitative analysis methods. The methods include Failure Modes and Effects Analysis (FMEA), Event Tree diagrams etc. Quantitative analysis is mostly done by measurements in the field and in the laboratory (such as the methodology of Accelerated Ageing Testing). These real-time methods usually require relatively long time of observations and are impractical in terms of providing fast feedback in the design process.

In recent times, the availability of significant and inexpensive computational power has made it possible to consider real-time simulations of the relevant physical processes as major tools in the design and engineering of systems. In this paper, a computational simulations based methodology for quantitative analysis of durability (reliability) of Insulated Glass Units (IGU), is presented.

The physical model of IGU is given by a set of coupled differential equations. Thermal, structural and mass diffusion models are solved simultaneously for a given time period and for a given time step. The simulations are real-time and, with a proper choice of time-step unit, can provide results equivalent to extremely long field observations. The failure modes are identified and incorporated in the model. The results of the simulations are subject to life data analysis. Right censored life data analysis is used as a natural choice for real-time simulations.

The possibility of utilization of real-time simulations for FMEA is discussed. Real-time simulations can be used selectively on separate units of the system. This way, the probabilities of failure of separate units can be estimated and can be incorporated in the FMEA. Real time simulations therefore can provide a method for obtaining additional quantitative accuracy in the qualitative methodology of FMEA.

KEYWORDS

Insulating Glass Units, Real-Time Durability Simulations, Event-Tree Diagrams, Life-Data Analysis.

1 INTRODUCTION

The durability of Insulating Glass Units (IGU) can vary significantly depending on the climate conditions they are exposed during their life. An accurate prediction of the life-time of an IGU under certain climate conditions is therefore essential when choosing the optimal IGU in a geographic area. The life-time of an IGU cannot be tested in the field, simply because there are too many possible climatic conditions to which the IGU would be exposed.

The climatic conditions can on the other hand be easily simulated by using available climate data i.e. a Typical Meteorological Year. In this paper we describe a model for real time simulation of the life time of an IGU realized in the simulation package **SealSim** [Velthuis *et al*. 2004]. The IGU is represented by a physical model that incorporates its permeation, thermal and structural behavior. The external conditions are taken from field observations compiled in a meteorological database. The results from real-time simulations are in principle subject to the same kind of analysis as the results from any field observations. The real-time simulations, however, deal with a finished product. Their usage in the design of a novel product is limited to simulations of a completed design solution. Traditionally, the actuarial approach of Failure Modes and Effects Analysis (FMEA) is used to identify the possible improvements in the design that can lead to higher durability of the product [Rausand & Hoyland 2004]. These FMEA methods unfortunately lack the quantitative accuracy of the real-time approach. In this paper we propose an approach of integrating the real-time simulations with the FMEA methods with the purpose of obtaining quantitative methods for design improvement.

In chapter 2 of this paper we describe the two classes of IGUs considered. In chapter 3 we explain the physical model representing the IGU. In chapter 4 we propose integration of the real-time simulations with the FMEA methods. In chapter 5 we conclude.

2. INSULATING GLASS UNITS

In this paper, durability of an IGU is considered. Several design solutions for the IGUs are currently available on the market. Most of the design solutions can be classified according to few design classes. In this paper we consider two general classes of IGUs: Homogenous Spacer System and Box Spacer System. The Homogenous Spacer System typically consists of two homogenous layers (spacer materials), representing structural and vapor diffusion layers. Typical spacers in this design class are Thermoplastic spacers, foam spacers (e.g., Super Spacer®, Edgetech), etc. The schematic representation of this spacer system design class is shown on Fig.1. The two glass panes are separated by two separate sealant layers. Both sealants are of polymer origin. The Inner Sealant (also called Primary Sealant) has favorable water vapor barrier properties, but usually very poor structural properties. In order to ensure structural stability of the IGU the spacer system is structurally enforced by the outer sealant (aka secondary sealant). The outer sealant has good structural strength properties, but usually is a very poor water vapor barrier. Together, both sealants provide moisture vapor transmission resistance (MVTR) and structural strength of the IGU. In addition to the sealant materials, a desiccant is embedded in the primary sealant. The role of the desiccant is to capture any water vapor that diffuses through the primary sealant.

The Box Spacer System is representative of hollow bar spacer designs, like metal (i.e. aluminum, stainless steel), plastic, etc. spacers. In addition to the primary and secondary sealant, this system includes a hollow bar, typically a metal. The desiccant in this case is placed inside the hollow bar. The primary role of the metallic box is to provide the stiffness for separation of the panes.

3. PHYSICAL MODELS AND FAILURE MODES OF THE INSULATING GLASS UNITS

The physical model of the IGU in **SealSim** is given by a set of three sub-models: Permeation sub-model, Thermal sub-model and Structural sub-model.

3.1 Permeation model

One of the most significant modes of failure of the IGU is condensation of water on the inner sides of the glass panes. In that case the unit fails both due to limited visibility through the unit and a failure of the isolation properties of the IGU. Condensation of water will occur due to failure of the sealant.

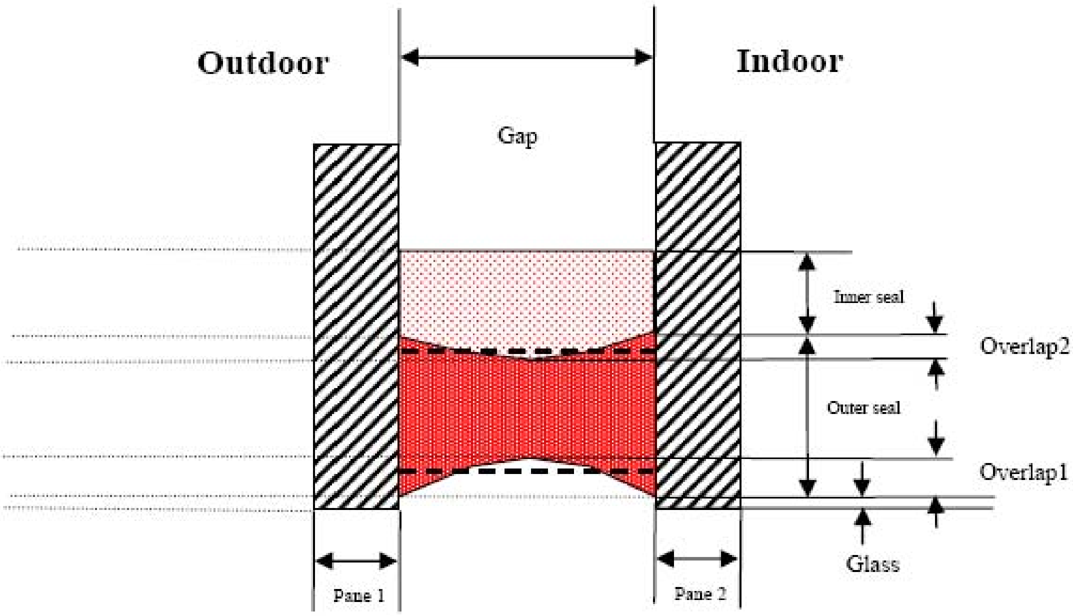

Figure 1. Thermoplastic Spacer System IGU.

Given the fact that the secondary sealant is typically a poor water vapor barrier, the most significant mode of failure is due to water permeation in the primary sealant and water overloading of the desiccant that is mixed with the primary sealant.

The main channels of water vapor transport through the sealant into the gas space of the IGU are:

- Permeation of water vapor through the secondary sealant
- Permeation of water vapor through the primary sealant combined with desiccant absorption/desorption.
- Transport and absorption/desorption of water vapor in the (porous) desiccant beads present in the spacer bar.

Simultaneous to water transport, transport and absorption/desorption of other gases takes place, i.e. loss of fill gases such as argon. These are governed by similar equations, but with different transport coefficients. The general equation for one-dimensional spatial, time dependent diffusion of a gas through a polymer slab, mixed with desiccant is modeled by the diffusion equation [Velthuis *et al.* 2004], [Toshima, 1992]:

$$v_p \frac{d\,c_{p,i}}{dt} + (1-v_p)\cdot\frac{d\,c_{d,i}}{dt} = \frac{v_p}{\tau}\cdot\frac{d}{dx}\left(D_i\cdot\frac{dc_{p,i}}{dx}\right)$$

where ‘t’ denotes time, ‘x’ the spatial coordinate, ‘i’ the specific gas involved, ‘v_p’ the volumetric polymer fraction. In regions where no desiccant is present, as in case of the secondary sealant, $v_p=1$. The concentration of gas ‘i’ soluted in the polymer material is assumed to be proportional to the (partial) gas pressure ‘p_i’ of gas ‘i’ [Pa] according to Henry’s law: $C_{p,i}=S_i\cdot p_i$ *[kg gas$_i$/m^3 polymer]* where S_i *[kg gas$_i$/m^3 polymer/Pa]* is the solubility of gas ‘i’ in the polymer material. The permeation coefficient ‘P_i’of gas ‘i’ in the polymer is defined by:

$$P_i = D_i \cdot S_i \ [\frac{m^2}{s} \frac{kg\ gas_i}{m^3\ polymer} \cdot \frac{1}{Pa}]$$

where D_i *[m²/s]* is the diffusion coefficient of gas 'i' in the polymer.

For simplicity it is assumed that the solubilities, diffusion coefficients and permeation constants of the gases are independent of each other, but are exponential functions of temperature that are different for the primary and secondary sealant. The absorbtion of multiple gases by the dessicant is assumed to be governed by the (LRC) Loading Ratio Correlation, an extension of the Langmuir isotherm for a single gases acording to:

$$c_{a,i} = c_{\max,i} \frac{b_i \cdot p_i}{1 + \sum\limits_{all\ gases} b_i \cdot p_i} \quad [kg\ gas_i / m^3\ desiccant]$$

The factor 'b' [1/Pa] determines the shape of the Langmuir soption isotherm. The dessicant in the polymer matrix not only acts as an immobilising agent, but also increases the distance over which diffusion takes in the polymer, which is described by the tortuosity factor τ.

For the description of the diffusion and absorption/desorption of gases in the porous desiccant beads present in the spacer bar, see [Velthuis *et al.* 2004]. The model is one dimensional, and the transport of gases through the secondary sealant is in series with the transport of gases through the primary sealant. The simultaneously coupled equations are solved by considering a finite grid of points in the x direction only. Although an oversimplification, a one dimensional model is expected to give satisfactory results for the simulations of an IGU. A more sophisticated model should incorporate all three or at least two dimensions and take into consideration the effects of the presence of edges and corners in the IGU.

3.2 Thermal model

The thermal model [Curcija 2004] includes three mechanisms for heat transfer through the IGU: conductive, convective and radiative heat transfer. The IGU has two layers of glazing, each characterized by three infra-red (IR) optical properties – the front and back surface emissivities, $\varepsilon_{f,i}$ and $\varepsilon_{b,i}$, and the transmittance τ_i where the index represents the two layers. The variables considered in the model are the temperatures of the external (front) and internal (back) facing surfaces, $T_{f,i}$ and $T_{b,i}$, plus the radiant heat fluxes leaving the front and back facing surfaces (i.e. the radiosities), $J_{f,i}$ and $J_{b,i}$. In terms of these variables the heat flux across the gap is:

$$q_2 = h_{c,2}[T_{f,2} - T_{b,1}] + J_{f,2} - J_{b,1}$$

where $h_{c,2}$ is the convective heat transfer coefficient in the gap. The thermal conductivity for each glazing layer is governed by the equation:

$$T_{b,i} - T_{f,i} = \frac{t_{g,i}}{2k_{g,i}}\left[q_{i+1} + q_i\right]$$

where $k_{g,i}$ is the conductivity coefficient and $t_{g,i}$ is the thickness of the glazing layer. The solution is obtained by solving the following system of equations:

$$q_1 = S_1 + q_2 \ ; \qquad J_{f,1} = \varepsilon_{f,1}\sigma T_{f,1}^4 + \tau_1 J_{f,2} \ ;$$

$$J_{b,1} = \varepsilon_{b,1}\sigma T_{b,1}^4 + \rho_{b,1} J_{f,2} \ ; \qquad T_{b,1} - T_{f,1} = \frac{t_{g,1}}{2k_{g,1}}\left[2q_2 + S_1\right];$$

for the first glazing layer and:

$$q_2 = S_2 + q_3\,; \quad J_{f,2} = \varepsilon_{f,2}\sigma T_{f,2}^4 + \rho_{f,2} J_{b,1}\,;$$

$$J_{b,2} = \varepsilon_{b,2}\sigma T_{b,2}^4 + \tau_2 J_{b,1}\,; \quad T_{b,2} - T_{f,2} = \frac{t_{g,2}}{2k_{g,2}}\left[2q_3 + S_2\right];$$

for the second glazing layer. The expression σT^4 is the black emissive power. The system of equations is not linear due to the presence of the σT^4 factor but they can be transformed into a linear system by introducing the black emissive power as a variable instead of the temperature.

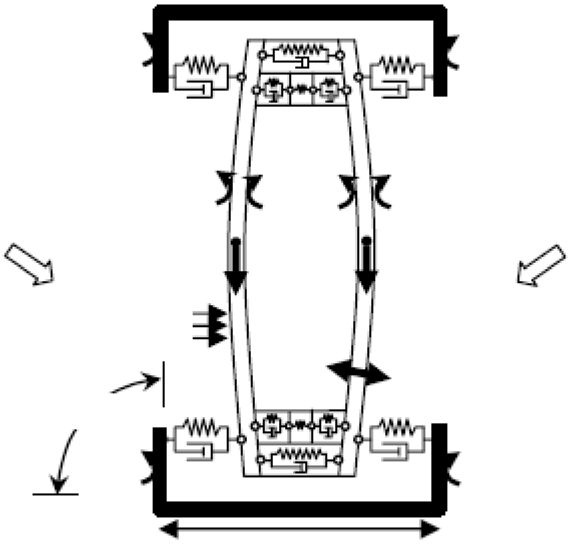

Figure 2. Structural model of the IGU, in this case Box Spacer.

3.3 Structural model

The structural model [Velthuis *et al.* 2004] of the IGU system is shown on Fig. 3. Linear elastic deformation of the glass panes is assumed. The visco-elastic behavior of each polymer element of the system is modeled as a damped oscillator, governed by an equation of the form:

$$B\dot{u} + Ku = f$$

where u is the displacement vectors, B and K are the damping and stiffness matrices and *f* is the load vector. The polymer material properties are highly dependent functions of temperature. The displacements are related to volume change, which in turn relates to the pressure in the IGU. Note that the volume of the gas space also changes due to temperature effects, that is gas expansion/contraction, and due to gas permeation effects, which are incorporated into the model.

3.4 Model integration and failure modes

The three sub-models are solved simultaneously during the simulation of the IGU life-time. The models are coupled through the common variables: The temperature is common variable in both the permeation and the thermal model, while the displacement in the structural model is related to the volume inside the IGU and therefore the pressure which in turn is a variable in the permeation model. The boundary conditions for the model are given by a database of Typical Meteorological Year on an hourly base. The boundary conditions of the simulation are therefore stochastic model of the real climatic conditions in the field. A single simulation run lasts until a failure of the IGU occurs or until the run is stopped by the user. A set of failure modes is defined. Each failure mode can be redefined by the user by setting the limits of tolerance. The set of failure modes include: condensation of water in the IGU, U-factor exceeds user's limit, average distance between panes drops below the specified limit, cohesive stress exceeds set limit, etc.

4. INTEGRATION OF THE PHYSICAL METHODS (REAL-TIME SIMULATIONS) AND THE ACTUARIAL APPROACHES (FMEA)

4.1 FMEA

So far we have described a physical method for prediction of IGU durability. Although the physical method provides an accurate and realistic estimation of the life-time of the unit, it does very little in terms of identifying the possible ways of improvement of the IGU design with the purpose of producing more durable and reliable units. Traditionally, during the design of the system several actuarial approaches are used for reliability analysis of the particular design. The most commonly used approach, Failure Modes and Effects Analysis (FMEA) has the purpose of identification of design changes that can lead to the greatest durability enhancement. Its downside, however, is the fact that it is not a quantitative analysis of the system's durability. Once the failure modes are identified by the FMEA, they are organized in a block diagram that reveals the cause and effect relationships between the failures of the parts of the system. In this paper we consider the Event Tree diagrams, although other methods can be used. The Event Tree diagrams provide a simple but efficient way of integration of the qualitative FMEA and the real-time simulations methods.

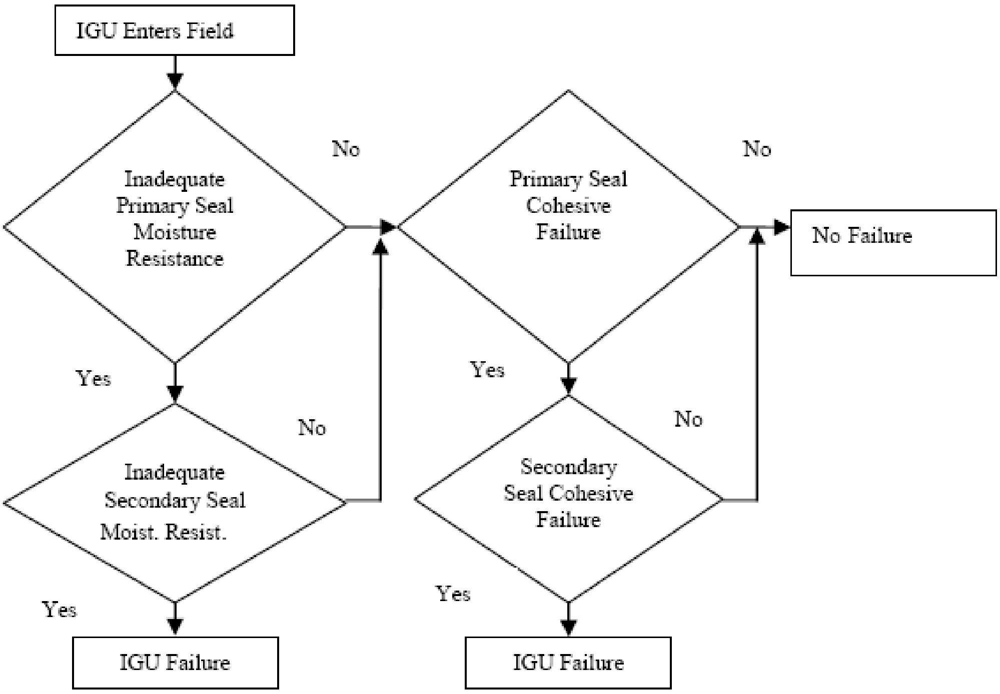

Figure 3. Example of an Event Tree diagram for an IGU.

4.2 Event Tree Analysis

An example of a typical actuarial method is the Event Tree Analysis. This method provides insight into all of the possible sequences of events that may lead to the failure of the system. An example of an Event Tree for the Box Spacer IGU is shown on Fig. 3. It is a network of failure events resulting in failure or non-failure of the entire system. Each failure event is represented by a decision block. The decision in each block is done according to a probability of failure assigned to each decision block. A series of events leads to the final failure mode. The main purpose of the Event Tree diagrams is to provide the designer of the system a detailed insight in the all possible scenarios for failure. The designer can therefore easily identify the "weak spots" in the design and concentrate on their improvement. In order to perform quantitative event tree analysis one must have a full knowledge of the probabilities of occurrence for each of the events. These probabilities can be obtained from statistical analysis of field data. This approach however has little value in the design of a novel IGU when the relevant field data does not exist. Also, the field data usually records failure of the entire system with very little knowledge about the series of events that leads to the failure of the entire system.

Instead of field measurements, a realistic physical model of a novel design, such as the one described above and implemented in the **SealSim** package, can be used to simulate its behavior under field conditions. Real-time simulations can be used selectively on separate units of the system. This way, the probabilities of failure of separate units ("unitized simulations") can be estimated and incorporated into the Event Tree analysis. The software package **SealSim** is organized in a way that the user can set the failure criteria and tolerance for each failure mode. In the language of Event Tree diagrams the user can fix the decision outcome in some of the decision blocks along a branch in the Event Tree. The real-time simulation is therefore forced along a certain branch in the event tree with only one of the decision blocks being really active. The relevant probability of failure for the isolated active block in that case equals the probability for failure of the entire system in this particular real-time simulation. I the next section we will describe a general methodology for extraction of failure probabilities from the analysis of the simulated life data.

4.3 Simulated Life Data Analysis

From a point of view of life data analysis there is no crucial difference between field observations and computational simulations of the system. The field observations are typically done on a sample of (more or less) identical systems. The life time of each system is recorded and life data analysis is performed on the set of life times. In a similar manner, real time simulations should be repeated several times until sufficient statistics on the life time of the system is collected. The advantage of real time simulations over field observations is that each simulation starts with known initial conditions so it is safe to assume that each simulation starts at the same point. In the language of life data analysis, simulation data can always be prepared to be right censored.

In this paper we will consider both cases when in the course of a series of simulations each run ends by a failure of the system (complete set of life data) and the case when a number of runs where terminated before the system failure occurred (incomplete set of life data). Our goal is to estimate the life distribution $F(t)$ of the IGU based on a limited number of real time simulations of the system. Furthermore, the goal is to estimate the probabilities of failure for each failure mode in the Event-Tree diagram through the failure rate function $Z(t)$ as defined below. The life distribution $F(t)$ of a system [Rausand & Hoyland 2004] is defined as the probability that the system fails within the time interval (0,t]. The survivor function is defined as: $R(t) = 1 - Z(t)$. The life distribution is defined in a probabilistic way. In other words, in order to obtain an accurate measurement of life distribution one would need to perform an infinite number of simulations over the period of time (0,t]. In reality one can perform only a very limited number of simulations. The goal of life data analysis is to provide an empirical estimate of $F(t)$ from a highly limited set of life data. Let's assume that an IGU has been simulated n times and each simulation was terminated after failure occurred. This way we obtain a complete set of simulated life times: $T_1 \leq T_2 \leq \ldots \leq T_n$ .The empirical estimation of the life distribution for this set of n life times can be obtained by: $F(t) = i/n$ where i is the number of life-times smaller than t: $T_i \leq t \leq T_{i+1}$. The survivor function is accordingly estimated as: $R_n(t) = 1 - F_n(t)$. The empirical life distribution and survivor functions are step-like functions with steps $1/n$ at the times of failure. In the case when the set of simulated life times is not complete, i.e. some of the simulations were aborted before a failure occurs, we use the Kaplan-Meier empirical estimator of the survival function:

$R_{KM}(t) = \prod_j \frac{n_j - 1}{n_j}$ where n_j is the number of surviving systems immediately before time $t = T_j$. In the case when the data set is complete the Kaplan-Meier estimator is identical to $R_n(t)$ In the case of right censored data set, the Kaplan-Meier estimator takes into account the fact that some of the simulations were aborted in the period between two failures and therefore the probability of survival must be modified accordingly. Once the survival function and the life distribution are estimated, a probability measure can be estimated for the observed failure mode. A quantity of interest is the failure rate function z*(t)* defined with $z(t)\cdot\Delta t$ being the probability that the system will fail in the interval *(t, t +* Δ*t]* if it was functioning at time *t*. Its relation to the life distribution and the survivor function is: $z(t)=\frac{dF(t)}{dt}\cdot\frac{1}{R(t)}$. The significance of the failure rate function for the Event Tree analysis is in the fact that it quantifies the probability of the system to fail at a given moment. This is exactly the probability according to which a decision will be made in a decision block of the Event Tree diagram. This way, the life data analysis provides a quantitative connection between the Event Three analysis and the results of the real-time simulations.

5. CONCLUSIONS

We presented a physical model for realistic simulations of an Insulated Glass Units. Two types of IGU were considered, each modeled by a set of three sub-models. The permeation, the thermal and the structural physical sub-models were explained. The life-data analysis of the simulations outcomes provides estimates for the durability of the system under given climate conditions. The real-time physical model simulations are necessarily done on the entire system and do not provide insight into the weak points of a given design. As applied to product development, FMEA methodology is traditionally used during the design process in order to eliminate problematic design solutions and ensure robust product attributes including the durability of the final product. The FMEA is however highly qualitative and not as accurate as real-time simulations. We proposed a general methodology for combining the actuarial and physical approaches to durability analysis into an integral methodology. This novel approach will benefit not only the consumer by providing the information for choosing the optimal IGU for his/her climate region but also it will assist the design engineer to find and eliminate potential weak points in the design and provide highly durable and reliable IGU.

6. ACKNOWLEDGMENTS

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7. REFERENCES

Hage, R., Anderson, J., Bender, T., Eastep, M., Fairman, J., Hendrickson, G., Lagos, G., Russell, P., Rozynov, B., Scripter, C., Slough, W. & Wilken, D., 2002, *An Insulating Glass Knowledge Base: Phase I Final Report.* Aspen Research Corporation, USA.

Curcija, C., 2004, *Window 6: Mathematical models and computer algorithms for calculations of thermal performance of glazing systems*. Carli, Inc. Amherst, MA, USA.

LBNL 2003, *WINDOW5 - A PC Program for Analyzing Window Thermal Performance of Fenestration Products*, Berkeley CA: Windows and Daylighting Group, Lawrence Berkeley Laboratory, 2003.

Rausand, M. & Hoyland, A., 2004, *System Reliability Theory: Models, Statistical Methods and Applications*. Wiley-Interscence, Hoboken, New Jersey.

Velthuis, H., Hegen, D & Riemersma, T., 2004, *SealSim 1.1 User Manual*. TNO Institute of Applied Physics, Delft, The Netherlands.

Toshima, N. 1992, “Polymers for Gas Separation”, VCH Publishers, Inc, New York.

Contribution from the Aspen Research Corporation, Pando Technologies

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A Methodology for Ensuring Durability of New Product Offerings

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A Methodology for Ensuring Durability of New Product Offerings

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Abstract

A methodology is presented for the reliability assessment of new product offerings, where product failures are driven by environmental conditions. The methodology is valid for the case of limited related product field data and understanding of underlying environmentally driven failure mechanisms. The methodology uses reliability theory in concert with failure mechanistic models to provide high resolution models which can be used to forecast liability exposure of new product offerings. The methodology has been successfully demonstrated for evaluation of several clients' proposed products. The quantitative results generated suggest environmental region risks, overall new product risk, and risk relative to existing related products.

Variable Definition

τ = time to failure
A, E, b = empirical constants
k = Boltzmann's constant
T = absolute temperature
S = stress level
F(t) = Cumulative unit failure at time t
t = time
β = Weibull shape parameter
θ = Weibull characteristic life

Objective

It is desirable to have a methodology which supports rapid time to market of new product offerings. The methodology must provide quantitative lifetime durability projections which support correct design decisions at the earliest phases of product development. Reliability theory coupled with quantifiable failure mechanism knowledge is necessary to support realization of this goal. A mathematically sound design based approach is crucial as there is often limited or no field data available for the proposed product, and the highest resolution and highest confidence estimate is desired.

Methodology

Reliability theory provides a means to quantifiably predict the success rate of a product over its intended life. It involves a synergistic coordination of probabilistic concepts, design knowledge, and failure mechanism understanding. It is useful for predicting product field performance, as it captures the inherent variabilities of both the stress imposed by the environment and the inherent strength of the product to resist the environment. This probabilistic nature of reliability theory is critical, as products have such distributed strengths competing with distributed environments, rather than having discrete strength and stress levels. The areas of overlap of stress and strength distributions will result in product failure, as is shown in Figure 1 [1].

The methodology developed towards the end result of capturing and quantifying such failure events for new products can be outlined as follows:

1. Statement of the problem
2. Failure Modes and Effects Analysis of the proposed product
3. Development of system model which incorporates the individual failure modes
4. Development of mechanistic models for each failure mode
5. Screening of field service data of relevant reference products
6. Failure distribution fitting of reference product field service data
7. Incorporation of relevant product distributions into mechanistic models
8. Projection of system reliability for proposed product

The first step, proper statement of the problem, is critical to success. The types of questions which need to be addressed at this point involve definition of what constitutes product failure, what environmental regions will it be exposed to, and what is the desired lifetime of the product. The answers to these questions should be stated in terms of quantifiable metrics if possible.

The Failure Modes and Effects Analysis (FMEA) effort must then be performed with a diverse group which includes all relevant product experts [2]. The team should at a minimum include representatives of quality, design, service, production, and marketing. The FMEA will provide a documented reference of the team's current best understanding of the system's potential failure modes. The causes and effects of the failure modes will be identified, as will the measures available for detecting the required metric. Severity, frequency of occurrence, and likelihood of detection will be determined. Risk priority numbers, based on severity, frequency, and detection likelihood will provide clarity as to how much resolution must be captured for the failure modes in the subsequent reliability development. A typical FMEA format is shown in Figure 2. The FMEA will support the reliability projections, in that it will provide the template from which a system model can be developed and it will also capture insight into the underlying failure mechanisms.

The system model is a mathematical representation which describes how individual failure modes interact to result in total system failure. The model will take the form of either a system block diagram or a fault tree diagram. System block diagrams, such as shown in Figure 3, are used when there is not interaction between failure modes [3]. System block diagrams can represent series systems, redundant systems, or a combination of both. Series systems are those where a failure of any subsystem will result in total system failure. Redundant systems have a great reliability advantage over series systems. In practice, however, redundant systems are often impractical to achieve due to cost and design constraints. Systems that can be modeled as series, redundant, or combination system block diagrams are relatively straightforward for analysis purposes, as they will result in an exact mathematical solution.

Event tree diagrams, such as shown in Figure 4, are used to represent systems with complexity beyond that which can be captured with block diagrams. In particular, they are necessary when there is either time or physical dependence among the failure modes. The diagram generally shows the chains of events which result in individual failure modes. Event tree analysis models in general can not be solved with a direct mathematical solution. Rather, simulation methods such as Monte Carlo simulation must be used.

Once the system model has been established, it is then necessary to model the mechanisms of the failure modes. The first step toward understanding the mechanism is to determine which environmental cause, or causes, drive the failure. Such causes could be, for example, cumulative UV dosage, range of temperature exposure, or duration at a critical temperature level. The hypothesized driving environmental cause must then be validated through research or experimentation. Once the driving environmental cause has been validated, the time to failure as a function of the cause is developed. This relationship may be developed either through empirical test data or through development of a physics-based failure model. Examples of physics-based time to failure models include the Arrhenius model and cyclic fatigue models [4]. The Arrhenius model, shown in Equation 1, is developed from chemical reaction rate principles. It expresses time to failure in terms of empirical constants as well as Boltzmann's constant. The model's form has been demonstrated to be useful for a wide variety applications which involve material degradation associated with temperature exposure. The cyclic fatigue model is shown in Equation 2. Its empirical constants are derived from exposures of the product to stated cyclic stress magnitudes.

$$\tau = A \cdot \exp\left\lfloor \frac{E}{k \cdot T} \right\rfloor \qquad (1)$$

$$\tau = \frac{A}{S^b} \qquad (2)$$

Alternatively, if there is insufficient mechanistic knowledge to specify a physics-based time to failure distribution, an approach referred to as the proportional hazards method can be utilized. This approach relates the reliability as a function of the stress levels, rather than developing models of the expected time to failure. It is useful if empirical reliability observations at various stress levels are available for interpolation.

The time to failure functions are the first step towards development of mechanistic distributions. The effort doesn't end at this point, as the probabilistic nature of the time to failure distributions still must be captured. In general, the time to failure probability is included by either having the predicted time to failure inserted as one term in a relevant probabilistic distribution or having the elements of the mechanistic model described in terms of probabilistically varying properties. An example of inserting the time to failure in a probabilistic distribution would be using the predicted time to failure as the expected life in an exponential or Weibull distribution.

When mechanistic models are not understood to a sufficient level of resolution, the forms of the models must be hypothesized and then validated by test. The FMEA must be used as a reference for the test plan. The tests should be planned such that they expose the identified failure modes by imposing stressors consistent with the causes identified. The measurement of test response must be consistent with the effects identified within the FMEA. During the performance of the tests, a control sample from the reference product must be run alongside a sample of the proposed product. The relative differences observed during test will be transposed to a quantifiable absolute statement when the field service data of the reference product is considered.

Existing test or field service data for relevant products must then be assessed for usefulness. In order to be useful, the data must contain time to failure data which can be attributed to identified failure modes. The resolution of the data in terms failure time resolution, failure mode resolution, and environmental condition at failure will all dictate the amount of resolution which can be expected from the reliability projections.

The time to failure data of relevant reference products, retrieved from the field service data, is then fit to appropriate reliability distributions. Of the available reliability probabilistic distributions, the Weibull distribution is often used as it is flexible enough to capture a wide variety of failure distribution forms [5]. The Weibull distribution for cumulative failures is described in Equation 3. Its parameters include a shape parameter and a characteristic life term. The shape parameter provides the distribution model flexibility to the Weibull. A shape parameter less than unity is used for infant mortality failures. A value greater than unity is used for wear out failures.

$$F(t) = 1 - \exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \qquad (3)$$

The next key is to develop reliability distributions at the failure mode level for the proposed product. This is achieved by coupling the relevant reference product's failure mode reliability distributions with understanding of the failure mechanism. The reference product failure mode distributions will allow statements as to the variational spread of the proposed product distributions, as well as providing an initial reference point for the reliability projections. Understanding of the failure mechanisms will allow the differences between the reference and proposed product's performance to be captured in the proposed product's reliability distribution and projections.

At this point, the reliability projections for the individual failure modes are incorporated into the system model. The failure mode reliability projections are thus mathematically joined and the overall system reliability projections can be determined. If a system block diagram was used as the construct, the reliability projections can be determined directly. If an event tree diagram was used, Monte Carlo simulation methods will be employed to determine the system reliability. Since the mechanistic models were developed in terms of environmental effect, the output reliability projections can be provided in terms of the levels of environmental stress anticipated. The projections can thus be captured in terms of potential sales regions with varying climatological characteristics, as shown in Figure 5. It is also possible to evaluate the contributions of individual failure modes to overall system reliability. By viewing the results at the failure mode level, as shown in Figure 6, design strengths and weaknesses can be observed to a higher degree of resolution. Viewing the failure mode contributions in this manner can also support tools such as pareto techniques for optimising product reliability

Conclusion

Aspen Research Corporation has employed the above stated methodology in several successful product development projects. By employing the reliability based methodology in concert with rigorous quantifiable understanding of failure mechanisms, quantifiable product life time assessments can be stated. The methodology provides a consistent, scientifically valid means of quantifying expected lifetime performance to support early stage design decisions.

Acknowledgements

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References

1. Elsayed, E., *Reliability Engineering*, Addison Wesley Longman, 1996
2. McDermott, R., Mikulak, R., Beauregard, M., *The Basics of FMEA*, Productivity, 1996
3. Billinton, R., Allan, R., *Reliability Evaluation of Engineering Systems: Concepts and Techniques, Second Edition*, Plenum Press, 1992
4. Nelson, W., *Accelerated Testing: Statistical Models, Test Plans, and Data Analysis*, John Wiley and Sons, 1990
5. Tobias, P., Trindade, D., *Applied Reliability, Second Edition*, Chapman and Hall/CRC, 1995

Figure 1. Continuous versus discrete stress-strength distributions

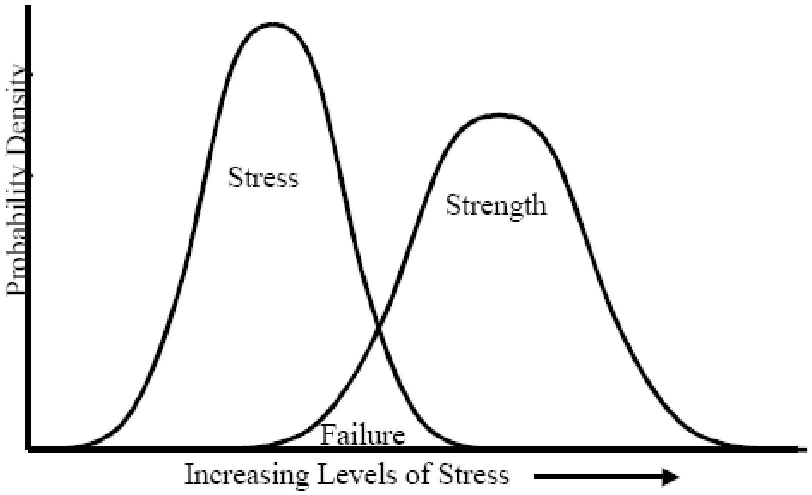
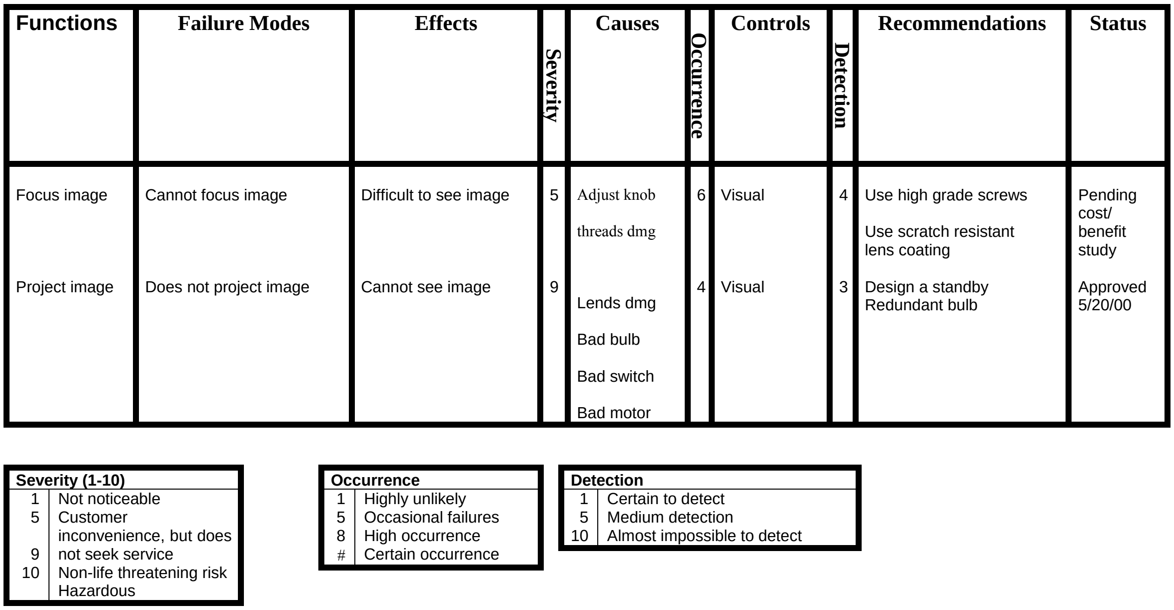


Figure 2. Failure Modes and Effects Analysis Template



Functions	Failure Modes	Effects	Severity	Causes	Occurrence	Controls	Detection	Recommendations	Status
Focus image	Cannot focus image	Difficult to see image	5	Adjust knob threads dmg	6	Visual	4	Use high grade screws Use scratch resistant lens coating	Pending cost/ benefit study
Project image	Does not project image	Cannot see image	9	Lends dmg Bad bulb Bad switch Bad motor	4	Visual	3	Design a standby Redundant bulb	Approved 5/20/00

Severity (1-10)	
1	Not noticeable
5	Customer
	inconvenience, but does
9	not seek service
10	Non-life threatening risk
	Hazardous

Occurrence	
1	Highly unlikely
5	Occasional failures
8	High occurrence
#	Certain occurrence

Detection	
1	Certain to detect
5	Medium detection
10	Almost impossible to detect

Figure 3. System Block Diagram

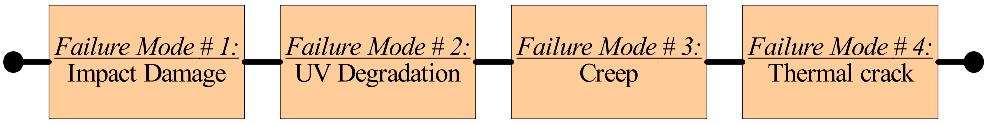


Figure 4. Fault Tree Diagram

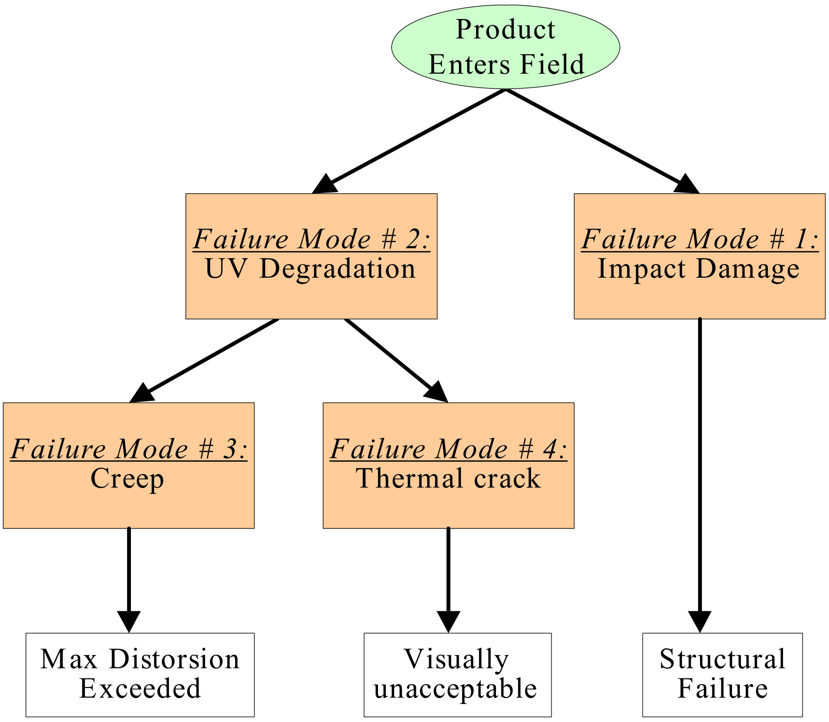
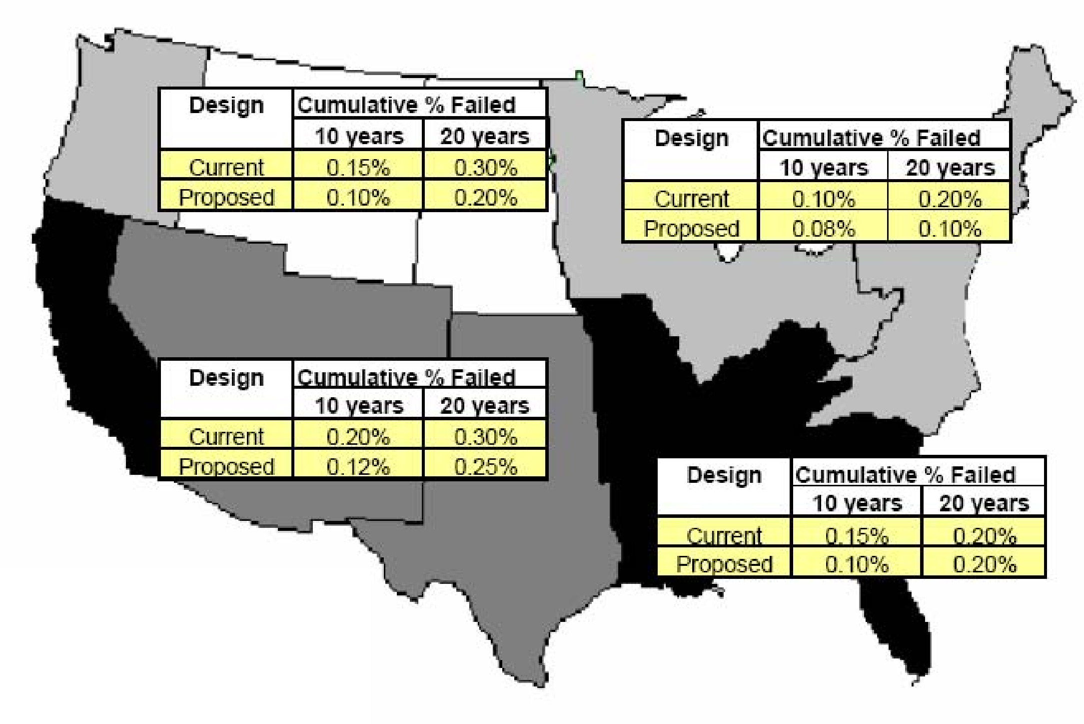


Figure 5. Absolute reliability projections as a function of climatological regions



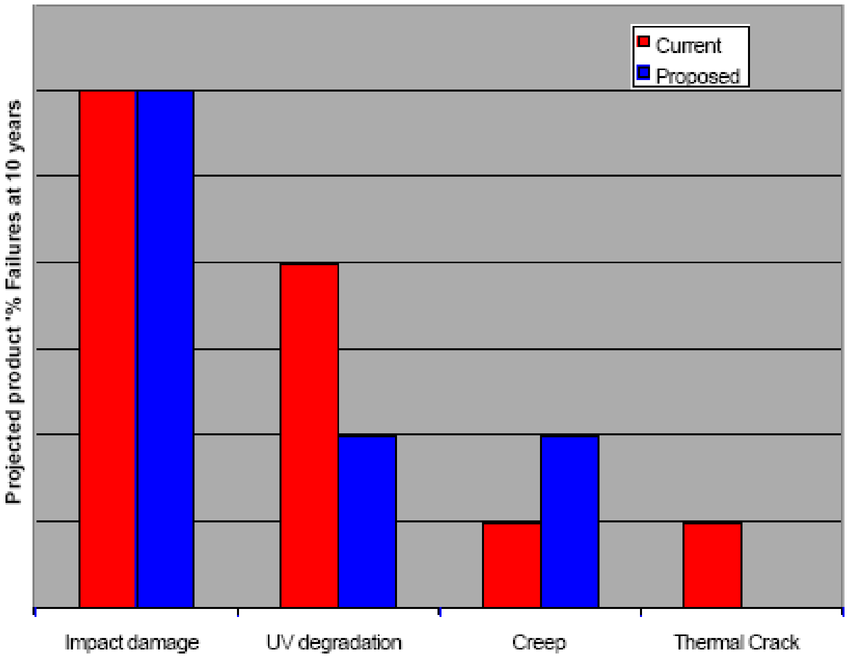
Design	Cumulative % Failed	
	10 years	20 years
Current	0.15%	0.30%
Proposed	0.10%	0.20%

Design	Cumulative % Failed	
	10 years	20 years
Current	0.10%	0.20%
Proposed	0.08%	0.10%

Design	Cumulative % Failed	
	10 years	20 years
Current	0.20%	0.30%
Proposed	0.12%	0.25%

Design	Cumulative % Failed	
	10 years	20 years
Current	0.15%	0.20%
Proposed	0.10%	0.20%

Figure 6. Comparison of failure mode contributions for proposed vs. current product



Contribution from the Aspen Research Corporation, Pando Technologies

R. Hage

Capturing Insulating Glass Failure Events Using Failure Modes and Effects Analysis and Event Trees

2002

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Proceedings of the IGMA Technical Division Meeting
August 2002

Capturing Insulated Glass Failure Events Using Failure Modes and Effects Analysis and Event Trees

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Objective

This work was performed in support of the U.S. Department of Energy funded effort entitled "An Insulated Glass Knowledge Base". The first year of this proposed two year effort involves developing and documenting a qualitative understanding of Insulated Glass (IG) failure events. There are two general aspects to this work. First the relevant failure events must be identified and their interrelationships captured. Secondly, the mechanisms of the identified failure events must be understood with consideration to both theoretical and practical concerns. This document discusses the approach to primarily address the first of these tasks. The approach outlined also provides the framework for bounding the questions of the latter task.

Two tools were chosen for their utility towards identifying and capturing the relevant failure events. They are Failure Modes and Effects Analysis (FMEA) and Event tree diagrams. The FMEA functions as both a conversation tool and a documentation tool for capturing the failure possibilities of a system. Event tree diagrams and fault tree diagrams are graphical means for representing the chain of events which can ultimately lead to product failure. The diagrams employ information generated from an FMEA.

Documenting the failure events in such a manner is of great importance to the industry as a whole. It is important to spacer system manufacturers as well as insulated glass manufacturers as it provides guidance to both the design and process which must be established and maintained to ensure installed spacer systems result in highly durable IG units.

Failure Mode Effect Analysis

FMEA is a communication and documentation tool. It is intended to capture existing knowledge regarding the failure potential of proposed or existing product. It facilitates communication of knowledge by drawing thoughts from a multi-disciplinary team of experts [1].

The format into which the FMEA is captured consists of the following entries [2]:

- Product functions
- Failure modes
- Effects
- Causes
- Controls
- Severity of Effect
- Probability of Occurrence
- Probability of Detection

When developing the FMEA it is necessary to determine whose perspective the product failure is viewed with respect to. The sense of perspective is often referred to as the "target" of the FMEA. The target can be the end consumer, the design team, the manufacturing center, or any number of individual or corporate entities. By defining the target, the definition of functions, failure modes and effects will all be more consistently and usefully defined. The target for this current effort was chosen to be the end consumer. This target makes sense as it is the perceptions of the end consumer which will determine whether or not a product is viewed as satisfactorily durable. FMEA entries are thus being developed with this target in mind.

Product functions are the capabilities which a product must satisfactorily provide in order for it to be viewed as a successful product. The functions are expressed in terms of attributes which are desirable to the target, or end consumer. For the IG system FMEA, example functions are as follows:

- Provide transparent view to outdoors
- Provide optimum thermal efficiency
- Maintain aesthetic appearance
- Isolate living space from outdoors
- Allow installation
- Allow transport to install site

Failure modes are representative categories which define a product failure. They represent the means by which driving causes reach expression as failure. For the purposes of this effort it is useful to think of how individual IG components experience failure. The boundary of components is also considered. A representative, but not necessarily exhaustive list of failure modes used for IG discussion is shown below.

- MVTR seal cohesive failure due to tension or compression
- Structural sealant shear stress failure
- MVTR seal adhesion loss at glass
- Spacer structural failure
- Desiccant saturation
- Total Glass structural failure

Causes are the perturbations of a system which cause a failure mode to occur; they can be any perturbing stress, including but not limited to environmental stressors, process inconsistencies, material flaws, and design weaknesses. During FMEA construction it is often a challenge to determine how deeply to delve into the cause of a failure. For instance, degradation due to solar exposure could be defined at a more macro level as caused by UV exposure. At the extreme depth of detail, the cause could be defined as initiating when photons are emitted. To support a useful FMEA it is useful to define the cause at a level which is actionable by methods of process or design detection. In the example, UV exposure would be chosen as the proper level of detail, as it is a quantity which can be measured and whose impact on the product is understood to some resolution.

Often FMEAs are performed independently for two classes of product issues: design related and process related. For the purpose of this effort it was found that the failure modes identified could in many cases be attributable to a multitude of either process or design issues. Whereas the causes were unique in that they were driven by either process or design issues, the resulting failure modes and their effects were common to the two cause regimes. Thus the failure mode and effect framework was found to be applicable for both process and design issues. The two different cause classes are captured within this framework by attributing them to design or process issues.

Examples of design related causes which lead to the failure mode of a structural sealant cohesive failure due to tension and compression are:

- Cyclic dishing fatigue
- High internal IG pressure
- UV embrittlement/cracking
- Chemical degradation

Examples of process related causes which lead to the structural sealant cohesive failure mode are:

- Improper applied thickness
- Process contamination
- Improper formulation
- Load exceedence before cure
- Improper application
- Internal voids due to process

Effects are the observable outcomes of failure modes. In developing the effects it is especially necessary to view the FMEA from the target's perspective. For the current effort, effects are the outcomes which result in some degree of displeasure to the end consumer. This end consumer could be a private homeowner or a commercial businessman. Some undesirable effects, from the end consumer's perspective, that are captured for the current effort are as follows:

- Internal condensation
- Loss of U-value
- Poor aesthetics
- Visible glass crack
- House open to outdoors
- Glass dishing
- Glass collapse

Controls are the procedures in place which are designed to capture faulty product. The controls are in many cases on-line process checks which are used during production to ensure quality product. The control procedures are not limited to on-line checks, however, vendor checks and milestone observations are also among valid controls alternatives. The types of control are somewhat driven by whether the failures are design driven or process driven. For process driven causes, potential controls could be, among others:

- Monitor process with SPC charts
- Incoming vendor inspection
- Automated on-line tolerance checks

Design driven causes may also involve such on-line inspections, but they may also involve a variety of screening tests and design tools. Often engineering rules of thumb and physical models will drive assessments. These will be considered controls as well, as when used properly they can eliminate the occurrence of the cause-failure-effect chain. Some examples of controls used to address design driven causes are as follows:

- Physics based mathematical modeling
- Stress exposure testing
- Accelerated testing
- Field Weathering
- Component level validation tests

The FMEA provides a means to capture the current understanding of which failure modes may occur, how they are caused, and what their effect will be. It also provides a means to capture current understanding of the severity of the effects, the probability of occurrence of the cause-failure-effect chain, and the likelihood of detecting the cause-failure effect chain. These ratings are developed using numeric values which are accepted by the FMEA team.

The severity rating is a quantitative measure of how detrimental a failure mode's effect is from the target's viewpoint. The severity scale used for the purpose of the IG effort is shown in Figure 2. The low extreme of the scale is no noticeable problem. The high extreme of the scale represents issues of safety and corporate brand erosion.

The probability of occurrence rating is a quantitative measure of the probability of the entire cause-failure-effect chain occurring. It is important to view the entire cause to effect chain when developing this ranking, because within a failure mode category there are often several effects as well as several causes. By providing the probability of occurrence of the entire chain of events, this rating can be performed to the resolution of the specific causes, which is generally a tighter resolution than if only a failure mode category is considered. The degree of resolution and validity of the probability estimate is limited by the degree of a priori design knowledge available. For the purposes of the IG durability assessment, the scale shown in Figure 3 was used. The extreme low end of the scale, a probability of zero, can be used if the systems physics dictate that no failure is possible. The next highest rating of one in a million is thought to capture failures which may only manifest themselves in a handful of units from an entire population. The highest rating represents convergence on failures which are approaching probable.

The probability of detection is a quantitative ranking which refers to the likelihood of detecting the cause-failure-effect chain of events. This rating is the exception to target perspective. This rating value differs from severity and probability of occurrence in that it is viewed from the producer's rather than the consumer's perspective. It represents the probability the potential or realized failure mode can be detected before it gets to the customer. The rank value for detection is higher for lower probabilities of detection. It is phrased in this manner because the purpose of an FMEA is to support minimization of observed product failure in the field. If a failure is unlikely to be detected, a high rating value will raise flags to indicate that greater thought must be given to catching these potential failures before they happen. The probability of detection scale used for the purposes of this effort is shown in Figure 4.

Event Tree

The event tree technique is a method for representing system failures which occur as a result of interrelated chain event subsystem failures [3]. Systems which have subsystem failures which are not interrelated are represented more easily by block diagram representations. Electronic systems often lend themselves to block diagrams since the failure rates of individual components are independent of the failures of neighboring components. Mechanical systems, however, are often best represented by event trees, due to the complex interactions of stress and strains among neighboring components [4].

As a complex mechanical system, Insulated Glass units are best represented by event trees. An example of such an event tree representation is shown in Figure 5. The benefits of using the event tree diagram are two-fold. First it allows a graphical representation of the chain of events which must occur in order for a failure to occur. Second it provides the logical framework from which system simulation assessment studies can be performed.

The event tree is especially useful in the present effort as it allows both the similarities and the differences of each IG spacer design class to be seen clearly. Although the FMEA captures the same information, it does not as clearly show the interdependencies among the failure modes. The event tree shows how the failure modes captured within the FMEA interact to result in product failure. Similarities and differences in the failure mode blocks and similarities and differences within the failure mode interactions are captured. The failure modes and resulting effects identified within the FMEA are captured in this construct for each design class.

