Accelerated ageing test of solar collector

Rodolphe Morlot / Bouzid Khebchache, CSTB
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SUMMARY

"Reliability" and "durability" terms gather the notion related to the maintenance in time of the functional characteristics of a product. Reliability applies more to the object taken as a whole, whereas durability is related to the materials which make it up.

The use of new materials for solar thermal collectors, increasingly more powerful, but could lead to problems (with medium term) of reliability and durability of the solar components. The principal constraints imposed on the solar collectors are the temperature, the pressure and the atmospheric agents (rain, UV, freezing...).

Consequently, with the aim of knowing if a test of one year ageing in natural exposure of a solar collector were relevant but also representative of the normal functioning of the collector during 15 to 20 years, we have chosen to practice a simulation on a solar water-heater and a combined solar system. With this intention, we developed a model with TRNSYS in order to be able to evaluate the value and the frequencies of the temperatures reached for the different components of the collector.

The second part of the document deals with an original methodology based on the use and adaptation of the Failure Modes, Effects and Analysis (previously used in the aeronautical and automotive domains). This methodology, would identify the failure modes (exhaustive search of the behaviours, degradations and failures of elements), their causes and effects, taking into account the potential problems and errors found on a solar collector.

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1. INTRODUCTION

"Reliability" and "durability" terms gather the notion related to the maintenance in time of the functional characteristics of a product. Reliability applies more to the object taken as a whole, whereas durability is related to the materials which make it up.

The use of new materials for thermal solar systems, increasingly more powerful, lead to problems (with medium term) of reliability and durability of the solar components. This is why the CSTB, has realized for several years, studies on the topic of corrosion, reliability and durability of the collectors.

These studies have mainly aimed at materials and components making up the system (held with the temperature and UV, life-time behaviour...), with tests in laboratories, and an active participation in international working groups on this field (International Energy Agency (IEA), Collector Testing Group of the European Community, UEAtc).

The constraints of operation of these systems (temperatures and pressures reached...), the modes of failures (defects in the processes of construction or maintenance, behaviour in time of the system) and the analysis of links between these different elements and of their impacts on the aptitude of the system to provide functions for which it is conceived (mechanical held, thermal performances...).

From our point of view, a series of tests on each separated components of the solar collector (absorber, transparent cover...) does not seem to be the most representative way. By the same one, the test of a small-scale solar collector was abandoned, because it is partially answering to the manufacturer's problematic wishing to test their product but also because the test results measured on this small sample are not easily representative and able to be extrapolated on a collector of standard size.

A solar collector must be made up on the basis of a suitable choice of materials in order to resist to high constraints, but must also answer to problems such as the mechanical resistance, watertightness, the corrosion resistance, the frost resistance. These kind of potential problems are examined in the UEAtc Directives and the standard EN 12975-2, in which several sequences of tests are presented, like tests in real size in stagnation and natural exposure on a whole collector.

Moreover, the method recommended in EN 12975-2, imposes an exposure test over 30 days that we regard as rather relevant in a procedure of operating requirement of the collector but not adapted to the forecast of durability. Indeed, if this test of exposure appears necessary to control the behaviour of the collector in severe conditions, it does not make it possible to consider an extrapolation of the long-term behaviour.

This is the reason why we think that an ageing test by a natural exposure of the solar collector during one year is more representative of reality, and thus the tested collector sudden of requests close to those we could await from a normal functioning on 15 to 20 years. The first part of this draft presents the justification of this choice of test, with the supply of elements allowing an analysis for a discussion on the subject.

In complement, the second part of this document presents a method of analysis used by the CSTB with the aim of preventing the potential failures of a product. This method, which is entitled FMEA (Failure Modes Effect and Analysis) was carried out partly on a solar collector, in order to wonder about the behaviour of materials subjected to the functioning constraints reigning inside the collector. This method could be used to check test results obtained after ageing but also in order to make a finer and more detailed analysis of results obtained.

