IEA SHC Task 27: Failure Mode Effect and Criticality Analysis
Application to windows and solar components

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Introduction

This paper is composed of two main parts:

1. The use of Failure Modes and Effects Analysis within IEA T27 – Project C2 is firstly presented (Jérôme LAIR). This part includes a description of the methodology (and the needed adaptations to take into account the building products' specificities), as well as some applications to window and solar components.

2. The "An Insulating Glass Knowledge Base" project led by Aspen Research Corporation and supported by The US Department of Energy is then presented (Richard Hage). It includes the joint use of FMEA and Event Tree methodologies on Insulated Glazing, and deeply presents an expert approach for criticality analysis.

These two similar approaches found their basement in different origins.

CSTB firstly searched how to assess the durability of building products and proposed a general methodology based on FMEA methodology (subjected to some improvements to take into account building specificities) and applies it to glazing and windows in the framework of IEA T27. ARC firstly searched how to assess the durability of Insulated Glazing in the framework of "An Insulating Glass Knowledge Base" and suggests the use of FMEA and Event tree in order to capitalise and document the available knowledge.

This paper is then dedicated to present both approaches.

Part 1: Failure Mode Effect and Criticality Analysis
Application to windows and solar components (IEA T27 – Project C2)

Introduction

Non-quality or poor quality problems in the building domain, the part of maintenance and operating stages in the cost of a building, as well as the new aim "Sustainable Development[1]" (natural resources preservation, energy saving, etc), led us to work out methods and tools for durability assessment.

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[1] "A development which answers the needs of the present generation without compromising the ability of future generations to answer theirs" (Charlot-Valdieu et al., 1999).

Methodology

FMEA has been used since the sixties in the aeronautic and car industry and is thus an efficient tool for the safety and risk analysis of these systems (Leroy, 1992). It is intended to check the ability of a system and its parts to meet user's needs and either is generally used during the design stage in order to target and examine weak points, before mass production (Modarres, 1993). It allows us to identify the potential future behaviours (success or failure) of construction products.

It leads to an exhaustive list of all failure modes, i.e. problems that might occur:
- at each stage in the construction process (design, manufacturing, installation, transportation, storage, etc),
- in service (influence on the product's performance, degradation or failure of one of the product's constituent materials/components constitutive material/element).

In the following paragraphs, each step in the methodology will be presented and illustrated with basic examples.

Structural Analysis

The principle of this study is to build an accurate description of the product:
- by dividing it into elements and by identifying the constituent materials,
- by identifying the environmental stresses.

From the product, we search for elements and materials.

This analysis allows us to describe the structure of the product being studied. The following are identified (Baloche et al. 1999):
- morphology (geometrical shape, dimensions, etc),
- topology of relations with other objects (contacts, fixing, …),
- physico-chemical composition of its constituent elements and their own description.

As an example, the following graph is a representation of a double glazing unit (left part of Figure 1), and its corresponding structural diagram (right part of Figure 1).
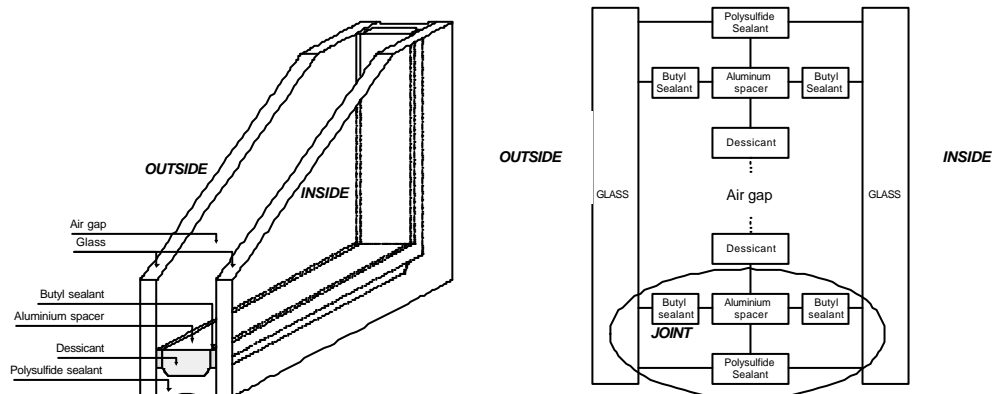

Figure 1   Section of a double glazing unit and structural representation

Outdoor and indoor environments have then to be defined. They are composed of all potential climatic and use factors that correspond to the environment in which the product will be in service (Figure 2).