The unique tree for each design class is also beneficial as it ties together the technical discussions developed for each of the failure mode blocks. The failure modes are one area of commonality across many of the IG design classes. In many cases, it is not so much the differences within these failure modes which is significant, but how they all interact to result in system failure.

The overall event tree thus captures the failure mode interactions and the effects of system failure. The individual causes, identified in the FMEA, for each failure mode are captured by using a different construct, which is a fault tree rather than event tree. An example fault tree construct for a failure mode block is shown in Figure 6.

A fault tree rather than an event tree is appropriate for representing the failure mode causes, because it is constructed to outline the logic that must occur for a specific failure to occur [3]. This differs from an event tree, which shows the failure paths which lead to a multitude of failures. For each failure mode, a failure is designated to occur if any of the identified causes occurs. The causes are categorized in terms of both design related causes and process related causes. The fault tree is constructed to capture causes, in concert with the event tree for capturing failure modes and effects. Together the event trees and fault trees are a necessary and effective means of communicating the understanding generated from the FMEA.

FMEA and Event Trees as Useful Dialogue Tools

In order to effectively support proper design and process guidance for the IG industry, the FMEAs and Event Trees must be accurate representations of reality. This accuracy can only be insured if the underlying principles are understood and captured and if the practical design and process issues are sufficiently captured.

This required accuracy can be obtained if the FMEA and Event trees are developed from first principle levels and then submitted for review by the industry. The first principle FMEAs and Event Trees can then be updated by incorporating the practical and theoretical observations from spacer system manufacturers and IG manufacturers. It is particularly important to capture the perceived probability of occurrence, severity, and probability of detection from the industry’s perspective. Also it is important to receive industry input regarding currently utilized controls for the process.

The FMEA is the tool for encouraging and capturing this dialogue. If this information is captured to sufficient resolution, with a view to practical considerations, it will provide a useful reference body of knowledge for the IG industry.

Acknowledgements

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References

1. Ireson, W., Coombs, C., and Moss, R., Handbook of Reliability Engineering and Management, Second Edition, McGraw-Hill, 1996
2. McDermott, R., Mikulak, R., Beauregard, M., The Basics of FMEA, Productivity, Inc., 1996
3. Billton, R., Allan, R., Reliability Evaluation of Engineering Systems: Concepts and Techniques, Second Edition, Plenum Press, 1992
4. Hage, R., A Simulation Model for Probabilistic Analysis of Space Shuttle Abort Modes, NASA Technical Memorandum 108432, Marshall Space Flight Center, 1993

Figure 1. A Section of an FMEA for IG Design Class

Functions	Failures Modes	Effects	S	Causes	O	Control	D
1 . Provide Transparent View to Outdoors 2 . Provide Optimum Thermal Efficiency 3 . Maintain Aesthetic Appearance	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishnig Fatigue	?	Modeling	?
		Poor SHGC	?	High internal IG Pressure	?	Modeling	?
				UV Embrittlement/cracking	?	Modeling & Tests	?
				Chemical degradation	?	Modeling & Tests	?
				Doesn't meet pressure requirement	?	Modeling	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR & Structural Seal Cohesive Failure due to shear	Internal condensation	?	**Design**			
		Loss of U-Value	?	Improper Glass to Spacer COTE match	?	Modeling	?
		Poor SHGC	?	Doesn't meet static load requirements	?	Modeling	?
				UV Embrittlement/Cracking	?	Modeling & Tests	?
				Chemical Degradation	?	Modeling & Tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Unsupported pane	?	Install inspection	?
				Process contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Ptocess	?

Figure 2. Severity ranking scale

Severity (1-10)	*Severity of the Failure Mode's Effect*
1	Effect exists, but is not noticeable
3	Customer inconvenience, but does not seek service
5	Customer annoyance/Service call likely
9	Person injury/ Severe dissatisfaction with product
10	Severe personal injury/Brand erosion

Figure 3. Probability of Occurrence rankins scale

Occurrence (1-10)	*Probability of the Cause-Failure-Effect Chain Occurring*
0	Physically impossible
1	1 in 1 million
2	1 in 500,000
3	1 in 100,000
4	1 in 50,000
5	1 in 10,000
6	1 in 5,000
7	1 in 1,000
8	1 in 100
9	1 in 10
10	1 in 2

Figure 4. Probability of Detection ranking scale

Detection (1-10)	*Likelihood of Detecting Cause-Failure-Effect Chain*
1	100%, Certain to detect
2	90%
3	80%
4	70%
5	60%
6	50%
7	40%
8	30%
9	20%
10	<10%, Very difficult to detect

Figure 5. Overall Event Tree for a Specific IG Design Class

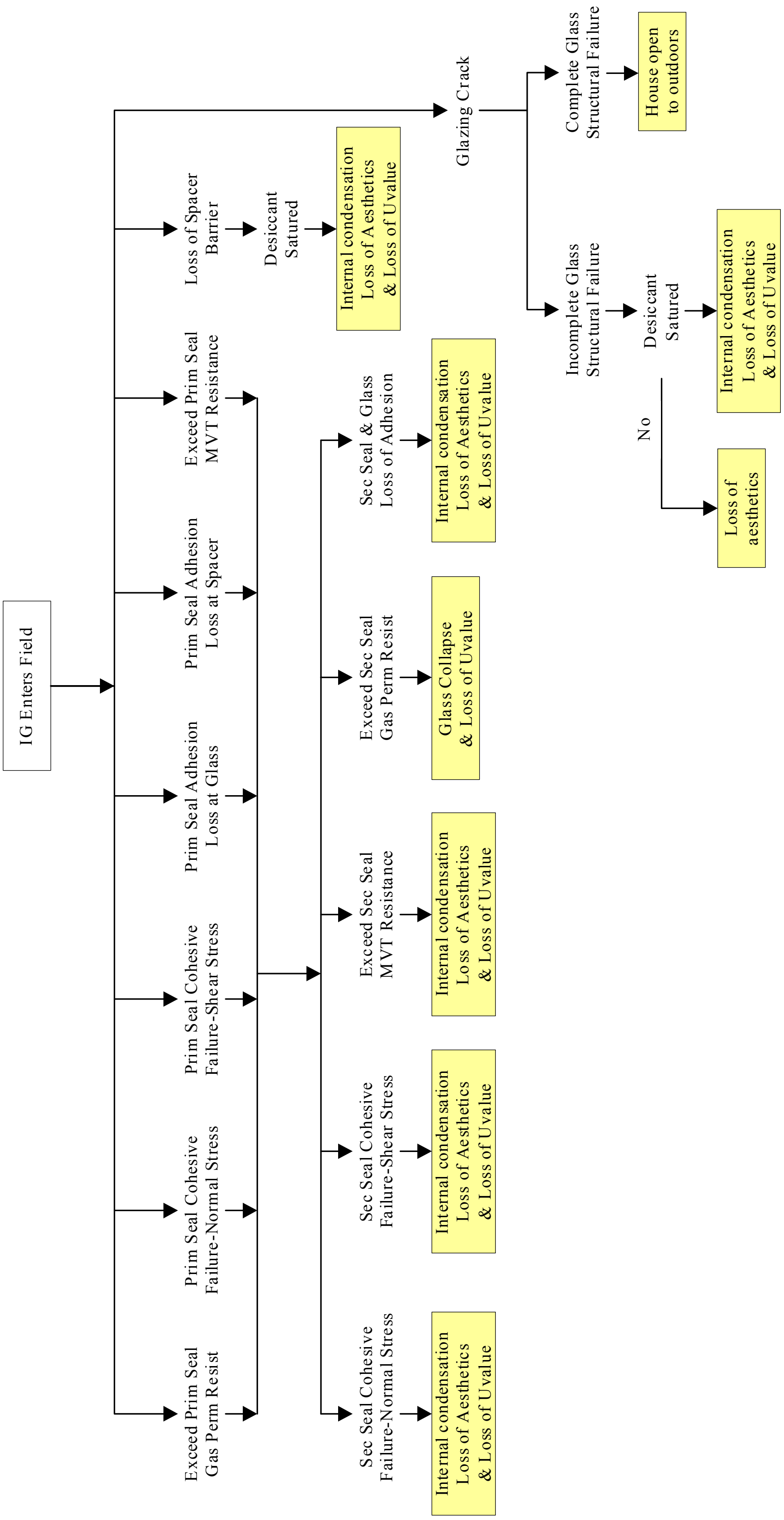
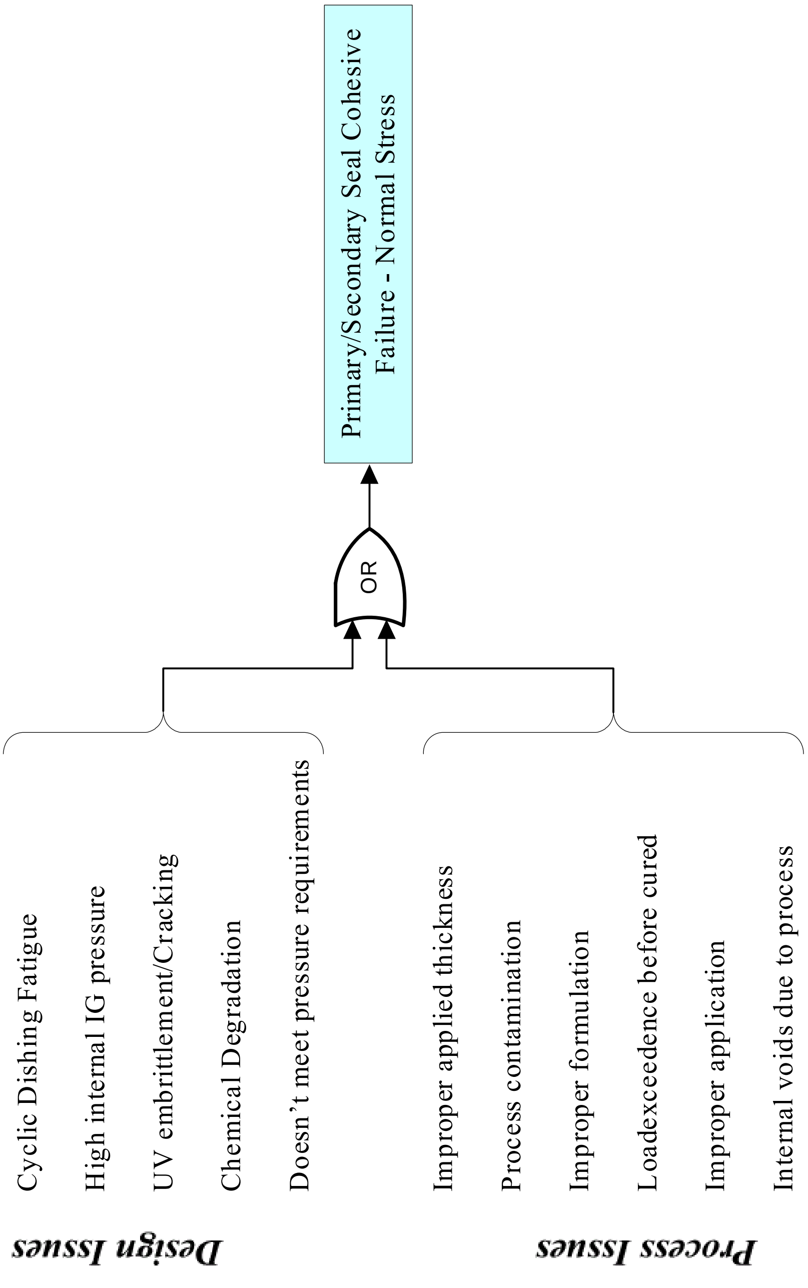


Figure 6. Fault Tree for a Specific Failure Mode



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Methodology for Top Level Durability Assessment of Existing Insulating Glass Units

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Methodology for Top Level Durability Assessment of Existing Insulating Glass Units

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Abstract

A methodology is presented which will result in top level system durability assessments for specific products which have field service data. The methodology involves capturing understanding of the system using Failure Modes and Effects Analysis, developing a system model consistent with available failure code information, capturing time to failure information, and mathematically combining the failure mode response to determined system durability.

Objective

The purpose of this paper is to discuss a methodology which can be employed to provide a reliability assessment of an existing product which has field service data. The specific implementation of this methodology will be to fulfill a task of Phase I of the DOE funded project, "An Insulating Glass Knowledge Base". This methodology provides a top level reliability assessment as it assesses the durability of specific defined product directly from observed field failures. It is contrary to a bottom up approach, which would involve capturing underlying failure mechanisms, inputting variation into the mechanisms, and then arriving at overall product durability estimates.

The approach has the advantage of only requiring field service data of a specific product. It has the disadvantage that the durability projections are only valid for the specific product design considered. The effect of design variations and environmental variations on product durability can only be captured at a macro level.

Methodology

The methodology developed towards the end result of capturing and quantifying such failure events for new products can be outlined as follows:

1. Statement of the problem
2. Failure Modes and Effects Analysis of the proposed product
3. Development of system model which incorporates the individual failure modes
4. Review of Field Service Data for resolution
5. Correlation of system model failure modes with field service failure codes
6. Determination of relevant design attribute variations
7. Capture of time to failure data at appropriate failure code and geographical resolution for all relevant design attribute variations
8. Fit probabilistic distributions to the time to fail data at the failure mode level
9. Combine the failure mode distributions into the system model
10. State the system level reliability for the defined warranty period, as a function of environment and design attributes

The first step is proper statement of the problem. This involves determination of which core product offering to assess and which of its design variants to consider. It also involves determining which geographic region to consider. What constitutes product must be defined. Finally the time periods of interest must be evaluated.

The Failure Modes and Effects Analysis (FMEA) must be performed with a diverse group which includes all relevant product experts [1]. The team should at a minimum include representatives of quality, design, service, production, and marketing. The FMEA results in a documented reference of the team's current best understanding of the system's potential failure modes. The causes and effects of the failure modes will be identified, as will the measures available for detecting the required metric. Severity, frequency of occurrence, and likelihood of detection will be determined. Risk priority numbers, based on severity, frequency, and detection likelihood will provide clarity as to how much resolution must be captured for the failure modes in the subsequent reliability development. A typical FMEA format is shown in Figure 1. The FMEA provides the template from which a system model can be developed.

It also captures insight into which design attributes and environmental parameters affect system durability.

The system model must then be constructed. It is a representation of how failure modes interact to result in product failure. The system model will typically take the form of a block diagram or an event tree. System block diagrams, such as shown in Figure 2, are used when there is no interaction between failure modes [2]. System block diagrams can represent series systems, redundant systems, or a combination of both. Series systems are those where a failure of any subsystem will result in total system failure. Redundant systems have a great reliability advantage over series systems. In practice, however, redundant systems are often impractical to achieve due to cost and design constraints. Systems that can be modeled as series, redundant, or combination system block diagrams are relatively straightforward for analysis purposes, as they will result in an exact mathematical solution.

Event tree diagrams, such as shown in Figure 3, are used to represent systems with complexity beyond that which can be captured with block diagrams [2]. In particular, they are necessary when there is either time dependence or physical interaction among the failure modes. The diagram generally shows the chains of events which result in individual failure modes. Event tree analysis models in general can not be solved with a direct mathematical solution. Rather, simulation methods such as Monte Carlo simulation must be used.

The field service data for the product must then be reviewed. The quantity and quality of the field service data will dictate the resolution of the assessment with respect to each of the following parameters:

- Geographic resolution
- Time to failure resolution
- Failure code resolution
- Design attribute resolution

In addition, the field data must include information on the sales volume within the defined geographical regions. The sales information is necessary as only a fraction of the product fails during its warrantable lifetime. The sales data is necessary so that the reliability statements can account for the unfailed products. It is desirable, although not necessary, that the field service data indicate the age of the product at failure. If the time to failure data is available, distributions such as the Weibull can be used, which capture the shape of the failure distribution. The shape of the distribution will indicate whether the failures are governed by infant mortality, random, or wear out failures. Capturing the shape of the distribution is important as it affects the magnitude of future failure projections. If time to failure data is not available, it is necessary to assume a constant failure rate for the failure mode, which may result in non-conservative failure projections. Finally, the quantity of both sales and failure data within the areas of geographical resolution with dictate the accuracy of the most likely durability estimates of the data. The quantity of data will also dictate the span of confidence intervals for the projections.

Ideally, the field service data will contain failure code information consistent with the failure modes included in the system block diagram. If this is not the case, the course of action is dictated by whether the failure codes are more course than the failure modes, or whether they are more detailed. If they are more course, the system block diagram must be simplified to be consistent with the reported failure codes. This is accomplished by grouping the failure modes into the groupings consistent with the failure codes. If the failure codes are to a greater level of detail than the failure modes, the failure code data must be grouped into a courser grouping consistent with the failure modes. It is also possible that a combination of the two situations is present. In this case, the failure codes must be aggregated for some failure modes and the failure modes aggregated to match other failure codes. The resolution of the time to failure data must be updated to include the failure code aggregation and the system block diagram must be updated to accommodate the aggregated failure modes.

It is then necessary to hypothesize which design attribute variations are relevant for the assessment. The design attributes which are thought to have an impact on the product's durability should be chosen. The design attributes are chosen based on the qualitative or quantitative physical understanding of which factors affect the magnitudes of physical stresses which the IG sees during exposure to its environment. Examples of potential design attributes of interest with respect to IG durability are the color of the window frame, and the length and width dimensions of the IG. The color of the window frame is relevant as solar absorption of the window frame dictates the temperature and thus thermal expansion response of the frame. The thermal expansion of the window frame may then result in a deleterious effect on the IG. The result may be glass fracture or spacer system failure. The length and width dimensions are relevant as they dictate both the thermal state and the pressure state within the IG interior. Everything else held constant, windows of greater dimensions would tend to flex more, than would windows of smaller dimensions, thus affected both the pressure state and the edge flexure conditions. Also the larger windows would have proportionately greater static weight, which may affect spacer durability. When assessing which design attributes to consider, it is necessary to choose a list which is consistent with the resolution of the failure data. The categorization of the data is then complete. The time to failure data is then presented for each combination of the following parameters:

- Geographical/Environmental region
- Design attribute 1
- Design attribute 2

  …
- Design attribute N
- Failure code groupings

The sales data for each combination of the above groupings are also tabulated. The time to failure data is constructed consistent with the resolution of the field service time to failure data. The number of failures within each time increment is captured. The quantity of product that has not failed is captured by subtracting the sum of failures from the total sales quantity.

The time to failure data for each combination of the above parameters is then fit to appropriate reliability distributions. The procedure for properly fitting a distribution involves the following three steps:

- Assume a distribution
- Calculate the distribution parameters
- Verify the proper fit of the distribution

The initially assumed distribution is generally determined by the failure mode considered. Three commonly used distributions are the Exponential, the Lognormal, and the Weibull. The exponential is generally used for systems with a several components which all experience independent failures [3]. For this reason it is often used for describing the behavior of electronics systems, such as computer motherboards. It has the characteristics of a constant failure rate. If time to failure data is not available, this distribution is assumed, as there is no evidence to negate the constant failure rate hypothesis.

The Lognormal distribution is used often for failure mechanisms which have significant early failure due to manufacturing issues, but then fail less frequently as their time exposure increases (3). For this reason it is often used to describe bearing failures and turbine failures, as they represent cases where manufacturing defects often manifest themselves early.

The most commonly used distribution is the Weibull, shown in equation 1 [4]. The Weibull distribution is often used as it is flexible enough to capture a wide variety of failure distribution forms. The Weibull distribution for cumulative failures is described in Equation 1. Its parameters include a shape parameter, β, and a characteristic life term, θ. The shape parameter provides the Weibull with its substantial flexibility in modeling varying distributions modeling flexibility. A shape parameter of 1.0 allows the distribution to model random failures. A shape parameter of less than 1.0 allows the distribution to model infant mortality failures. These early failures are often seen when initial manufacturing defects progress to failure early in a products life. A shape parameter of greater than 1.0 allows the distribution to model wear out failures, such as would be the case for cumulative fatigue failures. The versatility of the distribution is shown in Figure 4.

$$F(t)=1-\exp\left[-\left(\frac{t}{\theta}\right)^{\beta}\right] \qquad (1)$$

Once the distribution has been chosen, it is fit to the data. This is accomplished by mathematically valid statistical techniques, which generally use minimal error fits. The distribution is fit by finding the values of its parameters which minimize the fit error. The fit distribution must then be validated as properly reflecting the data. This is accomplished by comparing the observed data to that predicted with the fit distribution. If the error is within an acceptable range, the distribution is found to be the proper choice. If the error is greater than the allowed error band, the selection of distribution must be reassessed. Two common methods for accomplishing this “goodness of fit” assessment are the Kolomogorov-Smirnoff technique and the Chi-square technique [3].

At this point, the reliability projections for the individual failure modes are incorporated into the system model. The failure mode reliability projections are thus mathematically joined and the overall system reliability projections can be determined. If a system block diagram was used as the construct, the reliability projections can be determined directly. If an event tree diagram was used, Monte Carlo simulation methods will be employed to determine the system reliability.

The system reliability is thus set up to project the product’s reliability over the time period of interest. To evaluate the cumulative failures expected during a product’s warrantable lifetime, all that is required is to set the time parameter of the probability distributions to match that of the warrantable lifetime. The system reliability can thus be quantified for a warranty lifetime, as can the cumulative expected failures. The failure rate over a defined time interval can also be assessed.

Assessment Output

The output of this methodology will be top level durability assessments. For the specific product evaluated, the effect on durability of environmental region and design parameters can be assessed. It is possible that the effect of individual environmental quantities can be assessed, if the environmental regions are chosen to a sufficient level of resolution.

By employing this methodology for a variety of products, the relative reliability of differing products can also be assessed. If there are consistencies in the design attributes of various products, direct comparisons of different products can be provided.

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References

1. McDermott, R., Mikulak, R., Beauregard, M., *The Basics of FMEA*, Productivity, 1996
2. Billinton, R., Allan, R., *Reliability Evaluation of Engineering Systems: Concepts and Techniques, Second Edition*, Plenum Press, 1992
3. Elsayed, E., *Reliability Engineering*, Addison Wesley Longman, 1996
4. Tobias, P., Trindade, D*., Applied Reliability, Second Edition*, Chapman and Hall/CRC, 1995

Figure 1. Example Failure Modes and Effects Analysis Template

Functions	Failure Modes	Effects	Severity	Causes	Occurrence	Controls	Detection	Recommendations	Status
Focus image	Cannot focus image	Difficult to see image	5	Adjust knob threads dmg	6	Visual	4	Use high grade screws Use scratch resistant lens coating	Pending cost/ benefit study
Project image	Does not project image	Cannot see image	9	Lends dmg Bad bulb Bad switch Bad motor	4	Visual	3	Design a standby Redundant bulb	Approved 5/20/00

Severity (1-10)	
1	Not noticeable
5	Customer
	inconvenience, but does
9	not seek service
10	Non-life threatening risk
	Hazardous

Occurrence	
1	Highly unlikely
5	Occasional failures
8	High occurrence
#	Certain occurrence

Detection	
1	Certain to detect
5	Medium detection
10	Almost impossible to detect

Figure 2. System Block Diagram

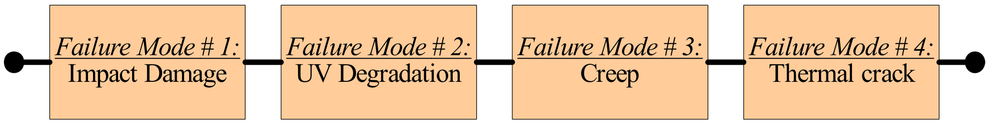


Figure 3. Fault Tree Diagram

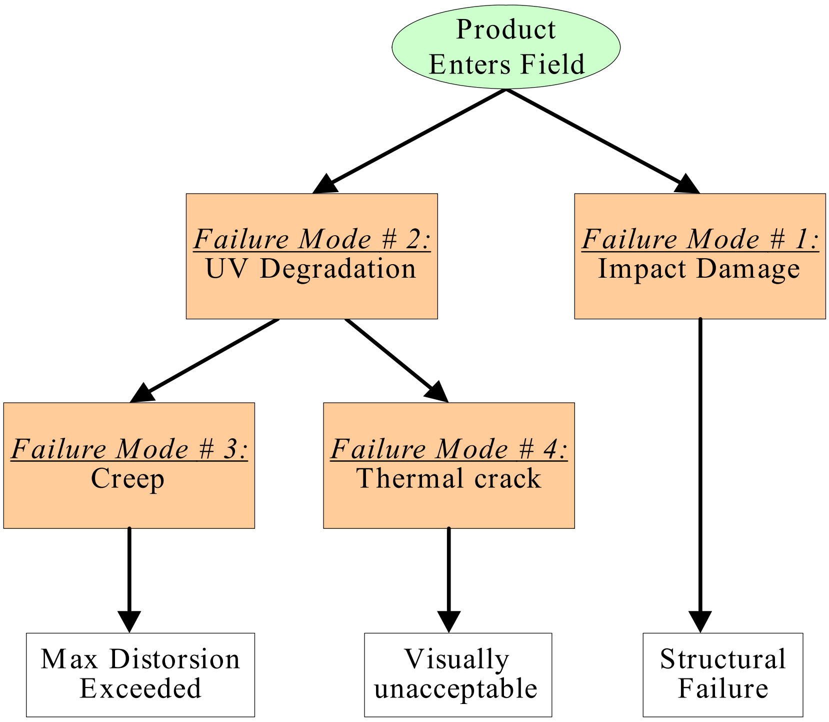
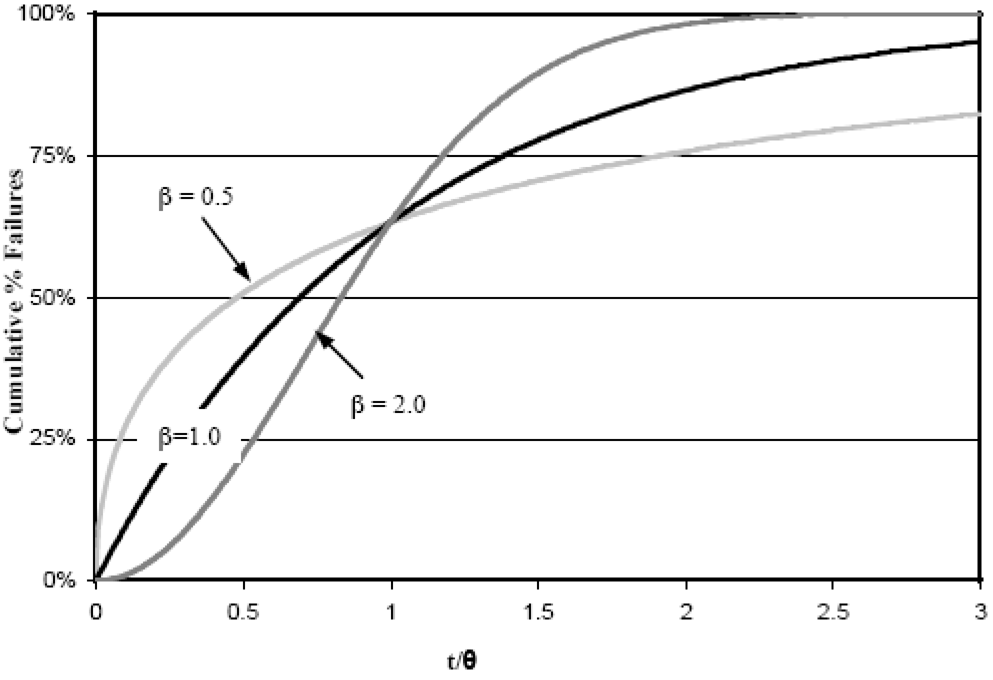


Figure 4. Effect of shape parameter on Weibull distribution form



Contribution from the Building Research Establishment

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Reliability and Whole Life Performance: Integrating the Supply Chain

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RELIABILITY AND WHOLE LIFE PERFORMANCE: INTEGRATING THE SUPPLY CHAIN

Reliability and whole life performance

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Durability of Building Materials and Components 8. (1999) *Edited by M.A. Lacasse and D.J. Vanier*. Institute for Research in Construction, Ottawa ON, K1A 0R6, Canada, pp. 1919-1923.

Abstract

This paper will discuss how research into building component service life and other whole life performance issues has led to the use of reliability engineering techniques. The UK construction industry has been looking at adopting a framework that allows the supply chain to consider service life, whole life cost and building component performance and environmental data during procurement and throughout the building's life. Integrated Logistics Support (ILS) is one possible framework developed for defence procurement that also includes these reliability techniques, and also allows whole life performance and cost issues to be integral. The paper will feature some of these techniques including Reliability Centred Maintenance and Failure Modes, Effects and Criticality Analysis (FMECA). The paper will also summarise recent research carried out in the UK that has examined the application of ILS to construction, and proposes an adapted framework that could allow the further development of ILS into a working model in construction (ILSC).

Keywords: Failure Mode Effects and Criticality Analysis, Integrated Logistics Support, maintenance, reliability, service life, supply chain, standards, whole life cost & performance

1 Introduction

Research into building services component service life and other whole life performance issues has led to the use of reliability engineering techniques. This adoption of cross-industry global techniques has created a shift in the way we look at buildings. We are encouraged to see buildings as products. There is a paradox here as buildings are seldom identical. The use of 'product' technology and procurement methods however can certainly be applied in order to meet cost reduction metrics being sought. Clients are also starting to demand demonstrated real value and performance together with benchmarks. For this we require some level of common framework. The construction industry has been looking at adopting a framework that allows the supply chain to consider service life, whole life cost and building component performance data during procurement and throughout the building's life.

There has been much work in this area and the best method for handling of performance and costs-in-use data has been debated strongly in recent years. Research carried out by BRE into this area under the UK LINK Construction Maintenance and Refurbishment programme with strong industry support came to the conclusion that the key to its success, was the implementation of 'Building Data Spine' or 'BDS' (Clift and Butler 1995). Huge amounts of data are required to model performance throughout the whole life of a building and an extremely robust and tested model is required. Integrated Logistics Support (ILS) is one possible model that provides a framework that could incorporate this level of sophisticated data. ILS developed for defence procurement with reliability techniques at its core, allows whole life performance and cost issues to be integral. This approach would also complement the current movement in service life planning of buildings in relation to British Standards (BSI 1997) and International Standard ISO 15686.

2 What is ILS?

Integrated logistical support (ILS) mechanisms have been adopted within defence applications as a means of bringing together and managing the processes associated with the important resources involved in carrying out a project from inception to disposal. Recent research carried out by BRE for the UK government indicated ILS as being one example of successful whole life costing strategies in defence industries world-wide (Clift & Bourke 1999). In the US navy ILS was adopted to respond to the shrinking budget and the maintenance of complex ships, which must be retained in a state of readiness at all times. The planned life expectancy of ships has gone up from 20 to 40 years. The US navy has responded by developing maintenance programmes such as Planned Maintenance System (PMS) and Current Ship's Maintenance Project (CSMP) to optimise readiness, modernisation and planned replacements of obsolete equipment. Associated initiatives include Computer aided acquisition and logistical support (CALS) to integrate and use automated technical information for weapon system design, manufacture and support. The concepts underlying all these military procurement initiatives can be summed up as "build a little, test a little, learn a lot" (Clift & Bourke 1999). This can be contrasted with the construction industry – which has rarely developed designs from prototypes into standard, tried and tested solutions.

Within the UK, both reliability and maintainability assessment procedures have been adopted as Defence Standards, following on from work within NATO on their standards (STANAGs). Exploration of the need for guidance in setting reliability requirements for military equipment has led to advances in this area. Decision support programmes have been developed for modelling development costs (CORD), in-service costs (COUP) and whole life reliability models (DOCTOR: Wheatcroft 1985) which describes a suite of three reliability cost models for armoured fighting vehicles, together with the results of example applications.

While the guidance is targeted towards equipment and moving plant, many of the principles described are transferable to construction. The military models and process maps were developed in respect of plant or equipment within a military context, but there is scope for technology transfer to construction processes and decision-making. These techniques may also foster the partnering and supply chain management approach, which the industry is encouraging.

ILS in its current format has four core activities within the framework that are applied throughout a product's whole life ('cradle to grave'):

1. Establishment of supply chain support status (develop, deliver, maintain, or terminate)
2. ILS support analysis - combines component reliability and failure analysis with the provision of maintenance requirements (e.g. Failure modes effect and criticality analysis, Reliability Centred maintenance)
3. Whole-life costing analysis
4. Other Integrated supply support procedures relevant to administration and human issues (e.g. documentation, ordering, invoicing, handling, skill requirements, training, testing etc.)

ILS also requires a plan, or an 'integrated logistics support plan' (UK MOD 1996), which is developed at design stage and remains in place throughout the life of the product. This optimises the reliability and maintainability (R&M) of the product in conjunction with the 'engineering support' or maintaining organisation. The plan addresses all lines and depths of maintenance as a coherent whole, which takes account of factors such as:

- The preventive maintenance requirements of the equipment in all environments in which it may be used or stored;
- The probable pattern of corrective maintenance operations;
- The maintenance opportunities arising in normal operations in order to schedule preventive maintenance into non-operational periods whenever possible.
- The spares and materials required supporting the predicted maintenance requirements;
- The maintenance logistic system;
- The test equipment and tools required for handling, maintenance and repair; sub-dividing these into special items, which will be provided by the equipment manufacturer, and the common tools and test equipment which will be provided by the maintenance organisation;
- The maintenance and repair information which will be needed by the maintenance organisation and the required format;
- The maintenance skills of personnel which will be needed by the maintenance organisation and what training will be required.

These reliability techniques and maintenance strategies that are part of ILS may be summarised as follows:

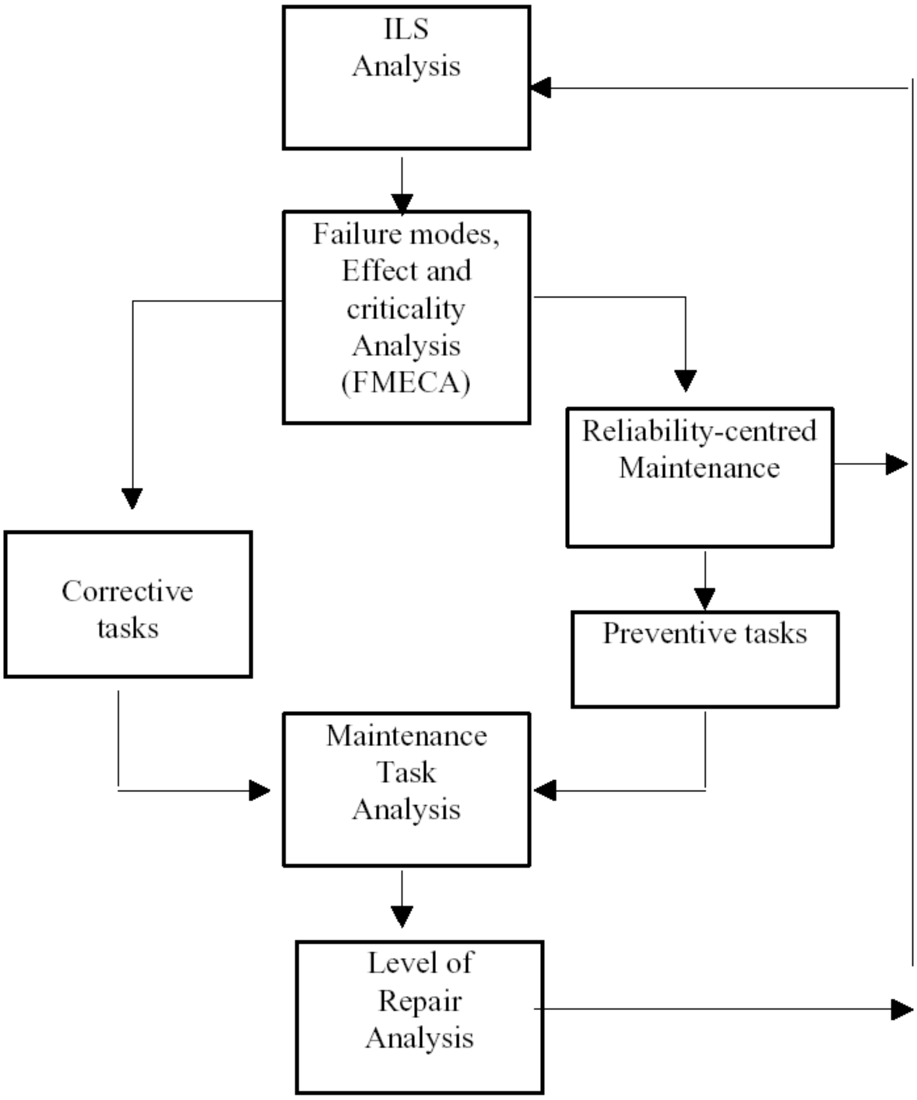

Fig. 1: Integrated logistics support analysis (UK MoD 1996)

As stated previously ILS has reliability engineering techniques at its core. The benefits of reliability engineering in construction have been demonstrated in relation to the assessment of building services component service life (Bartlett & Simpson 1998). Reliability Centred Maintenance (RCM) detailed above is a disciplined logic, or methodology, which is used to identify and implement preventive maintenance, tasks in order that the equipment attains its inherent reliability at minimum cost (UK MoD 1996). It is commonly used in the asset management of complex buildings involving large amounts of services components. RCM requires the identification of significant items; classified on the consequences of their failure; will failure affect safety, or have a significant impact on operations or economics. RCM demands the identification of the engineering causes for each functional failure, which may be accomplished by an

FMECA. Each engineering failure mode, for significant items, is to be analysed to determine if a technically feasible and effective maintenance task can be scheduled to safeguard the function of the item. If no task can be scheduled, then the equipment should be re-designed.

3 Recent related research & development

3.1 BRE research

A new approach to the assessment of the performance and costs-in-use of buildings was promoted by a BRE report (Clift & Butler 1995) which highlighted the need for a Building Data Spine as discussed in the introduction. Following on from this research work was carried out in the UK under the Partners in Technology (PiT) programme. This project team involved a major UK commercial organisation, an ILS software company, University of Reading, and BRE (University of Reading 1998). The aim of the project was to develop Integrated Logistic Support for Construction (ILSC) procurement, to achieve real cost reduction & improve operational performance (add value to client's business). This project introduced some of the key aspects of ‘supportability’ in the construction industry context (Fairey & Garnett 1998). The objectives were to:

- Identify and define the strategy of Integrated Logistic Support for Construction (ILSC).
- Determine how the methodology of ILSC can be used to reduce risk, improve the procurement process and optimise whole life costs.
- Determine how ILSC can achieve designs influenced by whole life cost, buildability, health and safety, operating and maintenance planning.
- Define standards for the use of ILSC within the construction industry.
- Define, develop and validate software, based upon a commercially available database customised to support ILSC.

Cultural changes were also addressed in order to ensure ILSC could add real value to construction, minimising client risk and ensuring efficient design on a whole life basis and thus fitness for purpose. This has yet to proven on a large scale and further development is needed to encourage client adoption of the approach. This is partly due to the fact that additional work is required to make ILS building specific and not an adaptation of a framework and software used in defence procurement in general. The project looked to use existing construction principles and existing software rather than develop expensive bespoke systems (Fairey & Garnett 1998). Successful case study applications of ILSC to lifts and package handling facilities in airports were carried out as part of the study.

In addition to this research, BRE carried out a project entitled ‘Computerised Exchange of Information in Construction Industry’ (Wix & Bloomfield 1995) which looked at CALS (Continuous Acquisition and Life Cycle Support) and its relevance to the UK construction industry. The report prepared for UK DETR found that further efforts should be made to establish ‘de facto’ standards for life cycle data exchange and sharing. The CALS approach is essential in providing the typical IT backup for ILS and is concentrated on the software provision. It does not however, provide a readily adaptable solution that is construction based. This possibly explains the lack of take-up of the approach at present. Further research is certainly needed in this area.

3.2 Other relevant research

Research at The Bartlett College (Young et al 1996) compared refurbishment in shipping and construction and identified substantial similarities and a number of transferable tools and techniques of benefit to both industrial sectors. This study did not specifically focus on whole life costs but emphasised the possibility of transferring ILS from defence to the construction sector. The University of Dundee (El-Haram et al 1998) has recently looked at the application of ILS to the development of cost-effective maintenance strategies for existing housing building stock. The project was funded under the UK EPSRC research program. The aim of the project was to determine the potential for applying ILS to the design of optimum support strategies, which would minimise the cost of maintaining existing building stock. This project came up with some interesting conclusions stating that there is considerable potential for the application of ILS to existing building stock. It was claimed that if the results of the study were replicated across all the UK publicly owned residential property, there would be a national annual saving of £250m or 18.5% (El-Haram et al 1998).

The developing series of standards on service life planning (ISO 15686) mentioned earlier includes parts on general principles, data requirements, maintenance and life cycle costing, and is also relevant in the context of ILSC. The application of this guidance could usefully take place with an ILSC framework.

4 ILSC – A proposed model & future research needs

It is noticeable that research carried out so far has been related to particular building types with ILSC being successfully applied to a number of M&E components and social housing. There is potential to adapt the framework for other building types and components. Using the UK Ministry of Defence (UK MoD 1994) framework as a base, a model is proposed in figure 2. There is scope for further research and robust testing of the model with it forming the basis of an ILSC toolkit that could be used throughout a building whole life cycle.

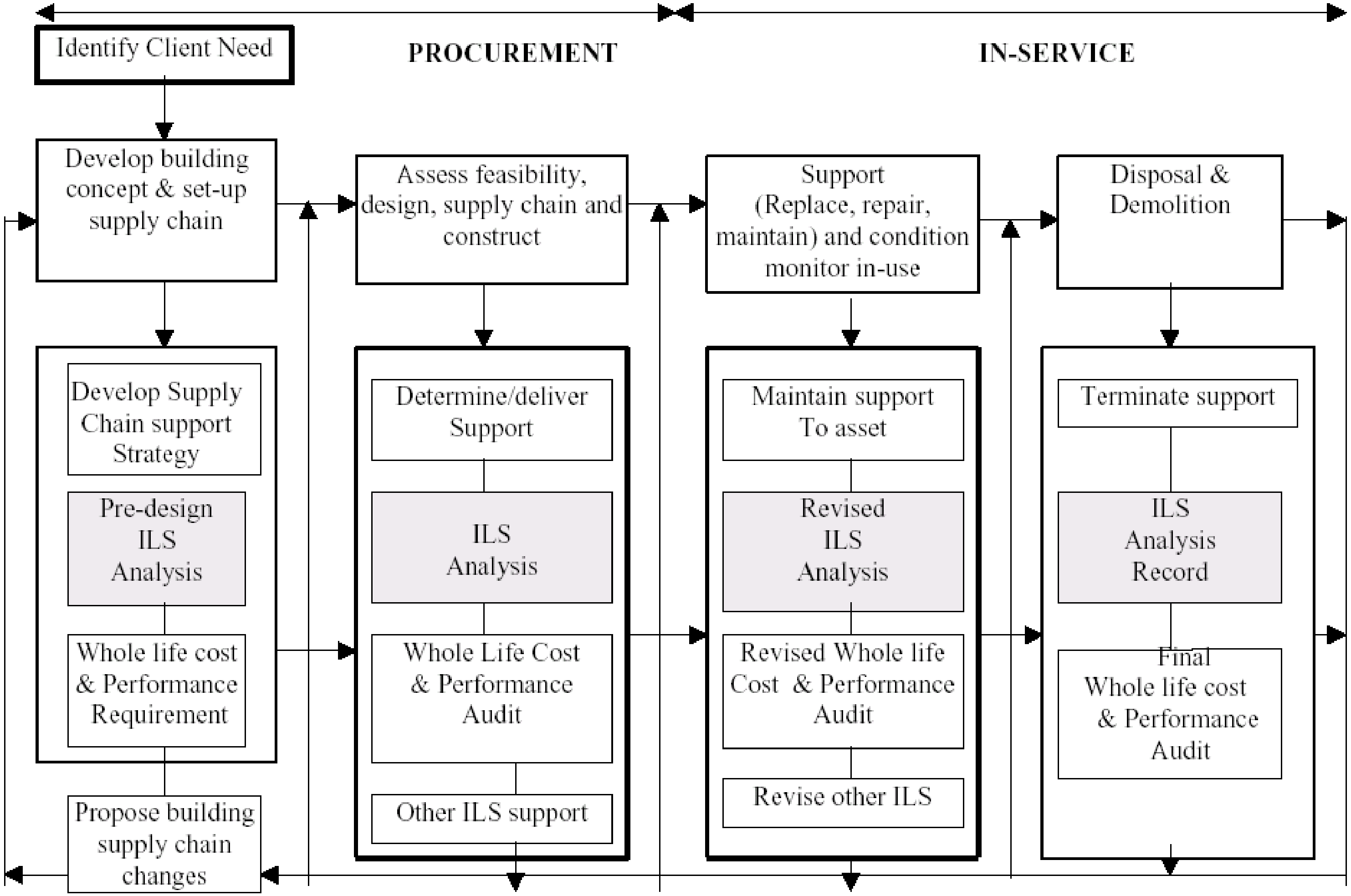

Fig. 2: Integrated Logistics Support Framework for Construction (adapted from UK MoD 1994)

5 Conclusion

ILSC is a framework that can integrate whole life cost data and performance data in one model. The framework and the process as a whole appear to fit in with international developments in service life planning. It is apparent however, that much of the work in ILS has been focused on the Information Technology implications of the framework. Questions need to be answered in future research in relation to the level of sophistication of buildings compared to defence products. Mapping of the similarities and differences of buildings compared to defence products is required. The level of IT use in ILSC will either force the change or make it too complex. Benefits of applying ILSC to certain building types have been demonstrated. The key to further development and successful use will depend on greater cross transfer of the technology to other building types over different stages of the building life cycle.

6 References

Bartlett, E. & Simpson, S. (1998) *"Durability and Reliability, Alternative Approaches to Assessment of Component Performance Over time",* CIB World Building Congress, 'Symposium A', Sweden, June 8-12 1998

BSI (1997) *BS HB 10141 - Buildings - Service Life Planning, Part 1: General principles*, British Standards Institute, London, 1997

Clift, M.R. & Bourke, K (1999) *Study On Whole Life Costing,* Building Research Establishment Client Report for DETR, Number CR 366

Clift, M.R. & Butler, (1995) A., *, The Performance And Costs-In-Use Of Buildings: A New Approach,* Building Research Establishment (BRE) Report,

El-Haram,M., Horner, R.M.W. & Munn,A.K. (1998) *Application Of ILS To The Development Of Cost Effective Maintenance Strategies For Existing Building Stock*, University of Dundee Construction Management Research Unit, 1998

Fairey, V. & Garnett, N. (1998) *How can construction benefit from the introduction of a supportability strategy,* Reading University and Dytechna Ltd.

Reading University (1998), *Cost of ownership through integrated logistics support for construction*, Advanced Construction Technology – Department of Construction Management and Engineering, Report - Jan 1998

UK Ministry of Defence (1996), *Integrated Logistic Support Part: 0 Application of integrated logistic support (ILS)* Defence Standard - 00-60 Issue: 1 Dated: 10-May-96

UK Ministry of Defence (1994), *Integrated Logistics Support – As A Basis For The Procurement Of Defence Equipment*, Section 51: Consultancy and Advisory Services guidance paper 062

Wheatcroft, P.A.C. (1985) *DOCTOR - Whole Life Reliability Cost Model*
Int.J.Quality Reliability Mgmt, 1985, vol.2, no.1, pp4-17

Wix, J. & Bloomfield, D.P. (1995*), THE Relevance of the Cals Concept For Building Construction*, Building Research Establishment (BRE) Client Report prepared for Construction Directorate

Young, B.A., Torrence, V.B., & Egbu, C.O. (1996*) Managing Refurbishment Works In The Construction And Shipping Industries*, The Bartlett, UCL

Contribution from the Centre for Window and Cladding Technology,University of Bath

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FMEA Applied to Cladding Systems – Reducing the Risk of Failure

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FMEA Applied to Cladding Systems - Reducing the Risk of Failure

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Failure Mode and Effects Analysis (FMEA) is a systematic and analytical quality planning tool for identifying and addressing what potentially could go wrong with a product or process. The project 'Failure Mode and Effects Analysis (FMEA) in the cladding industry' describes the FMEA technique, investigates failures of cladding on a system, comportent and process level, and maps the cladding supply chain and cladding-related decision making. The level of knowledge of failures and the fragmented industry structure prevents rigorous use of FMEA exemplified by other industries. However, a simplified form of FMEA can be performed based on the research findings to prioritize and inform decision-making and facilitate site inspection/ supervision.

L'analyse des modes de défaillance et de leurs conséquences (AMDC) est un outil systématique de planification de la qualité qui sert à détecter tout ce qui pourrait nuire à un produit ou un processus et à y remédier. Le projet 'Analyse des modes de défaillance et de leurs conséquences chez les fabricants de bardage' a pour objectif de décrire la technique AMDC, d'étudier les défaillances de bardages au niveau système, composant et processus, et d'établir une correspondance entre la chaîne d'approvisionnement en bardages et le processus décisionnel en matière de bardage. Le niveau de connaissances en ce qui concerne les défaillances et la structure fragmentée de cette industrie empêchent l'utilisation rigoureuse de l'AMDC comme en attesient d'autres industries. Une forme simplifice de l'AMDC peut toutefois être utilisée sur la base des résultats de recherches, qui permet d'indiquer au processus décisionnel les priorités et de faciliter les interventions d'inspection et de surveillance sur les chantiers.

Keywords: cladding, decision-making, failure, FMEA, feedback loop, risk analysis

Failure mode and effects analysis (FMEA)

Failure Mode and Effects Analysis is a systematic and analytical quality planning tool that was developed in the aerospace and defence industries to identify and prevent potential problems. The analysis comprises three stages:

(1) Identify potential and previously unknown failure modes and all corresponding failure mode causes an effects;

(2) Rank causes of failure according to likelihood (probability of occurrence and of nondetection) and impact (severity of the effects of the resulting failure mode);

(3) Provide for problem follow-up and identify corrective action to be taken.

Cladding

Cladding accounts for up to 25% of the cost of a building, has a major impact on its integrity and service life and provides and preserves its appearance. The term cladding embraces a broad range of building envelope constructions including traditional fully-sealed and modern pressure-

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equalized cladding panels, curtain walling and structural glazing systems.

FMEA of cladding

Successful application of FMEA depends on the availability of information regarding the manner in which failures occur and are caused, together with the frequency, severity and detectability of such occurrences.

Risk identification

Stage one of FMEA identifies all potential failures and their causes and provides a check list to ensure no aspect of performance nor cause of failure is overlooked. Table 1 identifies the manner in which cladding can fail on a system level. Each type of failure may be caused by design or construction errors at a system or component level.

A concept essential to FMEA is the breakdown of the system into 'elements', in order to identify failures which have consequences affecting the functioning of the system. The results of the above exercise applied to three cladding components are summarized in Table 2 where potential causes of one failure mode are identified.

Table 1. Potential effects of failures in priority order

1 Water penetration
2 Air permeability
3 Lack of fit
4 Durability
5 Condensation
6 Time overrun
7 Aesthetic
8 Structural performance
9 Maintenability
10 Budget overrun
11 Acoustic performance
12 Security
13 Thermal performance
14 Hygiene (resistance to vermin/rot)
15 Fire performance
16 Environmental

The FMEA thus identifies. the relationship between component failures and failures, degradation of performance or integrity, of the system (Table 2). For example, failure of a wet-sealed joint by loss of adhesion with the adjoining subsirate usually undermines substantially the performance of the joined components - the cladding system - in terms of weathertightness, thermal insulation etc.

Risk analysis

FMEA is a form of risk analysis and stage 2 requires 'real' data to determine the level of risk of the product/process being analysed. In the automotive industry, this takes the form of ranking the identified failure modes and causes according to probability of occurrence, severity of effects and probability of nondetection to form a risk priority number (RPN).

Occurrence ranking

In the automotive industry the occurrence ranking may be computed from service history data documenting internal process failures (i.e. from the quality assurance department) and external use failures (e.g. from warranty claims) of either the product being analysed or a similar product.

Table 2. Potential causes of one failure mode of three cladding components

Component	Sealant	Glass	Finishes
One failure mode	Adhesion loss	Breakage	Loss of durability
Effects (Table 1)	1, 2, 7, 13	8, 12, 13	4, 7
Causes	joint configuration joint preparation wrong sealant wrong or no primer poor installation (e.g. poor tooling) poor joint design poor miwing (two-part) material fault	impact edge damage glass design (thermal) material fault (e.g. NiS) glass design (wind) building movement	workmanship (cut edges/handling) coating application base metal/galvanizing architectural detailing poor maintenance weathering (colour/gloss/chalking) coating selection

In this study, qualitative failure data have been compiled from the experience of industry which enables the cladding system failure modes to be listed in order of occurrence (Table 1). A quantified study of cladding systems under test substantiates, in part, these findings: the first-time-pass rates for static water penetration, air permeability and structural serviceability tests of 26, 86 and 92% respectively, show water penetration as unequivocally the most common cladding failure mode under test (McDonald, Kerr and Layzell, 1997).

The causes of failure of the three cladding components listed in Table 2 are listed according to the experience of comportent manufacturers and specialist companies. This is supplemented, in part, by the study of cladding test failures in which 43 different causes of water penetration were identified in the 65 facade samples that leaked. Table 3 lists 21 of the most frequently occurring faults.

Severity ranking

The severity of the effects of failure can be assessed either subjectively or objectively. In the automotive industry failures are assessed in terms of their effects on system (i.e. vehicle) performance and hence customer satisfaction, which is clearly subjective (Table 4). As shown in Table 4, the saine analysis is also amenable to cladding, although in the construction industry the customer may be viewed as the person who pays for the building or those who occupy it. With collation of appropriate data, cladding failures can be ranked objectively, in terms of cost of repair, cost of loss of building use, cost of injury and so on.

Non-detection ranking

The third ranking is a measure of the probability of control procedures not detecting the cause of failure or failure mode before reaching the

Table 3. Common causes of water penetration/remedial work of cladding systems under test

Cause of failure (remedy)	Incidence	Cause of failure (remedy)	Incidence
Frame connections (sealed)	14 samples	Panel butt-joints (sealed)	7
Gaskets (corners sealed)	14		
		Screws (sealed)	6
Window perimeter (sealing)	12	Membrane gap (sealant application)	6
Window (mitre joints sealed)	12	Pressure/glazing beads (sealed)	6
Gaskets (re-selection)	11	Windows (mechanism)	5
		Membrane gap (extra/new membrane)	5
Sample to test rig (sealed)	10		
		Holes (added)	4
Glazing rebate/profile (sealed)	8	Holes (unblocked)	4
Panel/pressing to frame (sealed)	8	Holes (sealed)	4
		Windows (re-manufacture)	4
Screws (tightened)	7	Mullion expansion joints (sealed)	4
Gaskets (re-seated)	7		

Table 4. Ranking the severity of effects of failure

Rank	Effect(s) of failure	Automobile	Cladding
9/10	potential safety problems	loss of steering	structural (breakage, deflection)
7/8	high degree of dissatisfaction	inoperable vehicle	water penetration
4/5/6	some customer dissatisfaction	high pedal efforts	draughts, condensation, noise
2/3	slight customer annoyance	poor appearance	aesthetics (staining, colour, finish)
1	no noticeable effect		

customer. Based on the quality control checks in place, the automotive industry ranks the probability of an individual defect reaching the customer on a scale of 'l' (remote likelihood, e.g. 0-5% probability) to `10' (very high likelihood, e.g. 86-100% probability).