2. ACCELERATED AGEING TEST OF SOLAR COLLECTOR

2.1 THE ONE YEAR NATURAL EXPOSURE TEST REPRESENTATIVITY

2.1.1 Simulation

The principal constraints imposed on the solar collectors are the temperature, the pressure and the atmospheric agents (rain, UV, freezing...). Consequently, with the aim of knowing if a test of one year ageing in natural exposure of a solar collector were relevant but also representative of the normal functioning of the collector during 15 to 20 years, we have chosen to practice a simulation on a solar water-heater and a combined solar system. With this intention, we developed a model with TRNSYS, in order to be able to evaluate the value and the frequencies of the temperatures reached for the different components of the collector.

2.1.1.1 Solar domestic water heater (SDWH)

Two configurations were retained for the dimensioning of the systems studied:

- Configuration 1: a collector aperture area of 4 m², for a daily load volume of 250 l/d and a capacity tank of 300 litres. This system is a "normal" dimensioning in the ‘’Nice’’ location. For this configuration, the method SOLO gives a solar fraction ranging between 60 and 65 %.
- Configuration 2: a collector aperture area of 6 m², for a daily load volume of 125 l/d and a capacity tank of 300 litres. This system is an "oversize" dimensioning in the ‘’Nice’’ location. For this configuration, the method SOLO gives a solar fraction ranging between 85 and 90 %.

The assumptions of the Simulation are :

- File weather based on the location of Nice.

- Consideration of two desired temperatures of water for each configuration: 60°C: maximum temperature of distribution of hot water without appliance of safety limited temperature of water, and 90°C: a traditional temperature of heating.

The system was stopped during August (period of holidays when the constraints of temperatures applied to the system are significant).

The digital model doesn’t take into account the inertia of the system, we put forth additional assumptions during the treatment of the results resulting from modelling:

1. a stop due to hysteresis does not lead to a setting in stagnation of the collector because the primary circuit will start again when the temperature difference between the collector and the tank is higher than ΔT (5°C in our case),

2. a stop of the primary circuit due to a temperature of the tank higher than the desired temperature leads to a setting in stagnation of the collector.

2.1.1.2 Solar combined system (SCS)

The solar combined system was only modelled in its "summer" configuration (except period of heating) because during this period, constraints for the collector are highest. So the model is based on the normally dimensioned system (configuration 1) of the standard system of production of hot water.

The collector aperture area is 12 m² and corresponds to a solar fraction (heating + hot water) calculated of 60 % for a house of 100 m². We used two levels of daily load of hot water : 250 l/d with 50°C (approximately 4 persons) and 125 l/d with 50°C (approximately 2 persons).

2.1.2 Simulation results

The simulation showed that temperatures higher or equal to 90 °C can be reached, in the most critical cases, during 462 to 694 hours per years and, in the cases best dimensioned, during 76 to 436 hours per years.

The following tables show the distribution of the number of hours, for which the collector reached a higher temperature or equal to 90°C, according to the two configurations of system of water-heater but also for the combined solar system:

SDWH (Reached temperatures)	90	100	110	120	130	140	150	160	170	180	190	Total (h)
Configuration 2 (T_{tank} = 60 °C) (most critical case)	24	53	48	51	54	41	24	49	64	42	13	462
Configuration 2 (T_{tank} = 90 °C) (most critical case)	77	18	12	10	10	11	8	9	8	15	7	185
Configuration 1 (T_{tank} = 60 °C)	3	8	7	6	9	10	10	13	21	28	13	127
Configuration 1 (T_{tank} = 90 °C)	39	10	5	3	3	5	4	4	3	2	0	76

Table 1 : Number of hours corresponding of reached temperatures by the collector per year without any draw-off in August

Solar combined system (Reached temperatures)	90	100	110	120	130	140	150	160	170	180	190	Total (h)
Daily draw-off = 125 l/d T_{tank} = 60 °C (most critical case)	29	66	63	65	74	76	67	97	95	50	13	694
Daily draw-off = 250 l/d T_{tank} = 60 °C	26	59	54	54	55	51	34	55	66	42	13	507
Daily draw-off = 250 l/d T_{tank} = 90 °C	224	36	26	27	30	16	9	10	20	27	11	436

Table 2 : Number of hours corresponding of reached temperatures by the collector per year without any draw-off in August

Consequently, we can estimate:

- that a water-heater is subjected to constraints of temperatures higher than 90°C between 1 and 8 days per year according to its dimensioning,
- that a solar combined system is subjected to constraints of temperatures higher than 90°C between 3 and 14 days per year according to its dimensioning, this type of system is requested more in term of constraint of temperature than the standard system.