Outdoor	Indoor
Temperature (high or low)	Temperature
Mechanical stresses and shocks	Mechanical stresses and shocks
Rain, snow, hail, ice	Vapour
Sun, UV radiation	Indoor pollutants, cleaning agents …
Wind	…
Pollutants, Cleaning agents …	
Vegetation, Moss, lichen, etc	
…	

Figure 2   Climatic and use factors

A list of common climatic factors is defined in order to help the user (database of generic factors encountered in the construction domain). Some specific factors have to be defined according to the use (chemical products in some industries, etc).

Functional Analysis

A product meets users' needs. The functional analysis of the needs expresses these needs in terms of functions.

As an example, a double glazing unit should ensure two functions (amongst various others):
- thermal insulation (against temperature gradient),
- watertightness (against rain, snow, hail, vapour,…).

In addition to the function of the product, we also have to identify the functions of each element (i.e. the role of each element in the overall behaviour of the product).

As an example, in addition to these functions (user's needs), we have to consider the function(s) of each element:
- the butyl sealant prevents from water entry in the air gap,
- resistance of all elements to the environment (temperature, sun and UV radiations, rain, …).

Behaviour Analyses

Modelling Principle

A product is defined as an order of elements and materials that ensure a set of functions.

In the building domain, "The product fulfils a function" could be expressed as "The building product transforms climatic factors" (between input and output when considering the elements belonging to the envelope). It generally acts as a filter between two environments, filtering heat flows between outdoor and indoor environments (thermal insulation), stopping water from outdoor (watertightness function of the DGU), etc.

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But, the same climatic factors can have an impact on its constituent elements and could involve: modification of the materials properties, degradation and even failure, etc.

We can express the behaviour of elements on the same diagram, showing on the one hand that they fulfil a function, on the other hand that they are likely to be modified and degraded by climatic and use factors.

Behavioural Graph

In this context, once we have identified the structure and the functions of the product, the next step consists in modelling its behaviour.

The approach adopted is opposite to the structural analysis: from the behaviour of the materials, we deduce the behaviour of the elements and then the behaviour of the product itself.

For that purpose, a behavioural graph is plotted. The product is composed of n elements, placed "in series" or "in parallel".
- each block being an element,
- and each link being a relation between blocks (physical contact, flow transfer, etc).

Figure 3 is an example of a very simple graph (only series relations). It ensures a barrier role between outdoor and indoor environment, as the double glazing does.
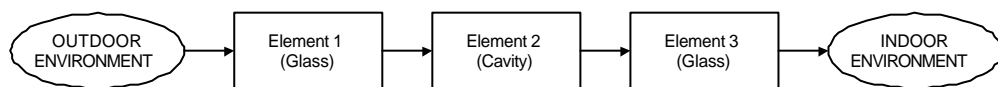

Figure 3:   Product behaviour

Elements 1 (respectively n) are the outdoor (respectively indoor) glass pane. We can add in between several elements which could be low-emissive coating or anti-reflective coating …

Special Cases

In order to have an accurate representation of the product, additional information is required:
- cavity (as the cavity between the internal and external glass of a double glazing unit or the cavity in a pipe),
- interface, either simple contact (DGU put on the setting blocks) or fixed interface (as the interface between seal and glass).

They are both represented as elements:

- in the first case to take into account thermal and acoustic characteristics, as well as flows (air, water, etc) and deposit (condensation, dust, etc),
- in the second case, mainly to take into account problems of compatibility/incompatibility of materials, gluing properties, watertightness and airtightness (we will be able to take into account the difference between adhesive and cohesive failure of seals for instance).

Nominal Behaviour (t = 0)

From this graph, we can deduce the nominal behaviour of the product, i.e. we know the response of a product (and its element) to a given set of climatic and use factors.

At t=0 (without any degradation and considering that the product was correctly installed/implemented), we can identify the initial state of stresses.

We thus have information on:
- the various flows in the product (e.g. thermal flow),
- the key elements (protecting elements, etc).

Degradation and Failure Analysis – Failure Modes (t > 0)

Introduction

Given the "nominal" functioning of the product, we start working on degradation and failure study. We study the behaviour of the product if the behaviour of a material or element deviates from its normal behaviour.

The principle is an iterative study.

Step 1: Degradation of elements due to climatic or use factors

We first analyse the influence of initial environmental stresses on each element.