Non-detection is very difficult to rank for construction because of the variable level of quality control of a labour intensive process. Practice shows that there is likely to be a high risk of defects going unrecognized during the construction phase and manifesting themselves as failures after building handover because of ineffective supervision. This problem is compounded by the fact that some causes of water penetration (the biggest area of concern, with on-site installation a major cause) are less easily detected than others.

Therefore, a reduction in the non-detection ranking will depend on the nature of the failure cause: some will require a higher level of knowledgeable site supervision (e.g. to check that the joint configuration and seal materials are correct), others, inspection (e.g. the removal of sealant to check its depth and the presence of primer, bond breaker tape etc.) and some, on-site testing (e.g. hose pipe test to detect incomplete sealing etc.). Having said this, reducing the risk of failure by increasing detection does not address the root cause of failure, unless it forms part of an education/learning process. With this in mind, perhaps a more certain, effective strategy would be to target the findings of FMEA at installers, as well as construction practitioners (sec below).

Risk responses

A thoroughly thought out and well developed FMEA will be of limited value unless the final stage of FMEA - implementation of positive and effective actions - is undertaken to address areas of concern. The simplicity of cladding compared with, say, an automobile, means evaluation of which failure causes to address can be simplified so that it is based largely on likelihood, but also recognizes impact of occurrence. The failure data can be translated into several forms of concerted action:

(1) Reducing/eliminating the likelihood of failuse by design (e.g. use of continuous frame gaskets to eliminate a cause of water leakage). This course of action can also take the form of a framework for decision-making, that is, a list of questions (relating to the potential failure modes and failure causes - Table 2) to be asked of suppliers when selecting components.

(2) Reducing/eliminating the likelihood of fail-ure by detection with the aid of a checklist of prioritized causes of failures to avoid. This course of action shows that, for instance, it is crucial for the Clerk of Works to alert the architect if a sealant joint width is found to be incorrect. Design actions can also be made that increase the effectiveness of the current quality controls; practically, this could take the form of choosing a cladding system with very few parts.

(3) Reducing the impact of failure. This can only be accomplished by design actions, for example, by introducing system redundancy (by the addition of a secondary seal) or by designing a fail-safe failure mode (by the use of laminated/wired glass or the incorpora- tion of drainage provision). Repair of the failed component will still be required.

(4) Defining the basis for training and product development in the cladding industry.

(5) Aiding fault diagnosis when failure occurs.

Implementation

The principles of FMEA have wide application with many possible extensions. As a result, each industry, or even individual company, tends to develop its own system and style peculiar to its own circumstances. In the case of cladding (an instance of high risk and severe consequences of failure) a simplified form of FMEA has been shown to be feasible (Layzell and Ledbetter, 1998). However, some questions concerning implementation of FMEA within the construction process remain, namely:

(1) Motivation
In the automotive industry for example, FMEA is performed by the vehicle assembler/manufacturer and the major parts suppliers. Use of FMEA in the parts supply community is often a mandatory

requirement which serves to both motivate use of the technique and, assign responsibility. The building client can drive the use of FMEA by demanding evidence that FMEA and the reseach findings have been considered and addressed in an appropri-ate manner.

(2) Participation and responsibility

In the automotive industry, responsibility for the preparation of FMEA is assigned to an individual having a good working knowledge of the process or design being analysed. Input from relevant departments ensures that the document is complete, and agreement is reached on the proposed corrective actions.

The systematic approach of FMEA formalizes the mental discipline that a designer normally adopts in any design process to prioritize and inform the design method and ensure every conceivable potential failure has been considered and addressed. The architect, contractor and cladding con-tractor may have experiences to add to the evidence of failures from the research to help build quality into the process by targeting corrective actions at the design stage. They are also in a position to effect and monitor follow-up actions on site.

(3) Feedback

The current FMEA of cladding is based on feedback of test failures and of failures/ problems experienced on site. Rigorous use of FMEA depends on the industry becoming a learning organization which, by establishing a stronger link between design and construction, undertakes feed-back of defects and their causes from site personnel and clients/tenants and trans-lates this into knowledge for future ex-ploitation. In this way, the industry drops what it did badly and replicates what it did well and FMEA becomes a living document that reflects the latest informa-tion and actions.

The next step

FMEA, as a potential cost saver and tool for reducing cladding failures, faces the following industry/cultural barriers to implementation:

- FMEA demands resources 'up front' (but will save money in the long run). Its use therefore faces commercial pressure and requires the industry to accept change (e.g. a price increase, increased inspection/supervision) which will entail a change in culture and a long-term learning process so that every operation is undertaken satisfactorily for those who follow. FMEA was developed in the automotive industry over time - the construction industry should take a similarly long-term view of how to improve.
- The main benefits of FMEA to the client are measured in terms of life-cycle costs. Unfortunately, the practice of life-cycle costing is not yet widespread within the construction industry. Moreover, additional capital costs to save overall costs are hard to justify to the client because the benefits of many decisions cannot be quantified. Further in-depth research on the actual causes of cladding failure and the cost of rectifying them is required before FMEA can be thoroughly practised and improvements fully realized.
- FMEA in itself is no panacea for the problem of cladding failures (but shows how the risk of failure can be reduced); cladding failures are symptoms of one or more of the following technical or process deficiencies:

Incorrect selection/specification

The four cladding components most likely to fail (sealants, gaskets, glass and metal finishes) too often receive inadequate consideration from initial selection through to incorporation within the building. For example, despite their fundamental role, sealants are low cost and seen to be a low priority, an afterthought or even the target for cost savings. Specifications for cladding components can be incorrect or contain vague requirements that transfer decision-making, potentially to a disreputable or unqualified contractor, greatly increasing the risk of failure.

FMEA provides a design methodology for selecting components and focuses attention on high-risk components and performance criteria regardless o their size or cost. Eradication of the nonsensical practice of targeting cost savings for low cost, high risk cladding components is an obvious and much needed initial benefit of FMEA.

Poor communication

Poor communication can be symptomatic of commercial pressures or a lack of knowledge and lead to misunderstandings or omissions that contractually force quality to be reduced. Correct, complete and timely communication is crucial to successful procurement.

Cost cutting

The culture of cutting capital costs is damaging to the cladding industry and is not in the client's long-term interests because it increases the risk of failure with repair costs disproportionate to any initial saving.

A change of culture, for example by the recognition of life-cycle costs, would mean the best value-engineered solution is selected as opposed to the cheapest solution. The fragmented structure of the construction industry and the inability to evaluate cost against worth, hinders communication of this message back to the client. Potentially, FMEA would play a greater part in the decision-making process to help argue the case for cladding systems, materials, components, processes, quality control measures and so on that yield lower overall costs.

Subversion of specifications

A correct and explicit specification may be under-mined by the practice of deliberate noncompliance later in the construction process in order to reduce costs. This can be reduced by a cultural change, whereby everybody strives to improve everything they do, and by effective site supervision.

Fabrication errors

Fabrication errors - typically incorrect sealing/ drainage provision - occur on both standard and bespoke cladding systems. The facilities for training system fabricators already exist but are largely under-utilized.

System suppliers and inquisitive specifiers can motivate fabricators to train. System suppliers should also explain their products better and check that they are being used as intended.

Installation errors

On-site practice was said to present the greatest potential for failure because of the lack of knowledge of installers. In defence of installers, they may be under pressure to complete the job or be required to build complex details, perhaps without proper assistance, installation manuals or appropriate drawings/instructions.

Trained installers who are familiar with the system to be installed and who preferably installed a test mock-up (if project testing was undertaken) will reduce the risk of installation errors. This must be coupled with proper communication to site, knowledgeable supervision and reasonable time-scales.

Poor supervision

The low level and superficial nature of supervision has been widely criticized. AI] parties should take an interest in the cladding installation process because the standard of site workmanship can be improved by rigorous, knowledgeable inspection and supervision, which the currently developed FMEA for cladding facilitates.

Poor motivation

Cladding installers can be left to their own devices and paid in a manner that rewards quantity and not quality of work. Site working conditions should be conducive to a high standard of workmanship and promote a regime of making sure every process is carried out satisfactorily for both internal and external customers. This can be achieved by high levels of supervision, reasonable contract time-scales, co-operation between trades, a higher regard for competent installers, modified methods of payment and so on.

Contractual pressures

Unreasonable cost and time pressures compromise quality, regardless of training. Increased

BUILDING RESEARCH & INFORMATION (1998) **26**(6), 351-357 lead times would allow increased planning so that problems are recognized and solved at the design stage rather than during construction where there is a greater risk of quality being compromised or subordinated by commercial pressures.

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References

Layzell, J. and Ledbetter, S. *(1998) Failure Mode and Effects Analysis in the Cladding Industry,* Centre for Window and Cladding Technology, University of Bath, UK.

McDonald, N., Kerr, D. and Layzell, J. *(1997)* The benefits of testing cladding for weathertightness, ICBEST *'97, pp. 295-300,* Centre for Window and Cladding Technology, University of Bath, UK.

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General Methodology Of Test Procedures For Assessment Of Durability And Service Life

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Summary: A general methodology for assessment of durability and service life by accelerated testing is described. A predictive failure modes and effect analysis is used as a starting point for planning of the accelerated life tests.The method includes several important steps: a) an initial risk analysis of potential failure modes with a checklist of failures and their links with material properties, degradation processes and environmental stress factors, b) screening testing/analysis for service life prediction including pretesting, analysis of material changes resulting from ageing and microclimate characterization, and c) service life prediction from results of accelerated testing with mathematical modelling, life testing and reasonability assessment and validation.

The applicability of the proposed methodology is demonstrated by utilizing previous results from a case study on accelerated life testing of selective solar absorber surfaces for domestic hot water production. The work presented forms part of Task 27 "Performance of Solar Façade Components" of the IEA Solar Heating and Cooling Programme.

Keywords: Materials, durability, methodology, accelerated tests, service life prediction

1 INTRODUCTION

To achieve successful and sustainable commercialisation, building products must meet three important criteria, namely minimum cost, sufficient performance, and demonstrated durability.

Durability assessment directly addresses all three segments of this triad. First, it permits analysis of life cycle costs by providing estimates of service lifetime, O&M costs, and realistic warranties. Understanding how performance parameters are affected by environmental stresses (for example by failure analysis) allows improved products to be devised. Finally, mitigation of known causes of failure directly results in increased product longevity. Thus, accurate assessment of durability is of paramount importance to assuring the success of solar thermal and building products.

Within the IEA Solar Heating and Cooling Programme, Task 27 on the Performance of Solar Facade Components started at the beginning of year 2000 with the objectives of developing and applying appropriate methods for assessment of durability, reliability and environmental impact of advanced components for solar building facades.

For the work on durability there are two main objectives. The first is to develop a general framework for durability test procedures and service lifetime prediction (SLP) methods that are applicable to a wide variety of advanced optical materials and components used in energy efficient solar thermal and buildings applications. The second is to apply the appropriate durability test tools to specific materials/components to allow prediction of service lifetime and to generate proposals for international standards.

This paper presents a general outline of methodology to meet the first objective. A thorough description of the methodology can be found in a Working Document of IEA Solar Heating and Cooling Task 27 (Carlsson *et al.* 2001)

2 GENERAL METHODOLOGY

Many efforts have been made to develop systematic approaches to service life prediction of components, parts of components and materials so that all essential aspects of the problem will be taken into consideration, see e.g. Gaines *et .al.* (1977), Sjöström (1985), CIB W 80/RILEM 71-PSL (1986), ISO 15686-1(2000) and ISO 15686-2 (2001)

In another methodology, which will be focused on in this report, a predictive failure modes and effect analysis serves as the starting point for service life prediction from accelerated life test results as is illustrated schematically in Fig. 1. The analysis is made on the component level.

The diagram in Fig. 1 is based on a similar scheme by Gaines et al. (1977). The diagram in Fig. 1 was originally developed for the purpose of accelerated life testing of selective solar absorber surfaces in a joint case study of Task 10 of the IEA Solar Heating and Cooling Program (Carlsson et al.1994)

- **PENALTY** is the level at which an assessment is made of the economic effects of a component failure. Based on this assumption, it is possible to set a reliability level that must be maintained for a given number of years.

- **FAILURE** is the level at which performance requirements are determined. If the requirements are not fulfilled, the particular component or part of component is regarded as having failed. Performance requirements can be formulated on the basis of optical properties, mechanical strength, aesthetic values or other criteria related to the performance of the component and its materials.

- **DAMAGE** describes the stage of failure analysis at which various types of damage, each capable of resulting in failure, can be identified.

- **CHANGE** is related to the change in the material composition or structure that can give rise to the damage of the type previously identified.

- **EFFECTIVE STRESS** is the level at which various factors in the microclimate, capable of being significant for the durability of the component and its materials, can be identified. An important point here is that it is possible to make quantitative characterisation.

- **LOADS**, finally, is the level that describes the macro-environmental conditions (climatic, chemical, mechanical), and which is therefore a starting point for description of the microclimate or effective stress as above

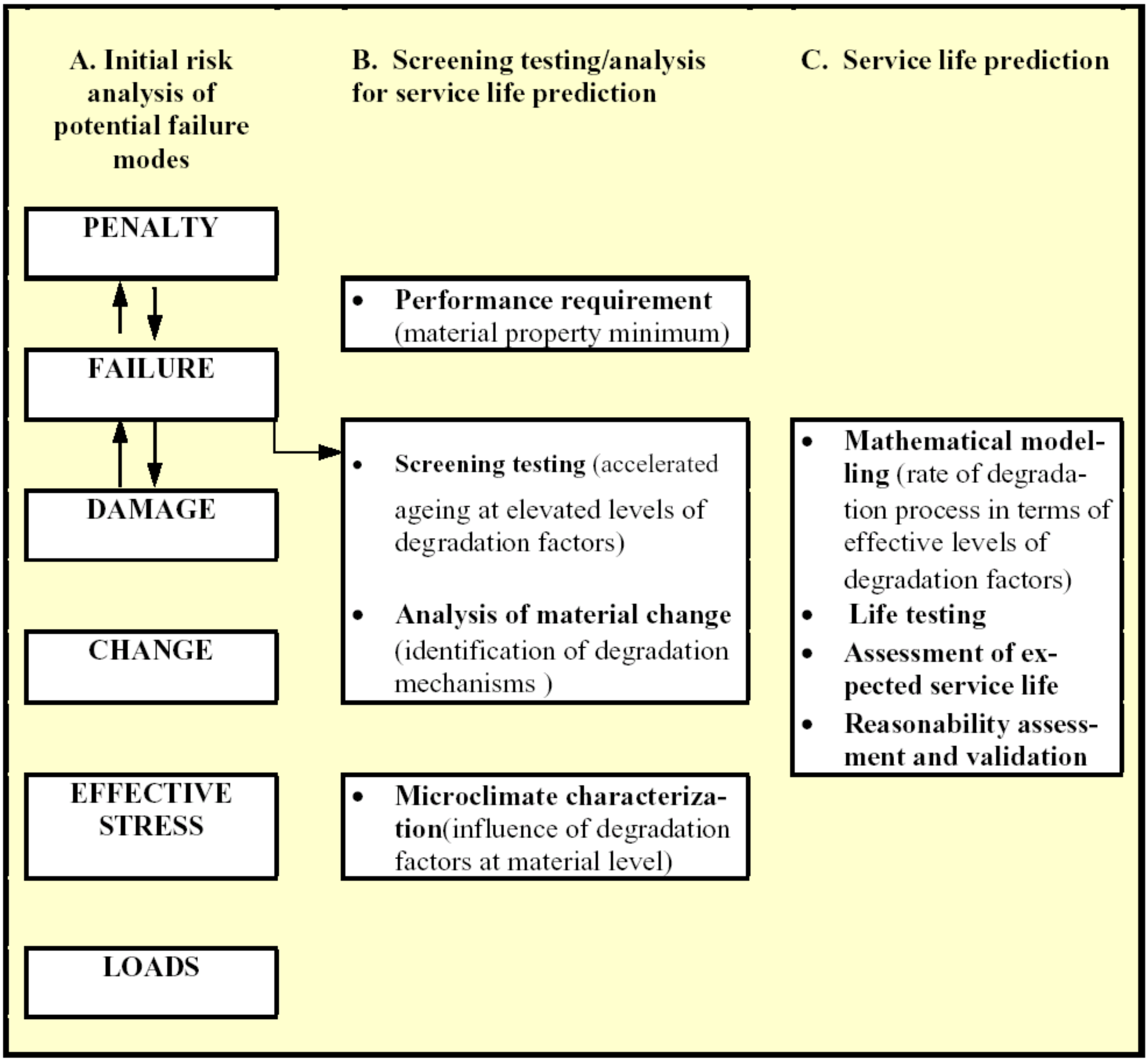


Figure 1. Failure mode analysis for planning of accelerated tests for service life prediction

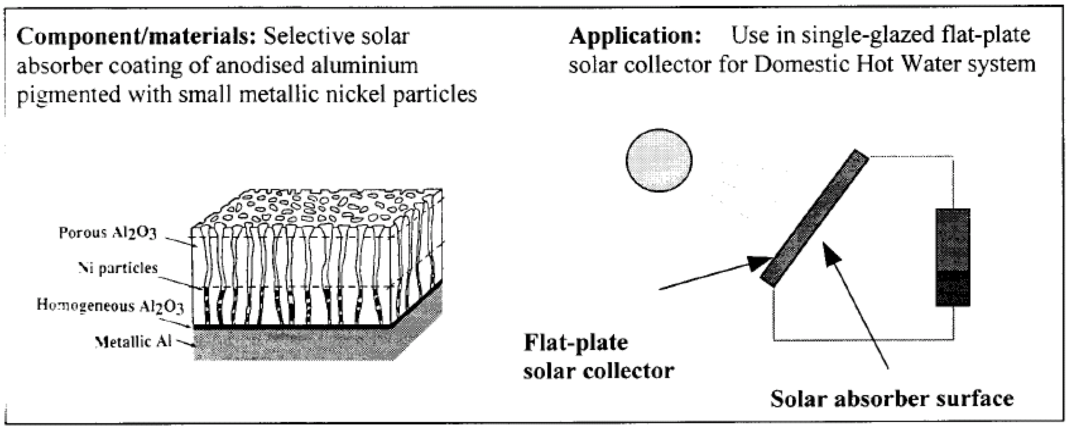
The first phase of work is an initial risk analysis of potential failure modes. Each step in the scheme related to the risk analysis shown on the left hand side of Fig.1 may be related to the subsequent step by an appropriate deterministic or statistical relationship. The second phase of work makes use of the results from the initial risk analysis and involves as major steps screening testing and analysis of associated material changes for identification and confirmation of the most important degradation mechanisms. After the assumptions of the predominating degradation mechanisms have been confirmed the most important degradation factors or environmental stress factors causing material degradation may also be confirmed. Their effective level and duration during service conditions are thereafter assessed by microclimate measurements. The third phase of work involves mathematical modelling, life testing and prediction of service life finely. Reasonability assessment and validation constitute the last steps in the service life prediction scheme.

3 INITIAL RISK ANALYSIS OF POTENTIAL FAILURE MODES

The first step in the scheme illustrated in Fig. 1 is an analysis of potential failure modes with the aim of obtaining

- a checklist of potential failure modes of the component and associated with those risks and critical component and material properties, degradation processes and stress factors,
- a framework for the selection of test methods to verify performance and service life requirements,

Table 1. Example of result from an initial risk analysis of potential failure modes based on information taken from the IEA Task 10 case study on selective solar absorber surfaces



Component/materials: Selective solar absorber coating of anodised aluminium pigmented with small metallic nickel particles

Application: Use in single-glazed flat-plate solar collector for Domestic Hot Water system

A. Specification of end-user and product requirements on component

Function and general requirements	*General requirements for long-termperformance during design service time*	*In-use conditions and severity of environmental stress*
-Efficiently convert solar radiation into thermal energy -Suppress heat losses in the form of thermal radiation	-Loss in optical performance should not result in reduction of the solar system energy performance (solar fraction) with more than 5%, in relative sense, during a design service time of 25 years	*- Behind glazing in contact with air.* - Casing of collector exchange air with the ambient, meaning that airborne pollutants will enter collector. - If the collector is not rain tight the humidity level of air in the collector may become high - Maximum temperature 200 °C

B. Specification of functional properties and requirements on component and its materials

Critical functional properties	*Test method for deter-mining functional property*	*Requirement for functional capability and long-term performance*
-Solar absorptance (α) -Thermal emittance (ε) -Adhesion (ad)	ISO CD 12592.2 ISO CD 12592.2 ISO 4624	**Functional capability** $\alpha > 0.92$ $\varepsilon < 0.15$ ad >0.5 MPa
		Long-term performance $PC = -\Delta\alpha + 0.25\,\Delta\varepsilon \leq 0.05$

- a framework for describing previous test results for a specific component and its materials or a similar component and materials used in the component and classifying their relevance to the actual application, and
- a framework for compiling and integrating all data on available component and material properties and material degradation technology.

From a practical point of view, but also from an economic viewpoint, an assessment of durability or service life has to be limited in its scope and focused on the most critical failure modes. An important part of the initial step in such an assessment is therefore estimating the risk associated with each of the potential failure modes of the component.

The programme of work in the initial step of service life assessment may be structured into the following activities (Carlsson, 1993):

a) Specify from an end-user point of view the expected function of the component and its materials, its performance and its service life requirement, and the intended in-use environments;

b) Identify important functional properties defining the performance of the component and its materials, relevant test methods and requirements for qualification of the component with respect to performance;

c) Identify potential failure modes and degradation mechanisms, relevant durability or life tests and requirements for qualification of the component and its materials as regards durability. When identifying potential failure modes, it is important to distinguish between 1) failures initiated by the short-term influence of environmental stress, the latter representing events of high environmental loads on the component and its materials, 2) failures initiated by the long-term influence of environmental stress, the latter causing material degradation so that the performance and sometimes also the environmental resistance of the component and its materials gradually decrease.

d) Estimation of risks associated with different failure modes

e) The result of the initial risk analysis of potential failure modes may be documented as shown in Table 1 and Table 2 using information from a case on accelerated life testing performed in Task 10 of the IEA Solar Heating and Cooling Programme (Carlsson *et al.* 1994)

The first activity specifies in general terms the function of the component and service life requirement from an end-user and product point of view, and from that identifies the most important functional properties of the component and its materials, see Table 1.

How important the function of the component is from an end-user and product point of view needs to be taken into consideration when formulating the performance requirements in terms of those functional properties. If the performance requirements are not fulfilled, the particular component is regarded as having failed. Performance requirements can be formulated on the basis of optical properties, mechanical strength, aesthetic values or other criteria related to the performance of the component and its materials. Defining performance requirement should be accompanied by an assessment of the economic effects of a component failure. Based on this, it is possible to define a service life requirement or set a reliability level that must be maintained for a given number of years.

Table 2. Risk assessment of potential failure modes by use of FMEA applied to the selective absorber surface studied in IEA Task 10, see Table 1

Failure mode / Degradation process	*Severity (S) (rating number)*	*Probability of occurrence(P_O) (rating number)*	*Probability of discovery(P_D) (rating number)*	*Rating-number for risk ($RPN = S\ P_O\ P_D$)*

Severity	**Rating number**
No effect on product	1
Minor Effect on product but no effect on product function	2-3
Risk of failure in product function	4-6
Certain failure in product functionning	7-9
Failure which may affect personal safety	10

Probability of detection	**Rating number**
Failure which always is noted. Probability for detection > 99.99%	1
Normal probability of detection 99.7%	2-4
Certain probability of detection >95%	5-7
Low probability of detection >90%	8-9
Failures will not be found - cannot be tested	10

Probability of occurance	**Rating number**
Unlikely that failure will occur	1
Very low probability for failure to occur	2-3
Low probability for failure	4-5
Moderate probability for failure to occur	6-7
High probability for failure to occur	8-9
Very high probability for failure to occur	10

C. Service reliability/service life

Failure/Damage mode / Degradation process	*Degradation indicator*	*Critical factors of environmental stress/ Degradation factors and severity*	*Estimated risk of failure/damage mode from FMEA*			
Unacceptable loss in optical performance	PC = $-\Delta\alpha + 0.25\ \Delta\varepsilon$; Adhesion		S	P_O	P_D	Risk *RPN*
(A) High temperature oxidation of metallic nickel	Reflection spectrum Vis-IR	High temperature	7	2	8	112
(B) Electrochemical corrosion of metallic nickel	Reflection spectrum Vis-IR	High humidity, sulphur dioxide (atmospheric corrosivity)	7	5	5[1]	175
(C) Hydatization of aluminium oxide	Reflection spectrum IR	Condensed water, temperature	7	7	4[1]	196
		[1] Result of glazing failure				

Potential failure modes and important degradation processes should be identified after failures have been defined in terms of minimum performance levels. In general, there exist many kinds of failure modes for a particular component and even the different parts of the component and the different damage mechanisms, which may lead to the same kind of failure and may sometimes be quite numerous.

The objective of analysis is to identify potential failure/damage modes and mechanisms that may lead to material degradation and the development of damage, and associated critical factors of environmental stress or degradation factors, see the example in Table 2.

The risk or risk number associated with each potential failure/damage mode identified can be estimated by use of the methodology of FMEA (Failure Modes and Effect Analysis) in a simplified way, see IEC Standard (1985) for a review of the FMEA methodology. The estimated risk number is taken as the point of departure to judge whether a particular failure mode needs to be further evaluated or not. The estimated risk number may also be used to determine what kind of testing is needed for qualification of a particular component and its materials, see the example in Table 2.

4 SCREENING TESTING/ANALYSIS FOR SERVICE LIFE PREDICTION

4.1 Screening testing by accelerated ageing

Screening testing is thereafter conducted with the purpose of qualitatively assessing the importance of the different degradation mechanisms and degradation factors identified in the initial risk analysis of potential life-limiting processes.

When selecting the most suitable test methods for screening testing, it is important to select those with test conditions representing the most critical combination of degradation factors, see example in Table 3.

Table 3. Programme for screening testing in the IEA case study on solar absorber absorbers

Possible degradation mechanism	*Critical periods of high environmental stress*	*Suitable accelerated test methods and range of degradation factors*
(A) High temperature oxidation of metallic Ni particles	Stagnation conditions of solar collector at high levels of solar irradiation (no withdrawal of heat from the collector)	Constant load high temperature exposure tests in the range of 200-500 °C
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	Under starting-up and under non-operating conditions of the solar collector when the outdoor humidity level is high	Exposure tests at constant high air humidity (75 – 95 % RH), constant temperature (20- 50°C), and in the presence of sulphur dioxide (0-1 ppm)
(C) Hydratization of aluminium oxide and electrochemical corrosion of metallic Ni particles by the action of condensed water	Under humidity conditions involving condensation of water on the absorber surface	Exposure tests under constant condensation (sample surface cooled 5 °C below surrounding air which is kept at 95 % RH) and temperature conditions ranging from 10 - 90 °C

4.2 Analysis of material change during ageing

Using artificially aged samples from the screening testing, changes in the key functional properties or the selected degradation indicators are analysed with respect to associated material changes. This is made in order to identify the predominant degradation mechanisms of the materials in the component. When the predominant degradation mechanisms have been identified also the predominant degradation factors and the critical service conditions determining the service life will be known.

Screening testing and analysis of material change associated with deterioration in performance during ageing should therefore be performed in parallel. Suitable techniques for analysis of material changes due to ageing may vary considerably. In Table 4 an example from the IEA absorber surface case study is shown that demonstrates how different techniques for analysing material changes resulting from ageing can be used to get information on what material degradation mechanisms are contributing to deterioration in performance.

Table 4. Techniques that were used in the IEA Task 10 solar absorber case study for analysis of material change upon durability testing

Degradation mechanism	*Techniques for analysis of material changes*	*Results*
(A) High temperature oxidation of metallic Ni particles	- UV-VIS-NIR reflectance spectroscopy - AES depth profiling - SEM-EDX - XRD	- Reduction of absorption in solar range corresponding to reduction in metal concentration - Formation of Ni oxides - Small changes in surface morphology - Formation of NiO
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	- UV-VIS-NIR reflectance spectroscopy - FTIR-IR reflectance spectroscopy - AES depth profiling -SEM-EDX	- Reduction of absorption in solar range corresponding to reduction in metal concentration - Formation of sulphate -Increase in surface concentration of Ni accompanied with sulphur at the surface - Surface morphology affected and detection of sulphur
(C) Hydratization of aluminium oxides and electrochemical corrosion of the metallic particles by the action of condensed water	- UV-VIS-NIR reflectance spectroscopy - FTIR-IR reflectance spectroscopy - AES depth profiling - SEM-EDX	- Some changes hard to explain - Formation of hydrated forms of alu-minium oxide leading to increased thermal emittance - Change in surface structure - Considerable change in surface morphology

4.3 Microclimate characterisation for service life prediction

In order to be able to predict expected service life of the component and its materials from the results of accelerated ageing tests, the degradation factors under service conditions need to be assessed by measurements. In Table 5 measurement techniques that were used in the IEA Task 10 absorber case study previously reviewed are given as an example of what factors were needed to take into consideration in this study. It is of extreme importance to characterize the service conditions in terms relevant for the most important degradation mechanisms identified for the materials of the component but also in terms relevant for and convertible into the test conditions for the environmental resistance tests to be used for accelerated life testing.

4.3.1 Distribution functions of single degradation factors or combinations of degradation factors

If only the dose of a particular environmental stress is important then the distribution or frequency function of a degradation factor is of interest. In the IEA absorber case study, only the distribution in the absorber temperature during service conditions was needed for predicting the service life limited by high temperature degradation, see Fig.1, left diagram. In case of service life prediction considering degradation caused by the action of high humidity and condensed water, both air humidity and surface temperature were taken into account, see Fig. 1, right diagram.

Table 5 Techniques that were used in the IEA Task 10 absorber case study for measurement of degradation factors in solar collectors operating under service conditions

Degradation mechanism	*Degradation factors/ Measurement variables*	*Sensors*
(A) High temperature oxidation of metallic Ni particles	*Temperature:* Surface temperature of absorber plate	Pt sensors in holders screwed directly on the absorber plate. To accomplish a good thermal contact heat conducting compound was used.
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	*Atmospheric corrosivity*: Measurement of corrosion mass loss rate of standard metal specimens *Air pollutants*: Measurement of sulphur dioxide concentration inside and outside of the solar collector.	Metal coupons of carbon steel, zinc and copper and evaluation of corrosion mass loss according to ISO 9226 Exposed metal coupons analysed in respect of the sulphate content of the corrosion products by EDX UV-fluorescence instrument for direct measurement of sulphur dioxide concentration in the air outside and inside of the solar collector
(C) Hydratization of aluminium oxide and electrochemical corrosion of metallic Ni particles by the action of condensed water	*Humidity:* Measurement of air humidity in the air gap between the absorber plate and glazing cover of the collector *Time of condensation:* Measurement of specular reflectance of absorber surface *Surface humidity:* Measured relative air humidity converted to relative humidity on surface by use of measured surface temperatures	Capacitance humidity sensors carefully shielded from solar radiation and thermal radiation of the ambient. Special designed reflectance mode condensation sensor

5 SERVICE LIFE PREDICTION FROM RESULTS OF ACCELERATED TESTING

5.1 Mathematical modelling

To perform an accelerated test, D, means that the level of at least one stress factor, X, causing degradation is kept at a higher level relative to the situation in service. Consequently this means the time to failure in the accelerated test, $\tau_{f,D}$, will be shorter relative to service life, τ_s. The ratio between the latter and the former is commonly referred to as the acceleration factor, A. If the applied stress is constant in time also for service conditions, the acceleration factor A can be expressed as

$$A = \tau_S / \tau_{f,D} = a_X = g(\underline{X}_D) / g(X_S) \quad (1)$$

where the expression $g(\underline{X}_D) / g(\underline{X}_s)$ is called the time transformation function or the acceleration factor function. Examples of time transformation functions can be found in e.g. reports by Martin (1982), Carlsson et al. (1988 and 2001). The time transformation functions, a_X, used in the absorber case study are shown in Table 6.

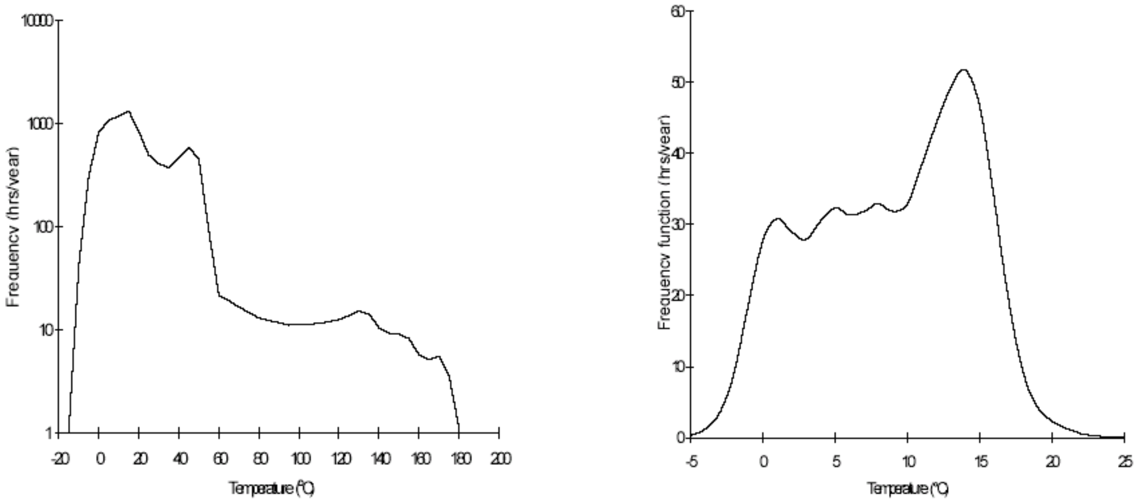


Figure 2. Results from measurement of microclimate for the absorber in the IEA absorber surface case study - Left diagram: Absorber temperature frequency function for one year. For one month of the year the collector was under stagnation conditions - Right diagram: Absorber temperature frequency function when RH ≥ 99% of that year. Metallic mass loss due to corrosion of zinc was determined to 0.3 g/m^2, year

5.2 Accelerated life testing and assessment of expected service life

Accelerated life testing means to quantitatively assess the sensitivity to the various degradation factors on the overall deterioration of the performance of the component and its materials in terms of the mathematical models set up to characterize the different degradation mechanisms identified. Life testing therefore requires conducting a series of tests.

From the accelerated life test results the parameters of the assumed model for degradation are determined and the service life then estimated by extrapolation to service conditions. If the service conditions vary, effective mean values of stress need to be assessed from measured service stress data (Carlsson *e al.* 2001), see also Fig 1.

As a result, it may be possible to express the importance of different degradation mechanisms in terms of expected service life values, see example from the absorber surface case study in Table 6.

5.3 Reasonability assessment and validation

By use of accelerated life testing, potential degradation mechanisms limiting the service life of a component may be identified. However, it is important to point out that it is only the service life determined by the material degradation mechanisms observed in the accelerated tests at relative high levels of stress that can be assessed. Life-limiting degradation mechanisms may exist that cannot be identified by way of accelerated life testing because the knowledge and experience in what may cause degradation of a particular material in a component may be too limited.

Table 6. Estimated service life of the nickel- pigmented anodised aluminium absorber surface in the IEA case study. Values are given for the different degradation mechanisms and assuming that the different degradation mechanisms are acting alone

Degradation mechanism	*Time transformation function* (a_X)	*Estimated service life with PC = -?a + ?e < 0.05* [1] *(years)*
(A) High temperature oxidation of metallic Ni particles	$a_T = \exp [-(E_a / R)\cdot(1/T_D - 1/T_s)]$ E_a = activation energy R = general gas law constant T_D = temperature of test T_s = effective mean temperature at service	$>10^5$
(B) Electrochemical corrosion of metallic Ni particles at high humidity levels and in the presence of sulphur dioxide	$a_{Co} = \tau_{M,s} / \tau_{M,D}$ $\tau_{M,s}$ = time to reach a certain extent of corrosion of reference metal in service $\tau_{M,D}$ = time needed to reach the same extent of corrosion of reference metal in test D (zinc used as reference metal)	12 (The coating is assumed to be installed in a non-airtight highly ventilated collector) 34 (The coating is assumed to be installed in an airtight collector with controlled ventilation)
(C) Hydratization of aluminium oxide and electrochemical corrosion of metallic Ni particles by the action of condensed water	$a^{-1}_{T,H} = \tau_H .\exp(-\frac{E_{H,T}}{R} \quad (T^{-1}_{H,eff} - T^{-1}_D))$ $T_{H,eff}$ = effective mean temperature of the absorber surface when the relative humidity in the air gap is equal to or higher than 99 %. τ_H = the time fraction of the year, time-of-wetness, during which the relative humidity in the air gap is equal to or higher than 99 %. $E_{H,T}$ = Arrhenius activation energy	9 (The coating is assumed to be installed in an non- airtight highly ventilated collector)

[1] PC = 0.05 correspond to a decrease in the solar system performance of 5%

The best approach in validating an estimated service life from accelerated testing, therefore, is to use the results from the accelerated life tests to predict expected change in material properties or component performance versus service time and then by long-term service tests check whether the predicted change in performance with time is actually observed or not.

The results of validation tests therefore can be used to revise a predicted service life and form the starting point also for improving the component tested with respect to environmental resistance, if so required. It should be remembered that the main objective of accelerated life testing is to try to identify those failures, which may lead to an unacceptable short service life of a component. In terms of service life, the main question is most often, whether it is likely or not, that the service life is above a certain critical value.

In order to validate the predicted service life data from accelerated life testing in the IEA absorber case study the actual service degradation in optical performance of the nickel pigmented anodized aluminium absorber coating was investigated (Carlsson *et al.* 2000). Samples from the coating taken from collectors used in solar DHW systems for time periods of ten years or more were analysed for that purpose. It could be concluded that the agreement between degradation data determined for the absorber samples from the DHW systems and that from accelerated life testing from the Task 10 study was astonishingly good both from a quantitative and a qualitative point of view. For the absorber coating in a properly designed solar collector, the service life seems good enough. For the absorber coating in a not air tight solar collector, probably because of glazing failures, the humidity level is raised to such high levels that the service life is reduced to an unacceptable level.

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7 REFERENCES

1. Carlsson B. (Editor) 1988, Survey of service life prediction methods for materials in solar heating and cooling, *International Energy Agency*, Solar Heating and Cooling Programme Task X: Solar Energy Materials Research and Development, Technical Report, Swedish Council for Building Research Document D16:1988.
2. Carlsson B.1993, "Methods for service life prediction", Chapters 4 and 5 in "Handbook in Life Time Technology", Swedish Defence Materiel Administration , 1993-06-21 (Swedish)
3. Carlsson B., Frei U., Köhl M., Möller K. 1994, "Accelerated Life Testing of Solar Energy Materials - Case study of some selective solar absorber coatings for DHW systems", International Energy Agency, Solar Heating and Cooling Programme Task X: Solar Materials Research and Development, Technical Report, SP- Report 1994:13.
4. Carlsson B., Möller K., Frei U., Brunold S., Köhl M. 2000, "Comparison between predicted and actually observed in-service degradation of a nickel pigmented anodized aluminium absorber coating for solar DHW systems,; Solar Energy Materials and Solar Cells 6 (2000)223
5. Carlsson, B.T., Möller K., Marechal J-M., Köhl M., Heck M., Brunold S., Jorgensen G. 2001, "General methodology of accelerated testing for assessment of service life of solar thermal components", Working document of IEA ´Solar Heating and Cooling Task 27: Solar Facade Components - Performance, durability and sustainability of advanced windows and solar components for building envelopes, Project B1: Durability assessment methodology development, May
6. CIB W 80/RILEM 71-PSL 1986, Final Report Materials and Structures, Vol 19, no 114
7. Gaines G.B., Thomas R.E., Derringer G.C., Kistler C.W., Brigg D.M., and Carmichael D.C. 1977
8. Methodology for Designing Accelerated Aging Tests for Predicting Life of Photovoltaic Arrays; Batelle Colombus Laboratories, Final report ERDA/JPL-954328-77/1
9. IEC Standard, Publ. No. 812, 1985, "Analysis Techniques for System Reliability - Procedure for Failure Mode and Effect Analysis (FMEA)"
10. ISO 15686 Building and constructed assets – Service life planning – Part 1: General principles (2000), Part 2: Service life prediction procedures (2001), Part 3: Performance audits and reviews, Part 4: Service life prediction data requirements, Part 5: Maintenance and life cycle costing; Standard under preparation by ISO/TC 59/SC14. ISO International Standardization Organization, http://www.iso.ch
11. Martin J.W. , 1982, "Time transformation functions commonly used in life testing analysis", Durability of Building Materials, 1 (1982) 175
12. Sjöström C. 1985, Overview of methodologies for prediction of service life, "Problems in service life prediction", Masters L. (editor), NATO ASI Series E No. 95, Martin Nijhoff Publishers

Contribution from the Polytechnic of Turin

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Service Life And LCC Assessment. The Use Of FMEA As Design Tool

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ABSTRACT

In this paper we suggest the use of the FMEA (Failure Modes and Effects Analysis) to simulate at the design stage the action of degradation factors on the building sub-systems performances and operating costs. Clients require to know what buildings will cost to operate throughout its service life. Service life planning techniques and LCC (Life Cycle Costing) can be successfully associated to the FMEA procedures. The FMEA is a design tool which allows the use of different sources of information. The forecast of planned maintenance requires knowledge of degradation rate for the building main components. However, information about degradation rate and building systems and components durability are usually lacking. Furthermore each case must be individually evaluated due to particular variables such as site, weather and other agents influencing building durability.

Timing, execution and maintenance costs for each component can be estimated from either internal (architects professional experience) or external sources of information (durability assessment, literature, in field simulation, results of laboratory tests etc.).

FMEA is a systematic collection of information about system component failures.

This method of analysis can help the design team to:

- forecast the degradation rate of the building sub-systems in its condition of use;
- improve the design in regards to components and sub-systems durability;
- determine maintenance needs and policies;
- improve maintainability;
- improve safety of maintenance operations;
- optimise total cost over the service life.

INTRODUCTION

In recent years many innovative solutions have been introduced into buildings as well as mechanical and electrical systems. Traditional and new components are integrated creating durability and maintenance problems. Moreover electronic equipment and monitoring systems now available for building systems are increasingly complex.

An example can be found in the double-skin facades where mechanical and electrical systems are strictly related to building envelope performance.

In these systems reliability and maintainability is a critical factor in the building operation and of inhabitant satisfaction in terms of comfort and safety.

Maintenance and operating costs of complex and innovative building systems can be very significant and must be well considered at the design stage.

In this way the Life Cycle Costing (LCC) techniques are very important for owners, inhabitants and designers.

Still an LCC implementation requires technical data availability and analysis. Such analysis starts from user need identification and requirement analysis. These needs and requirements can be related to technical specifications and standards. In other terms we have to define performance specifications to be accomplished during the service life of the building or of building subsystem.

At design stage we have to evaluate and compare different solutions. Costs and benefits associated to these alternatives must be estimated and made evident.

All costs, present and future, regarding the building process have to be considered. In other terms we must evaluate the effectiveness of the design alternative. This effectiveness can be described as the η ratio of cost

$$\eta = \frac{\text{Performance levels}}{\text{L.C.C.}} - \theta \quad (1)$$

Where θ is a availability index and L.C.C. the total cost over the service life of the building or the building subsystem.

The availability index θ can be taken as an evaluation of operating and total time ratio of the considered system.

The goal of design process is represented by reaching best operating time, maintainability and total cost.

In complex buildings and in particular where mechanical and electrical plants are fundamental to the building operation, availability can be an important concept.

Traditionally we consider only components durability paying little or few attention to maintainability and availability.

We must think about the relevance of availability in the operation of a business or conference centre and of the maintainability of a shopping centre where must be carried out while there are still clients on the premises.

The costs associated to the achievement of desired levels of maintainability and availability can be very high. That is why we must consider every design alternative at an early stage of the design process.

In building practice we have often seen high costs coming from an inadequate provision of space for mechanical and electrical systems. These provisions are an important component of maintainability and a specific analysis must be therefore carried out in every building design. Plants maintenance determines in a relevant measure direct maintenance costs, as costs of the work undertaken, and indirect, like costs for the stop in the use of the building facility.

The maintainability and availability analysis must be constantly developed throughout design stage, from the concept stage to the detail design, for building as well as for components.

At last an analysis of the failures modes and of the consequent maintenance operations has to be carried in order to develop a maintenance plan.

The FMEA tools, specifically adapted to the building design goals can be used to:

- plan maintenance;
- improve design solutions, traditional as well as innovative;
- improve building use safety;
- improve safety in maintenance works;
- prevent environment damages;
- estimate and plan costs in use.

The accuracy of provisions will be related to the availability of data and to design development stage. Moreover the estimated values used in evaluations can be adjusted in the building operation. Such data coming from experience of the maintenance management can be used for the design of the new buildings.

FMEA AND LIFE CYCLE COSTING

FMEA techniques can help the maintenance and building manager choose the best maintenance strategies and to determine the annual budget of maintenance costs.

LCC analysis represent a design and management tool in order to achieve a good balance between costs in use and construction costs. First the minimum performances and maintenance standards according to law prescriptions and building owner/user strategies must be fixed.

Maintenance allows satisfactory operating standards to be kept. Maintenance plan is made to optimise architectural design so as to achieve the maintenance goals. These goals are represented by the guarantee of satisfactory performances during building life at reasonable costs. In other words we must optimise at the design stage the effectiveness relation stated in (1).

The evaluation of effectiveness must take into consideration failures and maintenance occurrence rate to know direct and indirect associated costs. It would be better to estimate and measure the benefits coming from the performance levels achieved.

To operate the evaluation we must know the following technical and economic data:

- economic life of the building;
- estimated fuel , energy, electrical and operating costs;
- technical data about maintenance from the components suppliers;
- preventive maintenance required;
- durability and time of replacement estimated;
- provisional works and special equipment needed;
- opportune related maintenance works (e.g. gutter replacement with roof repairs);
- restraints to accessibility (e.g. outdoor spaces available and vehicular access).

Technical data from component suppliers are:

- preventive maintenance and maintenance plan including work schedule, time required for each work, personnel skills, spare parts and equipment;
- inspection schedule;
- check list for failure detection;
- instructions for the correct use of the component.

Moreover we must evaluate costs coming from:

- corrective maintenance;
- cleaning and adjustment;
- provisional work costs (e.g. scaffolding);
- non usability of building or of the part of building;
- safety provisions for maintenance work.

The estimate of such costs is particularly important in development of design alternatives, at the early stage of design, and in making maintenance plans.

FMEA AND MAINTENANCE COST PLANNING

In this paragraph we develop a short analysis of costs related to the maintenance and replacement of a metal frame door.

The analysis has been carried assuming an economic life of 60 years. The following preventive maintenance aimed at improving durability are foreseen:

- six monthly total inspection of system;
- painting of the frame and of the door every 5 years;
- adjustment of pulls and handles every 2 years;
- greasing of door hinges and closers every 2 years;

The evaluation is over a sixty year period, assuming that we will replace the whole door at year 30. The cost of replacement of all system is € 362.50. We assume labour cost at € 20 and € 25 per hour. The cost of material and spare parts is estimated for each task. The evaluation has been carried out separately for preventive maintenance costs and replacement costs (PM) (Table 1) and corrective maintenance (CM) (Table 2).

The maintenance costs has been converted in annual costs and the interest rate used is 5%. Labour and material costs are taken from Italian tariffs. The failure rates and preventive maintenance costs are from literature (1) and professional experience.

To calculate the annual cost of each planned maintenance and replacement (AEpm) expenditure we can use the following formulas:

$$AE_{pm} = PV\ (PM)\ \frac{(1+r)^N * r}{(1+r)^N - 1} \quad (2)$$

$$PV\ (PM) = .\sum_{k=1}^{N/f\ -1} \frac{PM}{(1+r)^{kf}} \quad (3)$$

where

r is the discount rate
f is the frequency
k is the number of each PM planned
N is the evaluation period

The annual cost of corrective maintenance (AE_{cm}) is:

$$AE_{cm} = CM * \lambda \ (4)$$

where

CM is the cost of corrective maintenance
λ is the failure rate

Logistic delay time has not been considered. Failure rates used in Table 2 are only estimates. We must consider particular conditions of use (e.g. schools or residential building) in addition to environmental exposure (rain, wind, dust etc.). The building manager is probably the person more qualified to give such precise data. In the first step of evaluation (e.g. design stage maintenance planning) we can also use failure rate from literature, if available, and adjust them during the operating life of the component. In the following tables we assume replacement and planned maintenance schedule from our experience and literature.

Table 1. Failure Modes Analysis and costs of PM maintenance and replacement

Component	*Fault*	*Failure*	*Consequences*	*Maintenance time Frequency (In years)*	*Maintenance required*	*Time (hours) x cost & Spare Parts Costs*	*Annual Cost (€)*
All system	-	-	-	0.5 at change of season	Inspection	2 x 0.125 x 25	6.25
Frame & Door	Visual deterioration	Painting detachment	Visual deterioration System wear and tear	5	Painting	(0.40 x 20) x 4 mq € 6.50	6.96
Handles & Pulls	Difficult opening	Seizure	System wear and tear	2	Greasing	0.25 x 20	2.43
Door Hinges	Difficult Opening	Seizure	System wear and tear	2	Greasing	0.25 x 20	2.43
Door Closers	Difficult Operatine	Seizure	System wear and tear	0.5 at change of season	Greasing	0.25 x 20	10.00
Door Closers	End of life			10	Replacement	0.50 x 10 € 120.00	7.90
All system	End of life			30	Replacement	€ 362.50	4.43

Table 2. Failure Modes Analysis and costs of CM maintenance

Component	*Fault*	*Failure*	*Consequences*	*Failure rate ((λ = Failures per year)*	*Maintenance required*	*Time (hours) x cost & Spare Part Costs*	*Annual Cost (€)*
Handles & Pulls	Out of order	Broken handles	System out of order	0.05	Handle Replacement	0.25 x 20 € 34.50	1.97
Door Hinges	Out of order	Broken hinges	System out of order	0.05	Hinge Replacement	0.50 x 20 € 5.50	0.77
Door Closers	Out of order	Broken closers	Security	0.02	Closers replacement	0.50 x 20 € 120.00	2.60

The annual cost of the planned maintenance as well as of the corrective maintenance and replacement of the system is estimated at € 45,74.

CONCLUSIONS

The simple model used in this evaluation must be compared to real operational costs during the service life of the building and of the component. This analysis can be useful at the design stage to estimate maintenance needs and operational costs. In this way alternative design can be compared and evaluated in respect to performance.

FMEA allows the collections of data available from different sources of information like literature, experience, laboratory tests. Moreover the reliability of these data has to be adequately considered and evaluated.

We also need information from the component suppliers and manufacturers about scheduling, timing, modes and costs of maintenance work.

The qualitative use of FMEA techniques can help the architect in the completion of the Maintenance Plans required by the Italian law (DPR 554/99) at the architectural design stage.

REFERENCES

Molinari, C. 2002, *Procedimenti e metodi della manutenzione edilizia*, Esselibri, Napoli.

Pollo, R. 1990, *Affidabilità, Qualità , Manutenzione*, Cortina, Torino.

Perret, J. 1995, *Guide de la mâintenance des batiments*, Éditions Le Moniteur, Paris.

Altamura, R., Abbate, S. 2001, 'Modello di calcolo del costo del ciclo di vita per valutare la fornitura di macchine', *Manutenzione, Tecnica e Management*, 4, 21-23.

Gieri, V. 1996, *Analisi dei prezzi unitari in edilizia*, Maggioli, Rimini.

Contribution from the Technical Consultant

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The Contribution of FMEA and FTA to Performance Review and Auditing of Service Life Design Constructed Assets

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The Contribution of FMEA and FTA to the Performance Review and Auditing of Service Life Design of Constructed Assets

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ABSTRACT

The need to demonstrate sustainable practices in all future constructed works suggests that the Performance Review and Performance Audit Process will grow in importance: As will demonstrating Facility and Constructed Asset life time design value and the elements and systems components, proposed service life care plans, projected whole life costs and end of service life scenarios.

Establishing such responses are however difficult, because life time management is in its infancy. Yet the user's experience and the opportunity to draw from time tested products in a wide range of construction environments remains to become an integral part of design decision making. It is against this back ground, that the Paper discusses the working and service life in the context of durability. The Paper suggests that performance, reliability and serviceability should be considered in a relational framework and addresses end of life evaluation and acceptance of fault tolerance in service life planning. In consequence, it is proposed that an additional attribute is adopted in service life planning, that of mistake proofing.

Mistake proofing in effect would be used to demonstrate a building design's capability over time, of meeting the six essential construction product directive requirements and justification of its maintenance or life care plan proposed together with the projected whole life costs.

The Paper considers three responses for design mistake proofing, firstly, using the factor approach, secondly, failure mode effect analysis (FMEA) and finally, fault tree analysis (FTA). In doing so, the Paper suggests that the forward pass of the performance review should focus upon adopting FMEA (as it is a process that offers an established structure in the anticipation and responses to life time matters for all parties involved in a project), whilst for the performance audit, (the backward pass), should focus on the verification of the mistake proofing by adopting FTA. The Paper concludes, by proposing a generic model for mistake proofing focusing on the site's attack regime and constructed works and its configuration's breakdown structure.

KEYWORDS Performance review, mistake proofing, failure mode effect analysis, fault tree analysis, life care plan.

1 INTRODUCTION

Today the proposed or stated designed life of many constructed works may be shorter than the physical replacement cycle of the building stock they join. In such situations, the physical condition and changing performance requirements over time, may pose serious economic and on going serviceability problems which militate against a sustainable hoped for future. So serious is this issue it suggested that the importance of durability, service life and working life will come to assume a critical dimension in both design and the whole life costing of construction.

Durability with its service life core component is also increasingly important for securing sustainable designed life based buildings. Yet durability must be considered in a defined context, that is to say, not only that period of time in service life planning for life cycle costing, but extended to reflect that understanding of material and behavioral changes over time. Especially in systems and element specifications and details proposed in given conditions with *normal* maintenance and their respective life care and end of life management. But subtle distinctions may exist between the working and the service life, especially where the expression, '*performance over time'*- (itself '*the capability of a material or product to with stand degradation in a given environment')* has to be considered (Cib 2004).

This working life (rather than solely service life) is taken to mean *'that period in which the performance* ***of the works*** *will be maintained at a level compatible with the fulfillment of the Construction Product Directive's six established essential requirements (*EOTA 1999). By suggesting this, the period of the working life is conditional and may not be how the service life is presented in service life planning, (specially in the use of the factor method) EOTA and the CPD (1993) also suggest or imply, that the working life *'depends upon its inherent durability and normal maintenance.* Perhaps the durability design objective is to, '*keep the probability of failure within a specified time interval or service life and below a threshold that depends upon on the consequence of failure of a component or system and ultimately optimal life cycle maintenance'.* (Lounis et al 1998) Equally, however, CSN TG Durability, N2 TF 207 N, Section E advises that *'Too an optimistic a view of the contributions of a fully performance-oriented approach to the questions related to the evaluation of durability may lead to serious disappointments in the future':* (TF N 207 1999).

Such distinctions are crucial in the introduction and use of failure mode effect analysis (FMEA), defect mapping (DM) or fault tree analysis (FTA) in service life planning. Especially, if the working life of components and systems used remain in service beyond their stated manufacturer's product life. This is also true where the life care to be afforded reflects *normal* maintenance (i.e. without incurring major costs for repair and replacement (CPD 1993) rather than the actual replacement cycle or end of life considerations expected in an environmental life cycle assessment or a whole life sustainable construction. But in terms of mistake proofing the CPD Guidance Paper F's telling comment is foreseeable actions.