2.1.2.1 Most critical cases

The following table presents the distribution of the number of hours of temperature reached (> = 90°C and > = 150°C), according to application (SDWH or SCS), brought back to 15 or 20 years:

	> = 90 °C		> = 150 °C	
*configuration 2	SDWH*	SCS	SDWH*	SCS
Numbers of hours per year	462	694	192	322
Numbers of hours per 15 years	6930	10410	2880	4830
Numbers of hours per 20 years	9240	13880	3840	6440

Table 3 : Number of hours of collector stagnation on 15 or 20 years without draw-off in August

The following figure presents the distribution of the annual irradiance on collector which led to these numbers of hours of stagnation for one year:

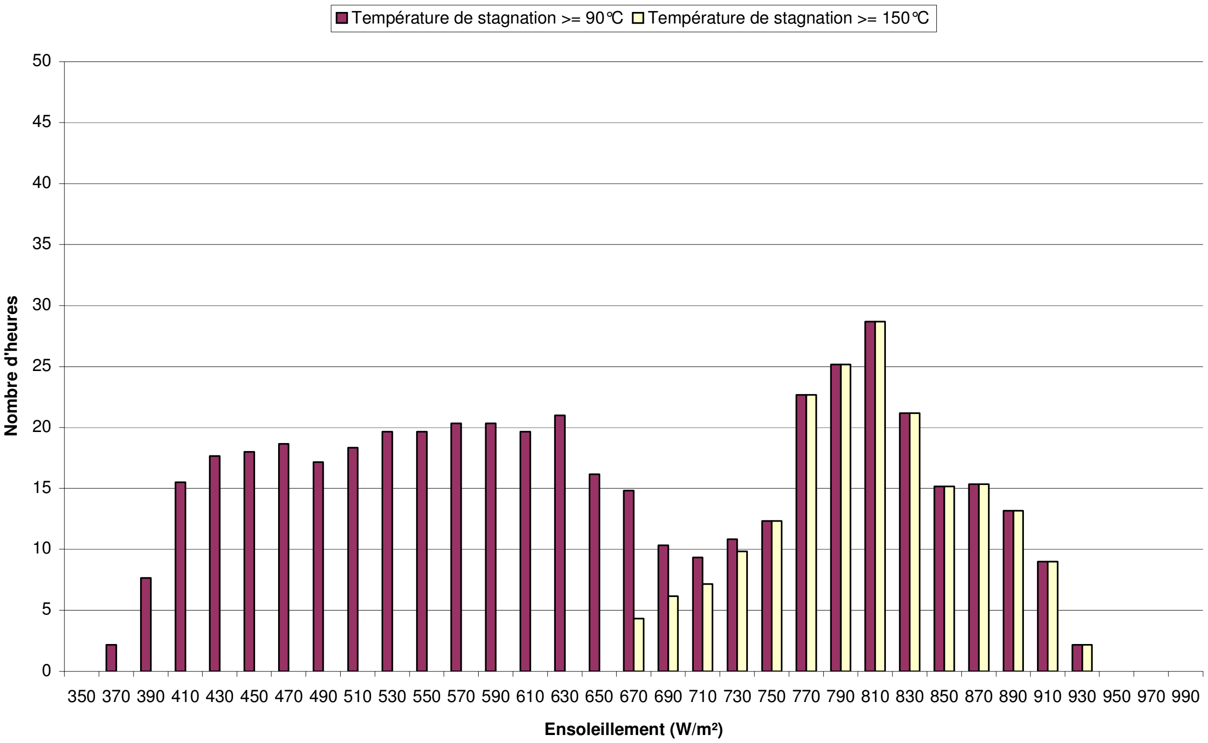


Figure 1: Irradiance distribution on solar collectors during stagnation periods on one year without any draw-off in August - SDWH - 60 °C.