For instance, we have to study the behaviour of the double glazing unit towards high and low temperatures, UV and sun radiation, water (rain, snow, hail, etc), ice, various pollutants, shocks …

We also have to take into account the scale effect: the building (neighbouring products) influences the product behaviour, and conversely. For instance, the various potential effects of the frames on the DGU are also studied within IEA T27 (behaviour of the product incorporated in the building).

The methodology used allows us to take into account not only these "single" factors but also the combination of these factors:
- combined factors from the "same" environment, either concomitant factors (water and low temperature from outdoor environment → freezing/thawing cycles) or successive factors (sun and high temperature followed by rain → thermal shock),
- combined factors from "different" environments (high temperature from outdoor and low temperature from indoor → temperature gradient in the element).

Knowing the element (and its constituent material) as well as the potential stress factors, we identify the potential behaviours:
- UV can involve ageing of sealants (cracking, …),
- high temperatures can involve thermal ageing of sealants (hardening),
- low temperatures can involve embrittling, and make tear easier under load stresses.
- …

Step 2: Structural or environmental modifications (degradation or failure identification)

The behaviour or the degradation of the first step leads to the modification of the environment or the structure.

As examples to degradation and failure, the following was observed. Under temperature and UV stresses, the polysulfide sealant gets old. This ageing causes hardening, cracking …. Although the sealant is degraded, the DGU still fulfils its functions. Moreover, it will not be able to withstand mechanical stresses as well as initially. If the polysulfide sealant has cracked, the butyl sealant is no more protected against humidity. This comes down to a new stress (Humidity stressing Butyl sealant). The initial state is updated and becomes a "State 2" condition for which we have to study the effect of humidity on Butyl sealant.

Step 3: Degradation of elements due to updated climatic or use factors

Given the modification of structural or environmental conditions (step 2), we now study again the behaviour under new environmental conditions (action of environmental factors on elements due to structural modifications, mainly loss of protection):
- effect of the humidity on butyl sealant,
- …

Again we identify the modification of both structure and environment (step 2), then step 3, and so on…

For instance, once the polysulfide sealant has failed since it was stressed by temperature and humidity, the butyl sealant is stressed by humidity and water (step 2). It will fail by cracking or tear, and then will not fulfil its "watertightness" function any more. Rain, humidity, pollutants … will go through the interface and reach the air gap (which will inevitably leads to condensation and dust in the air gap).

Note

We also take into account construction process problems, i.e. problems occurring during the following stages: design, transportation, storage, installation, use, etc.

We use the 5M rule to identify the various potential defaults, negligence or errors concerning:
- Material (quality, incompatibility, surface quality, etc)
- Manpower (surface cleanness, dimensions, etc),
- Middle, i.e. environment (temperature, humidity, etc),
- Means (non-adapted tools, etc),
- Method (time limit, etc).

They intervene as structural or environmental modifications in step 2.

The failure of a reinforced concrete element could be due not only to the impact of environmental factors impact (CO_2 …) but also to vibration, temperature, curing, position of reinforced bars, etc.

Results

We thus obtain:
- information on the "Nominal behaviour" of the product in a given environment in order to document "reference service life" (Sjöström and al., 2001),
- information on the degradation and failures, expressed as a list of degradation and failures (FMEA table) or a failure tree (with scenarios).

In this table are listed for each element, the modes, causes and effects.

In column "Causes", we distinguish errors and problems occurring during the process (cause type 0), and the different levels of degradation or failure: cause type 1 (initial environmental stresses), cause type 2 (occurring after the degradation or failure of an element), and so on …

Applications

Within IEA T27 – Project C2, three examples are currently under study:

- Double Glazing Unit (including the influence of the frames),
- Argon filled Low-e coated glazing (which also requires the study of the influence of the frames on the glazing),
- Solar collector.

In relation with SWIFT project, the FMEA of Gazochromic and Electrochromic glazings is also done.