In an end of life (EOL) sense, the working and service life may need re-defining at several levels. If this is the case, some feel for the state of the design's construction beyond the intended service life and the specification and details proposed becomes necessary. In turn, this may lead to developments that result in an acceptance of a service loss as a considered response for the design acceptability and where relevant an acceptable life care plan or risk as part of a design intent in service life planning. In short, adopting a fault tolerant approach beyond the design's service life time of any element or system or their components whilst maintaining the constructed work and its products six *Construction Product Directive's* essential requirements. In turn, this may lead to the need to both establish and acceptance of the relationship of the Reference service life (RSL) and service life (SL) with Reliability (R) and Performance (P) within a context of the working life (WL) as illustrated in Figure 1 below. Especially, where the in-service life period extends beyond the constructed work's design life intended, for example, reflecting the time to either the actual clearance or replacement constructed work or its portfolio EOL strategies. As indicated (Figure 1), durability (D) is seen as being over arching in nature between R and P for any constructed work or design. So the service life and in the manufacturer's context stated, working life (WL) may have several thresholds relating to serviceability relationships (S) as well as over time service losses that require specific maintenance responses- that is unless fault tolerance is accepted

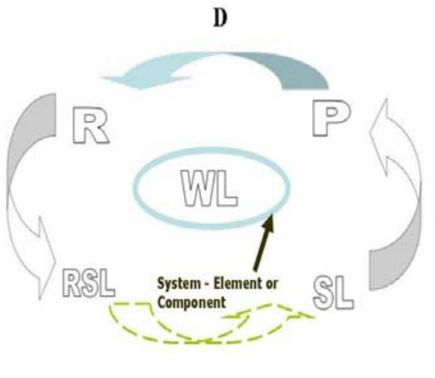

Figure 1 Relationships with the working life

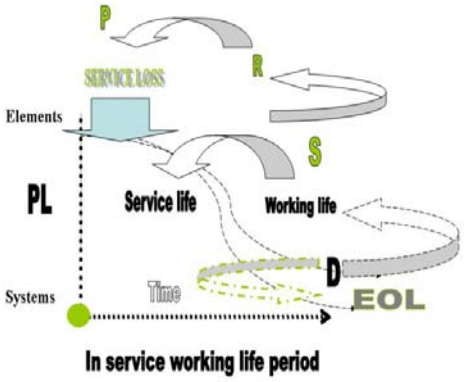

Figure 2 The life time relationships in elements and systems

Such serviceability or service loss may be established against known performances or performance level (PL) over time as suggested in Figure 2. In such a situation, PL becomes a *reference point that* would encourage fault tolerant considerations up to the EOL of a service working life period as well as establishing life cycle costs. But, in pursuing sustainable construction, through service life planning, an additional methodological attribute appears necessary, that of mistake proofing.

2 MISTAKE PROOFING WITH THE FACTOR METHOD

A number of avenues may be pursued for mistake proofing although not necessarily focused upon FMEA, DM or FTA, as follows:

1. A methodological response or framework using a dedicated assessment procedure in flow chart form. For example, in concrete structures (Quillin & Somerville 2002). Here the durability processes involved are mapped and the client is also asked *what constitutes the end of life*? This framework could readily be extended to include FMEA, DM and FTA.

2. A systematic break down of the constructed work into its respective core elements and systems, perhaps as clusters as intimated in Figure 4. Then adoption of a cause and effect extension is possible- but the difficulty of securing quality data should not be overlooked

3. The adoption and development of geographical information systems perhaps on a locality basis together with support from damage atlases as demonstrated by Haagenrud et al (2002).

4. Field based feed back from survey work of a specific construction or element (where probability can be related to common or known failure or recurring problems as proposed by Ansell et al (2002)). Such a practice would assist considerably in mistake proofing design proposals and in improving life care planning.

5. Compilation of a systematic field based DM on an element and system basis as a standard or reference work for use in service life planning design for given constructed work forms or life care management.

6. Otherwise, mistake proofing occurs when comparing a proposal with the likely working life found in practice, e.g. through the experience of a mutual insurer or housing authority who will know where durability problems and other service loss problems have occurred. But a caution too, for such appraisals may not look beyond a 30 or 60 year period. And in any event, such assessments in cost terms may not necessarily fit the specific focus of a material or component durability, nor life time risks.

In practice many projects do not have high probabilistic needs in design and service life planning so adapting the Factor Approach (ISO 15686-2001) might be used to secure 'a degree of mistake proofing: Especially for small works, and in areas like low rise housing. So a designer with experience might consider the framework relationships and context, as shown in Figure 3 below. Both to justify their life care plan proposed set against the reference conditions of Factors A-G in the and the design, details and specification as well as the likely consequences in terms of life cycle costs |(LCC) and whole life costs (WLC).

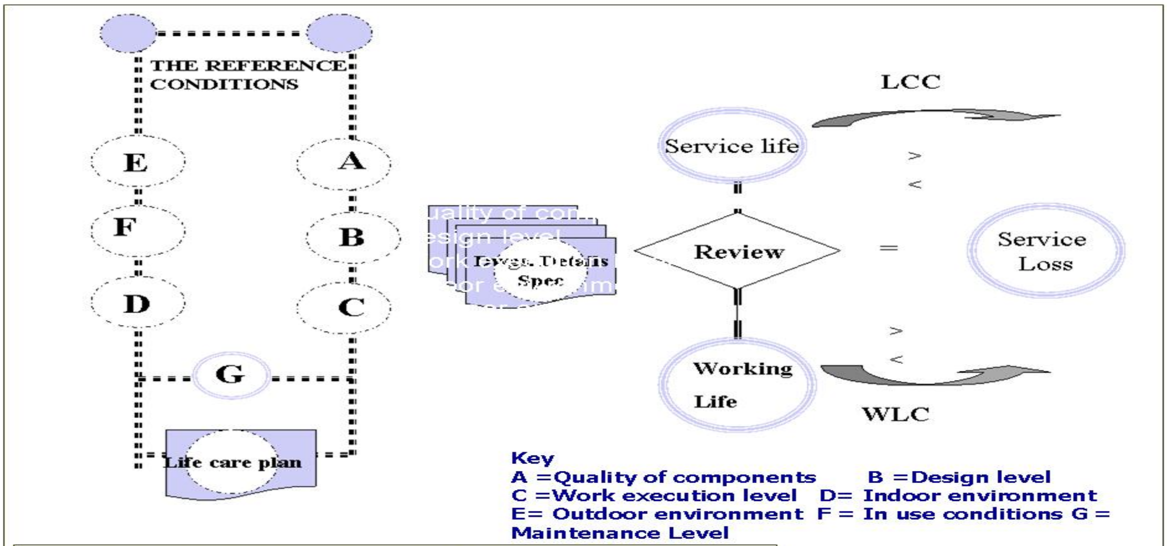

Figure 3 Factor Relationship for Mistake Proofing

The detailed design and specification in Figure 3 means that the technical advice on offer from both National Codes and Manufacturers Guidance should be used. But with a qualitative judgment of those relationships shown in Figures 1 and 2 and any subsequent service life assessment for the proposed design. It is however, the ability to develop the WLC in terms of the service loss anticipated through life over the given life spans and end of life and design life periods that makes robust mistake proofing attractive. Especially, as one can view and treat all components and system as populations with their respective mean time to servicing (MTTS), mean time to repair (MTTR) or replacement or mean time to failure (MTTF) as the case may be. Nevertheless, in Figure 3, in the process of mistake proofing the design and securing an adequate life care plan, (when addressing A, B and C) there is also a need to balance the Factors E, F and D with their support from G. Further, where C is a critical issue, (for example, in insulation and membrane installations), then checking and inspecting needs to be explicit and may have to be also followed up on site. It is also the practice side (See 4 and 5 above) that needs to bought together to ensure that the service life planning process is not re-inventing the wheel, for example, in housing projects using standard systems or house construction specifications.

3 MISTAKE PROOFING THROUH THE PERFORMANCE REVIEW

Lair J & Chevalier (2002) proposed and developed in their paper an integrated design framework with a risk and maintenance focus based on FMEA. In doing so, they suggested that a structural and functional analysis approach through the behavioral analysis of a product and a (roof) element should be adopted. What was particularly important was the focus on improving reliability of a design (as well as being able to apply the approach to the constructed works in use stage).

In essence, this Paper *opened up the way to mistake proofing a design by adopting techniques widely used in product based processes* and the electronic industry. Simply put, one identifies the reference area of the proposed design's elements, systems or components, likely service loss over time, its cause(s), the consequence(s) and risk(s) and where required, EOL status. The core point, however, is that the FMEA presents a structured way of thinking through establishing the likelihood of seriousness of a proposal at a detail level or scaled up to a whole system or element and up to the building level for the working, service or end of life proposed.

It is the ability to establish the construction cluster and context of the constructed work's principal and local relationships that is crucial for whole life assessment. This may require a managed approach for the design team's internal performance review and their data collection. At the same time analysis and modifications to the project design or work packages should coincide at convenient audit stages to avoid a paper work culture. The Principal designer must also make it clear from the client brief onwards that the working life design must take into consideration its attack regime as well as the FMEA, implications and risk. Likewise, the proposed life care plan and its specific intent for systems and components MTTS, MTTR and MMTF must be worked through and costs established.

Concluding, it is believed now that a strong case exists for now making FMEA an integral part of the service life planning review and for in some instances, also adopted for performance audits for example in complex claddings or warm roof construction.

4 MISTAKE PROOFING THROUH THE PERFORMANCE AUDIT

As the constructed work parts and its facility ages, durability and the working life conflict may arise both with its serviceability as well as rising costs or threats of obsolescence. Whilst one cannot fool proof for the real replacement life of the building, one may be able to mix systems and elements to maximize on value and minimize on cost. It is here with the EOL situation now beginning to become a sustainability consideration, that the Performance Audit could identify the working life situation for the constructed facilities systems, like air conditioning, electrical systems and fire detection systems working life times and their associated risks arising from failings or down time.

It is really a question of scale, and seriousness of the likely impact of a short fall in the design, that the balance of judgment has to be made. But, the fault tolerance approach may need to be formally developed. Like wise, the EOL and replacement cycle of the purpose group's population or common systems or elements reviewed from a recovery rather than material waste. At the same time, one should observe too, that the idea of fault tolerant working life is worth considering especially in evaluating the attack regime, and anticipated delays in responding to MTTR and MTTF in practice. So whilst FMEA may be used at a component, element or system level, as the building design progresses to completion and more decisions are fixed, and more information is brought together, a back ward pass may become necessary e.g. for specific design areas. In such instances, there may be a case then to adopt FTA, drawing upon known experience of failures and conditions or characterized the attack regime (e.g. making use of DM). It is useful to consider too Figure 2 and see how the design team has responded to those critical threats of a loss of performance or serviceability, or where reliability is threaten of the core 6 CPD Essential Requirements.

For the third or first party audit (which really is a backward pass), reviewing values, decisions and outcomes and benefits requires clear understanding through a generic break down model of the specific degradation of materials and components that lead to failure: Including those mechanisms, degradation in given environmental conditions and those risk arising from exposure and enlargement. In such a context, the critical events and enlargement need to be identified together with the effectiveness of arresting or terminating such service loss in the life care plan proposed and/or the risk implications.

5 MISTAKE PROOFING WITH FMEA AND FTA

Mistake proofing design proposals may in practice be brought about through the adoption of diagnostic techniques like failure mode effect analysis (FMEA), defect mapping (DM) and fault tree analysis (FTA): (Especially as an integral part of the design review and audit stages in service life planning (ISO 15686 2002)).

FMEA should consider the design and its details on a, what if basis, or, how can this fail? Or, what problems would arise if the construction sequence is incorrect or life care is not fully carried out? For example, if the work under construction is assembled in damp or wet weather or the adequacy of the life care plan itself is not followed nor can not be afforded? At the same time, the Checking, Inspection and Test Plan stage may need to also be included, especially where construction is known to be a cause of early service loss or failure over time if incorrectly carried out.

A wider understanding may by adopting FTA, with or without defect mapping based upon in use experiences of material, component and system failures: (Especially from established service losses, or serviceability failure problems, or associated costs that have arisen in practice). Inevitably here, such failures may include more than one single aspect of a service life component, or material failing, and may extend beyond the point of initial service loss to upwards of a catastrophic failures not originally contemplated in the design, or life care afforded. (Similarly, unexpected or hidden indirect costs not directly associated with the original area of the design itself may also be come to light)

It is particularly in EOL design considerations that FTA has a part to play. In that sense, when FTA is used in performance auditing one would in effect be proof testing a service life design proposal and examining its P, R, S and WLC of ownership and risks.

Concluding, FMEA is appropriate in design work as a forward pass in the service life planning review. FTA may be more appropriate for the backward pass, or proof testing of the in the service life planning through First or Third Party Performance Audits. DM can however, be used in both instances.

6 PROPOSED FMEA AND FTA REVIEW AND AUDIT MODEL

A considerable number of manufacturer's products are remarkably good- especially when the in use experience guidance and good detailing quality come together supported by prudent life care management. Equally, apart from poor specification and detailing or maintenance, one may find where neglect or misuse occurs, significant service loss and often avoidable costs.

It is suggested then, for design, that there is a case for a common forward and backward pass model (Figure 4). Such a model would include the context of the working and service life discussed in this Paper. Here the likely changes and risks of any component failure in an element or system, or other areas threaten would be established. (For example, how will the *six essential requirements, mechanical resistance and stability, safety in case of fire, hygiene health and the environment, safety in use, protection against noise, energy economy and heat retention, and normal maintenance for an economically reasonable working life* be met over varying periods of time, including EOL considerations)

In such situations, to focus on and establish the likely behavior over time of the design prior knowledge (experience and data) is necessary. So Figure 4 represents the bringing together the matters discussed in this Paper within the context of the design's attack regime to be addressed and the need to respond with an appropriate specification, design details, life care and construction method for the life times identified with a balance between working and service life, as shown.

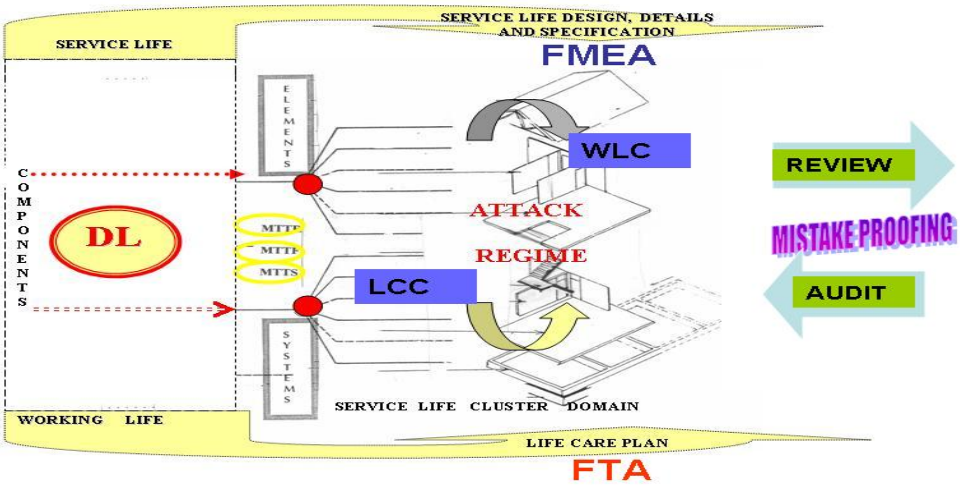

FIGURE 4 FMEA REVIEW AND FTA AUDIT CONTEXT

The site's building location establishes the macro environmental conditions to be designed for and be faced by the specific components and materials to be specified, placed and detailed. But for the given areas of the elevations, layouts and sections a more focused degradation micro and meso-climate regime may exist so the design must also address this. Here such assessments in cost terms, may not necessarily fit the specific focus of a material or component durability. Instead a broader treatment of materials and components may be necessary for given elements and certain key systems that are known to need replacing within the design life (DL) especially within a fault tolerant regime.

The life care plan may include responses from national and legal EOL requirements, as well as the client own requirements. Here through FMEA in order to establish what may need modifying, one may examine the implications of service loss in the service life clusters through their MTTS, MMTR and MMTF. Likewise for sustainable construction all diagnostic approaches have significant relevance for mistake proofing and for EOL Management and climate change scenarios.

DM and FTA may prove useful too, in considering behavioral issues over time and how durability is affected in P, R or S terms: For example, addressing the risks arising from structural movement in a three storey masonry and timber frame block of flats to be built in an expansive clay soil where there is a risk of cracking of the masonry skin, water penetration and eventually possible fungal attack of the timber.

7 CONCLUSIONS

If the EOL becomes part of a brief and or service life planning, the the tools and techniques for reliability and failure diagnostics must become increasingly part of its main stream work. Also as has already been said earlier, because in many cases, the replacement cycle of given building stock suggests a much longer or slow replacement cycle than the design lives being proposed. the issue of the aging effect (Kitsutaka & Matsuyama 2002) needs to be addressed.

It is really the direct application of FTA and FMECA in design that is attractive. Especially in service life profiling and identifying the likely service loss that could arise or their knock on effect and risk. Whilst not specifically focusing upon durability, such approaches nevertheless benefit from a performance review approach, for example based upon Figure 3 or 4, and acceptance of FMEA.

Finally, a method of certification could be developed for elements and systems and should be considered in life time management. (Stenstad & Haagenrud 2001) In consequence, it is believed that the contribution of FMEA and FTA in both the performance review and auditing of service life design constructed assets is now due. Further more it should become an integral part of service life planning and sustainable construction.

8 REFERENCES

Ansell A, Racutanu G & Sundquist H (2002) A Markov approach in estimating the service life of bridge elements in Sweden 9dbmc Proceedings Brisbane Paper 142 Vol. 2 10pp

CiB (2004) Guide and Bibliography to Service Life Durability Research for Building Materials and Components Joint Cib W80/RILEM TC 140 Publication 1-2

CSN TG Durability N2 TF 207 N Section E. Durability Treatment. Contribution to the work of the Task Force CPD/TG on durability 4pp

Construction Products Directive (1993) Guidance Paper F Durability and the Construction Products Directive 8pp

EOTA (1999) Assessment of Working Life of Products EOTA Guidance Document 003 European Organisation for Technical Approval Brussels Belgium

Freitag SA & Bruce SM (2002) Durability Design For New Zealand Concrete Infrastructure 9dbmc Proceedings Brisbane Paper 157 Vol. 2 9pp

Stenstad V & Haageenrud S (2001) Building Certification Measuring The Performance of Buildings Paper CL1 30 Vol. 2 CIB World Congress Performance In Product and Practice. Wellington. NZ 292-298

Haagenud SE, Krigsvo; G, Skancke T, & Gussias A (2002) An integrated GIS based system for service life and maintenance planning of the building stock of Oslo Municipality 9dbmc Proceedings Brisbane Paper 135 Vol. 2 8pp

ISO 15686-(2002) Buildings and Constructed Assets service life planning Part 3 Performance Audits and Reviews Standards Organisation Geneva 23

Kitsutaka Y & Matsuyama Y (2002 Aging Effect of External Building Materials 9dbmc Proceedings Brisbane) Paper 166 Vol. 2-6pp

Lair J & Chevalier JL (2002) Failure Mode Effect and Criticality Analysis for Risk Analysis (Design) and Maintenance Planning (Exploitation). 9dbmc Proceedings Brisbane Paper 032. Vol. 1 10pp

Lounis Z, Lacasse M, Siemes AJM & Moser K (1998) Further Steps Towards A Quantitative Approach To Durability Design Materials and Technologies for Sustainable Construction CIB World Building Congress Symposium A Vol. 1 315-324

Quillin KC, Somerville G, Hooper R & Nixon P (2002) A Framework for Service Life Design of Concrete Structures 9dbmc Proceedings Brisbane Paper 128 Vol. 2 11p

BIBLIOGRAPHY

Hutchinson TW (2002) Integrating Building Components in Roof System Design for Long Term Roof Performance 9dbmc Proceedings Brisbane Paper 146 Vol. 2 10pp

Sjostrom c, Jernberg P, Caluwaerts P,Kelly S, Haagenrud S & Chevalier JL (2002). Paper 10 Implementation of the European Construction Products Directive via the ISO 15686 Standard 9dbmc Proceedings Brisbane Vol .1- 9pp

Appendix 3: Selection of non-published reports

Selected contribution from the SWIFT Project:

Lair, J. (2002e) *Failure Modes and Effects Analysis for Electrochromic and Gasochromic Glazings*, SWIFT project, WP2 Task 3: Reliability assessment, 33p

Selected contribution from the IEA Task 27 Project C2 (Failure Mode Analysis):

Lair, J. (2003c) *Failure Modes and Effect Analysis, Service Life Prediction,* Intermediary report (D4-C2-jl-01 Draft 2), IEA Task 27 (Project C2 : Failure Mode Analysis), February 2003, 47p.

Selected contribution from the DOE *project "An Insulating Glass Knowledge Base"*:

Aspen Research Corporation (2002) *"Deliverables for Phase I of the DOE project – An Insulating Glass Knowledge Base"***,** Presentation, IGMA Technical Division Meeting, August 2002.

Selected contribution from the CIB W 80 / RILEM 175 – SLM: Service Life Methodologies – Prediction of Service Life for Buildings and Components:

Lair, J. (2003b) *Failure Modes Effects and Criticality Analysis – A Tool for Risk Analysis (Design) and Maintenance Planning (Exploitation),* Working document, CIB W 80 / RILEM 175 – SLM: Service Life Methodologies – Prediction of Service Life for Buildings and Components, February 2003, 15p.

Contribution from the SWIFT Project

J. Lair

Failure Modes and Effects Analysis for Electrochromic and Gasochromic Glazings

2002

Project SWIFT

Switchable Facade Technology

WP 2-Task 3
Failure Modes and Effects Analysis for Electrochromic and Gasochromic Glazings

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Starting date:	1-5-2000
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Report number:	swift-wp2-lair-011115-fmea-v3
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FMEA on EC and GC windows (SWIFT – Task 2.3)

1. Introduction

Used from the 1960s in the aeronautical and car industries, FMEA is a convenient tool for reliability studies of industrial systems. FMEA is intended for the verification of the product ability to satisfy client's needs (reliability, maintenance facility, disposability, safety). Commonly used in these industrial domains, it targets and checks weak points before mass production in order to define preventive measures.
With adaptations appropriate to building specificities, CSTB has developed a "risk assessment" approach, in order to know why a product has failed or how it will fail. Identifying and assessing risks, foreseeing the consequences and possibly proposing solutions, are the goals of such a study.

In the framework of SWIFT project, the methodology will be applied to types of switchable glazing (Electrochromic and gasochromic glazing).

2. FMEA methodology

The proposed approach is composed of two main steps:
- the analysis of the system (including structural, functional and process analysis),
- the search of failure modes.

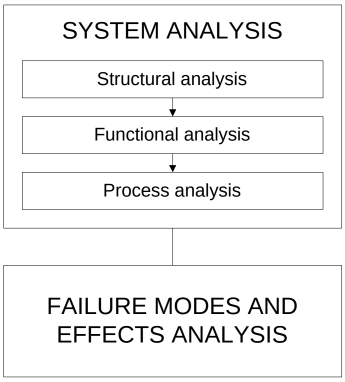

Figure 1

2.1 System analysis

The approach relies:
- on one hand, on the precise description of the system structure and its environment, as well as the identification of its functions,
- on the other hand, on the definition of the building process (design, manufacturing, transport, storage, setting up …).

Structural analysis
This first step consists in identifying the structure of the product, i.e. all the components, their characteristics as well as the environment in which they could be located.

The structure of the studied product is described with:
- morphology (geometrical shape, dimensions …),
- topology of relations with other objects,
- physico-chemical composition of its constitutive elements and their own description.

We also identify of the various climatic agents and use factors that will stress the product during its life.

Note:
Combined environmental stresses (successive or simultaneous stresses) should be taken into account:

- water AND low temperature is freezing,
- high temperatures AND rain fall is thermal shock,
- …

Functional analysis
This second step consists in identifying all the functions of the product and its components (role of each component in the global functioning):

- either needs as regards the user (The product is designed to fulfil user's needs, these needs are expressed in terms of functions: thermal insulation, …),
- or functions stemming from constructive choice (seals to prevent water entry in a glazing unit).

For building domain, "The product fulfils a function" could be generally expressed as "The building product transforms climatic factors". For envelope products, it acts as a filter between two environments, filtering heat flows between outdoor and indoor environments (thermal insulation), preventing entry of water from outdoors (watertightness of a roofing system), …

However, these same climatic factors can have an impact on its constitutive elements and could involve: modification of the materials properties, degradation and even failure…

Process analysis
This third step consists in identifying the various steps of the construction process. In contrast to a classical approach (we first define the specifications of the product in order that it fulfils the functions for which it was designed, and then check if the manufacturing process succeeds in reaching the defined specifications), we will first define the characteristics of the product according to the workmanship process (manufacturing and setting up stages) and then identify the product ability to fulfil the functions for which it was designed, given the workmanship quality.

This part will not be detailed in this study.

Conclusion
With structural functional and process analysis, we know why and how the product works (functions ensured by the product, and elements involved in the "success" of each function).
With FMEA, we will now identify why and how it could fail in fulfilling the functions.

2.2 Failure modes and effects analysis

FMEA consists in the identification of all failure modes for each function, the search for causes, and finally the identification of effects. We want to imagine, forecast and write the potential futures of the product.

The novelty of the approach concerns the search for causes and effects. The behaviour reacting to stress on an element, its degradation or failure can change the environment of neighbouring elements. For example, the degradation of the seal of a double glazing unit under UV and temperature stresses could involve stresses in generally protected elements (low-emissive layer towards humidity or pollutants).
We propose to investigate direct effects (influence of the degradation or failure on the considered element) as well as indirect effects (influence on other elements or on system)

The principle of the failure modes analysis is a multi-step approach leading to the following table (Figure 2).

Functions	Elements	Modes	Causes	Direct effects	Indirect effects

Figure 2: FMEA blank matrix

In the following paragraphs, we illustrate the approach with the Double Glazing Unit example.

Step 1 Initial stresses:

Thanks to structural and functional analysis, the first two columns are filled.

Functions	**Elements**	**Modes**	**Causes**	**Direct effects**	**Indirect effects**
Landscape vision	Extern. glass pane				
	Air gap				
	Intern. glass pane				
Resistance to environment	Glass				
	Polysulfide sealant				
	Butyl sealant				
	…				

Figure 3: Step 1

Once filled these columns, we have to search modes and causes.
Three types of causes could then be identified:
① classical cause as the action of an environmental agent on an element,
② unexpected behaviour due to a defect in the building process,
③ influence of the behaviour of a neighbouring element on the considered element.
The type 1 causes are deduced from the following table which draws up the potential initial stresses for each element.

	External glass	Air gap	Polysulfide sealant	Butyl sealant	Aluminium spacer	Dessicant	Internal glass	
Water (rain, snow)	x		x					
UV and solar radiations	x	x			x		x	
High or low temperatures	x	x	x	x	x	x	x	
Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	x		x					
Cleaning agents	x		x					
Hot vapour	x		x					
Dust	x		x					
Shocks	x							
Wind stresses	x	x	x	x	x	x	x	
Action of frames	x	x	x	x	x	x	x	
Movements of wall	x	x	x	x	x	x	x	
							x	Water (condensation)
	x	x	x	x	x	x	x	High or low temperatures
			x				x	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …
			x				x	Cleaning agents
			x				x	Hot vapour
			x				x	Dust
							x	Shocks

Figure 4: Step 1 – Initial stress conditions.

The type 2 causes are stated by experts. They include potential defects, negligence, errors due to materials (quality, homogeneity of concrete), processes (inefficient mixing or vibrating of concrete), method (surface cleanness…), on-site conditions (temperature, humidity for concrete casting), and manpower. Then, direct effects as well as indirect effects are identified.

Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	Extern. glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap				
	Intern. glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Moisture-related stress on butyl sealant
	Butyl sealant	Cracking	Process problem, Temperature	Permeability	-
	…				

Figure 5: Step 1 – FMEA table (Extract)

Step 2:

The previous step leads to the updating of environmental stresses conditions.

Indeed, some degradations or failures lead to modifications in the “answer” of the product to stresses.

	External glass	Air gap	Polysulfide sealant	Butyl sealant	Aluminium spacer	Dessicant	Internal glass	
Water (rain, snow)	x		x	**x**				
UV and solar radiations	x	x			x		x	
High or low temperatures	x	x	x	x	x	x	x	
Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	x		x	**x**				
Cleaning agents	x		x	**x**				
Hot vapour	x		x					
Dust	x		x	**x**				
Shocks	x							
Wind stresses	x	x	x	x	x	x	x	
Action of frames	x	x	x	x	x	x	x	
Movements of wall	x	x	x	x	x	x	x	
				x			x	Water (condensation)
	x	x	x	x	x	x	x	High or low temperatures
			x	**x**			x	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …
			x	**x**			x	Cleaning agents
			x				x	Hot vapour
			x	**x**			x	Dust
							x	Shocks

Figure 6: Step 2 – Updated stresses condition

With the updated environmental stresses condition table and the column indirect effect, new failures (modes, causes and the consequences) are identified.

Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	External glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap				
	Internal glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Moisture-related stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature, Water*, Pollutants*, Cleaning agents*, Dust*	Permeability	Water, dust penetration in air gap
	…				

Figure 7: Step 2 – FMEA table (Extract)

And so on… New stresses conditions, new degradation or failures…

Functions	**Elements**	**Modes**	**Causes**	**Direct effects**	**Indirect effects**
Landscape vision	External glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap	Condensation Dust deposit	Joint breaking	Bad vision	
	Internal glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Moisture-related stress on butyl sealant
	Butyl sealant	Cracking	Process problem, Temperature, Water*, Pollutants*, Cleaning agents*, Dust*	Permeability	Water, dust penetration in air gap
	…				

Figure 8: Step 3 – FMEA table (Extract)

2.3 Interest and perspectives

Though it is seldom used in construction, FMEA is a promising method that could be used efficiently in our context. It gives guidelines to improve the reliability and the quality of innovative products.

Various discussions raised several aspects concerning FMEA use:

- FMEA is a familiar tool (modelling expert reasoning),
- FMEA is a relevant and useful tool during the design stage, intended to identify weak points of products; weak points means either problems, neglecting, errors during manufacturing process,… or problems of materials behaviour (degradation or failure) concerning environmental stresses or behaviour of neighbouring materials.
- FMEA is a useful tool first for experience and know-how gathering, second because it allows a rigorous and exhaustive analysis of product behaviour.
- FMEA is used in order to identify and rank potential failure modes (thanks to criticality analysis), to determine their causes and effects, and thus to suggest relevant test to characterise their durability.

Additional information

An FMEA analysis is generally supplemented with a criticality analysis (FMECA).
It consists in assessing a criticality indicator for all identified failure modes, based on some criteria (occurrence probability, detectability, financial and human consequences gravity…).
The ranking or selection of failure modes is then possible. It directly influences the choice of the needed actions intended to increase the reliability and safety of the studied systems.

In the following chapter, we apply FMEA method to electrochromic and gasochromic glazing, detailing each step of the approach:

- structural analysis (Chapters ?-, 0 and 5 respectively for the structure, the environment and the functions),
- failure modes and effects analysis (Chapters 5and 6).

3. Structural analysis

3.1 Electrochromic glazing

Elements	Code	Materials
- External glass pane	G_1	Glass
- Electrochromic layers		
- Transparent conductive electrode	TCE_1	SnO_2:F
- Active electrode (WO_3)	AE	WO_3
- Ionic and electric conductor/laminating material	IEC	Li^+
- Counter electrode	CE	?
- Transparent conductive electrode	TCE_2	SnO_2:F
- Intermediate glass pane	G_2	Glass
- Cavity	C	Air
- Low emissivity coating	LEC	?
- Internal glass	G_3	Glass
Frames, spacer and seals	FS	Aluminium, butyl Polysulfide sealant
Power supplier and electric cables	PSC	/
Controller	C	/

Figure 9: Electrochromic glazing – Elements

We usually have to take the interface between elements into account because of chemical compatibility (e.g. problems of corrosion), physical compatibility (differential thermal expansion) and mechanical compatibility (behaviour of a multi-layer product stressed by flexion loads).

An additional interface has to be taken into account: electrical contacts between TCO and electrical cables.

It's even more important for EC device because of electrical interactions between the layers ("interface reactions that are known to be thermodynamically driven …").

Figure 11(a) is a structural representation of an EC device.

3.2 Gasochromic glazing

Elements	Code	Materials
- External glass pane	G_1	Glass
- Gasochromic layers		
- Gasochromic coating	GC	WO_3
- Catalyst coating	CAT	Pt
- Gas-filled cavity	C_1	O_2 or H_2 in Ar or N_2
- Intermediate glass pane	G_2	Glass
- Ar-filled cavity	C_2	Ar
- Low emissivity coating	LEC	Ag, BiO_x, NiCr
- Internal glass pane	G_3	Glass
Frames, spacers and seals	FS	Stainless steel, butyl Silicone sealant
Gas supplier and tubes	GST	Stainless steel, aluminium
Controller	C	Electronic components

Figure 10: Gasochromic glazing – Elements

We have to take into account the interface between the catalyst coating and the gasochromic coating.

Figure 11(b) is a structural representation of a GC device.

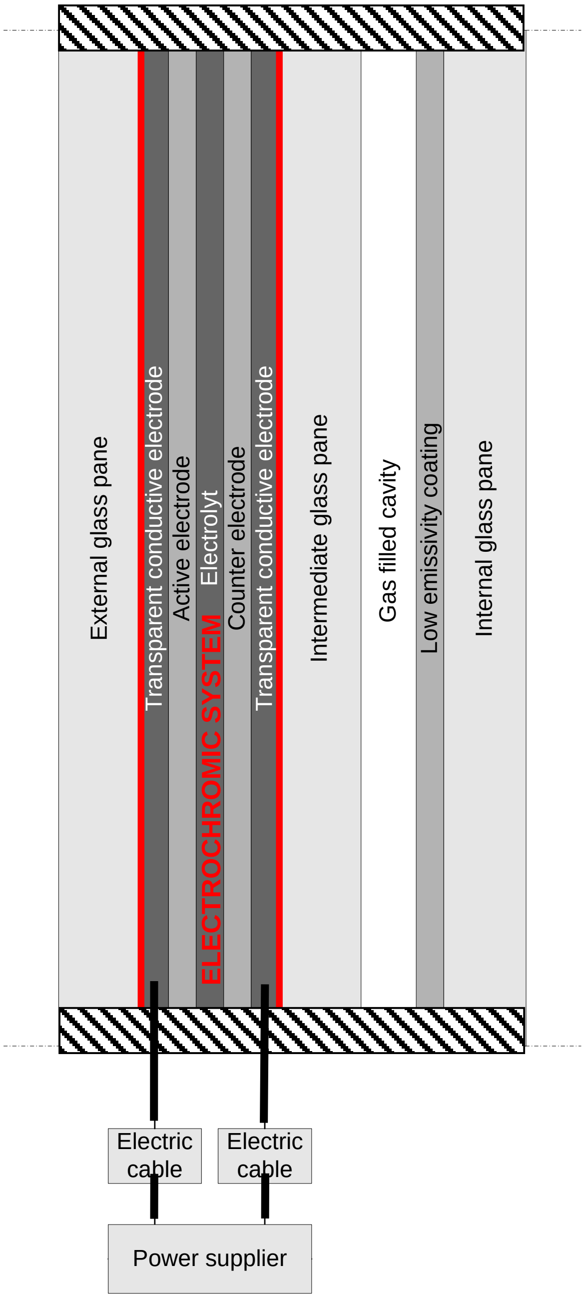

Figure 11(a) Electrochromic glazing

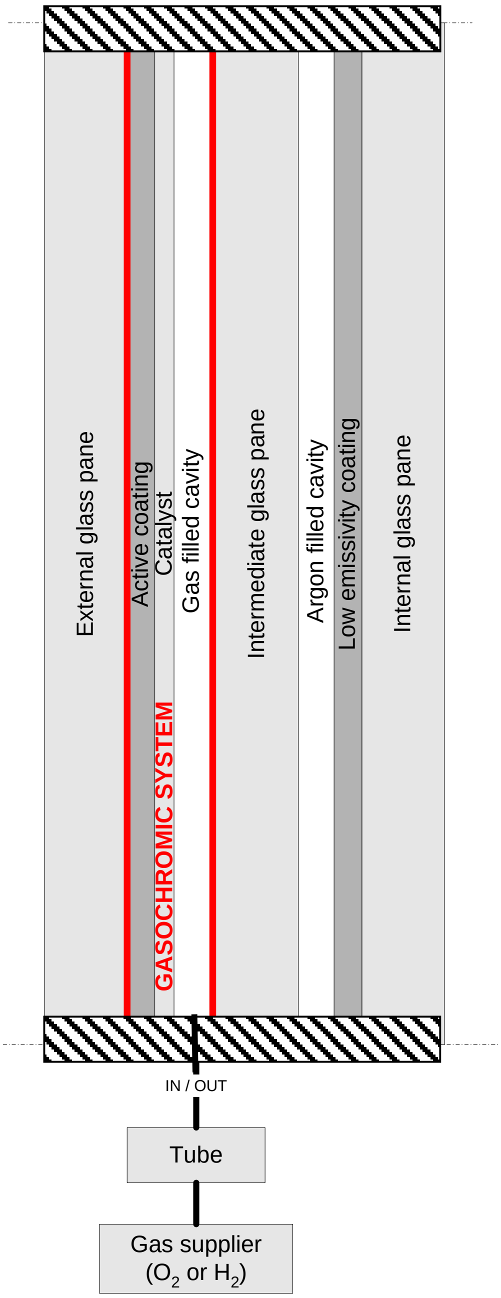

Figure 11(b) Gasochromic glazing

Note: Film thicknesses are not to scale.

4. What is the environment of EC and GC glazings?

The various stresses could be classified in three classes.

4.1 Environmental conditions

- sun, solar radiation (UV),
- rain, humidity, relative humidity (humid and dry),
- temperature (low and high), rapid temperature changes,
- snow, hail,
- wind,
- mechanical stresses
    - localised or distributed loads,
    - cyclic loads,
    - vibrations,
    - shocks (hard and soft),
- effect of the frames on the glazing
    - moisture in the glazing rabbet,
    - effect of temperature,
    - pressure changes on the seal,
    - mechanical stresses as vertical and horizontal racking, torsion and bending,
    - setting block problems,
    - design tolerances on frames contraction/expansion,
    - differential temperature effects,
    - contamination (chemical compatibility) of sealant and wood preservatives).
- oxygen, nitrogen, ozone, CO_2, VOC, NO_X, SO_X, CH_4, HCl, Dust … and various other pollutants,
- salt spray (buildings located close to the sea, i.e. distance < 2km)
- animals, birds, insects, bacteria, fungi, moss, algae …

4.2 Use conditions

- cleaning agents (acidic, basic),
- hot vapour,

4.3 Operational conditions

- voltage and charging current (switching stresses) for EC system.
- changing gas composition (H_2 or O_2 in Ar or N_2) – colouring/bleaching cycles (switching stresses) for GC system (H_2/O_2 produced by gas supplier flushed by a pump).

5. What are window functions?

Amongst all the functions of a window, we will take into account air and water tightness, thermal and acoustic insulation, as well as durability in time. They are "generic functions", common to all windows. They concern the glass and sealant (air and water tightness, acoustic insulation), low-e coating (thermal insulation) and gas-filled cavity (acoustic and thermal insulation).

Additionally to "light transmission" and "landscape vision", several specific functions concerning the dark state and switching ability have to be taken into account ("reduced light transmission", "switching time" and "memory") for the study of EC and GC glazing.

In comparison with the double glazing unit, the functions are (Figure 12):

Function
Light transmission (Bleached)
Reduced light transmission (Coloured)
Landscape vision (Bleached/coloured)
Switching time
Memory
Colour rendering / Blur
Air tightness
Water tightness
Thermal insulation (control heat flow)
Acoustic insulation
G value / solar factor (Bleached/Coloured)
Safety in case of fire
Opening ability
Aesthetic
Durable (Environment)

Figure 12: Functions

5.1 Electrochromic glazing

The following table checks the role of each element in the global functioning of the product.

EC	External glass pane	Transparent conductive electrode	Active electrode	Electrolyt	Counter electrode	Transparent conductive electrode	ntermediate glass pane	Cavity	Low emissivity coating	Internal glass pane	Frames and seals	Power supplier	Electric cables
Light transmission (Clear)	x	x	x	x	x	x	x	x	x	x			
Reduced light transmission (Dark)		x	x	x	x	x						x	x
Landscape vision (Clear/Bleached)	x	x	x	x	x	x	x	x	x	x			
Switching time		x	x	x	x	x						x	x
Memory		x	x	x	x	x						x	
Colour rendering / Blur		x	x	x	x	x						x	x
Air tightness	x						x	x		x			
Water tightness	x						x	x		x			
Thermal insulation	x						x	x	x	x			
Acoustical insulation	x						x	x		x			
G value / Solar factor	x	x	x	x	x	x	x	x	x	x	x		
Durable (Environment)	x	x	x	x	x	x	x	x	x	x	x	x	x

EC	External glass pane	EC layers	Intermediate glass	Cavity	Low emissivity coating	Internal glass pane	Frames and seals	Power supplier	Electric cables
Light transmission (Clear)	x	x	x	x	x	x			
Reduced light transmission (Dark)		x						x	x
Landscape vision (Clear/Bleached)	x	x	x	x	x	x			
Switching time		x						x	x
Memory		x						x	
Colour rendering / Blur		x						x	x
Air tightness	x		x	x		x			
Water tightness	x		x	x		x			
Thermal insulation	x		x	x	x	x			
Acoustical insulation	x		x	x		x			
G value / Solar factor	x	x	x	x	x	x	x		
Durable (Environment)	x	x	x	x	x	x	x	x	x

Figure 13: Role of each element – Electrochromic glazing

As an example, the "dark state" is obtained thanks to the EC device (TCE, AE, E, CE, TCE) and the power supplier and electric cables.

5.2 Gasochromic glazing

The following table checks the role of each element in the global functioning of the product.

GC	External glass pane	Gaso-chromic layer	Catalyst	Cavity	Intermediate glass pane	Cavity	Low emissivity coating	Internal glass pane	Frames and seals	Gas supplier	Tubes
Light transmission (Clear)	x	x	x	x	x	x	x	x			
Reduced light transmission (Dark)		x	x	x						x	x
Landscape vision (Clear/Bleached)	x	x	x	x	x	x	x	x			
Switching time		x	x	x						x	x
Memory		x	x	x							
Colour rendering / Blur		x	x	x						x	x
Air tightness	x			x	x	x	x	x	x	x	x
Water tightness	x			x	x	x	x	x	x	x	x
Thermal insulation	x			x	x	x	x	x			
Acoustic insulation	x			x	x	x	x	x			
G value / Solar factor											
Durable (Environment)	x	x	x	x	x	x	x	x	x	x	x

GC	External glass pane	Gasochromic	Intermediate glass pane	Cavity	Low emissivity coating	Internal glass pane	Frames and seals	Gas supplier	Tubes
Light transmission (Clear)	x	x	x	x	x	x			
Reduced light transmission (Dark)		x						x	x
Landscape vision (Clear/Bleached)	x	x	x	x	x	x			
Switching time		x						x	x
Memory		x							
Colour rendering / Blur		x						x	x
Air tightness	x		x	x	x	x	x	x	x
Water tightness	x		x	x	x	x	x	x	x
Thermal insulation	x		x	x	x	x	x		
Acoustic insulation	x		x	x	x	x			
G value / Solar factor	x	x	x	x	x	x			
Durable (Environment)	x	x	x	x	x	x	x	x	x

Figure 14: Role of each element – Gasochromic glazing

5.3 Expression of functions

Function	EC glazing	GC glazing
Light transmission (Bleached)	AE = clear (Li^+ or H^+ in the CE) Cavity = clean (No dust, no poisoning gas)	GC = clear $C_1 = O_2$ in Ar (or N_2) Cavities = clean (No dust, no poisoning gas)
Reduced light transmission (Coloured)	AE = coloured (Li^+ or H^+ in the AE) Cavity = clean (No dust, no poisoning gas)	GC = coloured $C_1 = H_2$ in Ar (or N_2) Cavities = clean (No dust, no poisoning gas)
Landscape vision (Bleached)	AE = clear Cavity = clean (No dust, no poisoning gas)	GC = clear $C_1 = O_2$ in Ar or N_2 Cavities = clean (No dust, no poisoning gas)
Landscape vision (Coloured)	AE = coloured Cavity = clean (No dust, no poisoning gas)	GC = coloured $C_1 = H_2$ in Ar or N_2 Cavities = clean (No dust, no poisoning gas)
Switching time (Bleached → Coloured)	Power supplier e^- from TCE_1 to TCE_2 Li^+ from CE to AE (via IEC)	Gas supplier $C_1 = H_2$ in Ar (decrease of O_2 concentration, increase of H_2 concentration) Catalyst = OK H_2 from GST to C_1 to CAT (H^+ is formed and the GC layer colours), O_2 from GC to C_1
Switching time (Coloured → Bleached)	Power supplier e^- from TCE_2 to TCE_1 Li^+ from AE to CE (via IEC)	Gas supplier $C_1 = O_2$ in Ar (decrease of H_2 concentration, increase of O_2 concentration) Catalyst = OK O_2 from GST to C_1 and further via CAT to GC (oxidation-bleaching), H_2 from GC to C_1
Memory (Coloured)	AE = bleached (Li^+ or H^+ in the CE)	GC = still bleached (O_2 in C_1)
Memory (Bleached)	AE = still coloured (Li^+ or H^+ in the AE)	GC = still coloured (H^+ in C_1)

Figure 15

6. Detailed FMEA (Component approach)

The analysis is an iterative steps approach:

- First step, we identify the potential degradations of elements towards **initial environmental stresses** (Causes type 1) and investigate the effects.
- Second step, these effects (degradations) involve **modifications in the structure of the product or in the environment**: we then have to identify the potential degradation of elements due to this **new environmental stresses** (Causes type 2), and so on (Causes type 3, 4 …).

The information concerning the cause level, i.e. either initial cause (type 1) or later causes (types 2 and following), is kept in the table (numbering in column "Causes"). Ageing scenarios resulting from initial causes should be treated with priority (for instance failure of the seals).

Due to confidentiality issues, we have only carried out the first step: identification of the couples, and illustrate the iterative approach with seal failure (Refer to chapters 9 and 0).

6.1 Electrochromic glazing

Initial stresses

At t = 0, without any degradation and considering that the product was correctly assembled and installed, the environmental factors that could stress the product (and each element) are the following.

EC	External glass pane	Transparent conductive electrode	Active electrode	Electrolyt	Counter electrode	Transparent conductive electrode	Intermediate glass pane	Cavity	Low emissivity coating	Internal glass pane	Frames and seals	Power supplier	Electric cables
OUTDOOR													
Rain	x										x		
Humidity	x										x		
Hail, snow	x										x		
Sun, UV	x	x	x	x	x	x	x	x	x	x	x		
Wind	x	x	x	x	x	x	x	x	x	x	x		
Shocks	x										x		
High temperature	x	x	x	x	x	x	x	x	x	x	x		
Low temperature	x	x	x	x	x	x	x	x	x	x	x		
O_2	x										x		
Ozon O_3	x										x		
CO_2 NO_x SO_x VOC HCl CH_4	x										x		
Cleaning agents	x										x		
Hot vapour	x										x		
INDOOR													
Humidity										x	x		
Shocks										x	x		
Temperature	x	x	x	x	x	x	x	x	x	x	x		
O_2										x	x		
Ozon O_3										x	x		
CO_2 NO_x SO_x VOC HCl CH_4										x	x		
Cleaning agents										x	x		
Hot vapour										x	x		
USE													
Switching stresses		x	x	x	x	x						x	x

EC	External glass pane	Electrochromic layers	Intermediate glass pane	Cavity	Low emissivity coating	Internal glass pane	Frames and seals	Power supplier	Electric cables
OUTDOOR									
Rain	x						x		
Humidity	x						x		
Hail, snow	x						x		
Sun, UV	x	x	x	x	x	x	x		
Wind	x	x	x	x	x	x	x		
Shocks	x						x		
High temperature	x	x	x	x	x	x	x		
Low temperature	x	x	x	x	x	x	x		
O_2	x						x		
Ozon O_3	x						x		
CO_2 NO_x SO_x VOC HCl CH_4	x						x		
Cleaning agents	x						x		
Hot vapour	x						x		
INDOOR									
Humidity						x	x		
Shocks						x	x		
Temperature	x	x	x	x	x	x	x		
O_2						x	x		
Ozon O_3						x	x		
CO_2 NO_x SO_x VOC HCl CH_4						x	x		
Cleaning agents						x	x		
Hot vapour						x	x		
USE									
Switching stresses		x						x	x

Figure 16

Note: because of a lack of information, we assume that power supplier, electric cables and controller are only stressed by switching cycles. Either they are protected, or failure modes are sufficiently well-known (No power, power decreases …). We could of course lead a FMEA for these sub systems.

Failure modes and effects – Step 1

First step is the analysis of each couple element/agent. That is to say for each element/agent, we search for the potential degradation and the effects of the degradation on the performance of the element itself or the product.

Concerning the EC devices, the study can be done for each layer or for an element merging all the layers.

Various degradation or failure modes (film dissolution, corrosion, etching …) due to initial stresses could involve modifications in the stresses (water impact …). They are identified by filling the column “Direct effect”. For each function, each element should be studied (identification of potential degradations or failures) as regards each environmental factor of “Causes column”.

Example

As an example, we assume that seals fail. We identify type 2 environmental stresses.

When considering the function “Light crossing (clear state)” of the electrochromic device (Figure 17), we have to study the behaviour of each elements towards the factors listed in column “Cause”.

The behaviour of Transparent Conductive Electrode TCE_1 (in relation to the considered function) should be first regarded towards (column “CAUSES”):

- UV radiation,
- high temperature or low temperature,
- temperature cycles,
- switching cycles (Voltage and current),
- wind stresses,
- shocks,
- compatibility with other elements.

The same is done for all other elements (AE, E, CE, TCE_2) and their contacts (interface between layers).

We detect several potential degradation or failure, in particularly the potential adhesive or cohesive failure of seals (whose one of the functions is “water and air tightness”).

Once we have identified the potential failure of seals, we then have to consider in a second step the behaviour of each element towards “new agents” (external factors now passing through the seals):

- humidity,
- oxygen,
- ozone,

- CO_2, NO_x, and various other pollutants,
- cleaning agents.

Function	**Element**	**Mode**	**Cause**
Light crossing (Clear) Landscape vision (Clear)	External glass	Scratching	1 - Cleaning
	Electrochromic device	Transparent Conductive Electrode (Loss of conductivity)	1 - UV
		Contact TCE/AE	1 - High temperature or low temperature
		Active Electrode (Non uncolouring - Loss of electrochromic efficiency)	1 - Temperature cycles
		Contact AE/E	1 - Switching cycles
		Electrolyt (Loss of electrolitic property)	1 - Wind stresses
		Contact E/CE	1 - Shocks
		Counter Electrode (Loss of ion capture or ion storage capacity)	1 - Process problem (manufacturing, transportation, setting up)
		Contact CE/TCE	1 - Chemical or physical compatibility
		Transparent Conductive Electrode (Loss of conductivity)	2 - Humidity
			2 - O_2
			2 - Ozone O3
			2 - CO_2 NO_x SO_x VOC HCl CH_4
			2 - Cleaning agents
		…	

Function	**Element**	**Mode**	**Cause**
Light crossing (Clear) Landscape vision (Clear)	External glass	Scratching	1 - Cleaning
	Electrochromic device	Transparent Conductive Electrode (Loss of conductivity) **Electrochromic layers**	1 - UV
		Contact TCE/AE	1 - High temperature or low temperature
		Active Electrode (Non uncolouring - Loss of electrochromic efficiency)	1 - Temperature cycles
		Contact AE/E	1 - Switching cycles
		Electrolyt (Loss of electrolitic property)	1 - Wind stresses
		Contact E/CE	1 - Shocks
		Counter Electrode (Loss of ion capture or ion storage capacity)	1 - Process problem (manufacturing, transportation, setting up)
		Contact CE/TCE	1 - Chemical or physical compatibility
		Transparent Conductive Electrode (Loss of conductivity)	2 - Humidity
			2 - O_2
			2 - Ozone O3
			2 - CO_2 NO_x SO_x VOC HCl CH_4
			2 - Cleaning agents
		…	

Figure 17: Detailed (all EC layers) or simplified (EC layers as a single element) study

We simply “model” the behaviour, in a first step the nominal behaviour (towards initial stresses), and then describing the future potential behaviours.
From information on elements, we produce information on the product.

6.2 Gasochromic glazing

By analogy with electrochromic study:

- First step, identification of the potential degradations of elements towards initial environmental stresses (Causes type 1).
- Second step and next steps, identification of the potential degradations of elements towards this new environmental stresses (Causes type 2, 3 and so on).

Concerning the GC devices, the study can be done for each layer or for an element merging all the layers.

Initial stresses

At t = 0, without any degradation and considering that the product was correctly set up, the environmental factors that could stress the product (and each element) are the following.

GC	External glass pane	Cavity	Catalyst	Electro-catalytic layer	Intermediate glass pane	Cavity	Low emissivity coating	Internal glass pane	Frames and seals	Gas supplier	Tubes
OUTDOOR											
Rain	x								x		
Humidity	x								x		
Hail, snow	x								x		
Sun, UV	x								x		
Wind	x								x		
Shocks	x								x		
High temperature	x	x	x	x	x	x	x	x	x		
Low temperature	x	x	x	x	x	x	x	x	x		
O_2	x								x		
Ozone O_3	x								x		
CO_2 NO_x SO_x VOC HCl CH_4	x								x		
Cleaning agents	x								x		
Hot vapour	x								x		
INDOOR											
Humidity								x	x		
Shocks								x	x		
Temperature	x	x	x	x	x	x	x	x	x		
O_2								x	x		
Ozone O_3								x	x		
CO_2 NO_x SO_x VOC CH_4								x	x		
Cleaning agents								x	x		
Hot vapour								x	x		
USE											
Switching stresses		x	x	x			x			x	x
Ar + O_2 or H_2		x	x				x				x

GC	External glass pane	Gasochromic system	Intermediate glass pane	Cavity	Low emissivity coating	Internal glass pane	Frames and seals	Gas supplier	Tubes
OUTDOOR									
Rain	x						x		
Humidity	x						x		
Hail, snow	x						x		
Sun, UV	x						x		
Wind	x						x		
Shocks	x						x		
High temperature	x	x	x	x	x	x	x		
Low temperature	x	x	x	x	x	x	x		
O_2	x						x		
Ozone O_3	x						x		
CO_2 NO_x SO_x VOC HCl CH_4	x						x		
Cleaning agents	x						x		
Hot vapour	x						x		
INDOOR									
Humidity						x	x		
Shocks						x	x		
Temperature	x	x	x	x	x	x	x		
O_2						x	x		
Ozone O_3						x	x		
CO_2 NO_x SO_x VOC CH_4						x	x		
Cleaning agents						x	x		
Hot vapour						x	x		
USE									
Switching stresses		x			x			x	x
Ar + O_2 or H_2		x			x				x

Figure 18

7. Rough FMEA: Product approach (link with visual inspection)

In this section, due to the complexity of the EC and GC glazing, as well as confidentiality considerations, we will conduct "simplified FMEA". The simplification concerns two aspects:

- firstly, the structural analysis will be less detailed, considering the various electrochromic and gasochromic layers as a single element, and thus studying the influence of environmental and operational stresses on this single element,
- secondly, the study will be based on the use of feedback from practice and the visual inspection: from the observed failures (effects), we deduce causes. Industrial experts and natural durability testing (SWIFT-WP2) provide us with failure modes information.