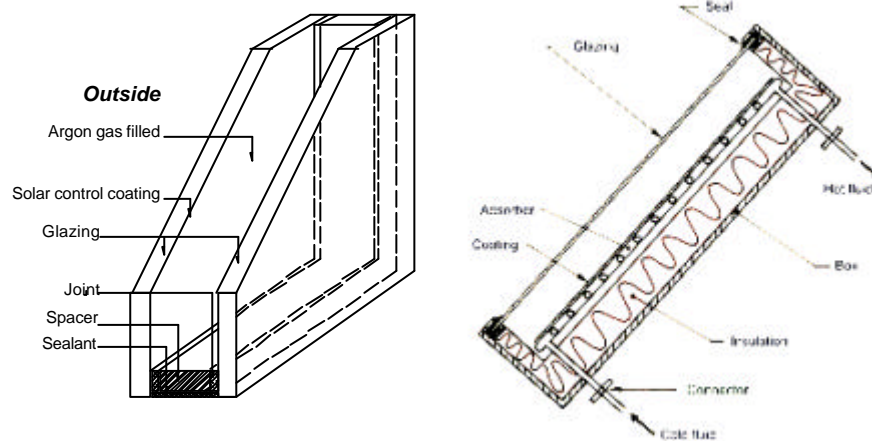Figure 4: FMEA for a Double Glazing Unit (extract)

Figure 5: Applications

Interests and Perspectives

This tool could be used at the different stages in the product life:
- Design and installation (risk analysis and maintenance planning),
- Use (maintenance planning or failure diagnosis).

The Figure 6 gives the results and the objectives of this tool.

Based on FMEA, the developed tool gives elements to assess the durability of construction products.

On the one hand, we can improve the reliability and quality of innovative products. With a risk analysis from the design stage, weak points are identified. We can define relevant preventive actions (risk analysis and quality procedure).

On the other hand, in a "diagnosis/refurbishment" context, the FMEA tool allows the "in-service follow-up" of existing products and supplies information for IMR procedures (Inspection/Maintenance/Repair) such as quality control and maintenance planning (conditional and corrective maintenance), failure diagnosis (capability of detecting degradation, prediction of the future degradation or failures, identification and selection of relevant maintenance or repair solutions).

Construction process stage		Results	Objectives
Design Installation	**1 - Risk analysis**	Identification of weak points of the product (characterised by a level of criticality)	*Improve quality and reliability from design stage by*: - identifying problems, - giving priorities.
	2 - Quality management	Identification of critical operations (Installation, use) or critical elements leading frequently to degradation and failure.	*Improve the construction procedures (transport, storage, setting up) and use by:* - identifying problems, - giving a check-list of key steps (scale of priority).
Use	**3 - Preventive maintenance**	Forecasting of potential behaviours in time. Assessment of the criticality of possible consequences.	*Improve **proactive** maintenance procedures by:* - identifying problems, - giving priorities, - proposing solutions to maintenance.
	4 – Conditional maintenance	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.	*Improve **reactive** maintenance procedures by:* - identifying problems, - giving priorities, - proposing solutions to maintenance or repair.
	5 - Corrective maintenance	Identification of failure causes from the observed failure (diagnosis of failure).	*Improve **corrective** maintenance procedures by:* - explaining failures, - proposing solutions to repair.

Figure 6:   Different uses of FMEA tool

It plays an important part in capitalising on experiments and knowledge within building management.

It is a real advantage for architects, owners, project managers, insurers, users... to:
- Have a guaranteed quality approach,
- Improve and reveal the quality of products and practices,
- Optimise design costs,
- Communicate reliable information between actors of construction,
- Improve products and practices quality,
- Optimise setting up and maintenance costs,
- Decrease environmental impacts at each stage in the construction process,
- Avoid errors, defects and omissions.

In a context where non-quality or poor-quality costs are being added to the general wish to decrease the global cost of construction, FMECA and management tools should have a determinant role.

Part 2: Capturing Insulating Glass Failure Events Using Failure Modes and Effects Analysis and Event Trees ("An Insulating Glass Knowledge Base")

Objective

This work was performed in support of the U.S. Department of Energy funded effort entitled "An Insulating 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 (Ireson et al., 1996).

The format into which the FMEA is captured (Figure 7) consists of the following entries (McDemott et al., 1996):
- Product functions
- Failure modes
- Effects
- Causes
- Controls
- Severity of Effect
- Probability of Occurrence
- Probability of Detection

Functions	Failure Modes	Effects	S	Causes	O	Control	D
1. Provide Transparent View to Outdoors	MVTR & Structural Seal Cohesive Failure due to Tension/Compression	Internal Condensation	?	**Design**			
2. Provide Optimum Thermal Efficiency		Loss of U-Value	?	Cyclic Dishing Fatigue	?	Modeling	?
3. Maintain Aesthetic Appearance		Poor SHGC	?	High Internal IG pressure	?	Modeling	?
				UV Embrittlement/Cracking	?	Modeling & Tests	?
				Chemical Degradation	?	Modeling & 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	?
				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 Process	?