We try to establish the connections between all the failure modes, allowing some question marks concerning some unknown or poorly known phenomena (for instance the influence of pollutants on the electrochromic or gasochromic layers).

Additional testing or study could be done in order to identify the environmental, use or operational conditions that should be taken into account.

7.1 Electrochromic glazing

Observed failure	Causes	Observation	Effects
Degradation of performance	Normal behaviour	Trapping of charge in the electrochromic layer	Increase in the transmittance in the coloured state (no effect in the bleached state)
	Moisture ingress in or on electrode during process	Bind free lithium, thus reducing the available charge in the device. Both electrodes still functioning but loss of performance	Translucent or foggy view through the window. It could also be noted some change of the colour (or better colour cordinates) of the coloured and bleached state of the EC device. Slower kinetic.
	Moisture ingress due to poor sealing of failure of the sealing	Bind free lithium, thus reducing the available charge in the device. Both electrodes still functioning but loss of performance	
	Overvoltage (Thermodynamic limit)	Overvoltage due to failure of the power supplier, or due to a non adapted algorithm (in case of high temperature)	Voltage higher than the potential required involving destructive reactions
	Excessive charging current (Kinetic limit)	Excessive charging current due to failure of the power supplier, or due to a non adapted algorithm (in case of high temperature)	Irreversible Li trapping on the surface.
Yellowing	Dissolution of the counter electrode	Rise in transmittance Yellow coloration in the polymer	Change of the colour in bleached state
Non bleaching dots	“De-attachment” or delamination of the ionic conductor to the electrodes	- Shrinkage (due to ageing, higher temperature or UV exposure) - Chemical interaction with electrodes	Blue dots are bleaching slower or not at all.

7.2 Gasochromic glazing

Observed failure	Causes	Observation	Effects
Slowing down of the coloration	Reduction of the diffusion constant for the protons along the pore surface	Change of water content due to high temperature	Loss of performance
Degradation of performance	Reduction of the catalytic activity	Adsorption of a blocking species like sulphur or carbon monoxide on platinum	Slowing down of bleaching and coloration
		Poisoning by gas in the air	Slowing down of bleaching and coloration
	Failure of the sealing and H_2 escape	Cavity is not tight, H_2 is escaping	GC system is not colouring (only slightly during the operation of the gas supplier and the pump)
	Failure of the gas supplier	Concentration of H_2 and/or O_2 in the cavity is increasing/decreasing slower	Slowing down of bleaching and coloration
	GC device exposed to high temperatures	Dehydration of the WO_3 layer or change of the WO_3 (crystallisation)	Higher transmittance of the coloured state. Bleaching is slower (but the colouring kinetic is similar)[1]
Non-bleaching dots[2]			Non-homogeneous coloration or bleaching

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[1] Effects observed at NIC

[2] Effects observed at CSTB

8. References

8.1 Concerning Electrochromic and Gasochromic glazing

Georg A. Graf W. Neumann R. Wittwer V. (2000). "*Stability of gasochromic WO_3 films*". Solar Energy Materials and Solar Cells 63 (2000) 165-176.

Cronin J.P. Gudger T.J. Kennedy S.R. Agrawal A. Uhlmann D.R. (1999). "*Electrochromic glazing*". Materials Research vol 2, n°1, 1-9, 1999

Wen S-J. Kerr J. Rubin M. Slack J. von Rottkay K. (1996). "*Analysis of durability in Lithium Nickel Oxide electrochromic materials and devices*" 2nd International meeting on Electrochromism, IME2, San Diego, CA, October 1996.

Lampert C.M. (1995). "*Chromogenic switchable glazing: towards the development of the smart window*" Conference proceedings of Window Innovations'95, June 1995, Toronto, Canada.

8.2 Concerning FMEA:

Lair J. Chevalier J-L. Rilling J. (2001). *"Operational methods for implementing durability in service life planning frameworks".* CIB World Building Congress, April 2001, Wellington, New-Zealand.

Modarres M. (1993). "*What every engineer should know about reliability and risk analysis*". New York. Ed.: Dekker. 350 pages.

Lair J. (2001). "*Failure modes and effects Analysis*" IEA T27 Solar heating and cooling programme. Building Envelope Components / Performance, durability and sustainability of advanced windows and solar components for building envelopes. Deliverable D2.1 – Project C2. Draft version (September 2001)

9. ANNEX 1: ELECTROCHROMIC GLAZING

Function	Element	Mode	Cause	Direct effect	Indirect effect
Light transmission and Landscape vision (Bleached)	External glass	Scratching	1 - Cleaning	Loss of performance	
	Electrochromic device	Yellowing	1 - Dissolution of the counter electrode due to charge, temperature, UV, …	Rise in transmittance - Yellow coloration in the polymer	More transparent in bleached state
		Loss of performance	1 - Trapping of charge in the electrochromic layer due to UV, Time, Temperature	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - Moisture ingress in or on the electrode during process 1 - Moisture ingress in or on the electrode due to poor sealing 2 - Moisture ingress in or on the electrode due to sealing failure	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - High or low temperature ?		
			2 - Effect of Oxygen, CO_2, NO_x, SO_x, VOC, HCl, CH_4 ?		
			1 - Overvoltage due to non high temperature-adapted voltage 2 - Overvoltage due to the failure of the power supplier and controler	Voltage higher than the potential required involving destructive reactions	Loss of performance of the glazing
			1 - Excessive charging current due to non high temperature-adapted current 2 - Excessive charging current due to the failure of the power supplier and controler	Irreversible Li trapping on the surface	Loss of performance of the glazing
	Intermediate glass				
	Cavity	Compounds intrusion	2 - Humidity (condensation) 2 - Dust		
	Low emissivity coating				
	Internal glass	Scratching	1 - Cleaning		

Function	Element	Mode	Cause	Direct effect	Indirect effect
Reduced Light Transmission (Colou	Electrochromic device	Loss of performance	1 - Trapping of charge in the electrochromic layer due to UV, Time, Temperature	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - Moisture ingress in or on the electrode during process 1 - Moisture ingress in or on the electrode due to poor sealing 2 - Moisture ingress in or on the electrode due to sealing failure	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - High or low temperature ?		
			2 - Effect of Oxygen, CO_2, NO_x, SO_x, VOC, HCl, CH_4 ?		
			1 - Overvoltage due to non high temperature-adapted voltage 2 - Overvoltage due to the failure of the power supplier and controler	Voltage higher than the potential required involving destructive reactions	Loss of performance of the glazing
			1 - Excessive charging current due to non high temperature-adapted current 2 - Excessive charging current due to the failure of the power supplier and controler	Irreversible Li trapping on the surface	Loss of performance of the glazing
		Non colouring dots	?		

Function	Element	Mode	Cause	Direct effect	Indirect effect
Switching time (Bleached to Colour	Electrochromic device	Loss of performance	1 - Trapping of charge in the electrochromic layer due to UV, Time, Temperature	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - Moisture ingress in or on the electrode during process 1 - Moisture ingress in or on the electrode due to poor sealing 2 - Moisture ingress in or on the electrode due to sealing failure	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - High or low temperature ?		
			2 - Effect of Oxygen, CO_2, NO_x, SO_x, VOC, HCl, CH_4 ?		
			1 - Overvoltage due to non high temperature-adapted voltage 2 - Overvoltage due to the failure of the power supplier and controler	Voltage higher than the potential required involving destructive reactions	Loss of performance of the glazing
			1 - Excessive charging current due to non high temperature-adapted current 2 - Excessive charging current due to the failure of the power supplier and controler	Irreversible Li trapping on the surface	Loss of performance of the glazing
	Power supplier + controller	Overvoltage	1 - Time, temperature, …		
			1 - Overvoltage due to high temperature (non adapted algorithm)		
		Insufficient voltage	1 - ?		
		Excessive charging current	1 - Time, temperature, …		
			1 - Overvoltage due to high temperature (non adapted algorithm)		
		Insufficient charging current	1 - ?		
	Electrical cables				

Function	Element	Mode	Cause	Direct effect	Indirect effect
Switching time (Coloured to Bleach	Electrochromic device	Loss of performance	1 - Trapping of charge in the electrochromic layer due to UV, Time, Temperature	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - Moisture ingress in or on the electrode during process 1 - Moisture ingress in or on the electrode due to poor sealing 2 - Moisture ingress in or on the electrode due to sealing failure	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - High or low temperature ?		
			2 - Effect of Oxygen, CO_2, NO_x, SO_x, VOC, HCl, CH_4 ?		
			1 - Overvoltage due to non high temperature-adapted voltage 2 - Overvoltage due to the failure of the power supplier and controler	Voltage higher than the potential required involving destructive reactions	Loss of performance of the glazing
			1 - Excessive charging current due to non high temperature-adapted current 2 - Excessive charging current due to the failure of the power supplier and controler	Irreversible Li trapping on the surface	Loss of performance of the glazing
	Power supplier + controller	Overvoltage	1 - Time, temperature, …		
			1 - Overvoltage due to high temperature (non adapted algorithm)		
		Insufficient voltage	1 - ?		
		Excessive charging current	1 - Time, temperature, …		
			1 - Overvoltage due to high temperature (non adapted algorithm)		
		Insufficient charging current	1 - ?		
	Electrical cables				

Function	Element	Mode	Cause	Direct effect	Indirect effect
Memory (Coloured)	Electrochromic device	Loss of performance	1 - Trapping of charge in the electrochromic layer due to UV, Time, Temperature	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - Moisture ingress in or on the electrode during process 1 - Moisture ingress in or on the electrode due to poor sealing 2 - Moisture ingress in or on the electrode due to sealing failure	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - High or low temperature ?		
			2 - Effect of Oxygen, CO_2, NO_x, SO_x, VOC, HCl, CH_4 ?		
			1 - Overvoltage due to non high temperature-adapted voltage 2 - Overvoltage due to the failure of the power supplier and controler	Voltage higher than the potential required involving destructive reactions	Loss of performance of the glazing
			1 - Excessive charging current due to non high temperature-adapted current 2 - Excessive charging current due to the failure of the power supplier and controler	Irreversible Li trapping on the surface	Loss of performance of the glazing
	Power supplier	Insufficient voltage	1 - ?		
		Insufficient charging current	1 - ?		
	Electrical cables				

Function	Element	Mode	Cause	Direct effect	Indirect effect
Memory (Coloured)	Electrochromic device	Loss of performance	1 - Trapping of charge in the electrochromic layer due to UV, Time, Temperature	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - Moisture ingress in or on the electrode during process 1 - Moisture ingress in or on the electrode due to poor sealing 2 - Moisture ingress in or on the electrode due to sealing failure	Reduction of the available charge in the device. Both electrodes still functioning but loss of performance	Loss of performance of the glazing
			1 - High or low temperature ?		
			2 - Effect of Oxygen, CO_2, NO_x, SO_x, VOC, HCl, CH_4 ?		
			1 - Overvoltage due to non high temperature-adapted voltage 2 - Overvoltage due to the failure of the power supplier and controler	Voltage higher than the potential required involving destructive reactions	Loss of performance of the glazing
			1 - Excessive charging current due to non high temperature-adapted current 2 - Excessive charging current due to the failure of the power supplier and controler	Irreversible Li trapping on the surface	Loss of performance of the glazing
	Power supplier	Insufficient voltage	1 - ?		
		Insufficient charging current	1 - ?		
	Electrical cables				

Function	Element	Mode	Cause	Direct effect	Indirect effect
Resistance to environment	Frames	Movements	1 - Thermal dilatation (especially because of device warming) 1 - Wind stresses 1 - Shocks		Stresses on seals
	Spacers	Movements	1 - Thermal dilatation		Stresses on seals
	Seals	Watertightness and air tightness	1 - Process problem 1 - Humidity 1 - O$_2$ 1 - Ozone O3 1 - CO$_2$ NO$_x$ SO$_x$ VOC HCl CH$_4$ 1 - Cleaning agents	Moisture or water ingress Oxygen, Ozone, CO2 NOx SOx VOC HCl CH4 ingress	Stresses on EC device
		Craking	1 - Process problem 1 - Humidity 1 - O$_2$ 1 - Ozone O3 1 - CO$_2$ NO$_x$ SO$_x$ VOC HCl CH$_4$ 1 - Cleaning agents 1 - High temperature 1 - Low temperature 2 - Movements of frames, of spacer (wind, shocks, temperature)	Moisture or water ingress Oxygen, Ozone, CO$_2$ NO$_x$ SO$_x$ VOC HCl CH$_4$ ingress	Stresses on EC device
	Glass/seals interface	Failure / Breaking	1 - Process problem involving surface aspect problems (dirt, dust, …) 1 - High temperature 1 - Low temperature 1 - Humidity 1 - O$_2$ 1 - Ozone O3 1 - CO$_2$ NO$_x$ SO$_x$ VOC HCl CH$_4$ 1 - Cleaning agents 2 - Movements of frames, of spacer (wind, shocks, temperature)	Moisture or water ingress Oxygen, Ozone, CO2 NOx SOx VOC HCl CH4 ingress	Stresses on EC device

10. ANNEX 2 : GASOCHROMIC GLAZING

		Degradation of perfromance	1 - Poisoning by gas in the air	Slowing down of bleaching and colouration
			2 - Adsorption of a blocking species (sulphur or carbon monoxide) on platinum	Slowing down of bleaching and colouration
	Gas supplier	Degradation of the performance	?	Slowing down of bleaching and colouration
	Tubes	Blocked	?	

Function	**Element**	**Mode**	**Cause**	**Direct effect**
Switching time (Coloured to Bleach	Gasochromic device	Degradation of perfromance	1 - Poisoning by gas in the air	Slowing down of bleaching and colouration
			2 - Adsorption of a blocking species (sulphur or carbon monoxide) on platinum	Slowing down of bleaching and colouration

Function	Element	Mode	Cause	Direct effect	Indirect effect
Switching time (Bleached to Colour	Gasochromic device	Slowing down of the coloration	1 - High temperature	Change of water content Loss of performance	
		Degradation of perfromance	1 - Poisoning by gas in the air 2 - Adsorption of a blocking species (sulphur or carbon monoxide) on platinum	Slowing down of bleaching and colouration Slowing down of bleaching and colouration	
	Gas supplier	Degradation of the performance	?	Slowing down of bleaching and colouration	
	Tubes	Blocked	?		

Function	Element	Mode	Cause	Direct effect	Indirect effect
Switching time (Coloured to Bleach	Gasochromic device	Degradation of perfromance	1 - Poisoning by gas in the air 2 - Adsorption of a blocking species (sulphur or carbon monoxide) on platinum	Slowing down of bleaching and colouration Slowing down of bleaching and colouration	
	Gas supplier	Degradation of performance	?	Slowing down of bleaching and colouration	
	Tubes	Blocked	?		

Function	Element	Mode	Cause	Direct effect	Indirect effect
Memory (Bleached)	Gasochromic device				
	Gas supplier	Flow, quality, quantity, ?			
	Tubes	Blocked	?		

Function	Element	Mode	Cause	Direct effect	Indirect effect
Memory (Coloured)	Gasochromic device				
	Gas supplier	Flow, quality, quantity, ?			
	Tubes	Blocked	?		

Function	Element	Mode	Cause	Direct effect	Indirect effect
Resistance to environment	Frames	Movements	1 - Thermal dilatation (especially because of device warming) 1 - Wind stresses 1 - Shocks		Stresses on seals
	Spacers	Movements	1 - Thermal dilatation		Stresses on seals
	Seals (Cohesive failure)	Watertightness and air tightness	1 - Process problem 1 - Humidity 1 - O_2 1 - Ozone O3 1 - CO_2 NO_x SO_x VOC HCl CH_4 1 - Cleaning agents	Moisture or water ingress Oxygen, Ozone, CO2 NOx SOx VOC HCl CH4 ingress	Stresses on GC device
		Craking	1 - Process problem 1 - Humidity 1 - O_2 1 - Ozone O3 1 - CO_2 NO_x SO_x VOC HCl CH_4 1 - Cleaning agents 1 - High temperature 1 - Low temperature 2 - Movements of frames, of spacer (wind, shocks, temperature)	Moisture or water ingress Oxygen, Ozone, CO_2 NO_x SO_x VOC HCl CH_4 ingress	Stresses on GC device
	Glass/seals interface (Adhesive failure of the seal)	Failure / Breaking	1 - Process problem involving surface aspect problems (dirt, dust, oil…) 1 - High temperature 1 - Low temperature 1 - Humidity 1 - O_2 1 - Ozone O3 1 - CO_2 NO_x SO_x VOC HCl CH_4 1 - Cleaning agents 2 - Movements of frames, of spacer (wind, shocks, temperature)	Moisture or water ingress Oxygen, Ozone, CO2 NOx SOx VOC HCl CH4 ingress	Stresses on GC device

Contribution from the IEA Task 27 Project C2 (Failure Mode Analysis)

J. Lair

Failure Modes and Effect Analysis, Service Life Prediction

2003

D4-C2-jl-01 Draft 2

INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

Task 27
Building Enveloppe Components

Performance, Durability and Sustainability of Advanced Windows and Solar Components for Building Envelopes

Subtask C : Sustainability
Project C2 – Failure Mode Analysis

Failure Modes and Effects Analysis And Service Life Prediction

February 2003

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Project C2 : Failure Modes Analysis

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Abstract

This working report is composed of three distinct parts.

The first part (Chapters 0 to 0) includes a brief description of objectives and partners of the project as well as terminology on service life planning (from ISO 15686 standards) and technical terms on window and facade (from SZFF Switzerland).

The second part (Chapters 0 to 0) presents the durability tools:

- FMEA concept, methodology and applications in order to search failure modes,
- Service life prediction by means of Factor Method (methodology and further developments),
- Service life prediction by means of Data fusion (methodology and application in order to assess a service life).

The last part includes the applications of FMEA on various innovative solar components:

- Chapter 0: Double Glazing Unit and actions of the frames on the DGU,
- Chapter 0: Ar filled low-e coated glazing unit,
- Chapter 0: Solar panel,
- Chapter 0: Gasochromic and electrochromic glazing (in relation with SWIFT EU project).

All these case studies have not been validated by the experts. The results have to be used very carefully.

Summary

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1. Objectives

This project is on management and processing of existing data and information (but not on data production!, hence giving an aspect of the complementarity with Project C3 and STB, where data will be produced), the aims of the projects have been validated and expressed with the following steps:

- reach a common level of knowledge in terms of concept and terminology on Service Life Prediction (SLP) and Failure Mode and Effects Analysis (FMEA),
- agree on appropriate methodologies to identify its possible premature terminations (FMEA),
- agree on appropriate methodologies to predict service life (SLP),
- perform application exercises on a several products through four steps: define clearly the products, collect data, conduct the procedure and communicate results.

2. C2 consortium

	Country	**Affiliation**	**Contact person**		**Men-month**
1	Canada	NRC	H. Elmahdy	HE	2
2	Switzerland	EMPA	H. Simmler	HS)	May contribute
3	Denmark	SBI	H. Krogh	HK	Observer
4	Denmark	DTU	O. Holck S. Svendsen T. Nilsen	OH SS TN	4
5	Denmark	VELUX	J. Fransson K. Duer	JFR KD	1
6	Denmark	DTI	R. Knudsen	RK	
7	Germany	ISE	M. Köhl M. Heck W. Platzer	MK MH WP	3
8	Germany	IFT	M. Freinberger	MF	May contribute
9	Germany	FLABEG	J. Cardinal	JC	May contribute
10	Finland	VTT	I. Heimonen T. Hakkinen	IH TH	3
11	**France**	**CSTB**	**J-L. Chevalier** **J. Lair**	**JLC** **JL**	**12**
12	Japan	NSG	H. Nakai	HN	May contribute
13	Mexico	CENIDET	J. Flores	JFL	Observer
14	Sweden	SP	B. Carlsson	BC	1
15	USA	ARC	J. Fairman	JFA	May contribute
16	USA	UMASS	D. Curcija	DC	May contribute
17	USA	NFRC	B. Shah	BS	May contribute
				TOTAL MM =	**26**

3. Terminology

In order to facilitate the mutual understanding (and to reach a common level of knowledge in terms of SLP and FMEA), it was decided to supply participants with multilingual lists of terms.
Until now, were provided lists on:

- Service life and durability concepts,
- Multilingual technical terms.

Service life planning and durability (ISO 15686)

Ageing	***Vieillissement***	Degradation due to long term influence of agents related to use	*Dégradation due à l'influence dans le temps des agents (environnement, utilisation).*
Agents	***Agents***	Whatever acts on a construction or its part to reduce its performance.	*Ce qui agit sur un bâtiment ou ses diverses parties et qui amenuise ses performances.*
Building	***Bâtiment***	Construction works that has the provision of shelter for its occupants or contents as one of its main purposes and is usually enclosed and designed to stand permanently in one place.	*Construction ayant principalement pour fonction d'abriter ses occupants ou son contenu ; elle est généralement fermée et conçue pour demeurer en place de façon permanente0.*
Building assembly	***Assemblage (de bâtiment)***	Set of components used together	*Ensemble de composants utilisés ensemble.*
Building component	***Composant (de bâtiment)***	Product manufactured as a distinct unit to serve a specific function or functions	*Produit fabriqué comme unité distincte pour remplir une ou plusieurs fonctions spécifiques.*
Building material	***Matériau (de construction)***	Substance that can be used to form products or construction works	*Matière servant à fabriquer des produits ou réaliser des ouvrages de construction.*
Building product	***Produit (de construction)***	Item manufactured or processed for incorporation in construction works.	*Tout élément fabriqué ou conçu pour être incorporé dans des constructions.*
Building sub-component	***Sous-composant (de bâtiment)***	Manufactured product forming par of a component	*Produit manufacturé faisant partie d'un composant.*
Client	***Client***	Person or organisation that requires a construction to be provided, altered or extended, and is responsible for initiating and approving the brief.	*Personne physique ou morale qui demande la construction, la transformation ou k'extension d'un bâtiment et responsable de l'établissement et de l'approbation du programme.*
Constructor (contractor)	***Entrepreneur (contractant)***	Person or organisation that undertakes the construction.	*Personne physique ou morale qui entreprend une construction.*
Critical property	***Propriété critique***	Property of an assembly, component or material that must be maintained above a certain minimum level if it is to retain the ability to perform its intended function.	*Propriété qui doit être maintenue au dessus d'un certain niveau pour que le bâtiment ou ses parties conservent l'aptitude à remplir leurs fonctions escomptées.*
Defect	***Défaut***	Fault or deviation in the aimed condition of an assembly, component or material.	*Défaillance ou écart par rapport à l'état prévu d'un bâtiment ou de ses parties.*
Degradation	***Dégradation***	Reduction over time in the performance of an assembly, component or material	*Modification dans le temps de la composition, de la micro-structure et des propriétés d'un composant ou d'un matériau amenuisant ses performances.*
Degradation mechanism	***Mécanisme de dégradation***	Chemical, mechanical or physical changes that reduce the performance of an assembly, component or material.	*Modifications d'ordre chimique, mécanique ou physique entraînant des changements d'une ou plusieurs propriétés critiques d'un produit de construction.*

Design life	***Durée de vie de conception***	Period of use intended by the design, e.g. as established by agreement between the client and the designer to support specification decisions.	*Durée de vie recherchée par le concepteur, par exemple celle qu'il a indiquée au maître d'ouvrage à l'appui des décisions de spécifications.*
Designer	***Concepteur***	Person or organisation responsible for stating the form and specification of a building or parts of a building.	*Personne physique ou morale chargée de définir la forme et la spécification d'un bâtiment ou des parties de bâtiment.*
Durability	***Durabilité***	Capability of an item to perform its required function over a period of time.	*Aptitude d'un bâtiment ou de ses parties à remplir sa fonction, pendant un laps de temps donné, sous l'influence d'agents prévisibles lors de son utilisation.*
Effect	***Effet***	Result of action of an agent.	
Estimated service life	***Durée de vie estimée***	Reference service life multiplied by factors related to specific conditions, e.g. materials, design, environment, use and maintenance (factors method).	*Durée de vie de référence multipliée par les facteurs liés aux circonstances spécifiques, par exemple matériaux, conception, environnement, utilisation et entretien (approche factorielle).*
Failure	***Défaillance***	Termination of the ability of an item to perform a specific function.	*Perte de l'aptitude du bâtiment ou de ses parties à remplir une fonction donnée.*
Feed back from practice	***Retour d'expérience***	Inspection of buildings. Performance evaluation or assessment of residual service life of building parts used in actual buildings.	
Maintenance	***Entretien / Maintenance***	Combination of all technical and associated administrative activities during the service life that are meant to retain an item in a state in which it can perform its required function. Includes cleaning, repair and replacement of parts.	*Recours à l'association d'actions techniques et administratives au cours de la durée de vie en vue de maintenir un bâtiment ou ses parties dans un état lui permettant de remplir ses fonctions.*
Obsolescence	***Obsolescence***	Inability of an item to satisfy changing requirements.	*Perte de l'aptitude d'un élément à satisfaire aux exigences requises suite aux diminutions de ses performances.*
Performance	***Performance***	*Capability of a building or parts of a building to perform their required functions under the influence of expected degradation agents.*	*Aptitude d'un bâtiment ou de ses parties à remplir leurs fonctions dans les conditions d'utilisation prévues.*
Performance requirement	***Exigence de performance***	Range of acceptable performance within which a critical property is maintained.	*Niveaux de performance quantitatifs et qualitatifs requis pour une propriété critique.*
Performance criterion	***Critère de performance***	A level of a performance characteristic, below which the corresponding critical property or properties of a component no longer are maintained.	
Performance evaluation	***Evaluation de performance***	Evaluation of critical properties on basis of measurement or inspection.	*Evaluation des performances critiques sur la base d'un mesurage ou de contrôle.*
Performance over time	***Performance dans le temps***	Description of how a critical property varies with time under the influence of degradation agents.	*Description de la façon dont une propriété varie dans le temps, sous l'influence d'agents de dégradation.*
Predicted service life	***Durée de vie prédite***	Service life predicted from recorded performance over time as found in service life models or testing.	*Durée de vie évaluée à partir de performances observées antérieurement, par exemple reprise de modèles de durée de vie ou à la suite d'essais de vieillissement.*
Property	***Propriété***	Inherent or acquired feature of an item.	*Caractéristique inhérente ou reconnue pour un élément.*

Reference service life	***Durée de vie de référence***	Service life established for a class of building or parts of a building for use as basis for estimating service life in specific items in specific conditions.	*Durée de vie attendue d'un bâtiment ou de ses différentes parties, servant de base pour l'estimation de la durée de vie.*
Refurbishment	***Réhabilitation***	Modification and improvements to an existing plant, building or civil engineering works to bring it up to an acceptable condition.	*Opérations et améliorations apportées à un bâtiment existant ou à ses parties afin de le remettre dans un état acceptable.*
Residual life	***Durée de vie résiduelle***	Time between the moment of consideration and the end of the service life.	*Temps restant entre le moment considéré et la fin de vie prévisionnelle.*
Restoration	***Restauration***	*Operations on building or parts of building that are meant to give back its original aspect or state..*	*Opération ayant pour but de rendre à un élément son aspect ou son état d'origine*
Service life	***Durée de vie***	Period of time after installation during which all essential properties of an item meet or exceed the required performance.	*Période débutant avec la mise en service, pendant laquelle un bâtiment ou ses différentes parties satisfont tout juste ou largement aux exigences de performance ou font mieux.*
Supplier / Manufacturer	***Fournisseur / Fabricant***	Person or organisation that supplies and/or manufactures buildings or parts of buildings.	Industriel : *Personne qui préfabrique des bâtiments ou des parties de bâtiment.* Fournisseur : *Personne physique ou morale qui fournit des bâtiment ou des parties de bâtiment.*
User	***Utilisateur***	Person who occupies, visits or operates a building.	*Personne physique ou morale ou animal auquel un bâtiment est destiné (y compris le propriétaire, le gérant et les occupants du bâtiment)*

Window and facade : Technical terms

C2 participants agree on the use of Swiss document (EMPA) on window and facade terminology when leading FMEA.

SZFF-CSFF (Schweizerische Zentrallstelle für Fenster- und Fassadenbau)
Fachwörter – Verzeichnis. Fenster- und Fassadenbau
German – English – French – Italian

4. FMEA Methodology

Used from the 1960s in the aeronautical and car industries, FMEA is a convenient tool for the safety studies of industrial systems. FMEA is intended for the verification of the product ability to satisfy client's needs (reliability, maintenability, disposability, safety). Commonly used in these industrial domains, it targets and checks weak points before mass-production in order to define preventive measures.
We want to apply a similar approach for building products. With adaptations due to building specificities, CSTB has developed a "risk assessment" approach, in order to know why he has failed or how he will fail. Identify and assess risks, foresee the consequences and possibly propose solutions, are the goals of such study.

This methodology will be applied to advanced windows and solar components for building envelopes.

The proposed approach is composed of two main steps:
- the analysis of the system (including structural, functional and process analysis),
- the search of failure modes.

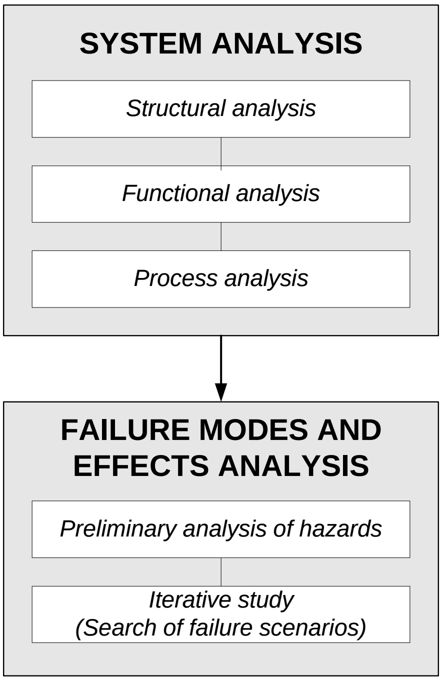


Figure 1

System analysis

The proposed approach relies, on one hand, on the precise description of the system, the identification of its functions and the definition of its environment.
On the other hand, we also consider the building process of the product (design, manufacturing, transport, storage, setting up …).

A double glazing unit case study illustrates each step of the approach.

Structural analysis

This first step consists in identifying all the components, their characteristics as well as the environment in which they could be located in.

The structure of the studied product is described with:

- morphology (geometrical shape, dimensions …),
- topology of relations with other objects,
- physico-chemical composition of its constitutive elements and their own description.

Example:

Figure 2 represents a double glazing unit (left part) and its structural representation (right part).

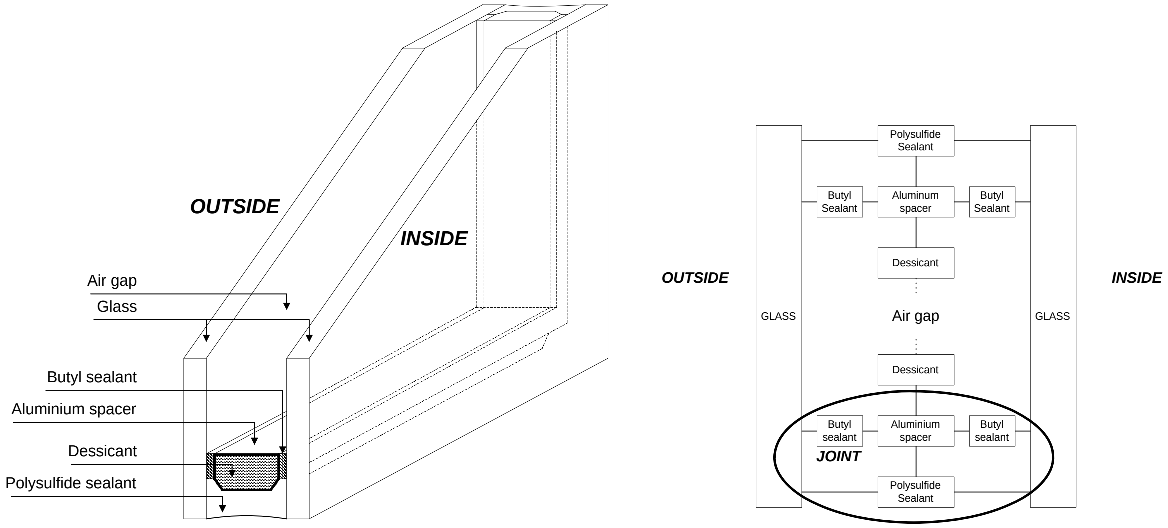


Figure 2: Structural analysis

OUTSIDE	INSIDE
Water (rain, snow)	Water (condensation)
UV and solar radiations	
High or low temperatures	High or low temperatures
Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …
Cleaning agents	Cleaning agents
Hot vapour	Hot vapour
Dust	Dust
Shocks	Shocks
Wind stresses	
Action of frames	
Movements of wall	

Figure 3: Stresses

Note:

Combined environmental stresses (successive or concomitant stresses) should be taken into account:

- water AND low temperature is Freezing,
- high temperatures AND Rain fall is Thermal shocks,
- …

Functional analysis

This second step consists in identifying all the functions of the product and its components (role of each component in the global functioning):

- either needs as regards the user (The product is designed to fulfil user's needs, these needs are expressed in terms of functions: thermal insulation, …),
- either functions stemming from constructive choice (seals to prevent water entry in a glazing unit).

For building domain, "The product fulfils a function" could be generally expressed as "The building product transforms climatic factors". For envelope products, it acts as a filter between two environments, filtering heat flows between outdoor and indoor environments (thermal insulation), stopping water from outdoor (watertightness of a roofing system), …

But, these same climatic factors can have an impact on its constitutive elements and could involve: modification of the materials properties, degradation and even failure…

Example:

Function		Elements
Needs	Landscape vision	Glass (1) + Air gap + Glass (2) (Transparency)
	Light transmission	Glass (1) + Air gap + Glass (2) (Transparency)
	Thermal insulation	Glass (1) + Air gap + Glass (2) (Emptiness)
	Acoustical insulation	Glass (1) + Air gap + Glass (2) (Emptiness)
Technical functions	Water resistance of joint	Joint
	Resistance to environment	Glass + Butyl sealant + Polysulfide sealant + Glass/sealant interface + spacer/sealant interface
	Water absorption	Desiccant

Figure 4: Functional analysis

Process analysis

This third step consists in identifying the various steps of the construction process. On the contrary of a classical approach (we first define the specifications of the product in order that it fulfils the functions for which it was designed, and then check if the manufacturing process leads in reaching the defined specifications), we will first define the characteristics of the product according to the workmanship process (manufacturing and setting up stages) and then identify the product ability to fulfil the functions for which it was designed, given the workmanship quality.

Example:

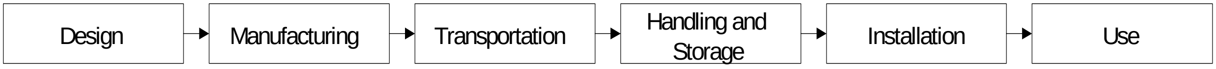


Figure 5: Process analysis

1 – Design
Nature and rigidity of frames

2 – Manufacturing
Squareness and rigidity
Planeness
Quality of joint (Water and air permeability)
    Adhesion (surface quality, cleanness)
    Materials (Butyl, Polysulfide)
Desiccant quality and quantity
Quality of desiccated air

3 – Transportation
Deformations
Degradation of joint

4 – Handling and Storage
Deformations
Degradation of joint

5 – Installation
Plumb and level
Blocking
Problems in adhesion (joint breaking)

Conclusion

With structural functional and process analysis, we know why and how the product works (functions ensured by the product, and elements involved in the "success" of each function).
With FMEA, we will now identify why and how he could fail in fulfilling the functions.

Failure modes and effects analysis

FMEA consists in the identification of all failure modes for each function, the search for causes, and finally the identification of effects. We want to imagine, forecast and write the potential futures of the product.

The novelty of the approach concerns the search of causes and effects. The behaviour towards solicitations of an element, its degradation or failure can change the environment of neighbouring elements. For example, the cracking of the seal of a double glazing unit under UV and temperature stresses could involve stresses in generally protected elements (low-emissive layer towards humidity or pollutants).
We propose to search direct effects (influence of the degradation or failure on the considered element) as well as indirect effects (influence on other elements or on system)

The principle of the failure modes analysis is a multi-step approach that leads to the following table (Figure 6).

Functions	Elements	Modes	Causes	Direct effects	Indirect effects

Figure 6: FMEA blank grid

Step 1: Preliminary analysis of hazards

Thanks to structural and functional analysis, the first two columns are filled.

Functions	**Elements**	**Modes**	**Causes**	**Direct effects**	**Indirect effects**
Landscape vision	Extern. glass				
	Air gap				
	Intern. glass				
Resistance to environment	Glass				
	Polysulfide sealant				
	Butyl sealant				
	…				

Figure 7: Step 1

Once filled these columns, we have to search modes and causes.
Three types of causes could then be identified:
① classical cause as the action of an environmental agent on an element,
② unexpected behaviour due to building process,
③ influence of the behaviour of a neighbouring element on the considered element.
The type 1 causes are deducted from the following table which draws up the potential initial stresses for each element.

		External glass	**Air gap**	**Polysulfide sealant**	**Butyl sealant**	**Aluminium spacer**	**Dessicant**	**Internal glass**
OUTSIDE	Water (rain, snow)	x		x				
	UV and solar radiations	x	x			x		x
	High or low temperatures	x	x	x	x	x	x	x
	Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	x		x				
	Cleaning agents	x		x				
	Hot vapour	x		x				
	Dust	x		x				
	Shocks	x						
	Wind stresses	x	x	x	x	x	x	x
	Action of frames	x	x	x	x	x	x	x
	Movements of wall	x	x	x	x	x	x	x
INSIDE	Water (condensation)							x
	High or low temperatures	x	x	x	x	x	x	x
	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …			x				x
	Cleaning agents			x				x
	Hot vapour			x				x
	Dust			x				x
	Shocks							x

Figure 8: Step 1 – Initial stresses condition.

The type 2 causes are stated by experts. They include potential defects, negligence, errors due to materials (quality, homogeneity of concrete), mean (inefficient mixing or vibrating of concrete), method (surface cleanness,…), middle (temperature, humidity for concrete casting), manpower. Then, direct effects as well as indirect effects are identified.

Functions	**Elements**	**Modes**	**Causes**	**Direct effects**	**Indirect effects**
Landscape vision	Extern. glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap				
	Intern. glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature	Permeability	-
	…				

Figure 9: Step 1 – FMEA table (Extract)

This leads to the updating of environmental stresses conditions.

		External glass	**Air gap**	**Polysulfide sealant**	**Butyl sealant**	**Aluminium spacer**	**Dessicant**	**Internal glass**
OUTSIDE	Water (rain, snow)	x		x	**x**			
	UV and solar radiations	x	x			x		x
	High or low temperatures	x	x	x	x	x	x	x
	Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	x		x	**x**			
	Cleaning agents	x		x	**x**			
	Hot vapour	x		x				
	Dust	x		x	**x**			
	Shocks	x						
	Wind stresses	x	x	x	x	x	x	x
	Action of frames	x	x	x	x	x	x	x
	Movements of wall	x	x	x	x	x	x	x
INSIDE	Water (condensation)				**x**			x
	High or low temperatures	x	x	x	x	x	x	x
	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …			x	**x**			x
	Cleaning agents			x	**x**			x
	Hot vapour			x				x
	Dust			x	**x**			x
	Shocks							x

Figure 10: Step 1 – Updated stresses condition

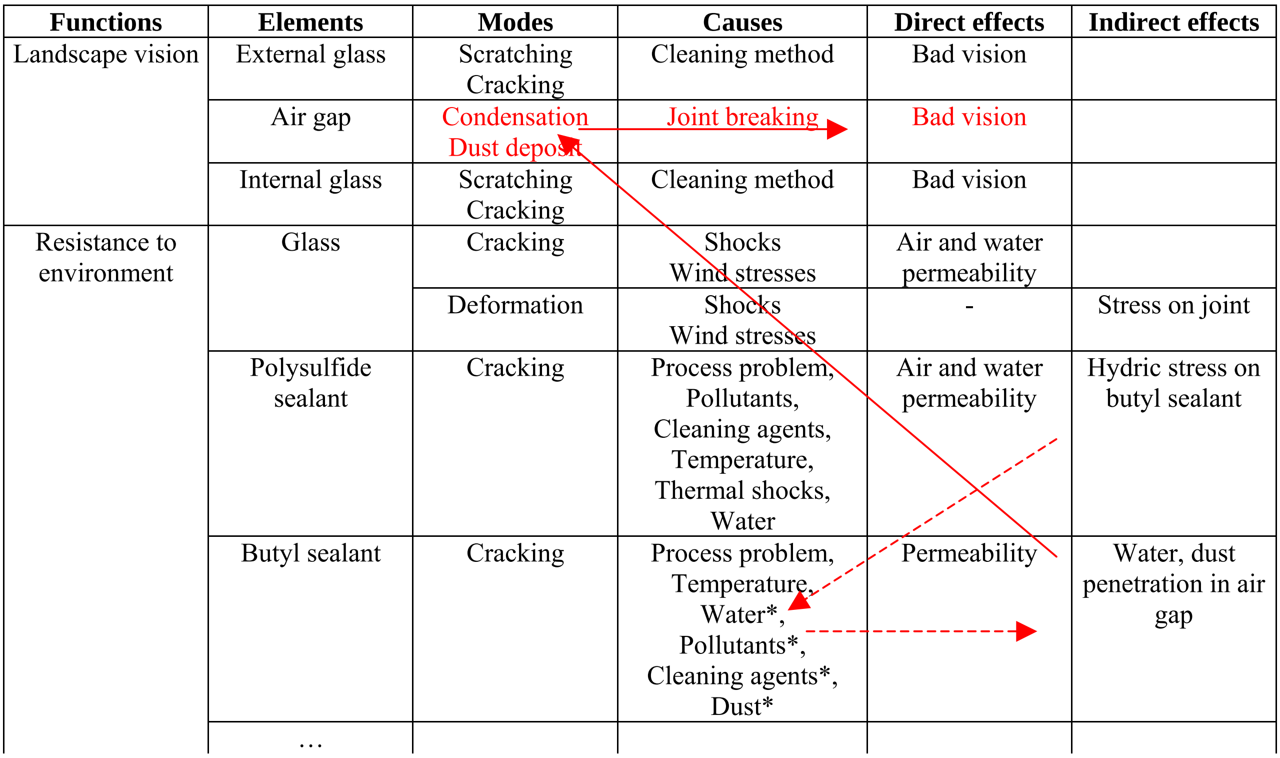
Step 2: Iterative study

With the updated environmental stresses condition table and the column indirect effect, new failures (modes, causes and the consequences) are identified.

Functions	**Elements**	**Modes**	**Causes**	**Direct effects**	**Indirect effects**
Landscape vision	External glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap				
	Internal glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature, Water*, Pollutants*, Cleaning agents*, Dust*	Permeability	Water, dust penetration in air gap
	…				

Figure 11: Step 2 – FMEA table (Extract)

And so on …



Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	External glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap	Condensation Dust deposit	Joint breaking	Bad vision	
	Internal glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Cracking	Process problem, Temperature, Water*, Pollutants*, Cleaning agents*, Dust*	Permeability	Water, dust penetration in air gap
	…				

Figure 12: Step 3 – FMEA table (Extract)

Interest and perspectives

Though it is seldom used in construction, FMEA is a promising method that could be used efficiently in our context. It gives guidelines to improve the reliability and the quality of innovative products.

From the Project C2 discussions raised several aspects concerning FMEA use :

- FMEA is then a familiar tool (modelling expert reasoning),
- FMEA is a relevant and useful tool during design stage, intended to identify weak points of products; weak points means either problems, neglecting, errors during manufacturing process,… or problems of materials behaviour (degradation or failure) facing to environmental stresses or behaviour of neighbouring materials.
- FMEA is a useful tool first for experience and know-how gathering, second because it allows a rigorous and exhaustive analysis of product behaviour.
- FMEA is used in order to identify and rank potential failure modes (thanks to criticality analysis), to determine their causes and effects, and thus to suggest relevant test procedure to characterise their durability.

Additional information

A FMEA analysis is generally supplement with a criticality analysis (FMECA).
It consists in assessing, based on some criteria (occurrence probability, detectability, financial and human consequences gravity…) a criticality indicator for all identified failure modes.
The ranking or selection of failure modes is then possible. It directly influences the choice of the needed actions intended to increase the reliability and safety of the studied systems.

Example: FMEA of a Double Glazing Unit

Function	***Element***	***Mode***	***Cause***	***Direct effect***	***Indirect effet***
Resistance to environment	Glass	Cracking	Shocks	Integrity	Permeability, Transparency
			Wind stresses	Integrity	Permeability, Transparency
			Wind, shocks and T°C ... Action of frames	Integrity	Permeability, Transparency
		Deformation	Temperature	Integrity	Stress on joint
			Shocks	Integrity	Stress on joint
			Thermal shocks (cleaning hot vapour)	Integrity	Stress on joint
	Polysulfide sealant	Cracking	Process problem	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Stress on butyl sealant
			Pollutants	Permeability (air&water)	Stress on butyl sealant
			Cleaning agents (Acid, base)	Permeability (air&water)	Stress on butyl sealant
			Temperature	Permeability (air&water)	Stress on butyl sealant
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Stress on butyl sealant
			Water	Permeability (air&water)	Stress on butyl sealant
	Butyl sealant	Cracking	Process problem	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Failure of joint
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Failure of joint
			Temperature	Permeability (air&water)	Failure of joint
			Polysulfide failure … Pollutants	Permeability (air&water)	Failure of joint
			Polysulfide failure … Cleaning agents	Permeability (air&water)	Failure of joint
			Polysulfide failure … Water	Permeability (air&water)	Failure of joint
	Aluminium	Expansion	Temperature	Movements	Stress on joint
		Corrosion	Polysulfide failure …Water	Loss of material	Weak points (mechanical resistance)
			pollutants or Acid/base	Loss of material	Dust
				Expansion	Stress on joint
	Glass/sealant or spacer/sealant interfaces	Breaking	Process problem	Integrity	Permeability (air and water)
			Wind, shocks and T°C ... Action of frames	Integrity	Permeability (air and water)
			Wind, shocks and T°C ... Action of glass	Integrity	Permeability (air and water)
			Aluminium … Action of aluminium (T°C)	Integrity	Permeability (air and water)
			Incompatibility of materials	Integrity	Permeability (air and water)
			Temperature	Integrity	Permeability (air and water)
			Pollutants	Integrity	Permeability (air and water)
			Cleaning agents (Acid, base)	Integrity	Permeability (air and water)
			UV	Integrity	Permeability (air and water)
			Thermal shocks (cleaning hot steam)	Integrity	Permeability (air and water)
	Dessicant	Loss of absorption ability	? (Temperature, time, …)	Integrity	Increasing of humidity in cavity
Landscape vision	Glass (1&2)	Scratching	Cleaning method	Bad vision	-
		Cracking	Resistance to environment	Bad vision	-
	Air gap	Condensation	Water and air permeability (joint)	Bad vision	-
			Dessicant … Condensation	Bad vision	-
		Dust deposit	Water and air permeability (joint)	Bad vision	-
			Corrosion aluminium … deposit	Bad vision	-
Light transmission	Idem landscape vision				
Thermal insulation	Glass	Decreasing of insulating property	Cracking (resistance to environment)	Bad thermal insulation	-
	Air gap	Decreasing of insulating property	Water and air permeability (joint)	Bad thermal insulation	-
Acoustical insulation	Glass	Decreasing of acoustic property	Cracking (resistance to environment)	Bad acoustic insulation	-
	Air gap	Decreasing of acoustic property	Water and air permeability (joint)	Bad acoustic insulation	-

Comparison IFMA / FMEA

In project B3, a tool called IFMA is used to define the ageing test characteristics.
Even though they are very similar, their use is rather different given that objectives are different.

IFMA **Initial Failure Modes Analysis**	**FMEA** **Failure Modes and Effects Analysis**
Objectives:	***Objectives:***
To identify relevant durability tests for components	To identify: - weak points (from design stage), - potential problems in construction process, - future in service behaviour.
Component approach	***Product approach*** ***(product behaviour deducted from material knowledge)***
Functional and general requirements (User's point of view) ↓ In use conditions definition ↓ Critical functional property (Required value and test methods) ↓ Failure / Damage / Degradation identification (Expert opinion / Field tracking studies) ↓ Degradation indicator and critical degradation factors ↓ Risk assessment (S, P_0, P_D) ↓ Ranking of failure modes: → relevant tests selection	Identification of functions (Product functions, role of components) ↓ Identification of in use conditions and construction process ↓ Modelling of product behaviour ↓ Degradation and failure modes, causes and effects ↓ Criticality analysis ↓ Ranking of failure modes: → durability information / relevant actions
Observation:	***Observation:***
- Reasoning based on the study of consequences (non ability to fulfil the functions). - Choice of the relevant test. - Quantitative approach (environmental stresses and required performance).	- Reasoning based on the modelling of product behaviour from materials behaviour. We take into account events chaining (normal behaviour or degradation of components) leading to product failure. - Decision elements for the choice of the relevant actions, i.e. product modification (risk analysis at design stage), maintenance planning or diagnosis (exploitation stage). - Qualitative approach.
Durability characterisation of a component towards environmental stresses (for the most probable and hazardous failure modes)	**Improvement of design, construction, use of product by identification of all failure modes and selection of the most probable and hazardous one.**

5. Service life prediction: Factor method

History

The Factor method is described in the standard ISO 15686-Part 1, published in 2000 by ISO (ISO, 2000), which is the first part of a series of standard dealing with service life planning of building and constructed assets.

The method is presented as a simple and deterministic approach. It is based on similar factorial methods which have been developed in Japan, and has been under discussion and evaluation for several years within the international committee CIB W80 / RILEM 175-SLM "Service life methodologies".

On one hand, the ISO factor method represents a simplification compared to the Japanese methods. On the other hand, this simplification gives less opportunity to take care of important issues as material used, special climatic conditions and other circumstances.

Factor method (ISO 15686-1)

The factor method described in (ISO, 2000) allows an estimate of the service life to be made for a particular component or assembly in specific conditions. It is based on a reference service life (normally the expected service life in a well-defined of in-use conditions that apply to that type of component or assembly) and a series of modifying factors that relate to the specific conditions of the case.

The various modifying factors are:

- A (quality of the components),
- B (design level),
- C (work execution level),
- D (indoor environment),
- E (outdoor environment),
- F (in-use conditions),
- G (maintenance level).

They can be detailed as follow:

Factors		**Relevant conditions (examples)**	
Agent related to the inherent quality characteristics	A	Quality of the components	Manufacturing, storage, transport, materials, protective coatings, …
	B	Design level	Incorporation, sheltering by rest of the structure
	C	Work execution level	Site management, level of workmanship, climatic conditions during the work execution
Environment	D	Indoor environment	Aggressiveness of the environment, ventilation, condensation
	E	Outdoor environment	Elevation of the building, micro-environment conditions, traffic emissions, weathering factors
Operating conditions	F	In-use conditions	Mechanical impact, category of users, wear and tear
	G	Maintenance level	Quality and frequency of maintenance

Originally, the factors were assessed on a [0.8 ; 1.2] scale (refer to Figure 13 for an example).

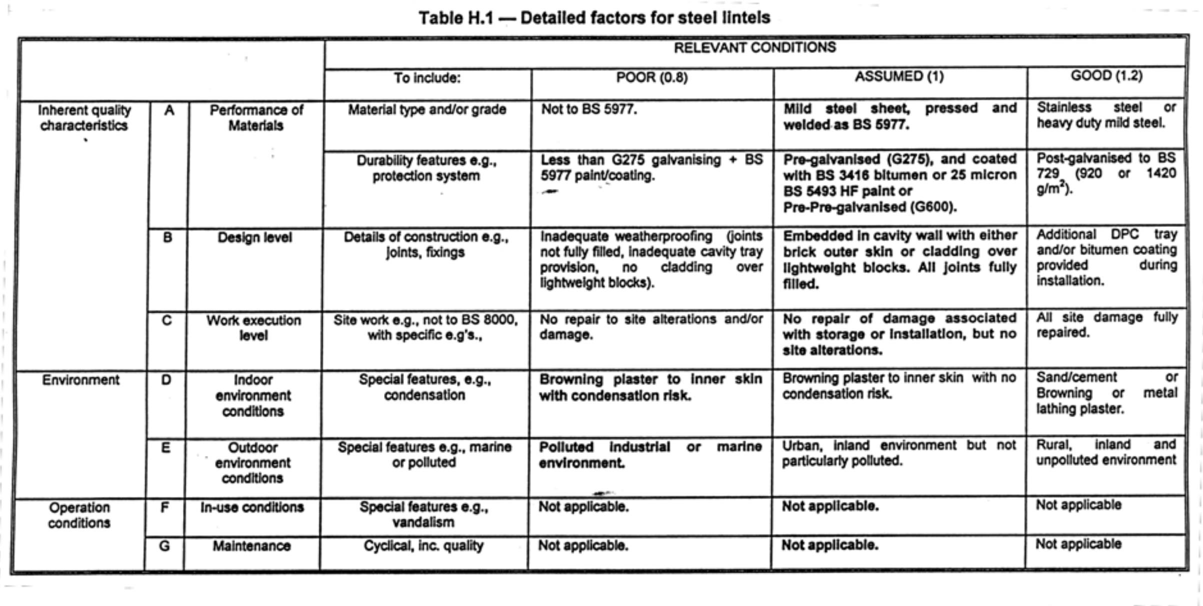


Table H.1 — Detailed factors for steel lintels

			RELEVANT CONDITIONS			
			To include:	POOR (0.8)	ASSUMED (1)	GOOD (1.2)
Inherent quality characteristics	A	Performance of Materials	Material type and/or grade	Not to BS 5977.	Mild steel sheet, pressed and welded as BS 5977.	Stainless steel or heavy duty mild steel.
			Durability features e.g., protection system	Less than G275 galvanising + BS 5977 paint/coating.	Pre-galvanised (G275), and coated with BS 3416 bitumen or 25 micron BS 5493 HF paint or Pre-Pre-galvanised (G600).	Post-galvanised to BS 729 (920 or 1420 g/m^2).
	B	Design level	Details of construction e.g., joints, fixings	Inadequate weatherproofing (joints not fully filled, inadequate cavity tray provision, no cladding over lightweight blocks).	Embedded in cavity wall with either brick outer skin or cladding over lightweight blocks. All joints fully filled.	Additional DPC tray and/or bitumen coating provided during installation.
	C	Work execution level	Site work e.g., not to BS 8000, with specific e.g's.,	No repair to site alterations and/or damage.	No repair of damage associated with storage or installation, but no site alterations.	All site damage fully repaired.
Environment	D	Indoor environment conditions	Special features, e.g., condensation	Browning plaster to inner skin with condensation risk.	Browning plaster to inner skin with no condensation risk.	Sand/cement or Browning or metal lathing plaster.
	E	Outdoor environment conditions	Special features e.g., marine or polluted	Polluted industrial or marine environment.	Urban, inland environment but not particularly polluted.	Rural, inland and unpolluted environment
Operation conditions	F	In-use conditions	Special features e.g., vandalism	Not applicable.	Not applicable.	Not applicable
	G	Maintenance	Cyclical, inc. quality	Not applicable.	Not applicable.	Not applicable

Figure 13 : Assessment of factors (example)

"Any one (or any combination) of these variables can affect the service life. The factor method can therefore be expressed as a formula:

The Estimated Service Life of a Component (ESLC) is defined with:
ESLC = RSLC x Factor A x Factor B x Factor C x Factor D x Factor E x Factor F x Factor G"

The Reference Service Life of a Component (RSLC) is defined as the "service life that a building or parts of a building would expect (or is predicted to have) in a certain set (reference set) of in-use conditions."

"The factor method is a way of bringing together consideration of each of the variables that are likely to affect service life. It can be used to make a systematic assessment even when little or no reliable test data is available. Its use can bring together the experience of designers, observations, intentions of managers and manufacturers assurances as well as some data from test houses

The factorial approach is not a rigid one. Several more worked out methods based on this principle have been proposed. This way of presenting factor method is in fact to remind the parameters that have to be taken into account when using available data (refer to the following chapter).

Evaluation, Practical use and further developments

Most of the discussion and evaluation has been on a theoretical basis (Architectural Institute of Japan, Jonathan W. Martin, Kathryn Bourke, Klaus Rudbeck, Per J. Hövde, Konrad Moser) and so far there has been limited experience using the method in practice.

Several applications are quoted by P.J. Hövde:
- D.P. Wyatt and A. Lucchini (1998, 1999),
- E. Vesikari (2000) on concrete facades,
- G. Hed (2000) on several components and products,
- B. Marteinsson (2001) on wooden window (biological deterioration).

Improvements are suggested in several studies: individual statistical treatment of each factors, range of service life instead of deterministic value, refinement in the definition of the factors (sub-factors), …

For instance, some authors propose variances (formula, factors, …), so that the method is adapted to the product studied. They can be expressed on a generic way with the following formula: $\mathrm{ESL} = \sum_{j} \left(\mathrm{RSL}_j \times \prod_{i} \mathrm{F}_{j,i} \right) + \sum_{k} \mathrm{F}_k$.

> *Example: Wooden building in the case of biological deterioration*
> *The estimated service life is given by* $y = y_s \times B \times C \times D + M$ *, where*
>
> > y_s *is the standard durability value of structural members*
> > *B the coefficient of the design level,*
> > *C the coefficient of the work execution level*
> > *D the coefficient of the site, environment and building conditions*
> > *M the coefficient of the maintenance level.*

Others have tried to include a probabilistic approach in the selection of the factors value, to use probabilistic distribution for each factors, …

The objective of these further developments (refer to (HOVDE, 2000)) is always to give a more reliable and credible service life estimation (given the uncertainty on the collected data), without increasing the complexity (which leads to non applicable methods).

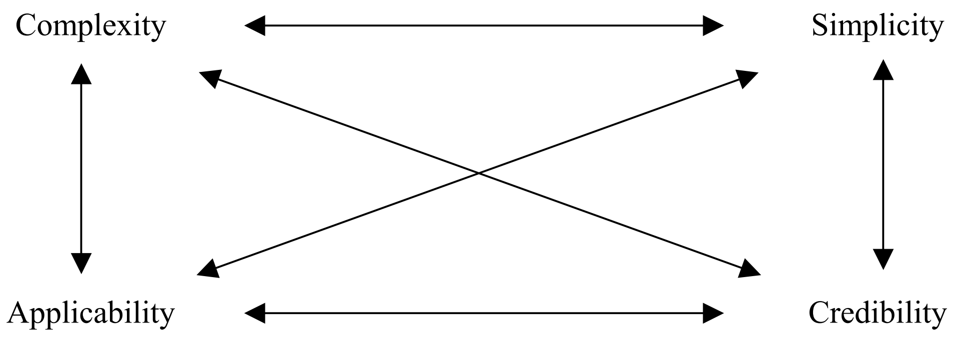


Figure 14: Service life prediction methodologies – Constraints (Hövde, 2000)

We can at least use the “basic” factor method proposed in the ISO standard, or develop a more accurate factor method that take into account the expertise:
- refining factors in order to focus on the most probable degradation phenomena,
- using probabilistic distribution (based on field tracking studies) for the definition of factors.

By means of a Failure Modes and Effects Analysis, we are able to define more accurately the factors (parameters influencing the service life) and thus estimate the parameters that affect the service life.

Factors		**Relevant conditions (examples)**	
Agent related to the inherent quality characteristics	A	Quality of the components	Quality of the frame (material, assemblies, …) Quality of the protection (coating, paint, …) Quality of the DGU (sealant, spacer, …)
	B	Design level	Water evacuation (glazing bed) Stresses on the DGU sealant …
	C	Work execution level	Quality Assurance Plan of the supply chain (geometrical tolerances, oil deposit on glass, …) Incorporation in the building (air pressure, wall geometry, …) …
Environment	D	Indoor environment	Temperature Humidity Mechanical stresses …
	E	Outdoor environment	Temperature Humidity Mechanical stresses Pollutants …
Operating conditions	F	In-use conditions	Aggressiveness of Opening/Closing stresses …
	G	Maintenance level	Quality and frequency of maintenance actions (protection, water evacuation, …)

Figure 15: FMEA results as a justification of factors

References

ISO 15 686-1. "Buildings and constructed assets – Service Life Planning". Part 1: General principles. International Organisation for Standardisation. Geneva, Switzerland, 2000.

The English Edition of Principal Guide for Service Life Planning of buildings. Architectural Institute of Japan, 1993.

Martin, J.W. et al. *Methodologies for predicting the service life of coating systems.* NIST Building Science Series 172. National Institute of Standards and Technology.

Bourke, K and Davies H. *Factors affecting service life prediction of buildings: a discussion paper.* Laboratory paper, Building Research Establishment. Garston, Watford, United Kingdom, 1997.

Aarseth L.I. and Hövde P.J. *A stochastic approach to the factor method for estimating service life.* 8th International Conference on Durability of Buildings, Materials and Components, Vancouver, Canada, 30. May – 3. June 1999.

Rudbeck C. *Methods for designing building envelope components prepared for repair and maintenance.* PhD thesis report R-035. Department of buildings and Energy. Technical University of Denmark. Lyngby, Denmark.

Wyatt D.P. and Lucchini A. *A service life design for lifecare management.* 8th International Conference on Durability of Buildings, Materials and Components, Vancouver, Canada, 30. May – 3. June 1999.

Moser K. *Towards the practical evaluation of service life – Illustrative application of the probabilistic approach*. 8th International Conference on Durability of Buildings, Materials and Components, Vancouver, Canada, 30. May – 3. June 1999.

Hed G. *Service life planning of building components*. 8th International Conference on Durability of Buildings, Materials and Components, Vancouver, Canada, 30. May – 3. June 1999.

Marteinsson B. *Durability of wood windows and the factor method of ISO 156686-1*. Project report Nordic Research Training Course "Service life of buildings – From theory to practice" The Icelandic Building Research Institute. Keldnaholt. Iceland 2001.

Vesikari E. *Estimation of service life of concrete facades by the factor approach*. International RILEM workshop on life prediction and ageing management of concrete structures, Cannes, France, 16-17 October 2000.

6. Service Life Prediction: Data Fusion

Principle: From data to decision

Confronted with a complex problem (meteorology, toxicology, traffic management…), an expert adopts the following approach:

- first, he collects all data concerning the system (definition of the product, its environment,…) ;
- then he tries to understand and model all involved phenomena ;
- finally, from this modelling, he extracts decision elements (recommendations, elements for comparison of alternatives, assessment parameters to be used in other models, …).

In this context and especially in service life assessment problem, one of the major obstacles to decision-making is to be able to handle this both uncertain and heterogeneous information.

Experts need tools and procedure intended to extract the decision elements from all the available information, often with management of uncertainty and ignorance. The solution is data co-exploitation, that is to say “Simultaneous exploitation of several points of view on a data or on a method to process it.”

Such approach enriches the analysis (complementary information, analysis and exploitation of conflict) and leads to synthesised and consensual information. Furthermore, managing uncertainty and ignorance increases the credibility of the results.

Proposed approach

The four main steps are:

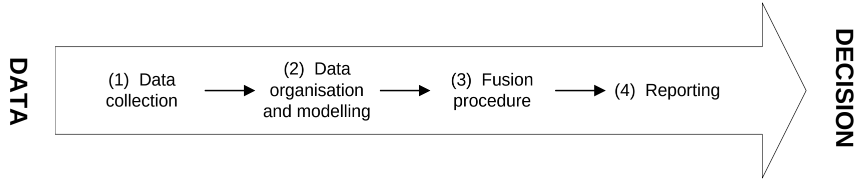


Figure 16: Proposed approach

The two steps (1) and (2) lead to several models (several points of view) allowing service life assessment of building products.

Data fusion procedure (3) then extracts consensual information, which is presented as a useable format (4).

We will not detail each step, but briefly present the main aspect and key information.

Data collection

Several tools and methods for durability assessment currently exist (field tracking studies, expert opinion, accelerated testing, natural weathering, modelling (reliability models…), materials science …

But their use implies some problems: non reproducibility and tracability of field tracking studies, subjectivity of expert opinion, length of accelerated tests and natural weathering, relevance of torture test, required quality and quantity of knowledge for modelling (these studies are only available for simple and well-known materials or products, for one or two degradation phenomena).

Data collection consists in the collection of every available durability data on the product or one of its components, in its predicted environment or one of its parts.

Indeed, two types of service life data could be collected:

- Data wholly representing the system in its predicted environment;
- Data only representing a part of the system (component), and/or a part of the predicted environment (one degradation phenomena).

All this information is dispersed (multitude of sources and studies), dissimilar (scale, uncertainty formalism) and of different quality (strength of hypothesis...).

Example:
Let us illustrate this concept with a basic example.
We want to assess the service life of an external painted reinforced concrete wall.
Data collection is the search for:

- data on the system (RC wall),
- data on the system but in a specific environment (RC wall with respect to cracking under mechanical loads),
- data on RC wall components (concrete, paint and steel),
- data on degradation phenomena of these components (carbonation of concrete, corrosion of steel bars, …).

We have to keep all information that will be used for the quality assessment of data (see next paragraph “Model quality assessment”). We then provide the participant with a data collection sheet.

Data Organisation and Modelling

We want to assess the service life of the product in its predicted environment, but we have either global answer (type 1), or part of the answer (type 2). This problem could be explained in terms of **granularity**, that is to say the “fineness of the modelling grain”. Each data represents the system more or less finely, according to the “power of the zoom”.
This fineness is characterised by three dimensions of granularity.

- We define Geometrical granularity G_G and Phenomenological granularity G_P on a qualitative scale. G_G scale is “Materials, components, product”; and G_P scale is expressed according to the number of agents: “One, several and all agents”.
- Temporal granularity G_T (“raw” service lives SL = 60 years or precise modelling of degradation state, with regular time intervals).

An organisation step is needed in order to build models allowing a global answer from these partial answers. Data of similar granularities are simply placed on a same level.
For each level, a system behaviour model is built (let’s remind that it have to allow the assessment of product service life).
According to the level, various cases could be seen:

- If $G_G = G_P = 1$, datum represents completely the system (Service life of a reinforced concrete wall for instance).
- If $G_G < 1$ and $G_P = 1$, data represent partially the system, we have to geometrically aggregate these data (Degradation model of concrete, aggregated with degradation models of steel).
- If $G_G < 1$ and $G_P < 1$, then we have to do a double aggregation (Carbonation model, freeze/thawing model… and all degradation models of concrete phenomenologically aggregated to obtain a degradation model of concrete, then geometrically aggregated to obtain a system degradation model).

It implies that a good knowledge of the product and its behaviours is required, at a macro level (product, environment) as well as a micro level (materials, degradation agents).

Example:
RC wall behaviour could be represented knowing concrete, steel, paint behaviours and their interrelation.

Each component could be represented by sub-components or phenomena. Figure 17 gives Concrete example.

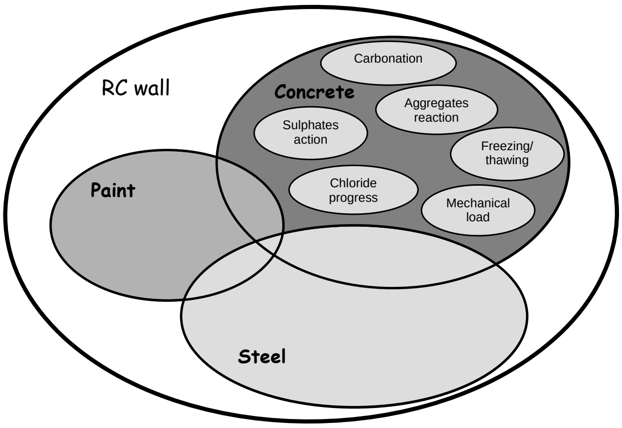


Figure 17: Multi-model aspect of RC wall

Model quality assessment

We then associate with each service life assessment, a quantitative attribute *m* called "belief mass". *m* belongs to [0, 1] (0 represents "no confidence" and 1 represents "certainty"). It represents the confidence we could have in an assessment and then should express the strength of hypothesis, uncertainties … of models, methods.

As an operational method, we proposed a simple multicriteria analysis, based on the Pedigree concept approach (developed by Funtowicz et Ravetz). Pedigree reflects the quality of information, and thus allows the characterisation of data production process with relevant pedigree criteria.
We have:

- chosen the relevant criteria which characterise the quality of an information,
- defined the assessment method for each criterion,
- proposed an aggregation method.

The chosen criteria C_i characterise according to us the three aspects of information quality: the way the service life data is produced (Granularity level, Theoretical structure, Input parameters, Reference), its format (Credibility), and the relevance of its use in our study (Geographical correlation, Temporal correlation…[1]).
Each criteria is defined on a 5-levels qualitative scale [0, 1, 2, 3, 4], with a lexicographical correspondence. Aggregation method is simply a normalised average mean in order to obtain a [0, 1] mass.

We thus have a set of couples (SL, m) resulting from modelling step

Fusion procedure

Definitions

Each model giving a service life (SL) is called *evidence* (answer to the question: "what is the service life of this product?").

An *evidence* is:

---

[1] The service life of a window in Sweden in 1960 is different of a window in France in 2000

- focusing on a subset (of service lives) A of time scale [0, T], the set of possible answers (called "*frame of discernment*"). Let's remark that we will work on a continuous and orderly frame of discernment,
- characterised by a confidence attribute m. m(A) is the probability we only know "that", that is to say SL∈A.

An *evidence* is translated in belief function: a mass m is associated with A (probability to know only A), and its complement (1-m) is associated with the frame of discernment (probability to know only [0, T], that is to say to know nothing). The whole mass is thus distributed on time scale: Σ = 1 (i.e. certainty).
It's a mean to represent the knowledge contained in this considered model.

Principle

Let 1 and 2 be two evidences, respectively focusing on service lives subset A_1, …, A_n and B_1, …, B_m , with belief masses m_1 and m_2.
Data fusion, which consists in the search of the resulting mass distribution grouping the knowledge of evidences 1 and 2 (see example) is done with Dempster rule:

$$m(\theta) = k \sum_{\substack{i,j \\ A_i \cap B_j = \theta}} m_1(A_i).m_2(B_j) \qquad [1]$$

Because of associativity, this rule is easily generalised to the fusion of several data (data fusion result is equal whatever the fusion order is).

Example

For example, if we fusion the two following data:
1 – A = [20, 40] with $m_1(A) = 0,6$
2 – B = [30, 60] with $m_2(B) = 0,7$

then the resulting distribution of masses m_r is:

$m_r(A) = m_r([20,40]) = 0,6.(1–0,7) = 0,18$
$m_r(B) = m_r([30,60]) = (1–0,6).0,7 = 0,28$
$m_r(A \cap B) = m_r([30, 40]) = 0,6.0,7 = 0,42$
$m_r(T) = (1–0,6).(1–0,7) = 0,12$

The sum of the four resulting masses is of course 1. It's a new evidence, grouping the knowledge contained in evidences 1 and 2, now focusing on three subsets and the frame of discernment.
That is to say: service life is probably [30, 40] (belief 0,42), without forgetting the sets [20, 40] et [30, 60] (respective belief values 0,6 and 0,7). Perhaps we are totally wrong and the result will be in any case "somewhere else" (Frame of discernment).

Limits

The existence of "**conflict**" (two conflictual data A∩B=∅) limit the validity of Dempster rule. A part of the resulting mass ($m_1.m_2$) is associated with empty set : it is called conflicting mass m_c.
Adaptations to Dempster rule are proposed in bibliography, association of m_c mass:
- to the union set, that is to say supposing one of the source is exact (Dubois),
- to the set "ignorance", representing indecision between the two sources (Yager),

The second problem is **"weak coherence"** (A∩B≈∅). A weak coherence is the intermediate case between coherence and conflict. It leads to counter-intuitive results (the major part of the mass is associated with a small interval A∩B). We then propose a rule in case of weak coherence. From a given overlapping limit *lim*. the mass is not associated with A∩B but with A∪B (when in doubt, we prefer indecision to uncertain choice).
But these rules involve either the loss of associative aspect, or the loss of informativity (SL = 60 yrs is informative, SL ∈ [0, 200] yrs is non informative).

Given these various problems, a universal rule, suitable for any set of data, can't be found.

Solution

We have to define decision rules allowing the choice of the most relevant rule for the initial set of data: to define a **fusion strategy**.

Reporting

After fusion, the resulting mass distribution on T subsets is obtained.

Failure distribution

The result presentation generally used in durability domain is failure probability distribution. Adapted to our approach, the a priori probability (pignistic probability of Smets) we could observe a failure before t, is given with the following formula, $[x_i, y_i]$ is the interval n°i resulting from fusion:

$$P([0,t]) = \sum_{x_i<t} \frac{m([x_i,y_i])}{\|[x_i,y_i]\|} \qquad \textbf{[2]}$$

With Evidence Theory, two curves called belief (BEL) and plausibility (PL) curves are associated with the cumulative probability distribution, from the same information.

Bel ([0, t]), the belief at t, is the measure of the belief we have to observe a failure before t.

Pl([0, t]), the plausibility at t, is a measure of how much we can believe in a failure before t, assuming all unknown parameters are supportive of a failure after t.

$$\mathrm{Bel}([0,t]) = \sum_{[x_i,y_i]\subseteq[0,t]} m([x_i,y_i]) \quad \& \quad \mathrm{Pl}([0,t]) = \sum_{x_i<t} m([x_i,y_i]) \qquad \textbf{[3]}$$

These curves surround probability curve, it's in some way optimistic and pessimistic values of P. They draw a zone, which we call "uncertainty zone" (Figure 18).

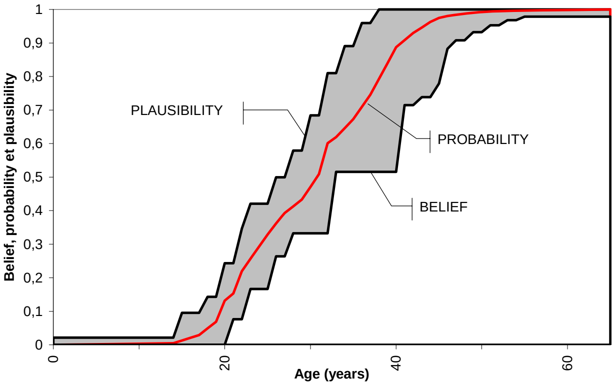


Figure 18: Failure distributions

Characteristic service lives

From this graph, characteristic service lives ***SL_k*** are assessed as follows, for an acceptable risk ***k*** (depending on gravity and cost of consequences, impact on system and environment, human and goods…):

$$SL_k \; / \; P(SL \leq SL_k) \leq k \qquad \textbf{[4]}$$

It is the service life SL_k for which the probability of observing a lower real service life SL than the characteristic service life SL_k, is lower than the considered k.

On this example, $SL_{10\%} = 20$ years, with the interval [15, 26] years.

Consensual curve

The consensual service life or "contour function" is the distribution of masses on the frame of discernment.

For a given service life t is consequently the sum of the masses of all resulting sets t belongs, that is to say :

$$C_f(\{t\}) = \pi(t) = \sum_{t \in R_i} m_i \qquad \textbf{[5]}$$

C_f verifies $0 \leq C_f \leq 1$ since $\sum_{R_i} m_i = 1$.

These curves give the service life which groups the majority of consensus, [70, 75] (Figure 19). That is to say: "[70, 75] years groups most of the vote".
For this value, the complement to 1 indicates the existence of conflict (some data don't predict this service life).

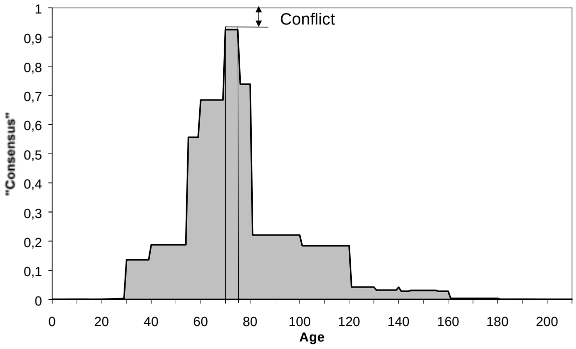


Figure 19: Consensual curve

Results qualification

We wished results qualification. In this purpose, two indicators are defined:

- Q_A = quality and relevance of the used fusion rule, according to quoted parameters (conflicting mass which govern the validity of Dempster rule, loss of information due to non relevant fusion strategy),
- Q_I = information contained in the result (surface of the uncertainty zone).

It's very important to remember that we could obtain a result even in case of poor quality data ("Garbage in, garbage out"), but it involves:

- a bad Q_I (wide uncertainty zone) synonymous of bad knowledge,
- a bad Q_A which means conflicting data or loss of information (not credible and not usable results).

The solution is obviously an improvement of input data, increasing the accuracy and the confidence in the first case, increasing the coherence in the second case.

The other interesting advantage of this method is to point out a lack of data. Then we focus data research or production (products or degradation phenomenon seldom studied).

Example: Wooden window

Case study

As an example, we will study a basic wooden window with a double glazing unit.

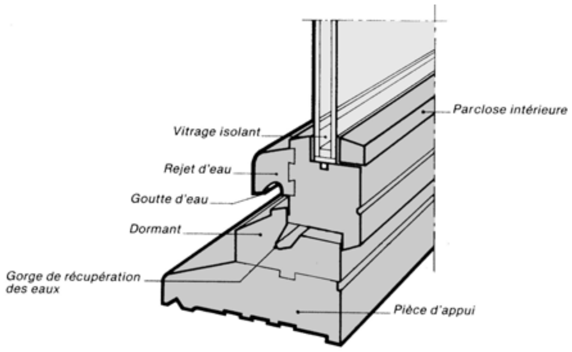


Figure 20

Data collection, Data organisation and modelling

Data n°	**Level**	**Sources & service life**		**1**	**2**	**3**	**4**	**5**	**6**	**Masses**
1	**1**	[OCF,85]	{25 ; 30 ; 35} yrs	4	0	1	1	0	1,80	***0,33***
2	**1**	[EPFL,95]	30-70 yrs	4	1	4	2	2	3,14	***0,67***
3	**1**	EPFL-LESO (1)	30-50 yrs	4	1	1	1	2	2,55	***0,48***
4	**1**	EPFL-LESO (2)	40-60 yrs	4	1	1	1	2	2,55	***0,48***
5	**1**	EPFL-LESO (3)	{30 ; 50 ; 70} yrs	4	1	1	1	2	2,97	***0,50***
6	**1**	[GUMPERTZ,96]	25-50 yrs	4	0	2	1	1	2,74	***0,45***
7	**1**	[AMMAR,80]	{30 ; 45 ; 60} yrs	4	1	1	1	1	2,73	***0,45***
8	**2**	Model	Distribution	2	2	3	3	2	3,56	***0,65***

– DDV (Wooden window) = 30 yrs
– DDV (Wooden window) = 30-70 yrs (80 % degradation)
– DDV (Pine window) = 30-50 yrs
– DDV (Pine window) = 40-60 yrs
5 – DDV (Wooden window) = 50 yrs
6 – DDV (Window) = 25-50 yrs
7 – DDV (Window) = 45 yrs (mean)
but minimum 30 yrs
8 – DDV (Statistical study wooden window) = distribution.

Data n°8 stems from a complete statistical study (Figure 21) of failures.
We have the distribution of probability according to the failure mode and the corresponding service life.

Failure	Component	Cause	Probability	Service life
Water tightness	Assembly	Wood contraction	7.5	20-35
		Faulty glueing	2.8	1-10
		Others	2.6	30-70
	Opening / fixed pieces	Faulty draught-proofing	2.9	< 10
		Others	0.4	30-70
	Opening piece / windowsill		17.2	20-35
	Opening / Opening pieces		2.9	20-35
	Glazing unit / Wood	Glass rebate failure	3.1	30-70
		Glazing bead failure	0.5	1-10
		Others	0.3	30-70
	Wood / Wall	Faulty draught-proofing	17.6	10
		Faulty sealing	10.5	15-20
		Others	1.3	30-70
Air tightness		Wood contraction	3.4	20-35
		Faulty sealing	1.3	15-20
		Gap between opening	1.2	20-30
		Others	0.9	30-70
Materials degradation		Wood rotting	4.8	10-100
		Insect	0.4	10-100
		Glazing	1.8	15-20
Deformation		Wood contraction	2.2	20-35
		Glazing blocking	0.5	7
Fittings		Alloy weathering, wear of mechanisms	2.0	15

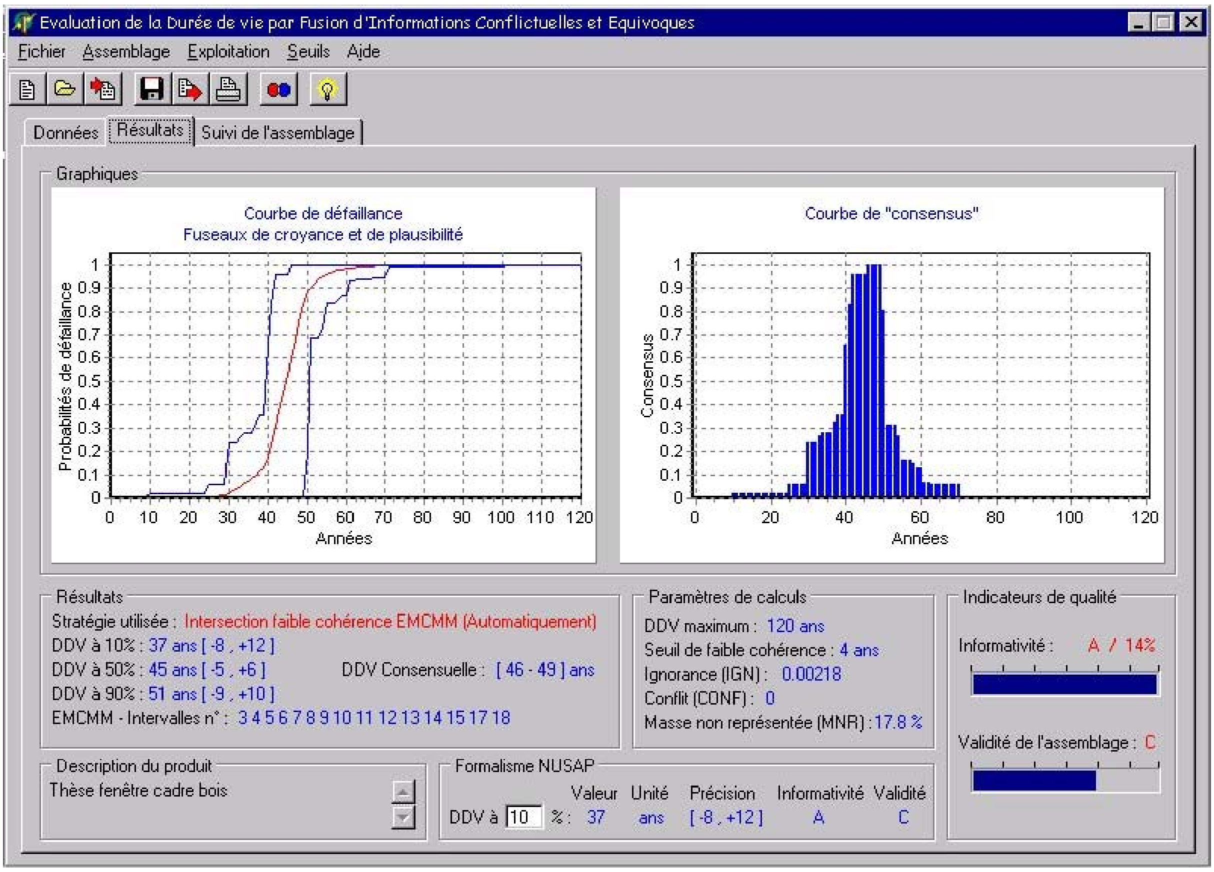
Figure 21: Wooden window model

Fusion procedure and Reporting

Fusion procedure is done with the software developed in CSTB.

Figure 22 is a screen copy of the results. It includes:

- probability distribution of failure and its uncertainty zone (upper left part of the graph),
- consensual curve (upper right part),
- characteristic service lives (lower left part),
- quality assessment (lower right part).



Stratégie utilisée : Intersection faible cohérence EMCMM (Automatiquement)
DDV à 10% : 37 ans [-8 , +12]
DDV à 50% : 45 ans [-5 , +6]   DDV Consensuelle : [46 - 49] ans
DDV à 90% : 51 ans [-9 , +10]
EMCMM - Intervalles n° : 3 4 5 6 7 8 9 10 11 12 13 14 15 17 18

DDV maximum : 120 ans
Seuil de faible cohérence : 4 ans
Ignorance (IGN) : 0.00218
Conflit (CONF) : 0
Masse non représentée (MNR) : 17.8 %

Informativité : A / 14%
Validité de l'assemblage : C

Thèse fenêtre cadre bois

	Valeur	Unité	Précision	Informativité	Validité
DDV à 10 % :	37	ans	[-8 , +12]	A	C

Figure 22: Service life assessment of a wooden window (Reporting)

The result is:
- $SL_{10\%}$ = 37 years [-8, +12],
- SL_C = [46, 49] years.

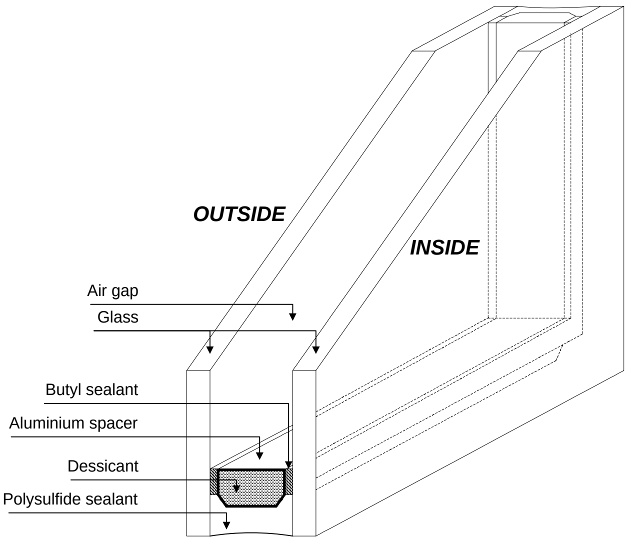
Result is medium-quality; they are informative (quality A) but don't take into account some conflicting data (nearly 18%).

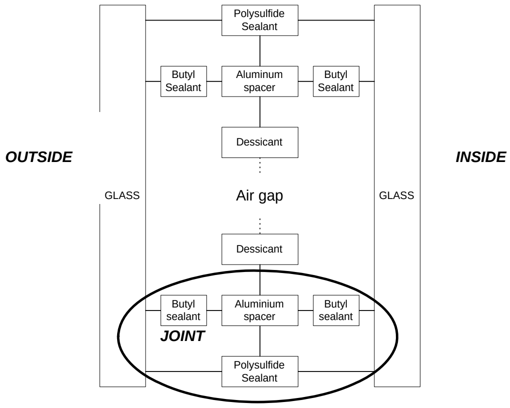
7. Case study: Double Glazing Unit

System analysis

→ identification of each components (and materials), of links between these elements. (1)
(physical, chemical, mechanical links)
→ identification of each potential solicitations (use, environment) (2)

(1) Elements





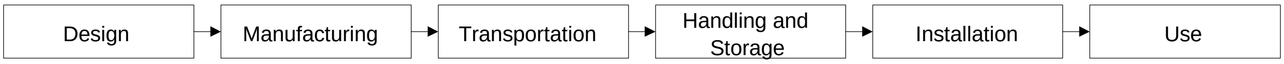
(2) Environment

Water (liquid, vapour) → rain falls, condensation (bathroom)
Wind stresses
Shocks
Temperature → > and < 0°C, gradient between external and internal part, thermal shocks
UV (especially south facade)
Air and pollutants → O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl …
Cleaning agents (Acid, base)
Dust
Action of frames → Thermal dilatation

Functional analysis

Function		Elements
Needs	Landscape vision	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Transparency)
	Light transmission	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Transparency)
	Thermal insulation	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Emptiness)
	Acoustical insulation	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Emptiness)
Technical functions	Water resistance of joint	Joint
	Resistance to environment	Glass + Butyl sealant + Polysulfide sealant + Glass/sealant interface + spacer/sealant interface
	Water absorption	Desiccant

Process steps



1 – Design
Nature and rigidity of frames

2 – Manufacturing
Squareness and rigidity
Planeness
Quality of joint (Water and air permeability)
    Adhesion (surface quality, cleanness)
    Materials (Butyl, Polysulfide)
Desiccant quality and quantity
Quality of desiccated air

3 – Transportation
Deformations
Degradation of joint

4 – Handling and Storage
Deformations
Degradation of joint

5 – Installation
Plumb and level (*aplomb*)
Blocking (*calage*)
Problems in adhesion (joint breaking)

Failure Modes and Effects Analysis

Function	***Element***	***Mode***	***Cause***	***Direct effect***	***Indirect effet***
Resistance to environment	Glass	Cracking	Shocks	Integrity	Permeability, Transparency
			Wind stresses	Integrity	Permeability, Transparency
			Wind, shocks and T°C ... Action of frames	Integrity	Permeability, Transparency
		Deformation	Temperature	Integrity	Stress on joint
			Shocks	Integrity	Stress on joint
			Thermal shocks (cleaning hot vapour)	Integrity	Stress on joint
	Polysulfide sealant	Cracking	Process problem	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Stress on butyl sealant
			Pollutants	Permeability (air&water)	Stress on butyl sealant
			Cleaning agents (Acid, base)	Permeability (air&water)	Stress on butyl sealant
			Temperature	Permeability (air&water)	Stress on butyl sealant
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Stress on butyl sealant
			Water	Permeability (air&water)	Stress on butyl sealant
	Butyl sealant	Cracking	Process problem	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Failure of joint
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Failure of joint
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Failure of joint
			Temperature	Permeability (air&water)	Failure of joint
			Polysulfide failure … Pollutants	Permeability (air&water)	Failure of joint
			Polysulfide failure … Cleaning agents	Permeability (air&water)	Failure of joint
			Polysulfide failure … Water	Permeability (air&water)	Failure of joint
	Aluminium	Expansion	Temperature	Movements	Stress on joint
		Corrosion	Polysulfide failure …Water	Loss of material	Weak points (mechanical resistance)
			pollutants or Acid/base	Loss of material	Dust
				Expansion	Stress on joint
	Glass/sealant or spacer/sealant interfaces	Breaking	Process problem	Integrity	Permeability (air and water)
			Wind, shocks and T°C ... Action of frames	Integrity	Permeability (air and water)
			Wind, shocks and T°C ... Action of glass	Integrity	Permeability (air and water)
			Aluminium … Action of aluminium (T°C)	Integrity	Permeability (air and water)
			Incompatibility of materials	Integrity	Permeability (air and water)
			Temperature	Integrity	Permeability (air and water)
			Pollutants	Integrity	Permeability (air and water)
			Cleaning agents (Acid, base)	Integrity	Permeability (air and water)
			UV	Integrity	Permeability (air and water)
			Thermal shocks (cleaning hot steam)	Integrity	Permeability (air and water)
	Dessicant	Loss of absorption ability	? (Temperature, time, …)	Integrity	Increasing of humidity in cavity
Landscape vision	Glass (1&2)	Scratching	Cleaning method	Bad vision	-
		Cracking	Resistance to environment	Bad vision	-
	Air gap	Condensation	Water and air permeability (joint)	Bad vision	-
			Dessicant … Condensation	Bad vision	-
		Dust deposit	Water and air permeability (joint)	Bad vision	-
			Corrosion aluminium … deposit	Bad vision	-
Light transmission	Idem landscape vision				
Thermal insulation	Glass	Decreasing of insulating property	Cracking (resistance to environment)	Bad thermal insulation	-
	Air gap	Decreasing of insulating property	Water and air permeability (joint)	Bad thermal insulation	-
Acoustical insulation	Glass	Decreasing of acoustic property	Cracking (resistance to environment)	Bad acoustic insulation	-
	Air gap	Decreasing of acoustic property	Water and air permeability (joint)	Bad acoustic insulation	-

Analysis of the influences of the frames

When leading the FMEA of a given product, we have to take into account the building scale, that is to say the effect of the neighbouring products. For instance, the FMEA of a window requires the taking into account of the window/wall assembly and the wall (contraction and expansion …).

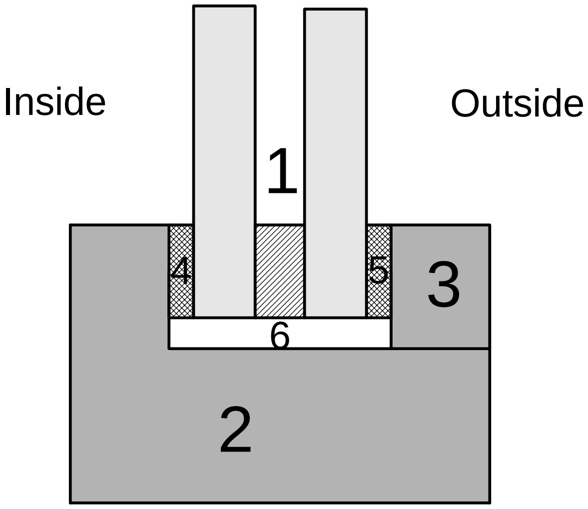
For the double glazing unit FMEA, we have to know more accurately the behaviour of the frame so that we could identify its various influences on the behaviour of the double gazing unit.

Since we don't know a priori in which frame the DGU will be integrated, we have to consider all possibilities (aluminium, wood …).

Problem statement

To summarise the problem, we want to answer the following question:

"How can the frame affect the glazing lifetime?"



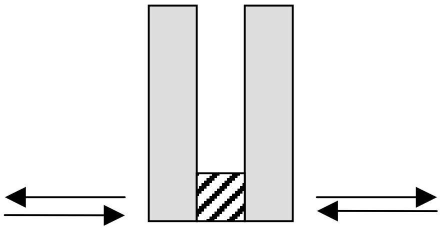
Eight potential stresses were identified:

1. Moisture/water in the glazing bed (humidity stressing the sealant)

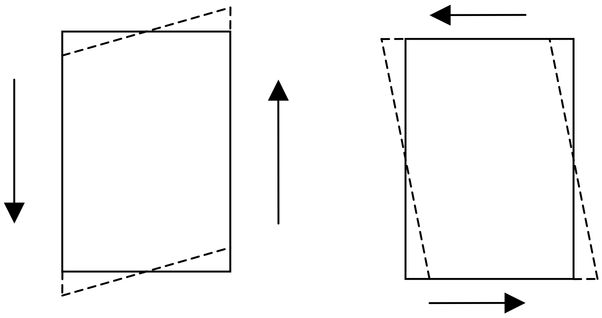
   Water could stagnate in the glazing bed zone due to:
   - design problem,
   - construction errors,
   - too much maintenance (non adapted or excessive painting that stop water),
   - not enough maintenance (blockage of evacuation holes by dust, insects, …)

2. Temperature

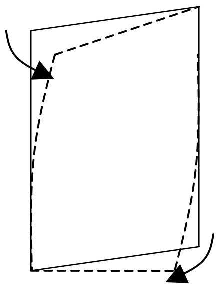
3. Pressure changes (due to water, temperature …)



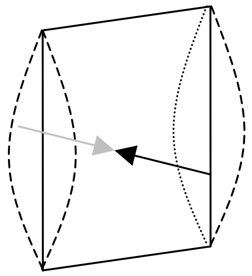
4. Mechanical stresses



Vertical and horizontal racking

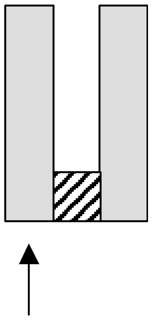


Torsion

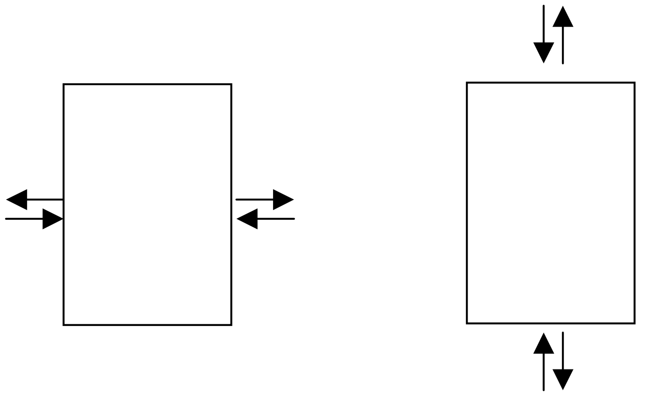


Bending

5. Setting blocks problems



6. Design tolerances on expansion and contraction of the frames



7. Differential temperatures effect (Shadow in case of sheltering, colour of the frames …)

8. Contamination (chemical compatibility) of sealant and wood preservatives, paints …

8. Case study: Argon filled low-e coated glazing unit

This case study being very close to the DGU study, it's not worth doing the same study than for the DGU.

We will just have a look on:
- the influence of the new element "Low emissive coating",
- the effect of Argon filling instead of Air filling.

System analysis

Structural analysis

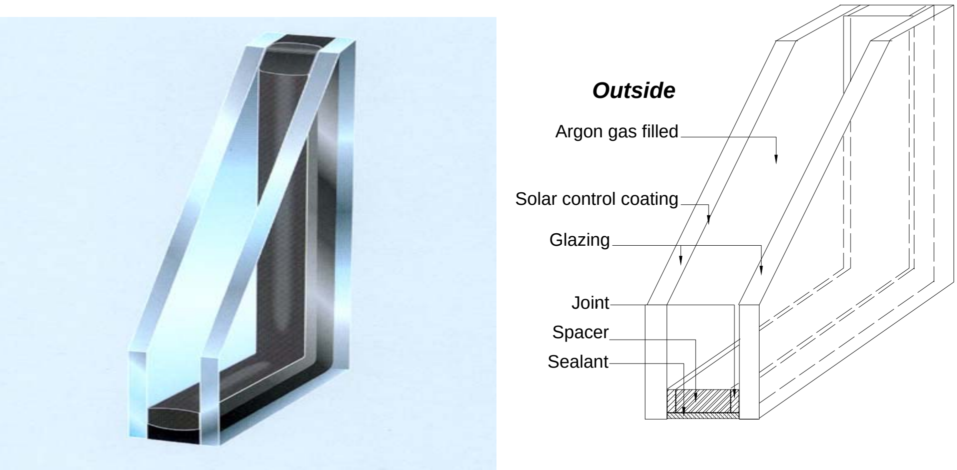


Figure 23: Argon filled low-e coating window section

Elements	Materials
External glazing	4mm float glass
Low-e coating	
Cavity	Inert gas : Argon
Spacer	Composite material with stainless steel foil (incorporating high percentage of desiccant-fill material)
Joint	3mm Polysulfide foam 0,3mm Butyl sealant
Internal glazing	4mm Low iron glass

Figure 24: Structural analysis

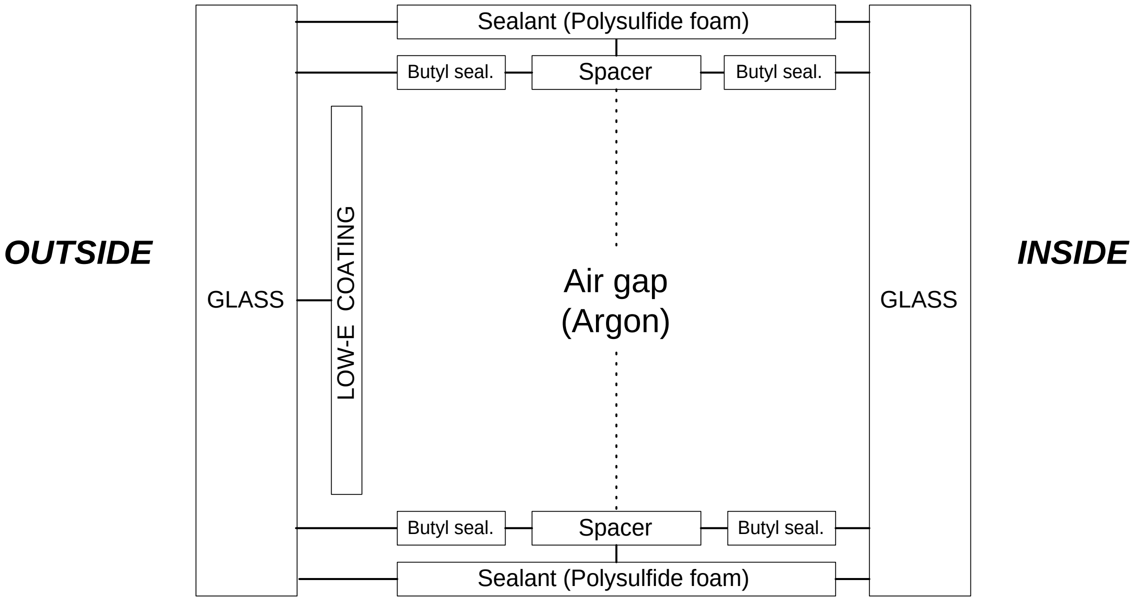


Figure 25: Structural diagram of Argon filled low-e coating window
(elements are not to scale)

Environment

Environmental stresses

- Water, humidity (liquid, vapour)
- Rain, Snow, Hail
- Wind stresses and other mechanical stresses (including vibrations)
- Temperature → > and < 0°C, gradient between external and internal part, thermal shocks
- UV radiation
- Air → O_2, CO_2, CO, Ozone
- Salt spray
- Pollutants → NO_x, SO_x, HCl …
- Cleaning agents (acid, base)
- Bacteria and fungi,
- Dust

Operational conditions

- Shocks
- Air pressure (in the air gap) in the supply chain, in service.
- Action of frames → Thermal dilatation, Opening/closing stresses (refer to the detailed study)
- Cleaning agents (Acid, base)

Functional analysis

Function		Elements
Needs	Landscape vision	Glass $^{(1)}$ + Low-e coating + Air gap + Glass $^{(2)}$
	Light transmission	Glass $^{(1)}$ + Low-e coating + Air gap + Glass $^{(2)}$
	Thermal insulation	Glass $^{(1)}$ + Coating + Air gap + Glass $^{(2)}$ + Spacer
	Acoustical insulation	Glass $^{(1)}$ + Coating + Air gap + Glass $^{(2)}$ + Spacer
Technical functions	Water resistance of joint	Joint
	Resistance to environment	All elements and interfaces between elements
	Water absorption	Desiccant incorporated in spacer

Figure 26: Functional analysis

Failure Modes and Effect Analysis

Note:
All the problems that could occur during the process are summarised under the term “Process problems”. The most common ones are:

- fingerprints one the glass,
- oil deposit in the glass (decrease in the gluing ability of the coating or the sealants),
- removing of the coating from the edge of the glass (?),
- …

Function	***Element***	***Mode***	***Cause***	***Direct effect***	***Indirect effet***
Resistance to environment	Glass	Cracking	Shocks	Integrity	Permeability, Transparency
			Wind stresses	Integrity	Permeability, Transparency
			Wind, shocks and T°C ... Action of frames	Integrity	Permeability, Transparency
		Deformation	Temperature	Integrity	Stress on joint
			Shocks	Integrity	Stress on joint
			Thermal shocks (cleaning hot vapour)	Integrity	Stress on joint
		Loss of performance	Flaw (Stone, scratch, …)	Reduce strength	-
	Polysulfide sealant (Sec. sealant)	Cracking	Process problem	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Stress on butyl sealant
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Stress on butyl sealant
			Cyclic stresses	Permeability (air&water)	Stress on butyl sealant
			Pollutants	Permeability (air&water)	Stress on butyl sealant
			Cleaning agents (Acid, base)	Permeability (air&water)	Stress on butyl sealant
			Temperature	Permeability (air&water)	Stress on butyl sealant
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Stress on butyl sealant
			Water absorption	Permeability (air&water)	Stress on butyl sealant
	Butyl sealant (Prim. sealant)	Cracking	Process problem	Permeability (air&water)	Failure of joint / Condensation
			Wind, shocks and T°C ... Action of frames	Permeability (air&water)	Failure of joint / Condensation
			Wind, shocks and T°C ... Action of glass	Permeability (air&water)	Failure of joint / Condensation
			Wind, shocks and T°C ... Action of spacer	Permeability (air&water)	Failure of joint / Condensation
			Thermal shocks (cleaning hot steam)	Permeability (air&water)	Failure of joint / Condensation
			Cyclic stresses	Permeability (air&water)	Failure of joint / Condensation
			UV radiation	Permeability (air&water)	Failure of joint / Condensation
			Temperature	Permeability (air&water)	Failure of joint / Condensation
			Polysulfide failure … Pollutants	Permeability (air&water)	Failure of joint / Condensation
			Polysulfide failure … Cleaning agents	Permeability (air&water)	Failure of joint / Condensation
			Polysulfide failure … Water absorption	Permeability (air&water)	Failure of joint / Condensation
	Composite spacer	Expansion	Temperature	Movements	Stress on joint
		Breaking	lysulfide failure …Water, pollutants or Acid/ba	Loss of material	Weak points (mechanical resistance)
				Loss of material	Dust
				Expansion	Stress on joint

	Glass/sealant or spacer/sealant interfaces	Breaking	Process problem Wind, shocks and T°C ... Action of frames Wind, shocks and T°C ... Action of glass Aluminium … Action of aluminium (T°C) Incompatibility of materials Temperature Pollutants Cleaning agents (Acid, base) UV Thermal shocks (cleaning hot steam)	Integrity Integrity Integrity Integrity Integrity Integrity Integrity Integrity Integrity Integrity	Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water) Permeability (air and water)
	Low-e coating				
	Dessicant	Loss of absorption ability	? (Temperature, time, …) Process problem (water absorption before manufacturing) Not enough amount used	Integrity	Increasing of humidity in cavity Increasing of humidity in cavity Increasing of humidity in cavity
Landscape vision	Glass (1&2)	Scratching	Cleaning method Collision or friction Accumulation of dirt	Bad vision Bad vision Bad vision	- - -
		Cracking	Resistance to environment	Bad vision	-
	Low-e coating				
	Air gap (Argon)	Condensation	Water and air permeability (joint) Dessicant … Condensation	Bad vision Bad vision	- -
		Dust deposit	Water and air permeability (joint) Corrosion aluminium … deposit	Bad vision Bad vision	- -
Light transmission	Idem landscape vision				
Thermal insulation	Glass	Decreasing of insulating property	Cracking (resistance to environment)	Bad thermal insulation	-
	Low-e coating				
	Air gap (Argon)	Decreasing of insulating property	Water and air permeability (joint)	Bad thermal insulation	-
Acoustical insulation	Glass	Decreasing of acoustic property	Cracking (resistance to environment)	Bad acoustic insulation	-
	Air gap (Argon)	Decreasing of acoustic property	Water and air permeability (joint)	Bad acoustic insulation	-

9. Case study: Solar panel

System analysis

Structural analysis

For this first step, we suggest a two-level structural decomposition:

- the first one gives a general description of solar panel,
- the second one gives more details and allow the representation of the specificities of each captor.

A solar collector is composed of 8 major elements:

- the glazing (generally coated),
- the absorber (generally coated) including the plate and the pipes,
- the insulation,
- the box,
- the frame of the glazing,
- the seal (between the glazing and its frame),
- external elements as connector, fixings …

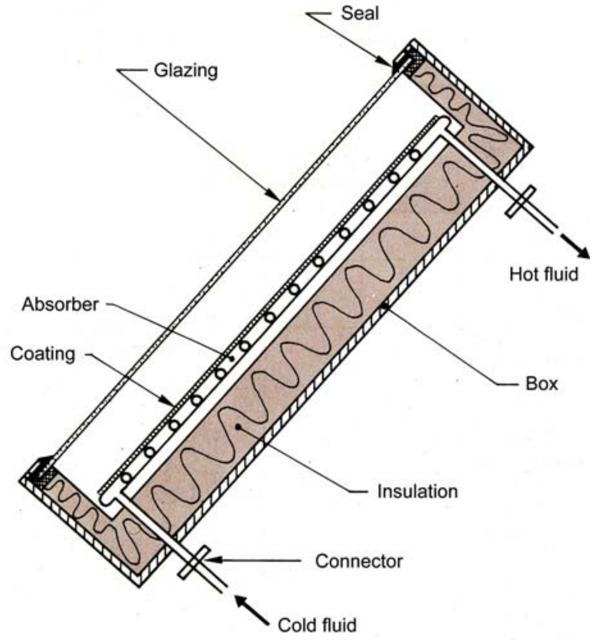


Figure 27: Solar collector section

Each of these elements presents specificities from a solar captor to another.

For instance, the absorber is made of:

- a plate on which is fixed a heating coil,
- a plate on which is fixed a set of parallel pipes, a general and collector,
- two stamped plates.

The junction between the glazing and the box is made of a frame fixed to the box by means of screwing, riveting, gluing … The seal between the glazing and the frame is also composed of various elements.

N°	**Components**		**Materials**
1	Glazing	Glass	Glass, Polymeric glazing
		Anti-reflective coating	
2	Absorber	Coating	
		Absorber	Metallic or organic materials
		Pipes	Metallic material (copper, …)
	Fixing (absorber on the box)		Metallic materials
3	Insulation		Glass wool
4	Box		Metallic or organic materials
5	Frames of the glazing		Metallic or organic materials
6	Seal (Glazing / Frame)		Rubber
7	Pipes		Metallic material
	Connector		Metallic material
	Evacuation (+filter)		
	Fixings on support		Metallic material

Figure 28: Structural analysis

Within the IEA T27 – Project C2 group, and to be consistent with B3 project, the following case study is defined.