Figure 7   A Section of an FMEA for IG Design Class

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

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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 8. The low extreme of the scale is no noticeable problem. The high extreme of the scale represents issues of safety and corporate brand erosion.

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 8   Severity ranking scale

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 9 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.

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

Figure 9:   Probability of Occurrence ranking scale

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 10.

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 10:   Probability of Detection ranking scale

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 (Hage, 1993).

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 11. 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.

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The failure modes and resulting effects identified within the FMEA are captured in this construct for each design class.
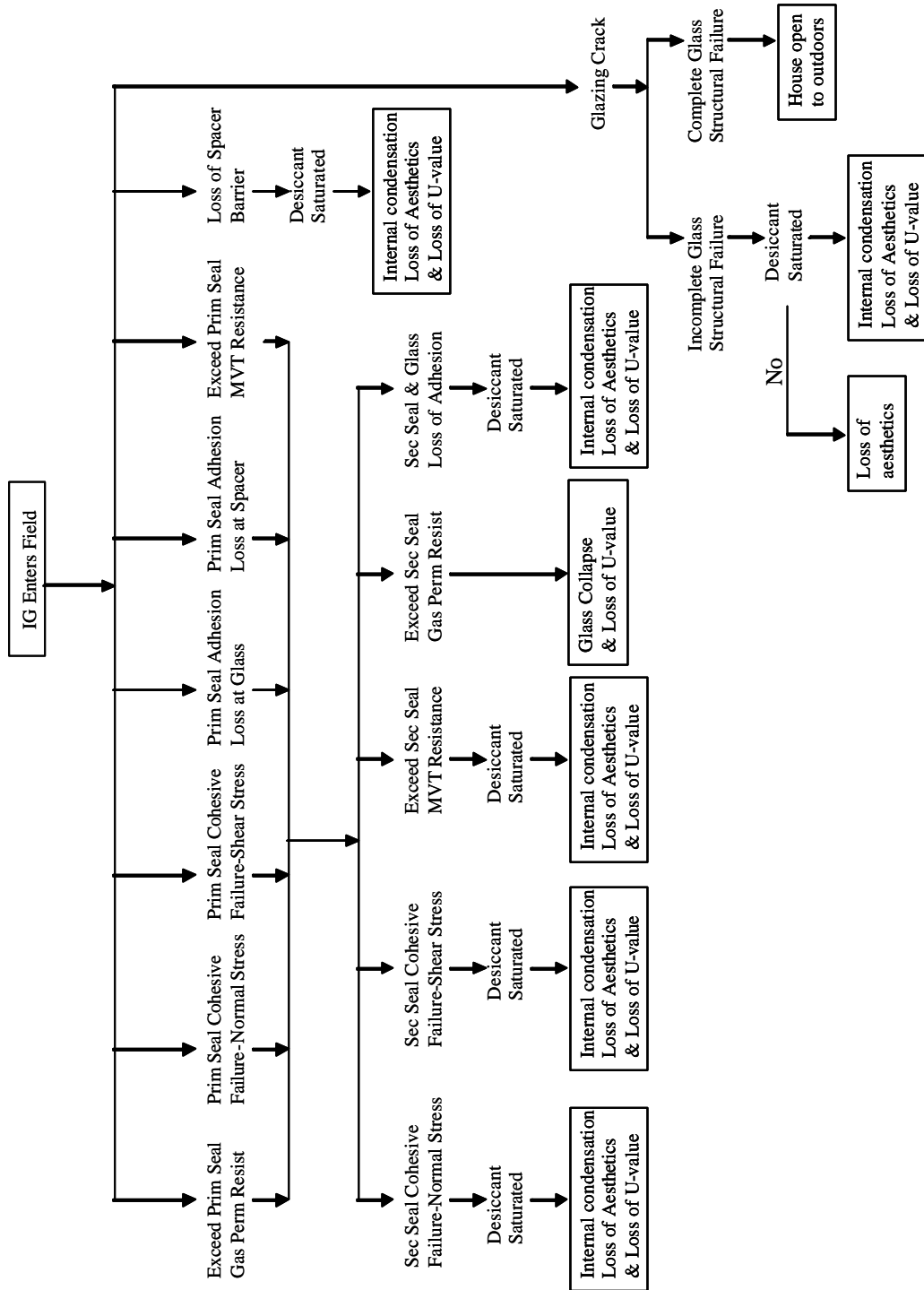

Figure 11   Overall Event Tree for a Specific IG Design Class

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.

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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 12.
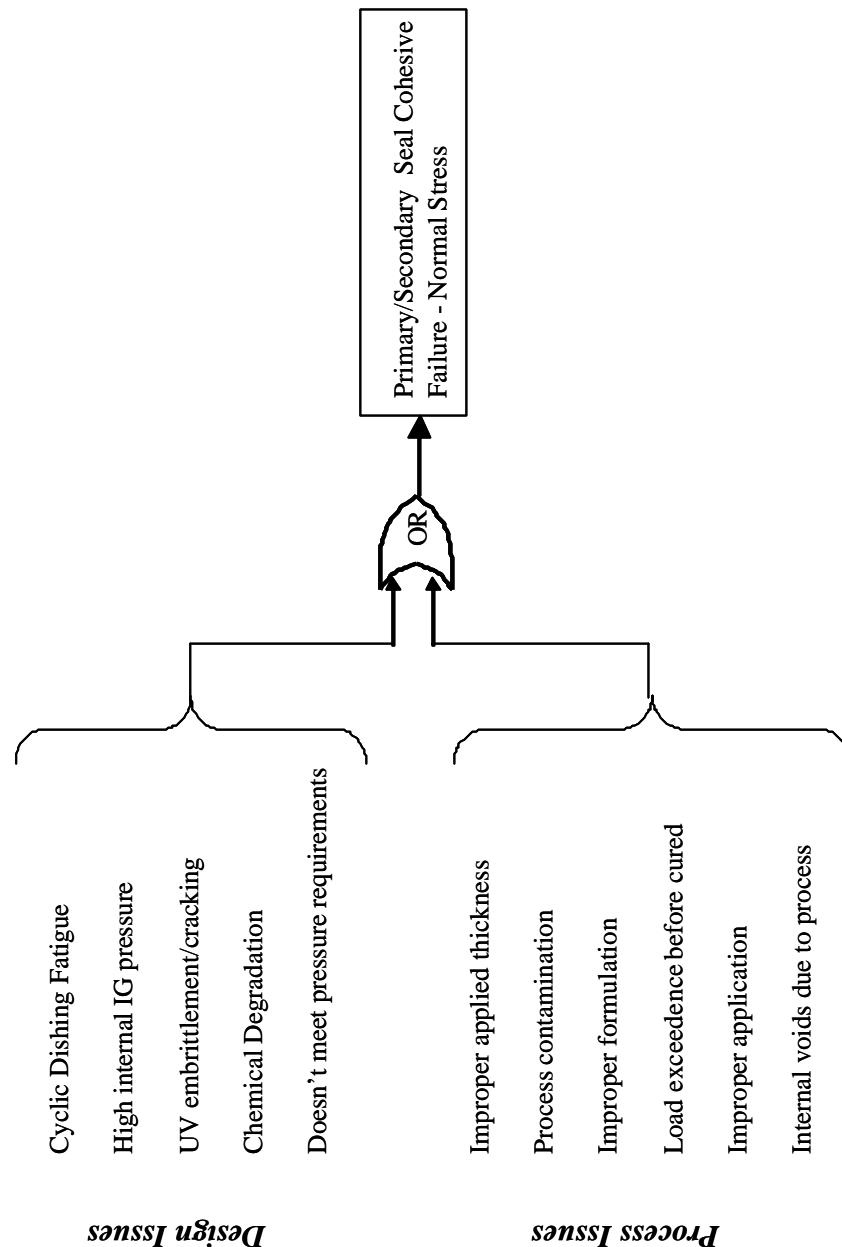

Figure 12   Fault Tree for a Specific Failure Mode

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 (Bilton and Allan, 1992). 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

Conclusion

This paper presents two similar approaches intended to assess the durability of building products, especially glazing, windows and solar components.

Though the original problem was slightly different (durability of building products on the one hand, failure of the Insulated Glazing on the other hand), both approaches are based on the use of Failure Modes and Effects Analysis.

They bring interesting new developments. The main ones are:
- the detailed structural and functional analysis procedure allowing the study of any building product (refer to part 1),
- the iterative search principle in order to be able to found complex failure scenarios, i.e. failure of a product can be due to the degradation or the failure of one of its elements (refer to part 1),
- the criticality analysis by use of expert knowledge concerning occurrence, detection and severity indicators (refer to part 2),
- the combined use of FMEA and event trees to identify and represents all potential failure modes (refer to part 2).

The use of all these advantages will lead to a high-performance tool.

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