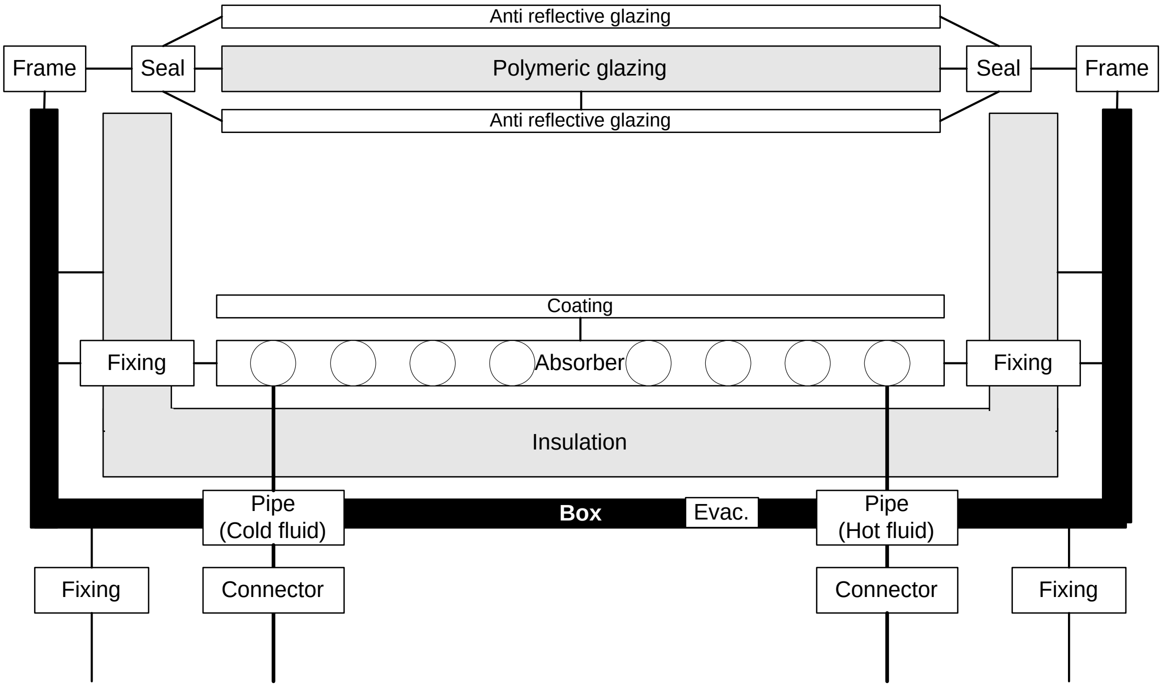


Figure 29: Structural diagram of selected solar collector

Components are not to scale

Environment

Three environments have to be defined:

- outdoor environment,
- inside environment (inside the box),
- heat-conveying fluid.

The first one is composed of all climatic stresses. We have identified the various climatic stresses and use conditions that can affect the solar panel.
It's not an exhaustive list of possible stresses. The only relevant stresses are listed in the table. The ones that are improbable (seismic stresses …) or that are known to have no or few influence on the considered materials have been removed.
Moreover, all the possible pollutants and cleaning agents are grouped under a generic term.

Outdoor	**Inside**	**Heat-conveying fluid**
UV radiation / Sun	Temperature (< or > 0°C)	Antigel
Temperature (< or > 0°C)	Air / Ozone / CO_2	Hot or cold fluid
Air / Ozone / CO_2		Stagnation temperature
Rain / Snow / Hail		
Pollutants		
Cleaning agents		
Wind		
Loads		
Shocks (hard and soft)		
Vegetals (sleeves…)		
Animals (Birds, insects, faeces…)		

Figure 30: environmental stresses and use conditions

Functional analysis

The major function of the solar collector is the production of heat from the solar energy.
It is divided in Energy collection (UV radiation to the absorber), Energy transformation (Heat to hot water) and Energy transport (Hot water circulation).
Two additional functions are required: Confinement and Structural resistance (which means resistant to physical, chemical or mechanical degradation). The later concerns all elements.

The Figure 31 lists the role of each element in this context.

	Energy collection	Energy transformation	Heat transport	Confinement	Resistance to environment
Glazing	X			X	X
Low emissive coating	X				X
Frames				X	X
Seals				X	X
Box				X	X
Fixing box / roof					X
Insulation	X				X
Absorber ("plate")		X			X
Absorber (selective coating)		X			X
Absorber (pipes)		X	X		X
Fixing absorber / box					X
Pipes			X		X
Connectors					X

Figure 31: Functional analysis

Failure Modes and Effect Analysis

Function	Components	Mode	Cause	Direct effect
Resistance to environment	Box	Corrosion	Humidity + pollution	
	Fixings (on roof)	Corrosion	Humidity + pollution	Ruin
	Seal	Cracking	UV + Temperature Pollutants or cleaning agents	Loss of watertightness
		Creep	Dimensional variations of box (T°C) Wind, shocks, …	Loss of watertightness
	Glazing	Scratching	Cleaning	Decreasing of transmission
		Cracking	Shocks	Loss of watertightness
	Low emissive coating	Loss of performance	UV Humidity + Pollutants, Cleaning agents	Decreasing in thermal efficiency
	Absorber (Selective coating)	Loss of efficiency	Corrosion Humidity + Pollutants, Cleaning agents Excessive heating	Blistering, unsticking
	Absorber ("Plate")	Corrosion	Humidity + Pollutants, Cleaning agents	
	Absorber (Heat-conveying pipes)	Dissociation (Bad contact)	Corrosion (humidity, pollutants) Expansion / contracting cycles Design / manufacturing problem	Decreasing in thermal efficiency
		Breaking	Damages due to freeze	Ruin
		Obstruction	Sludge due to corrosion Chemical incompatibility in hydraulic circuit Corrosive action of heat-conveying fluid	Decreasing of flow
		Flow problems	Decreasing - Air trapping Excessive - Controller	Decreasing in thermal efficiency
	Fixing absorber / box	Corrosion	Corrosion (Humidity + pollutants)	Loss of performance
		Rupture	Corrosion (Humidity + pollutants) Wear (dimensional variations of absorber)	Ruin
	Connectors	Leakage	Wear of seal Corrosion (Humidity + pollutants)	Loss of watertightness
	Pipes	Corrosion	Humidity + pollution	
		Breaking	Damages due to freeze	Ruin
		Obstruction	Sludge due to corrosion Chemical incompatibility in hydraulic circuit Corrosive action of heat-conveying fluid	Decreasing of flow
		Flow problems	Decreasing - Air trapping Excessive - Controler	Decreasing in thermal efficiency
	Insulation	Ageing	High temeratures Water	Binder "departure" Water absorption

Function	Components	Mode	Cause	Direct effect
Confinement	Glazing	Cracking	Shocks Differences in thermal expansion	Loss of watertightness
	Glazing / seals	Dissociation	Incompatibility seal and glazing Design / manufacturing problem Movements of glazing	Loss of watertightness
	Seals	Cracking	UV + Temperature Pollutants or cleaning agents	Loss of watertightness
		Creep	Dimensional variations of box (T°C) Wind, shocks, …	Loss of watertightness
	Seals / Box	Dissociation	Incompatibility seal and box Design / manufacturing problem Movements of box (temperature...)	Loss of watertightness
	Box	Corrosion	Humidity + pollution	Loss of watertightness
	Box / pipes	Dissociation	Corrosion Design / manufacturing problem Movements of pipes Movements of box (wind, temperature...) Movements of box (problem in fixings)	Loss of watertightness
Energy collection	Glazing	Scratching	Cleaning	Decreasing of transmission
		Cracking	Shocks	Decreasing of transmission
		Dirt	External deposit dust, vegetation, pollutants Internal deposit (condensation) Internal deposit (binder of insulation)	Decreasing of transmission
	Insulation	Loss of efficiency	Confinement problem … Water absorption Manufacturing problem	Output heat flow (through the box)
	Low emissive coating	Loss of efficiency	UV, temperature Confinement … Humidity, Pollutants, Cleaning agents	Output heat flow (through glazing)
Energy transformation	Coating	Loss of efficiency	Corrosion Confinement … Humidity + Pollutants, Cleaning agents Excessive heating	Loss of thermal efficiency
	Absorber	Corrosion	Confinement … Humidity, Pollutants, Cleaning agents	Decreasing in thermal efficiency
	Absorber / HC pipes	Dissociation (Bad contact)	Corrosion (humidity, pollutants) Expansion / contracting cycles (excessive temperature) Design / manufacturing problem	Decreasing in thermal efficiency
	Heat-conveying pipes	Breaking	Damages due to freeze	Ruin
		Obstruction	Sludge due to corrosion Chemical incompatibility in hydraulic circuit Corrosive action of heat-conveying fluid	Decreasing of flow
		Flow problems	Decreasing - Air trapping Excessive - Controller	Inefficiency of heat exchanges
Heat transport	Pipes	Breaking	Damages due to freeze	Ruin
		Obstruction	Sludge due to corrosion Chemical incompatibility in hydraulic circuit Corrosive action of heat-conveying fluid	Decreasing of flow
		Flow problems	Decreasing - Air trapping Excessive - Controller	Inefficiency of heat exchanges
	Connector	Leakage	Corrosion	Decreasing in thermal efficiency

10. Case study: Electrochromic/Gasochromic glazing

Refer to the SWIFT report

Contribution from the DOE project
"An Insulating Glass Knowledge Base"

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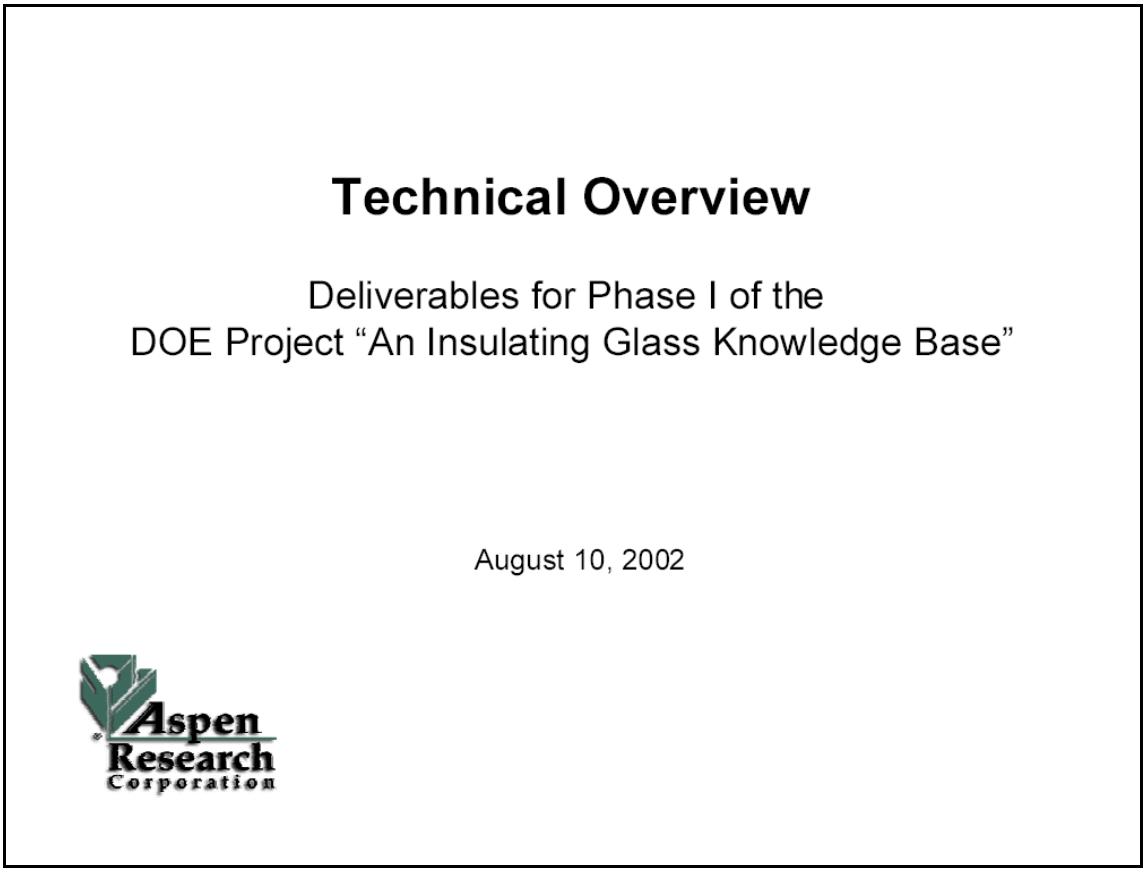
Deliverables for Phase I of the DOE project – An Insulating Glass Knowledge Base

2002



Technical Overview

Deliverables for Phase I of the
DOE Project “An Insulating Glass Knowledge Base”

August 10, 2002

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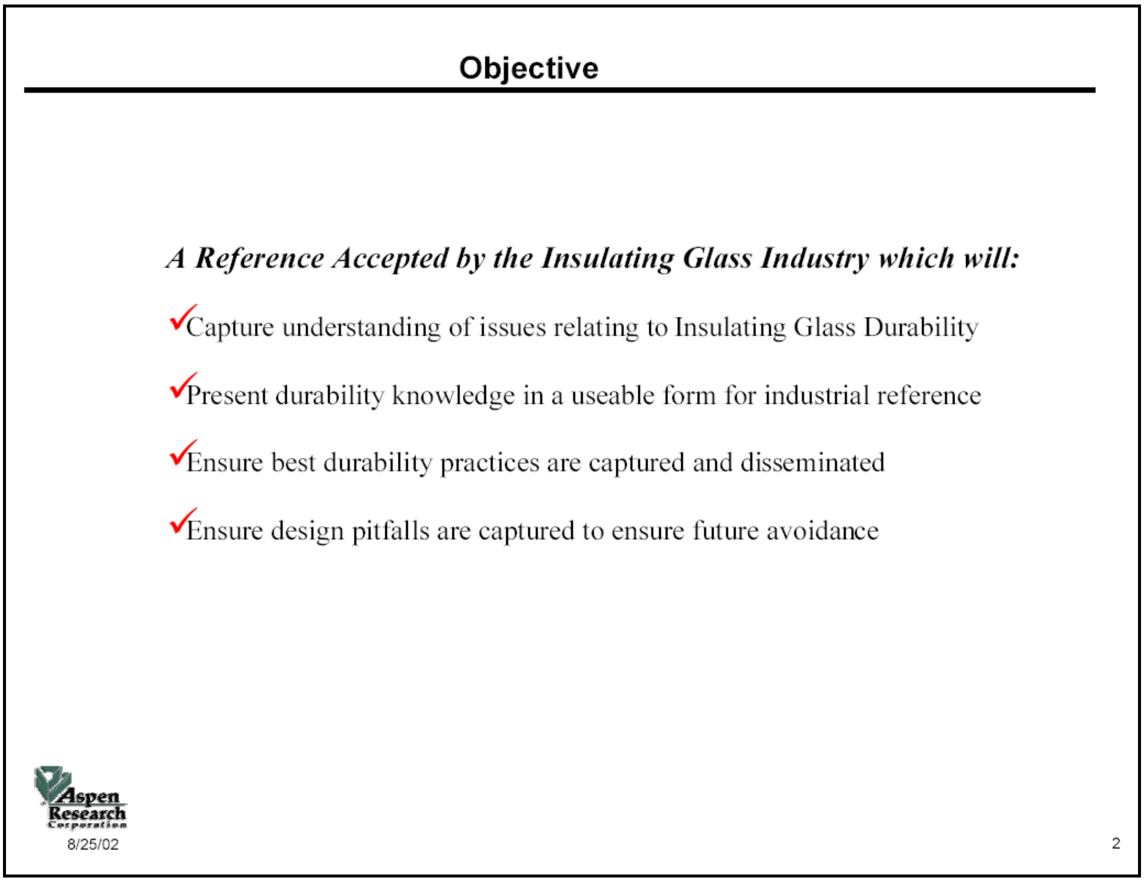

Objective

A Reference Accepted by the Insulating Glass Industry which will:

- ✓Capture understanding of issues relating to Insulating Glass Durability
- ✓Present durability knowledge in a useable form for industrial reference
- ✓Ensure best durability practices are captured and disseminated
- ✓Ensure design pitfalls are captured to ensure future avoidance

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A Two Year Phased Project

Phase 1/Year 1

- ➔Qualitative understanding of failure mechanisms
- ➔Top level durability assessment of specific spacer designs

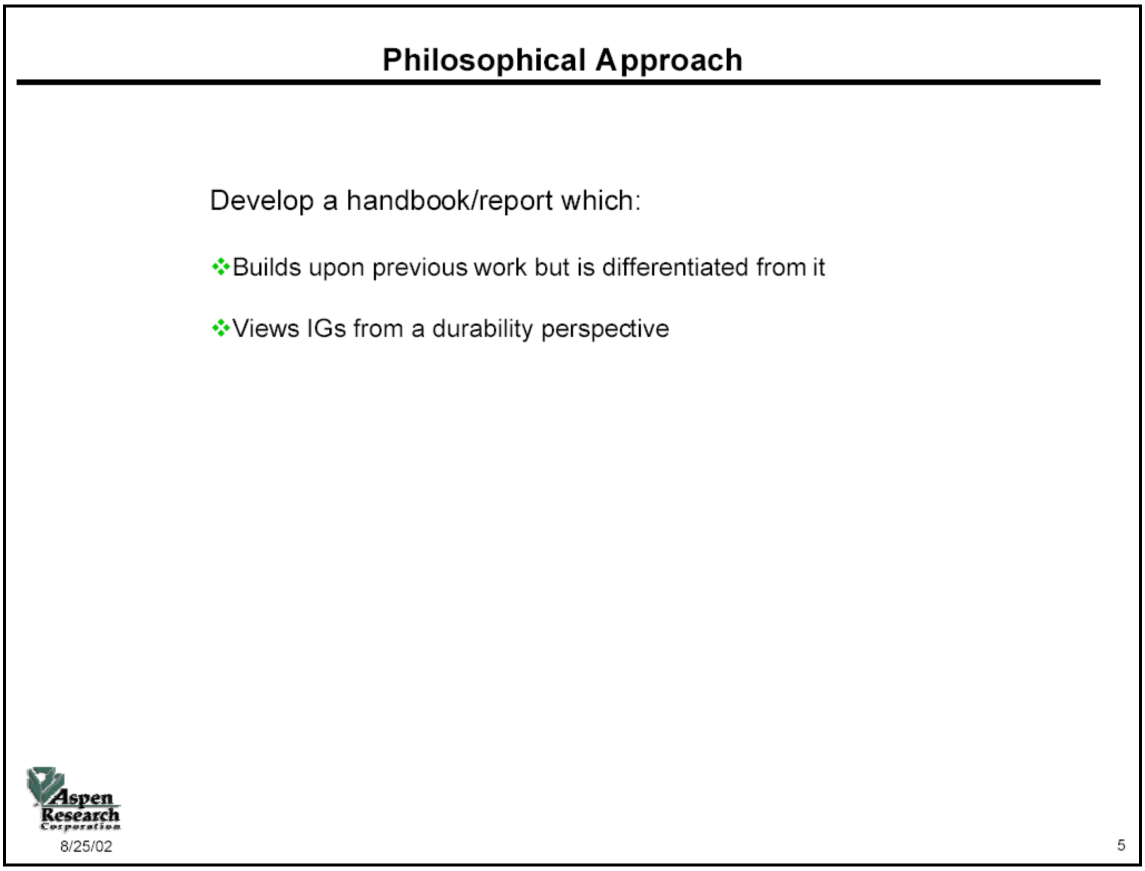
Phase 2/Year 2

- ➔Quantitative understanding of failure mechanisms
- ➔Durability Models based on mechanistic understanding
- ➔Development of accelerated test protocols

Philosophical Approach

Currently available knowledge regarding IG performance exists:

- ➢ Standard references
  - ✓Aamstock (Handbook of Glass in Construction)
  - ✓Carmody (Residential Windows Guide)
  - ✓Klosowski (Sealants in Construction)
- ➢ Publicly available manufacturer literature
- ➢ Related relevant literature
- ➢ Internal knowledge



Philosophical Approach

Develop a handbook/report which:

❖Builds upon previous work but is differentiated from it

❖Views IGs from a durability perspective

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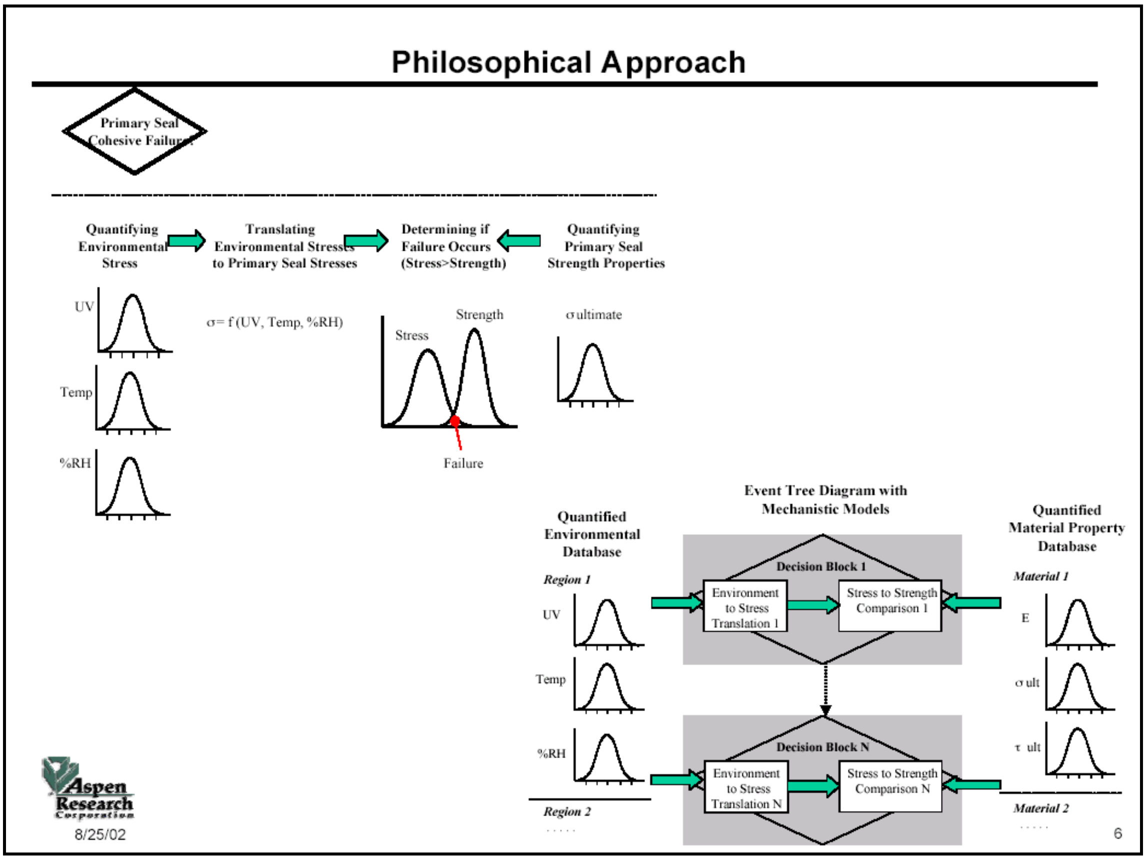

Philosophical Approach

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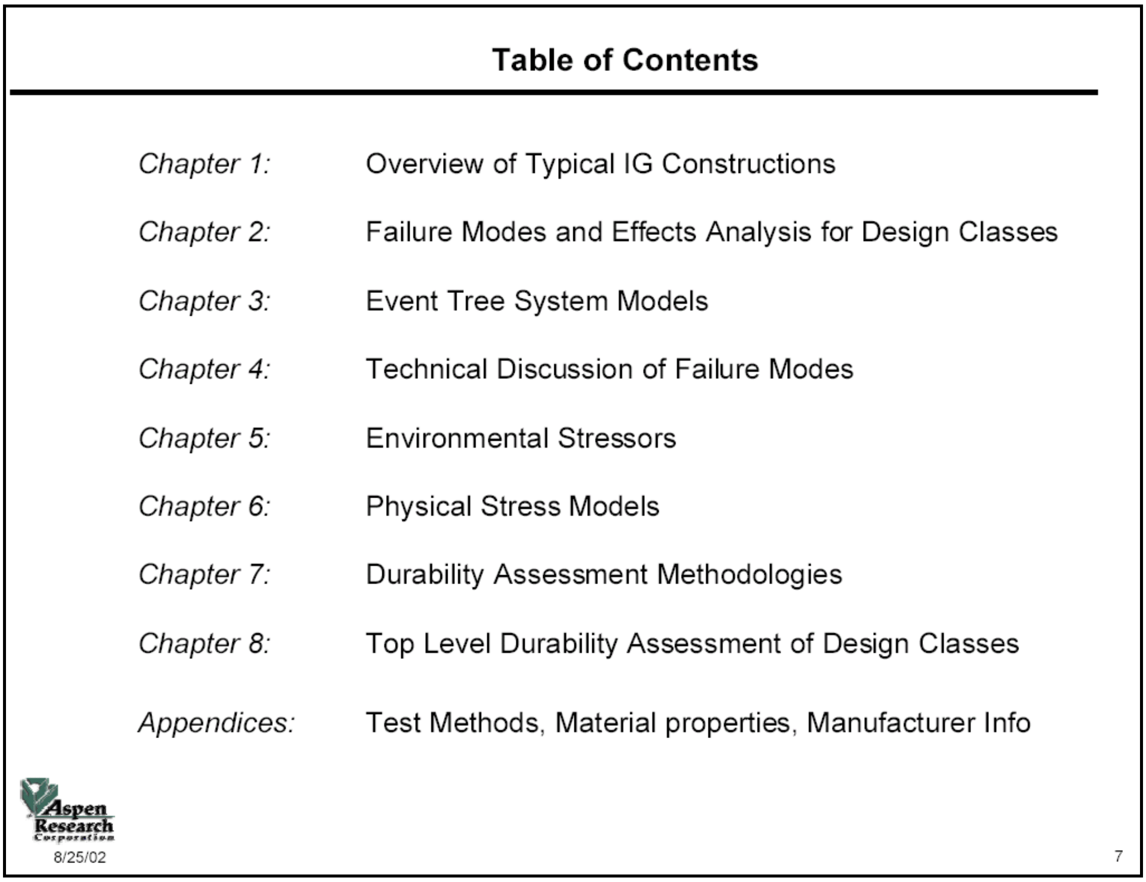
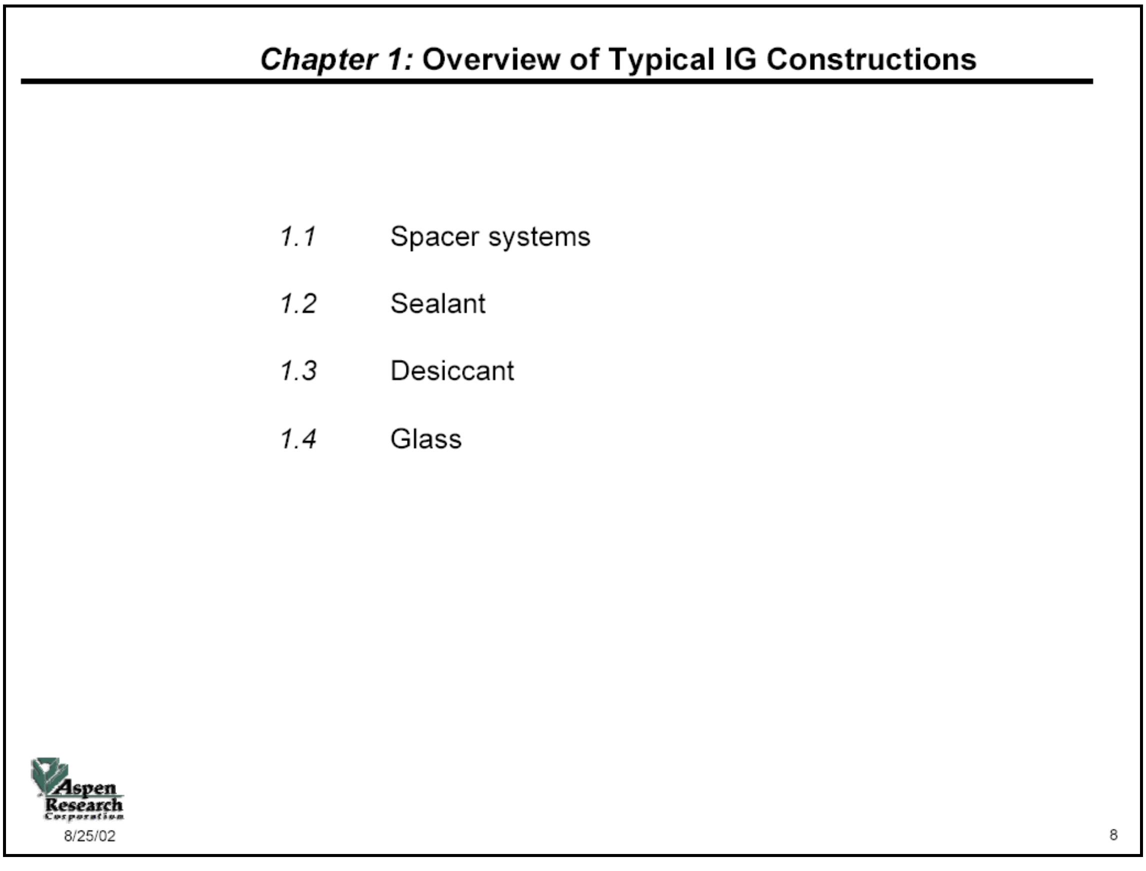


Table of Contents



Chapter 1: **Overview of Typical IG Constructions**

1.1 Spacer systems

1.2 Sealant

1.3 Desiccant

1.4 Glass

Chapter 1: Overview of Typical IG Constructions

1.1: Spacer System Overview

Functional requirements for a Durable IG Design

- Connect glass panes
- Maintain IG pane edge spacing
- Minimize water vapor transport
- Ensure dry interior
- Minimize gas permeability
- Optimize pane flexure
- Minimize thermal conductance

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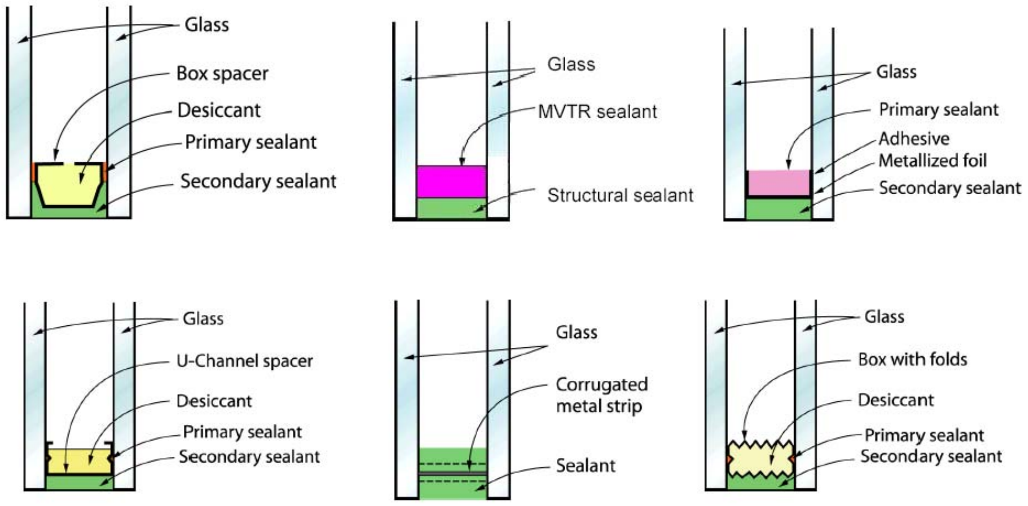
Chapter 1: Overview of Typical IG Constructions

1.1: Spacer System Overview

Design Classes



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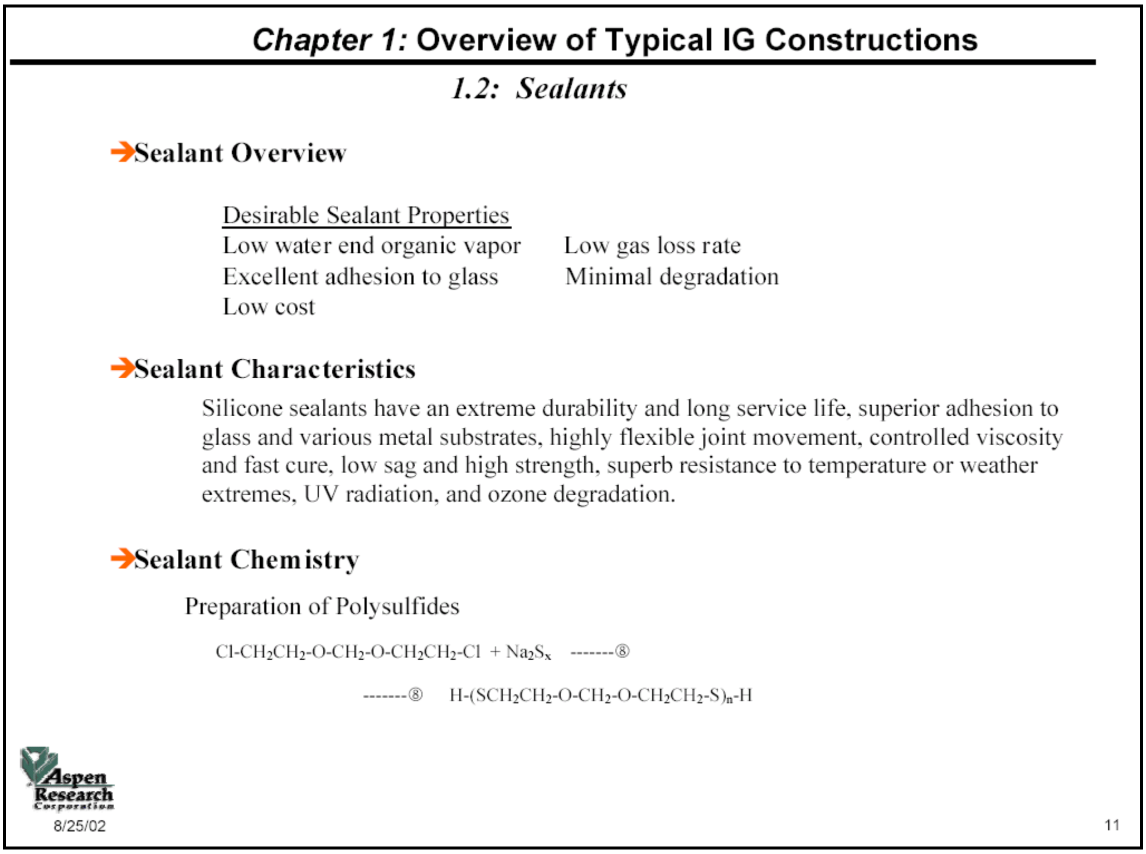

Chapter 1: Overview of Typical IG Constructions

1.2: Sealants

➔Sealant Overview

<u>Desirable Sealant Properties</u>

Low water end organic vapor	Low gas loss rate
Excellent adhesion to glass	Minimal degradation
Low cost	

➔Sealant Characteristics

Silicone sealants have an extreme durability and long service life, superior adhesion to glass and various metal substrates, highly flexible joint movement, controlled viscosity and fast cure, low sag and high strength, superb resistance to temperature or weather extremes, UV radiation, and ozone degradation.

➔Sealant Chemistry

Preparation of Polysulfides

$Cl\text{-}CH_2CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2CH_2\text{-}Cl + Na_2S_x$ -------®

-------® $H\text{-}(SCH_2CH_2\text{-}O\text{-}CH_2\text{-}O\text{-}CH_2CH_2\text{-}S)_n\text{-}H$

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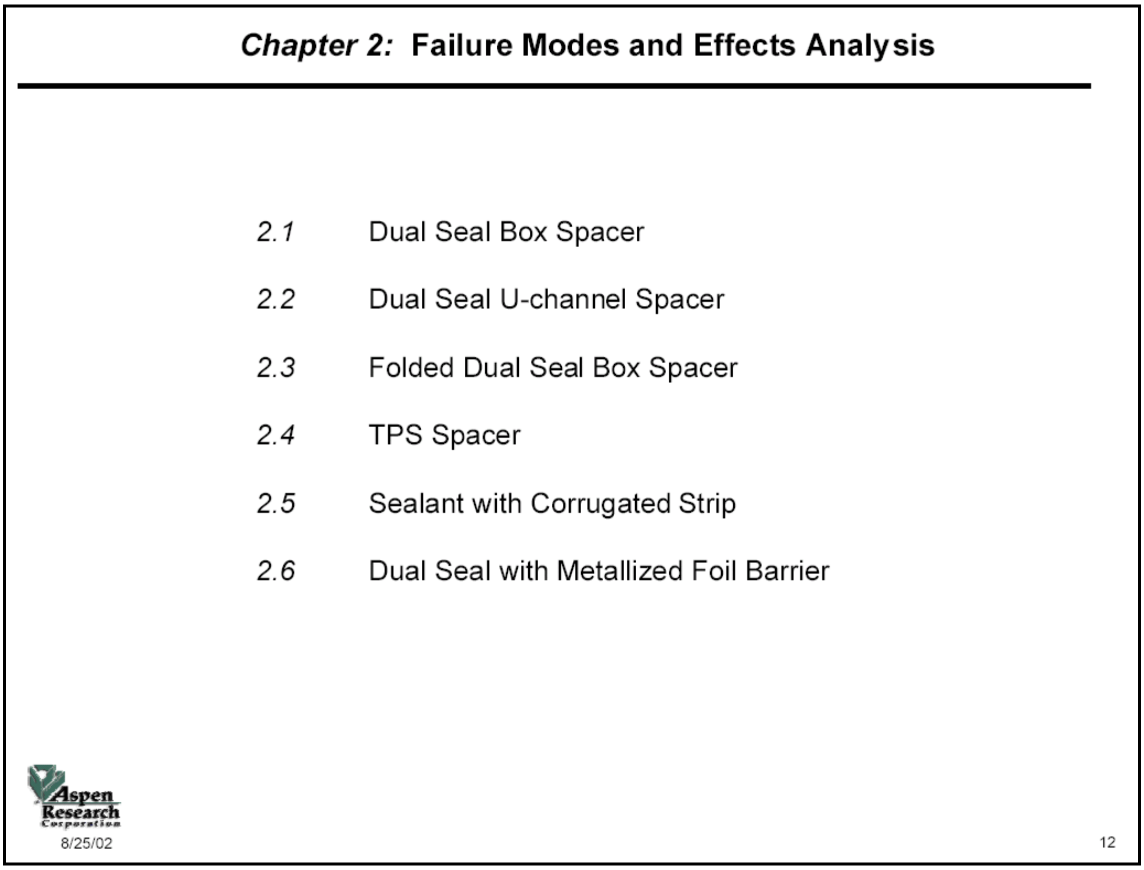

Chapter 2: Failure Modes and Effects Analysis

2.1	Dual Seal Box Spacer
2.2	Dual Seal U-channel Spacer
2.3	Folded Dual Seal Box Spacer
2.4	TPS Spacer
2.5	Sealant with Corrugated Strip
2.6	Dual Seal with Metallized Foil Barrier

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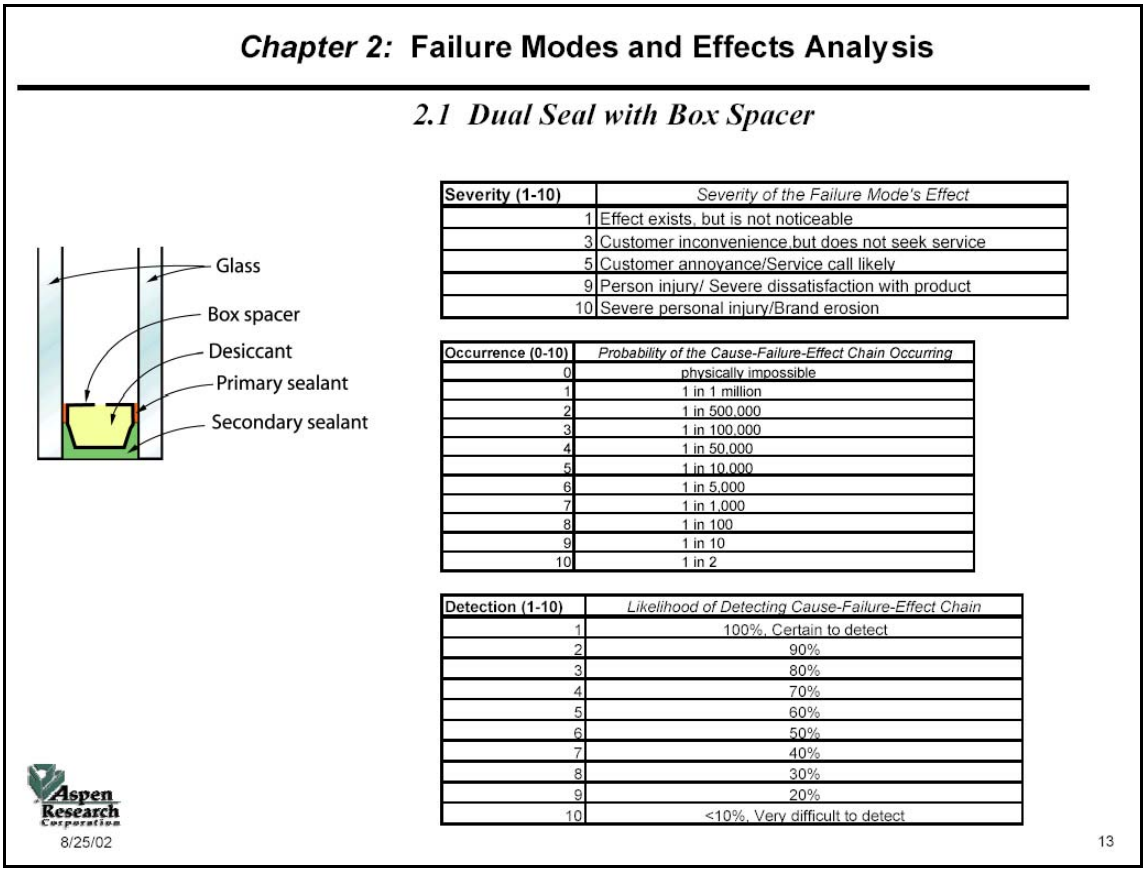

Chapter 2: Failure Modes and Effects Analysis

2.1 Dual Seal with Box Spacer

Severity (1-10)	*Severity of the Failure Mode's Effect*
1	Effect exists, but is not noticeable
3	Customer inconvenience,but does not seek service
5	Customer annoyance/Service call likely
9	Person injury/ Severe dissatisfaction with product
10	Severe personal injury/Brand erosion

Occurrence (0-10)	*Probability of the Cause-Failure-Effect Chain Occurring*
0	physically impossible
1	1 in 1 million
2	1 in 500,000
3	1 in 100,000
4	1 in 50,000
5	1 in 10,000
6	1 in 5,000
7	1 in 1,000
8	1 in 100
9	1 in 10
10	1 in 2

Detection (1-10)	*Likelihood of Detecting Cause-Failure-Effect Chain*
1	100%, Certain to detect
2	90%
3	80%
4	70%
5	60%
6	50%
7	40%
8	30%
9	20%
10	<10%, Very difficult to detect

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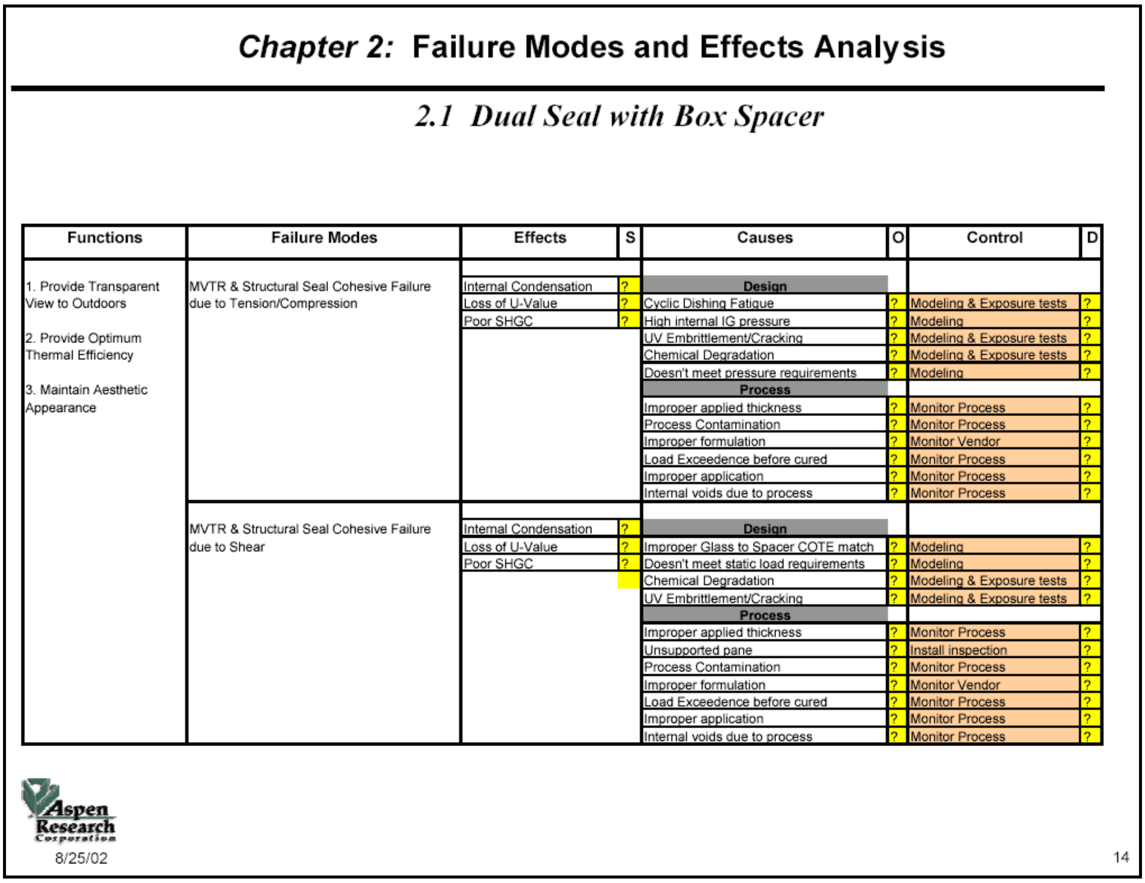

Chapter 2: Failure Modes and Effects Analysis

2.1 Dual Seal with Box Spacer

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors 2. Provide Optimum Thermal Efficiency 3. Maintain Aesthetic Appearance	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling & Exposure tests	?
		Poor SHGC	?	High internal IG pressure	?	Modeling	?
				UV Embrittlement/Cracking	?	Modeling & Exposure tests	?
				Chemical Degradation	?	Modeling & Exposure tests	?
				Doesn't meet pressure requirements	?	Modeling	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?
	MVTR & Structural Seal Cohesive Failure due to Shear	Internal Condensation	?	**Design**			
		Loss of U-Value	?	Improper Glass to Spacer COTE match	?	Modeling	?
		Poor SHGC	?	Doesn't meet static load requirements	?	Modeling	?
				Chemical Degradation	?	Modeling & Exposure tests	?
				UV Embrittlement/Cracking	?	Modeling & Exposure tests	?
				Process			
				Improper applied thickness	?	Monitor Process	?
				Unsupported pane	?	Install inspection	?
				Process Contamination	?	Monitor Process	?
				Improper formulation	?	Monitor Vendor	?
				Load Exceedence before cured	?	Monitor Process	?
				Improper application	?	Monitor Process	?
				Internal voids due to process	?	Monitor Process	?

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Chapter 3: Event Tree System Models

3.1 Dual Seal Box Spacer

3.2 Single Seal Box Spacer

3.3 Folded Dual Seal Box Spacer

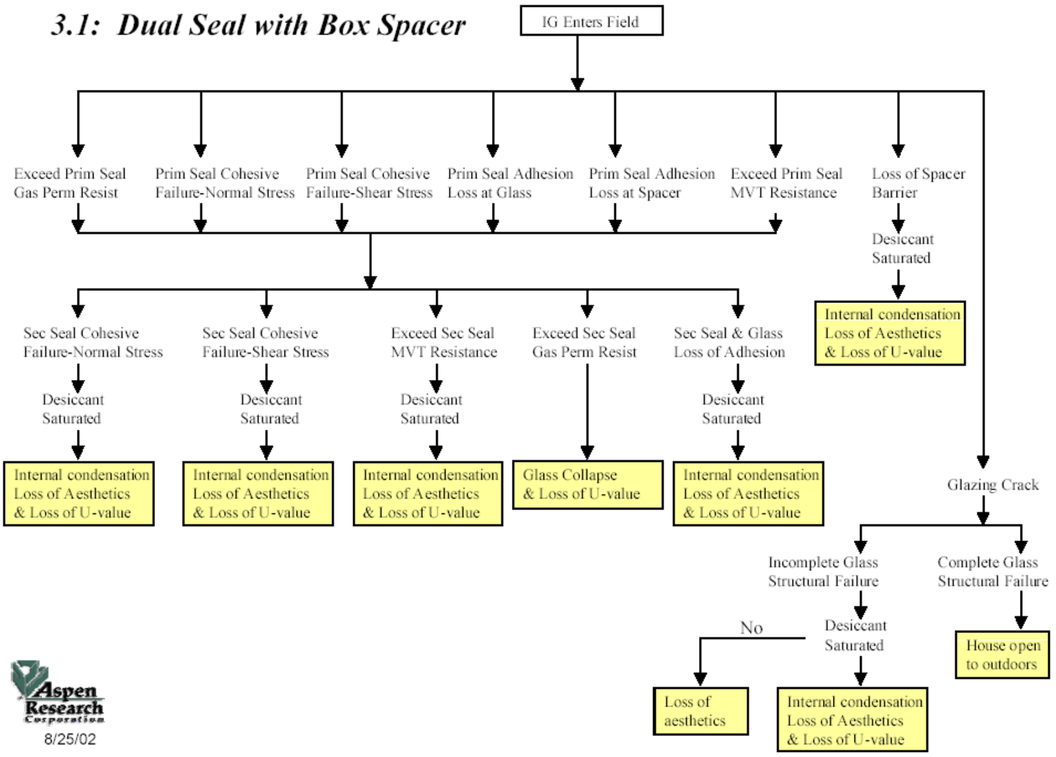
3.4 Dual Seal U-channel Spacer

3.5 Sealant with Corrugated Strip

3.6 Dual Seal with Metallized Foil Barrier

Chapter 3: Event Tree System Models

3.1: Dual Seal with Box Spacer



IG Enters Field

Exceed Prim Seal Gas Perm Resist

Prim Seal Cohesive Failure-Normal Stress

Prim Seal Cohesive Failure-Shear Stress

Prim Seal Adhesion Loss at Glass

Prim Seal Adhesion Loss at Spacer

Exceed Prim Seal MVT Resistance

Loss of Spacer Barrier

Desiccant Saturated

Internal condensation Loss of Aesthetics & Loss of U-value

Sec Seal Cohesive Failure-Normal Stress

Desiccant Saturated

Internal condensation Loss of Aesthetics & Loss of U-value

Sec Seal Cohesive Failure-Shear Stress

Desiccant Saturated

Internal condensation Loss of Aesthetics & Loss of U-value

Exceed Sec Seal MVT Resistance

Desiccant Saturated

Internal condensation Loss of Aesthetics & Loss of U-value

Exceed Sec Seal Gas Perm Resist

Glass Collapse & Loss of U-value

Sec Seal & Glass Loss of Adhesion

Desiccant Saturated

Internal condensation Loss of Aesthetics & Loss of U-value

Glazing Crack

Incomplete Glass Structural Failure

Desiccant Saturated

No

Loss of aesthetics

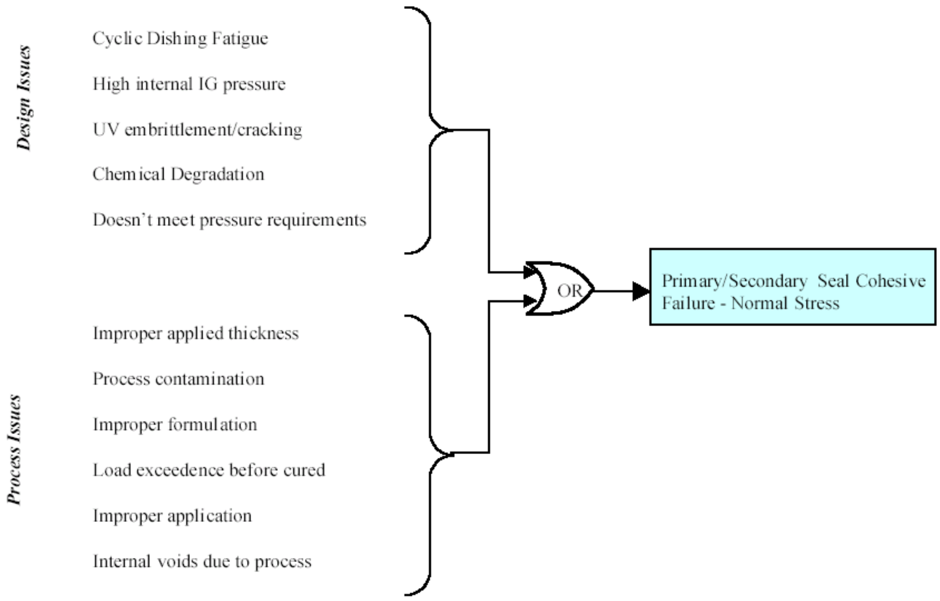
Internal condensation Loss of Aesthetics & Loss of U-value

Complete Glass Structural Failure

House open to outdoors

Chapter 3: Event Tree System Models

3.1: Dual Seal with Box Spacer



Design Issues

- Cyclic Dishing Fatigue
- High internal IG pressure
- UV embrittlement/cracking
- Chemical Degradation
- Doesn't meet pressure requirements

Process Issues

- Improper applied thickness
- Process contamination
- Improper formulation
- Load exceedence before cured
- Improper application
- Internal voids due to process

Primary/Secondary Seal Cohesive Failure - Normal Stress

Chapter 4: Technical Discussion of Failure Modes

4.1	Sealant Normal Stress Cohesive Failure
4.2	Sealant Shear Stress Cohesive Failure
4.3	Sealant Adhesive Failure
4.4	Glass Structural Failure
4.5	Excessive Moisture Vapor Transmission
4.6	Excessive Argon Loss

Chapter 4: Technical Discussion of Failure Modes

4.1: Sealant Normal Stress Cohesive Failure

Required Elements of Failure Mode Discussion Papers

- ➔Environmental Stress Quantification
- ➔Environmental to Physical Stress Translation
- ➔Physical Strength
- ➔The Failure Event
- ➔References

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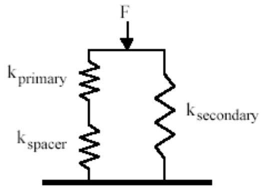
Chapter 4: Technical Discussion of Failure Modes

4.1: Sealant Normal Stress Cohesive Failure

Environmental to Physical Stress Translation



$$k = \frac{F}{\Delta t} = \frac{E \cdot A}{t} \qquad \sigma = E \cdot \varepsilon$$

$$\frac{F_{spacer\,\&\,primary}}{F} = \frac{k_{primary} \cdot k_{spacer}}{k_{primary} \cdot k_{spacer} + k_{primary} \cdot k_{\sec ondary} + k_{spacer} \cdot k_{\sec ondary}}$$

$$\frac{F_{\sec ondary}}{F} = \frac{k_{primary} \cdot k_{\sec ondary} + k_{spacer} \cdot k_{\sec ondary}}{k_{primary} \cdot k_{spacer} + k_{primary} \cdot k_{\sec ondary} + k_{spacer} \cdot k_{\sec ondary}}$$

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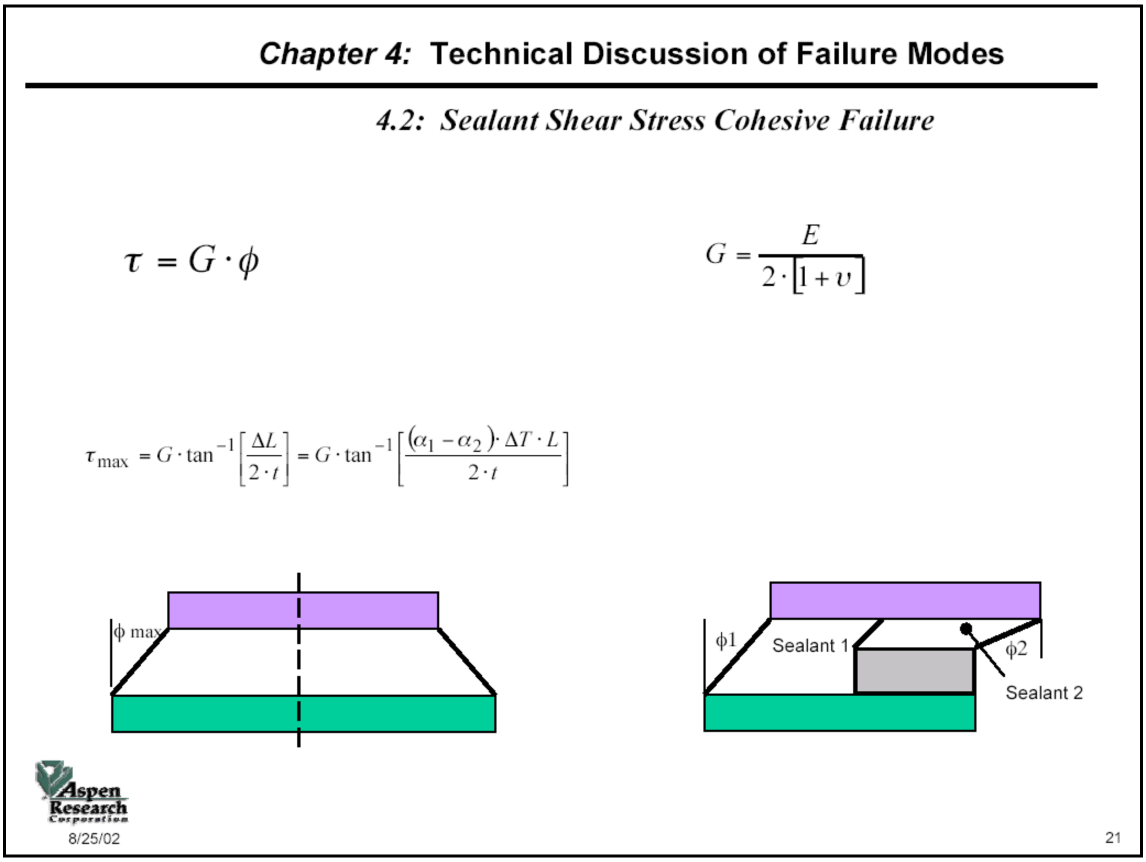

Chapter 4: Technical Discussion of Failure Modes

4.2: Sealant Shear Stress Cohesive Failure

$$\tau = G \cdot \phi$$

$$G = \frac{E}{2 \cdot [1 + \upsilon]}$$

$$\tau_{\max} = G \cdot \tan^{-1}\left[\frac{\Delta L}{2 \cdot t}\right] = G \cdot \tan^{-1}\left[\frac{(\alpha_1 - \alpha_2) \cdot \Delta T \cdot L}{2 \cdot t}\right]$$

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Chapter 5: Environmental Stressors

5.1 Environmental Stressor Matrix

5.2 Quantification of Relevant Environmental Stressors

5.3 Environmental Severity Index

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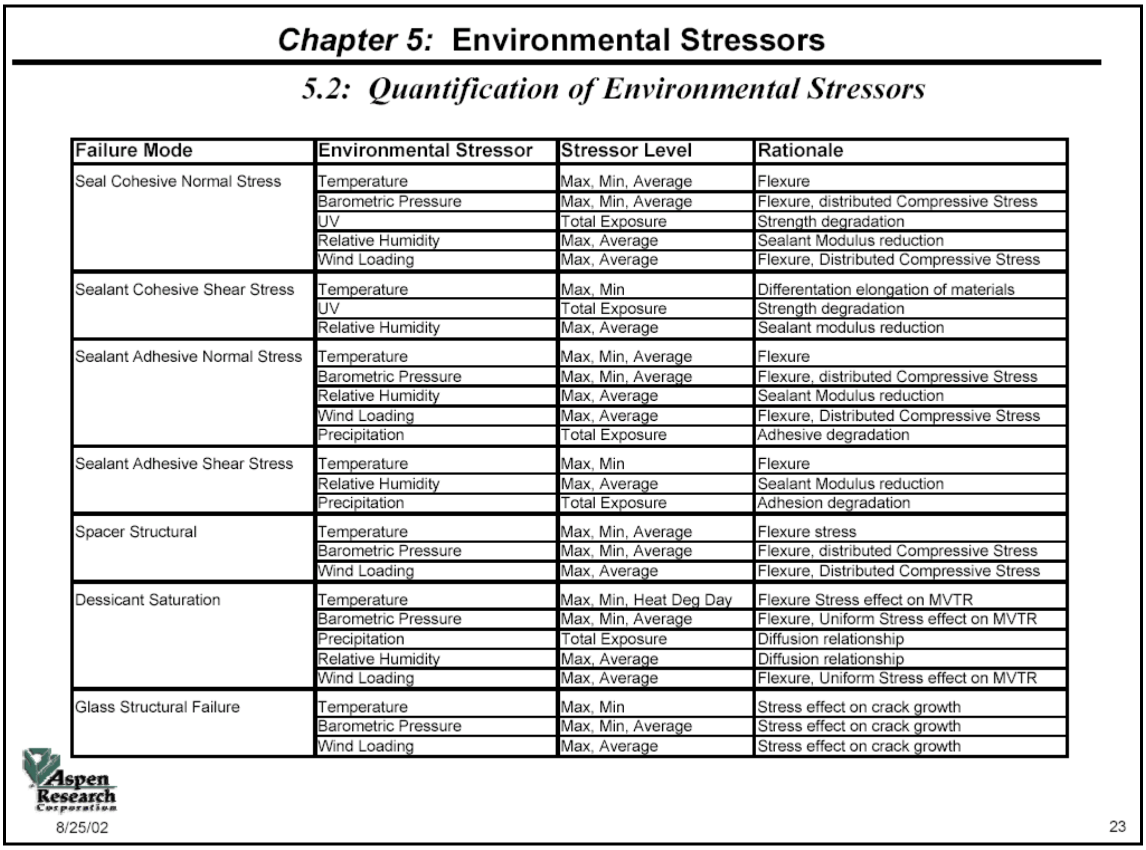

Chapter 5: Environmental Stressors

5.2: Quantification of Environmental Stressors

Failure Mode	Environmental Stressor	Stressor Level	Rationale
Seal Cohesive Normal Stress	Temperature	Max, Min, Average	Flexure
	Barometric Pressure	Max, Min, Average	Flexure, distributed Compressive Stress
	UV	Total Exposure	Strength degradation
	Relative Humidity	Max, Average	Sealant Modulus reduction
	Wind Loading	Max, Average	Flexure, Distributed Compressive Stress
Sealant Cohesive Shear Stress	Temperature	Max, Min	Differentation elongation of materials
	UV	Total Exposure	Strength degradation
	Relative Humidity	Max, Average	Sealant modulus reduction
Sealant Adhesive Normal Stress	Temperature	Max, Min, Average	Flexure
	Barometric Pressure	Max, Min, Average	Flexure, distributed Compressive Stress
	Relative Humidity	Max, Average	Sealant Modulus reduction
	Wind Loading	Max, Average	Flexure, Distributed Compressive Stress
	Precipitation	Total Exposure	Adhesive degradation
Sealant Adhesive Shear Stress	Temperature	Max, Min	Flexure
	Relative Humidity	Max, Average	Sealant Modulus reduction
	Precipitation	Total Exposure	Adhesion degradation
Spacer Structural	Temperature	Max, Min, Average	Flexure stress
	Barometric Pressure	Max, Min, Average	Flexure, distributed Compressive Stress
	Wind Loading	Max, Average	Flexure, Distributed Compressive Stress
Dessicant Saturation	Temperature	Max, Min, Heat Deg Day	Flexure Stress effect on MVTR
	Barometric Pressure	Max, Min, Average	Flexure, Uniform Stress effect on MVTR
	Precipitation	Total Exposure	Diffusion relationship
	Relative Humidity	Max, Average	Diffusion relationship
	Wind Loading	Max, Average	Flexure, Uniform Stress effect on MVTR
Glass Structural Failure	Temperature	Max, Min	Stress effect on crack growth
	Barometric Pressure	Max, Min, Average	Stress effect on crack growth
	Wind Loading	Max, Average	Stress effect on crack growth

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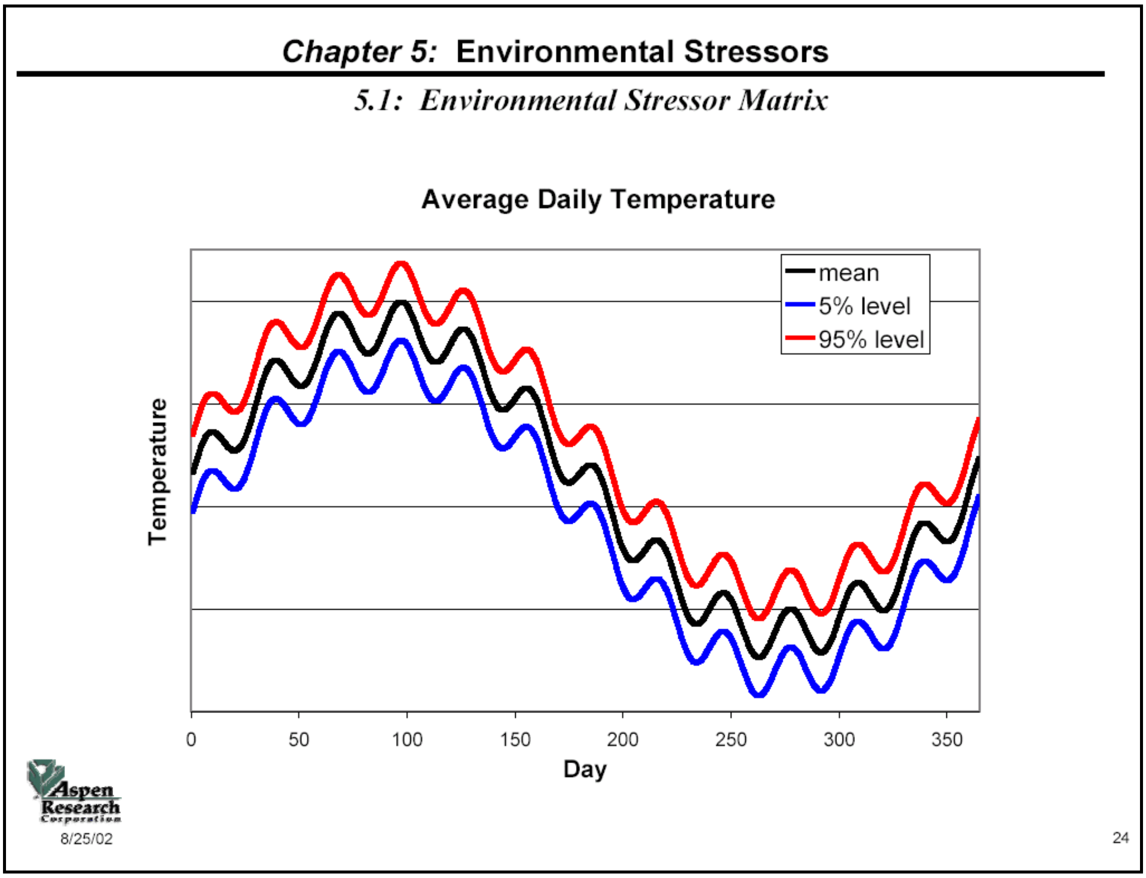

Chapter 5: Environmental Stressors

5.1: Environmental Stressor Matrix

Average Daily Temperature

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Chapter 6: Physical Stress Models

6.1	Internal Pressure as a function of Environment
6.2	Argon Loss
6.3	Moisture Vapor Transmission

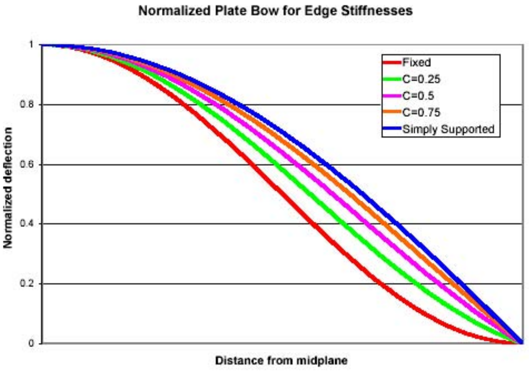
Chapter 6: Physical Stress Models

6.1: Internal Pressure as a function of Environment

$$\Delta V = \Delta P\left[\frac{8\cdot\alpha\cdot w^4}{Et^3}\right]\left[\frac{1}{\cos\left(\left(1+{}^{c}/_{2}\right)\pi\right)+\cos\left(\left({}^{c}/_{2}\right)\pi\right)}\right]^2\cdot$$

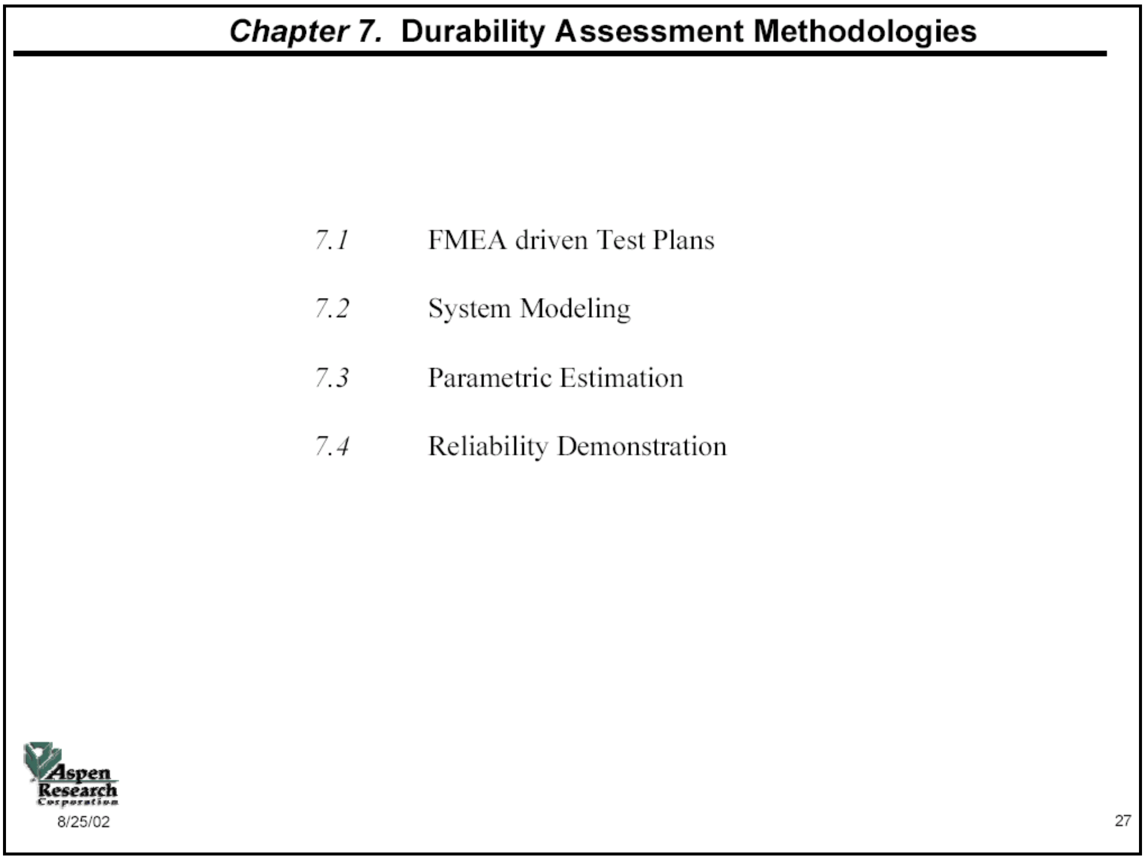
$$\left[\left(\frac{wL}{4}\right)\cos^2\left(\frac{\pi\cdot c}{2}\right)+\left(\frac{wL}{\pi(2-c)}\right)\cos\left(\frac{\pi c}{2}\right)\sin\left(\pi\left(1-{}^{c}/_{2}\right)\right)+\left(\frac{wL}{\pi^2(4-2c)}\right)\sin^2\left(\pi\left(1-{}^{c}/_{2}\right)\right)\right]$$

$$\Delta V_{normalstress}=\frac{\Delta P\cdot t\cdot L^2\cdot W^2}{E\cdot w\cdot\left(2\cdot L+2\cdot W\right)}$$



Iteratively Solve →

$$\boxed{\left[\Delta P+P_{assembly}\right]\left[\Delta V_{flexure}+\Delta V_{normalstress}+L\cdot W\cdot t_{airgap}\right]-\left[\frac{T_2\cdot P_{assembly}\cdot L\cdot W\cdot t_{airgap}}{T_{assembly}}\right]=0}$$



Chapter 7. Durability Assessment Methodologies

7.1 FMEA driven Test Plans

7.2 System Modeling

7.3 Parametric Estimation

7.4 Reliability Demonstration

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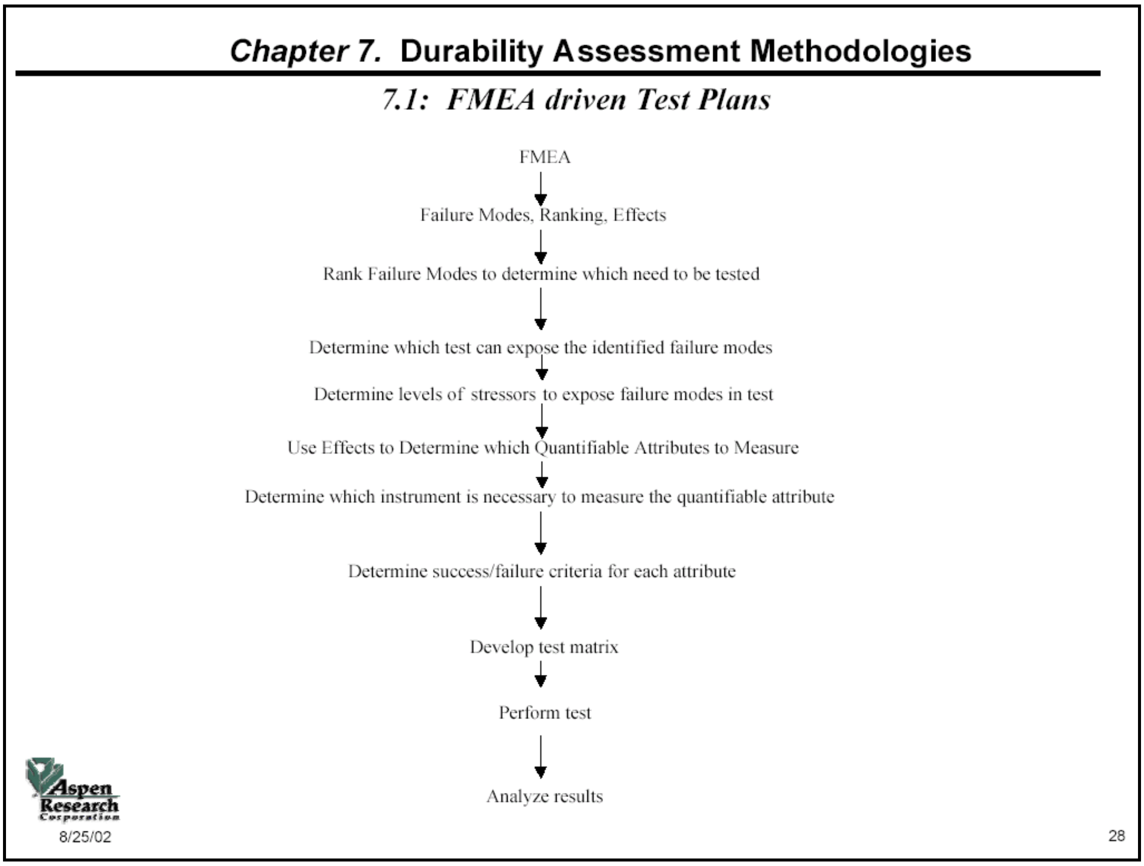

Chapter 7. Durability Assessment Methodologies

7.1: FMEA driven Test Plans

FMEA
↓
Failure Modes, Ranking, Effects
↓
Rank Failure Modes to determine which need to be tested
↓
Determine which test can expose the identified failure modes
↓
Determine levels of stressors to expose failure modes in test
↓
Use Effects to Determine which Quantifiable Attributes to Measure
↓
Determine which instrument is necessary to measure the quantifiable attribute
↓
Determine success/failure criteria for each attribute
↓
Develop test matrix
↓
Perform test
↓
Analyze results

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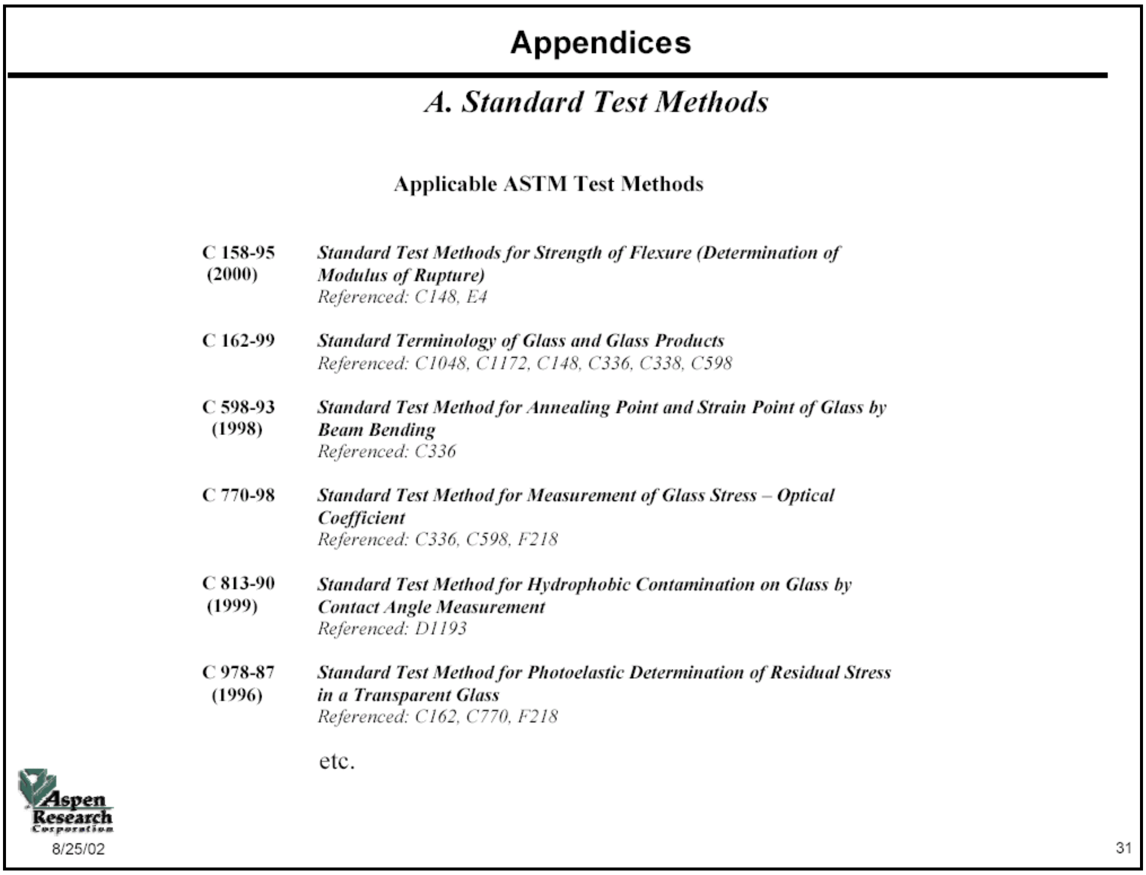
Chapter 8: Top Level Durability Assessment of Design Classes

8.1 Assessment of Dual Seal Box Spacer

8.x Assessment of other design classes as industry participation permits

Appendices

- Standard Test Methods
- Properties of Commonly Used Materials
- Public Domain Information from IG Manufacturers
- Etc.



Appendices

A. Standard Test Methods

Applicable ASTM Test Methods

C 158-95 (2000)	***Standard Test Methods for Strength of Flexure (Determination of Modulus of Rupture)*** *Referenced: C148, E4*
C 162-99	***Standard Terminology of Glass and Glass Products*** *Referenced: C1048, C1172, C148, C336, C338, C598*
C 598-93 (1998)	***Standard Test Method for Annealing Point and Strain Point of Glass by Beam Bending*** *Referenced: C336*
C 770-98	***Standard Test Method for Measurement of Glass Stress – Optical Coefficient*** *Referenced: C336, C598, F218*
C 813-90 (1999)	***Standard Test Method for Hydrophobic Contamination on Glass by Contact Angle Measurement*** *Referenced: D1193*
C 978-87 (1996)	***Standard Test Method for Photoelastic Determination of Residual Stress in a Transparent Glass*** *Referenced: C162, C770, F218*

etc.

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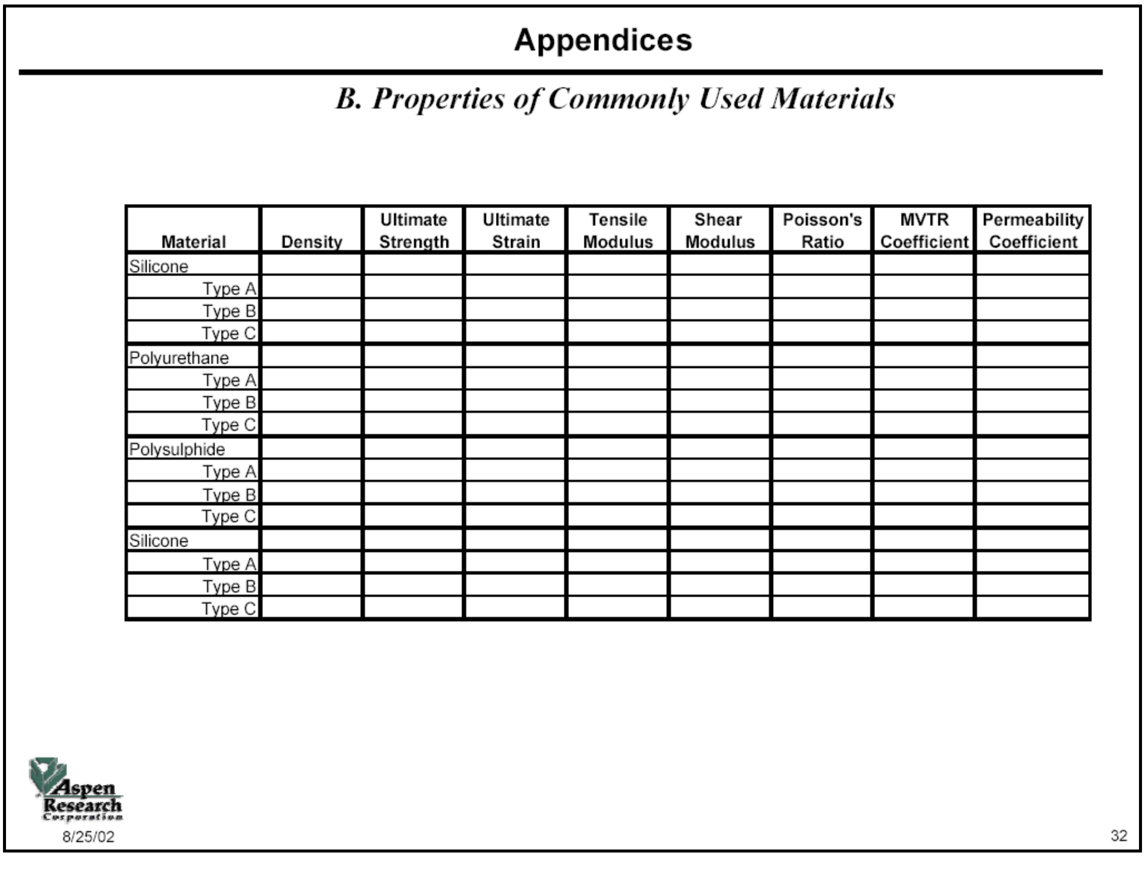

Appendices

B. Properties of Commonly Used Materials

Material	Density	Ultimate Strength	Ultimate Strain	Tensile Modulus	Shear Modulus	Poisson's Ratio	MVTR Coefficient	Permeability Coefficient
Silicone								
Type A								
Type B								
Type C								
Polyurethane								
Type A								
Type B								
Type C								
Polysulphide								
Type A								
Type B								
Type C								
Silicone								
Type A								
Type B								
Type C								

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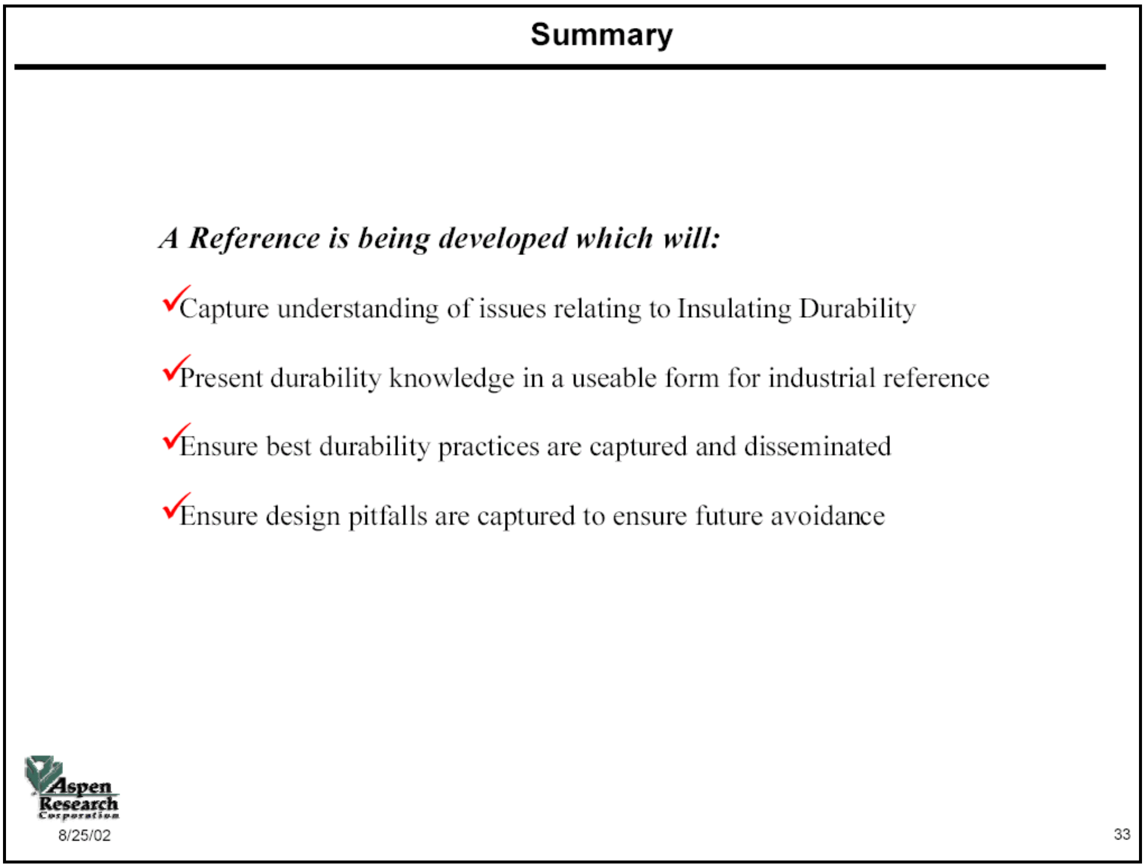

Summary

A Reference is being developed which will:

✓Capture understanding of issues relating to Insulating Durability

✓Present durability knowledge in a useable form for industrial reference

✓Ensure best durability practices are captured and disseminated

✓Ensure design pitfalls are captured to ensure future avoidance

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Contribution from the CIB W 80 / RILEM 175 – SLM Service Life Methodologies – Prediction of Service Life for Buildings and Components

J. Lair

Failure Modes Effects and Criticality Analysis – A Tool for Risk Analysis (Design) and Maintenance Planning Exploitation)

2003

CIB W 80 / RILEM 175
SLM: Service Life Methodologies
Prediction of Service Life for Buildings and Components

FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS
A Tool for Risk Analysis (Design) and Maintenance Planning (Exploitation)

Jérôme LAIR – CSTB (France)

15-02-2003

le futur en construction

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FAILURE MODES EFFECTS AND CRITICALITY ANALYSIS
A Tool for Risk Analysis (Design) and Maintenance Planning (Exploitation)

Contents

1. Scope

Used from the 1960s in the aeronautical and car industries, FMEA is a convenient tool for the safety studies of industrial systems. FMEA is intended for the verification of the product ability to satisfy client's needs (reliability, maintenability, disposability, safety). Commonly used in these industrial domains, it targets and checks weak points before mass-production in order to define preventive measures.

We wanted to apply a similar approach for building products. With adaptations due to building specificities, CSTB has developed a "risk assessment" approach, in order to know why he has failed or how he will fail. Identify and assess risks, foresee the consequences and possibly propose solutions, are the goals of such study.
This methodology has then been applied to several building products.

The proposed approach is composed of two main steps:
- the analysis of the system (including structural, functional and process analysis),
- the search of failure modes.

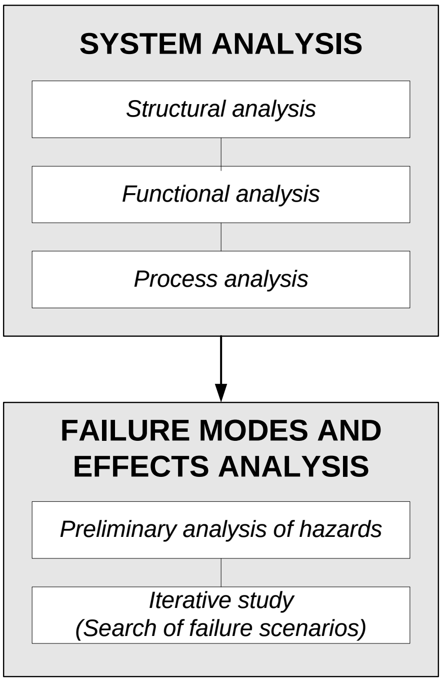


Figure 1: Approach

2. System analysis

The proposed approach relies, on one hand, on the precise description of the system, the identification of its functions and the definition of its environment.
On the other hand, we also consider the building process of the product (design, manufacturing, transport, storage, setting up …).

A double glazing unit case study illustrates each step of the approach.

2.1 Structural analysis

This first step consists in identifying all the components, their characteristics as well as the environment in which they could be located in.
The structure of the studied product is described with:

- morphology (geometrical shape, dimensions …),
- topology of relations with other objects,
- physico-chemical composition of its constitutive elements and their own description.

Example:

Figure 2 represents a double glazing unit (left part) and its structural representation (right part).

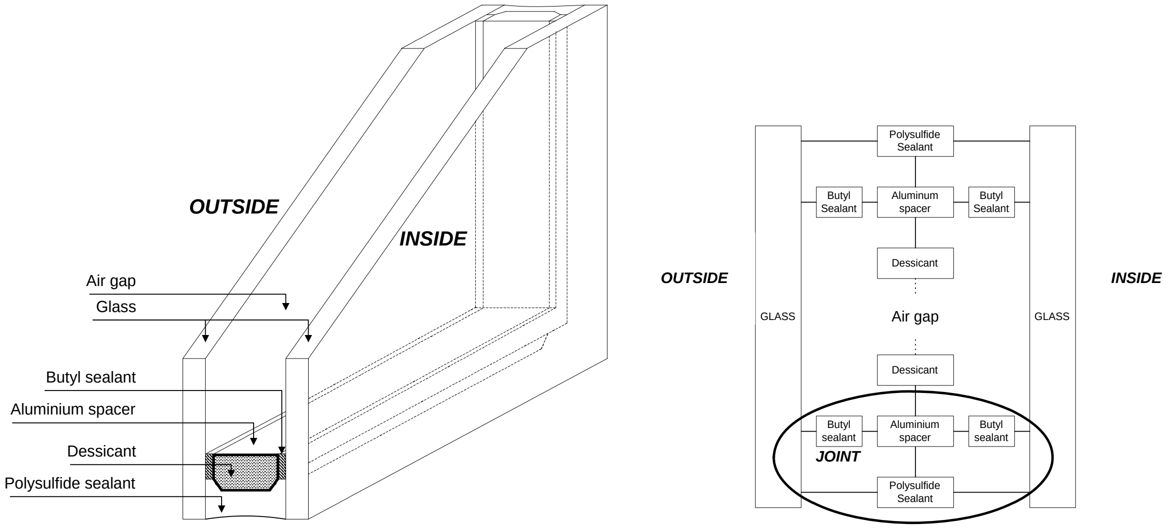


Figure 2: Structural analysis

OUTSIDE	**INSIDE**
Water (rain, snow)	Water (condensation)
UV and solar radiations	
High or low temperatures	High or low temperatures
Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …
Cleaning agents	Cleaning agents
Hot vapour	Hot vapour
Dust	Dust
Shocks	Shocks
Wind stresses	
Action of frames	
Movements of wall	

Figure 3: Stresses

Note:
Combined environmental stresses (successive or concomitant stresses) should be taken into account:

- water AND low temperature is Freezing,
- high temperatures AND Rain fall is Thermal shocks,
- …

2.2 Functional analysis

This second step consists in identifying all the functions of the product and its components (role of each component in the global functioning):

- either needs as regards the user (The product is designed to fulfil user's needs, these needs are expressed in terms of functions: thermal insulation, …),
- either functions stemming from constructive choice (seals to prevent water entry in a glazing unit).

For building domain, "The product fulfils a function" could be generally expressed as "The building product transforms climatic factors". For envelope products, it acts as a filter between two environments, filtering heat flows between outdoor and indoor environments (thermal insulation), stopping water from outdoor (watertightness of a roofing system), …

But, these same climatic factors can have an impact on its constitutive elements and could involve: modification of the materials properties, degradation and even failure…

Example:

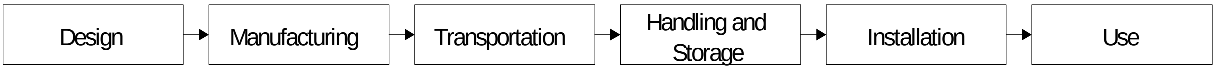
Function		Elements
Needs	Landscape vision	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Transparency)
	Light transmission	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Transparency)
	Thermal insulation	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Emptiness)
	Acoustical insulation	Glass $^{(1)}$ + Air gap + Glass $^{(2)}$ (Emptiness)
Technical functions	Water resistance of joint	Joint
	Resistance to environment	Glass + Butyl sealant + Polysulfide sealant + Glass/sealant interface + spacer/sealant interface
	Water absorption	Desiccant

Figure 4: Functional analysis

2.3 *Process analysis*

This third step consists in identifying the various steps of the construction process. On the contrary of a classical approach (we first define the specifications of the product in order that it fulfils the functions for which it was designed, and then check if the manufacturing process leads in reaching the defined specifications), we will first define the characteristics of the product according to the workmanship process (manufacturing and setting up stages) and then identify the product ability to fulfil the functions for which it was designed, given the workmanship quality.

Example:



1 – Design Nature and rigidity of frames *2 – Manufacturing* Squareness and rigidity Planeness Quality of joint (Water and air permeability) Adhesion (surface quality, cleanness) Materials (Butyl, Polysulfide) Desiccant quality and quantity Quality of desiccated air Oil fingerprints	*3 – Transportation* Deformations Degradation of joint *4 – Handling and Storage* Deformations Degradation of joint *5 – Installation* Plumb and level Blocking Problems in adhesion (joint breaking window/wall)

Figure 5: Process analysis

2.4 *Conclusion*

With structural functional and process analysis, we know why and how the product works (functions ensured by the product, and elements involved in the "success" of each function). With FMEA, we will now identify why and how he could fail in fulfilling the functions.

3. Failure modes and effects analysis

FMEA consists in the identification of all failure modes for each function, the search for causes, and finally the identification of effects. We want to imagine, forecast and write the potential futures of the product.

The novelty of the approach concerns the search of causes and effects. The behaviour towards solicitations of an element, its degradation or failure can change the environment of neighbouring elements. For example, the cracking of the seal of a double glazing unit under UV and temperature stresses could involve stresses in generally protected elements (low-emissive layer towards humidity or pollutants).
We propose to search direct effects (influence of the degradation or failure on the considered element) as well as indirect effects (influence on other elements or on system)

The principle of the failure modes analysis is a multi-step approach, which leads to the following table (Figure 6).

Functions	Elements	Modes	Causes	Direct effects	Indirect effects

Figure 6: FMEA blank grid

3.1 Step 1: Preliminary analysis

Thanks to structural and functional analysis, the first two columns are filled.

Functions	**Elements**	**Modes**	**Causes**	**Direct effects**	**Indirect effects**
Landscape vision	Extern. glass				
	Air gap				
	Intern. glass				
Resistance to environment	Glass				
	Polysulfide sealant				
	Butyl sealant				
	…				

Figure 7: Step 1

Once filled these columns, we have to search modes and causes.
Three types of causes could then be identified:
① classical cause as the action of an environmental agent on an element,
② an unexpected behaviour due to the building process,
③ the influence of the behaviour of a neighbouring element on the considered element.
The type 1 causes are deducted from the following table which draws up the potential initial stresses for each element.

		External glass	Air gap	Polysulfide sealant	Butyl sealant	Aluminium spacer	Dessicant	Internal glass
OUTSIDE	Water (rain, snow)	x		x				
	UV and solar radiations	x	x			x		x
	High or low temperatures	x	x	x	x	x	x	x
	Air and pollutants: O_2, CO_2, CO, Ozone, NO_x, SO_x, HCl, …	x		x				
	Cleaning agents	x		x				
	Hot vapour	x		x				
	Dust	x		x				
	Shocks	x						
	Wind stresses	x	x	x	x	x	x	x
	Action of frames	x	x	x	x	x	x	x
	Movements of wall	x	x	x	x	x	x	x
INSIDE	Water (condensation)							x
	High or low temperatures	x	x	x	x	x	x	x
	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …			x				x
	Cleaning agents			x				x
	Hot vapour			x				x
	Dust			x				x
	Shocks							x

Figure 8: Step 1 – Initial stresses condition.

The type 2 causes are stated by experts. They include potential defects, negligence, errors due to materials (quality, homogeneity of concrete), mean (inefficient mixing or vibrating of concrete), method (surface cleanness…), middle (temperature, humidity for concrete casting), and manpower. Then, direct effects as well as indirect effects are identified.

Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	Extern. glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap				
	Intern. glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature	Permeability	-
	…				

Figure 9: Step 1 – FMEA table (Extract)

This leads to the updating of environmental stresses conditions.

		External glass	Air gap	Polysulfide sealant	Butyl sealant	Aluminium spacer	Dessicant	Internal glass
OUTSIDE	Water (rain, snow)	x		x	**x**			
	UV and solar radiations	x	x			x		x
	High or low temperatures	x	x	x	x	x	x	x
	Air and pollutants: O$_2$, CO$_2$, CO, Ozone, NO$_x$, SO$_x$, HCl, …	x		x	**x**			
	Cleaning agents	x		x	**x**			
	Hot vapour	x		x				
	Dust	x		x	**x**			
	Shocks	x						
	Wind stresses	x	x	x	x	x	x	x
	Action of frames	x	x	x	x	x	x	x
	Movements of wall	x	x	x	x	x	x	x
INSIDE	Water (condensation)				**x**			x
	High or low temperatures	x	x	x	x	x	x	x
	Air and pollutants: O2, CO2, CO, Ozone, NOx, SOx, HCl, …			x	**x**			x
	Cleaning agents			x	**x**			x
	Hot vapour			x				x
	Dust			x	**x**			x
	Shocks							x

Figure 10: Step 1 – Updated stresses condition

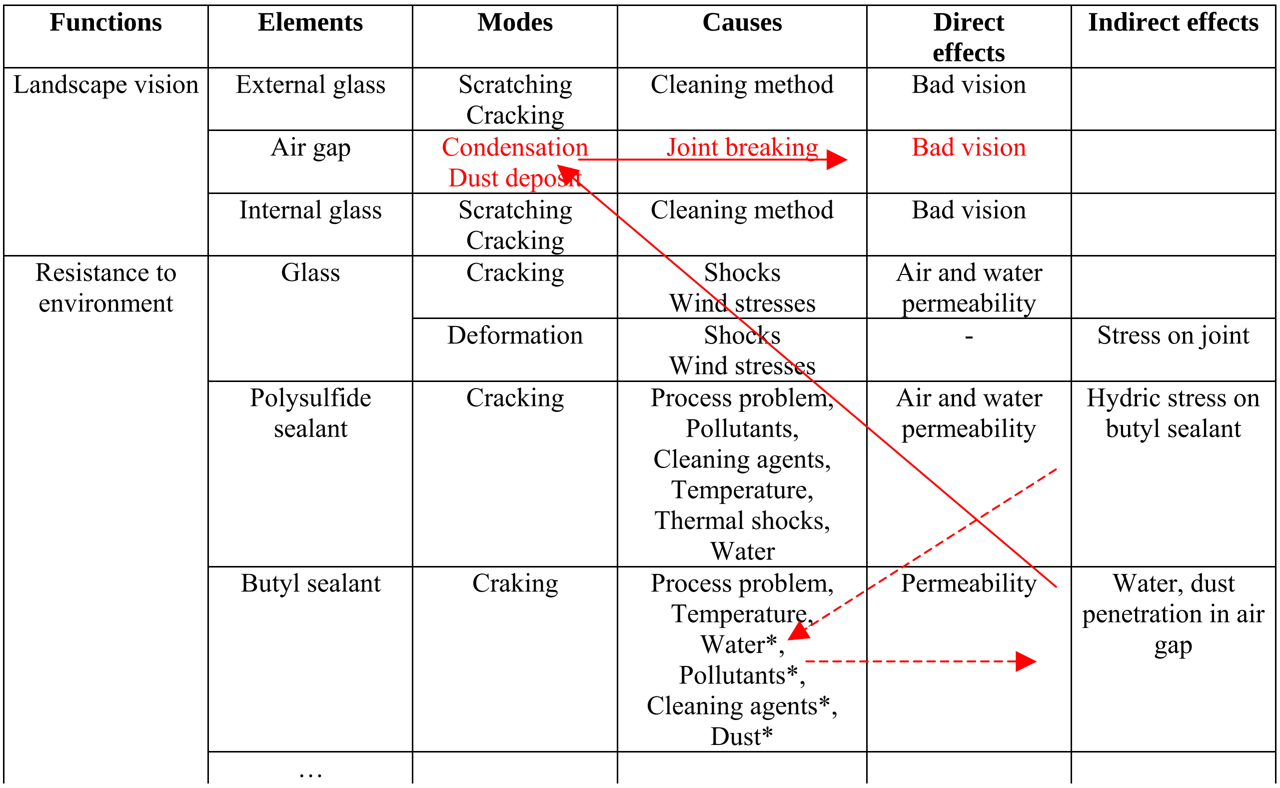
3.2 Step 2: Iterative study (search of the failure scenarios)

With the updated environmental stresses condition table and the column indirect effect, new failures (modes, causes and the consequences) are identified.

Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	External glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap				
	Internal glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature, Water*, Pollutants*, Cleaning agents*, Dust*	Permeability	Water, dust penetration in air gap
	…				

Figure 11: Step 2 – FMEA table (Extract)

And so on …



Functions	Elements	Modes	Causes	Direct effects	Indirect effects
Landscape vision	External glass	Scratching Cracking	Cleaning method	Bad vision	
	Air gap	Condensation Dust deposit	Joint breaking	Bad vision	
	Internal glass	Scratching Cracking	Cleaning method	Bad vision	
Resistance to environment	Glass	Cracking	Shocks Wind stresses	Air and water permeability	
		Deformation	Shocks Wind stresses	-	Stress on joint
	Polysulfide sealant	Cracking	Process problem, Pollutants, Cleaning agents, Temperature, Thermal shocks, Water	Air and water permeability	Hydric stress on butyl sealant
	Butyl sealant	Craking	Process problem, Temperature, Water*, Pollutants*, Cleaning agents*, Dust*	Permeability	Water, dust penetration in air gap
	…				

Figure 12: Step 3 – FMEA table (Extract)

4. Interest and perspectives

Though it is seldom used in construction, FMEA is a promising method that could be used efficiently in our context. It gives guidelines to improve the reliability and the quality of innovative products:

- FMEA is a familiar tool (modelling expert reasoning),
- FMEA is a useful tool first for experience and know-how gathering, second because it allows a rigorous and exhaustive analysis of product behaviour.
- FMEA is used in order to identify and rank potential failure modes (thanks to criticality analysis), to determine their causes and effects, and thus to suggest relevant test procedure to characterise their durability.
- FMEA is a polyvalent tool that could be used at the different stages in the product life: Design and installation (risk analysis and maintenance planning) and use (maintenance planning or failure diagnosis).

This last item is further developed in the next chapter (Figure 13 and explanations).

A FMEA analysis is generally supplemented with a criticality analysis (FMECA).
It consists in assessing, based on some criteria (occurrence probability, detectability, financial and human consequences gravity…) a criticality indicator for all identified failure modes.
The ranking or selection of failure modes is then possible. It directly influences the choice of the needed actions intended to increase the reliability and safety of the studied systems.

Construction process stage		**Results**	**Objectives**
Design Installation	**1 - Risk analysis**	*Improve quality and reliability from design stage by*: - identifying problems, - giving priorities.	Identification of weak points of the product (characterised by a level of criticality)
	2 - Quality management	*Improve the construction procedures (transport, storage, setting up) and use by:* - identifying problems, - giving a check-list of key steps (scale of priority).	Identification of critical operations (Installation, use) or critical elements leading frequently to degradation and failure.
Use	**3 - Preventive maintenance**	*Improve* ***proactive*** *maintenance procedures by:* - identifying problems, - giving priorities, - proposing solutions to maintenance.	- Forecasting of potential behaviours in time. - Assessment of the criticality of possible consequences.
	4 – Conditional maintenance	*Improve* ***reactive*** *maintenance procedures by:* - identifying problems, - giving priorities, - proposing solutions to maintenance or repair.	- Identification of symptoms, warning signs of failure (condition assessment, diagnosis of degradation) - Forecasting of future behaviours (given actual state). - Assessment of the criticality of possible consequences.
	5 - Corrective maintenance	*Improve* ***corrective*** *procedures by:* - explaining failures, - proposing solutions to repair.	Identification of failure causes from the observed failure (diagnosis of failure).

Figure 13: Objectives

1 – Risk analysis

This tool is intended to help industrial partners, to contribute to innovation.
A successful experience with an industrialist was conducted on an innovative cladding system. Two potential failure modes were detected and solved.

Even if the failure modes are uncertain, it is worth pointing out the fact that the product could fail in use. We then analyse its behaviour more accurately using a traditional procedure (artificial testing, natural ageing, etc).
Based on the FMEA study, we know that: "Such materials will be stressed by UV"
By means of traditional methods for durability characterisation, we try to know whether "the product is designed to withstand such stresses?"

2 – Quality management

FMEA is used as a tool allowing experience and knowledge to be capitalised (as well as the production of information) concerning the frequent defects, errors, negligence occurring during the construction process, expressed in checklists.
For the following three maintenance strategies, other considerations have to be taken into account. For example, the degradation could be accepted because of high maintenance costs.

3 – Preventive maintenance

FMEA produces information concerning the key elements, i.e. elements on which the good working of the product depends (top elements in the failure tree).
This justifies the updating of existing lists of maintenance operations.

Example:

Product/element	Operation
Heavy added protection in a flat roofing system	Limited thickness No vegetation
Draining pipes in a wooden window	Preventing water accumulation (rotting of wood pieces)
…	…

Figure 14: Preventive maintenance

4 – Conditional maintenance

FMEA is particularly useful for degradation and failure modes with symptoms (warning signs).
With a condition assessment of the building and the products (surveying only the critical elements, guided by FMEA results), we identify symptoms, search for causes and propose relevant cure (maintenance or repair solutions).
We are thus able to prevent costly and/or hazardous failures by identifying warning signs.

Example:

Symptoms	Cause	Solution
Water accumulation on a roofing system	Obstruction of draining pipes because of bad maintenance	Cleaning of the draining pipes
Degradation (cracking) of seals in a window	Climatic factors	Change of seals
…	…	…

Figure 15: Conditional maintenance

5 – Corrective maintenance (repair)

FMEA is used to explain a degradation and a failure, i.e. to identify the top event and the different events leading to failure, in order to propose relevant repair solutions instead of temporary solutions (searching top event).

Example:

Failure	Scenario / Top event	Solution
Air permeability of a window	1 - Defect in hinges adjustment 2 - Wear of seals 3 - Air permeability	Hinges adjustment
Humidity on the wall paper	1 - Water evacuation out of order 2 - Condensation and accumulation of water 3 - Streaming down on the wall	Cleaning out the holes for evacuation Changing the wall paper
…	…	…

Figure 16: Corrective maintenance

5. Conclusion

5.1 Applications

This method has been successfully applied to several products:

- in a certification context within CSTB (supporting the experts in the selection of ageing tests for the assessment of the durability of products),
- in European R&D projects and international working groups.

Applications on solar panel, roofing system, innovative cladding system (made within CSTB), a double glazing unit and the influence of the frames, an Argon filled Low emissive coating glazing (International Energy Agency Task 27), electrochromic and gasochromic glazing (SWIFT project results, soon available) have been conducted.

5.2 Perspectives

A Ph-D study started in CSTB on this subject (Starting date: November 2002).
We already have obtained a graphical representation of all the potential behaviours of the product (by means of causal graphs).

Several additional improvements are targeted:

- the use of databases to capitalise the knowledge and experience on degradation phenomena (input of the method) and the identified failure modes (output of the method),
- a clear definition of the links between the scales (building, product, material),
- introduction of a more accurate description of the degradation phenomena (continuous scale of degradation instead of the binary vision Functioning/Not functioning),
- the elaboration of a software in order to simplify and automate the procedure.

6. References

ISDF *AMDEC - Analyse des Modes de Défaillances, de leurs Effets et de leur Criticité* - Guide pédagogique, Ed.: ISDF - Institut de la Sûreté de Fonctionnement, 36 pages.

ISO TC59/SC14 (1998) *Buildings and constructed assets – Service life planning*. ISO/DIS 15686.

Lair, J. Chevalier, J.L. Rilling, J. (2001). *Operational methods for implementing durability in service planning frameworks.* CIB World Building Congress, April 2001, Wellington, New-Zealand.

Lair, J. Le Téno, J.F. Boissier, D. (1999). *Durability assessment of building systems.* Durability of Building Materials & Components 8, Vancouver, Ed : NRC - CNRC.

Lair, J. Chevalier J-L (2002). *Failure Mode Effect and Criticality Analysis for risk analysis (design) and maintenance planning (exploitation).* 9th Durability of Building Materials and Components (9th DBMC) Brisbane, Australia – 17/21 Mars 2002.

Le Brigand, S. (1998). "*1996-1997, photographie de la sinistralité.*" In CSTB Magazine n°119 (Nov. 98): pp 34-37.

Leroy, A. and Signoret, J. (1992). *Le risque technologique*. Paris. Ed.: Presses Universitaires de France. Que sais-je ? n° 2669. 128 pages.

Modarres, M. (1993). What every engineer should know about reliability and risk analysis. New York. Ed.: Dekker. 350 pages.

Sjöström, C. Jernberg, P. Frohnsdorff, G. (2001). *Interoperational methods for implementing durability in service planning frameworks.* CIB World Building Congress, April 2001, Wellington, New-Zealand.

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