Consequently, if we cross the distribution of the number of hours of stagnation with the irradiance, we obtain the following table:

SDWH	T Stag >= 90 ℃	T Stag > = 150 ℃
< 850 W/m²	407	138
> = 850 W/m²	55	55
Total	462	192
	12 %	29 %

Table 4: Numbers of hours of stagnation according to Irradiance - SDWH.

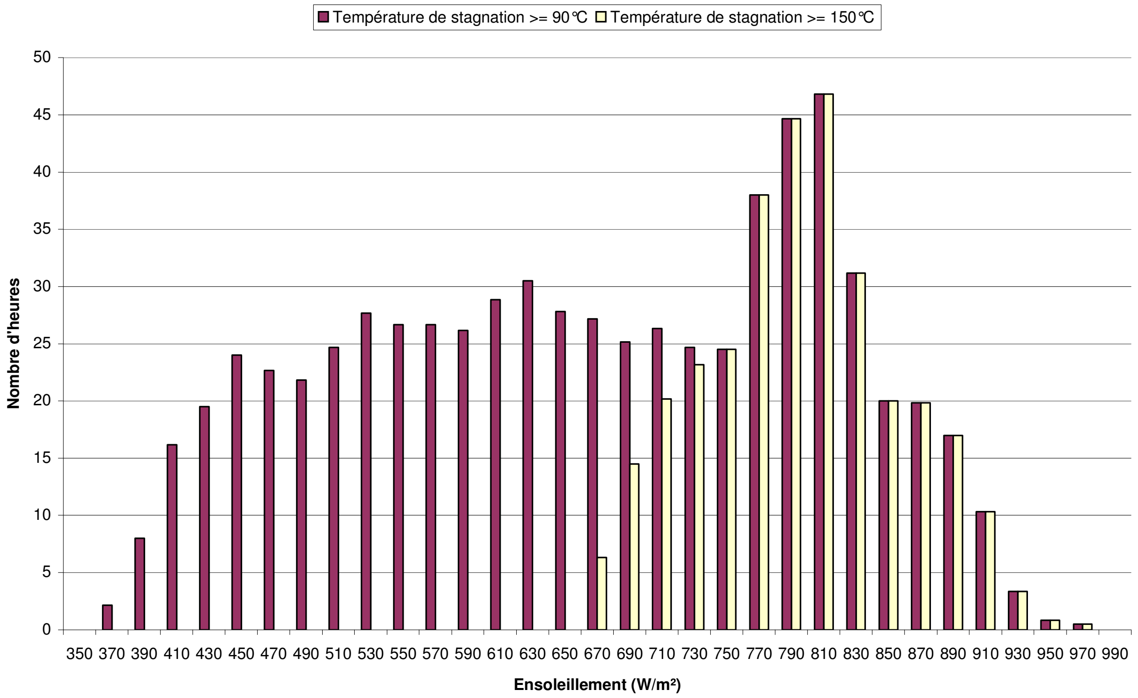


Figure 2: Irradiance distribution on solar collectors during stagnation periods on one year without any draw-off in August – SCS - 125 l - 60 ℃.

Solar combined system	T Stag >= 90 ℃	T Stag > = 150 ℃
< 850 W/m²	622	249
> = 850 W/m²	72	72
Total	694	322
	10 %	22 %

Table 5: Numbers of hours of stagnation according to Irradiance - SCS.

We notice that to obtain temperatures of stagnation higher or equal to 150 ℃, the irradiance received on the collector is higher than 850 W/m² during 29% of time for configuration 2 for the SDWH and 22 % of time for the SCS.

2.1.2.2 Normal sized cases

The following table presents the distribution of the number of hours of temperature reached (> = 90℃ and > = 150℃), according to application (SDWH or SCS), brought back to 15 or 20 years:

SDWH	> = 90 ℃		> = 150 ℃	
*configuration 1	SDWH*	CSS	SDWH*	CSS
Numbers of hours per year	76	436	13	77
Numbers of hours per 15 years	1140	6540	195	1155
Numbers of hours per 20 years	1520	8720	260	1540

Table 6 : Numbers of hours of stagnation for 15 or 20 years without draw-off in August

The following figure presents the distribution of the Irradiance on the collector which led to these numbers of hours of stagnation for one year:

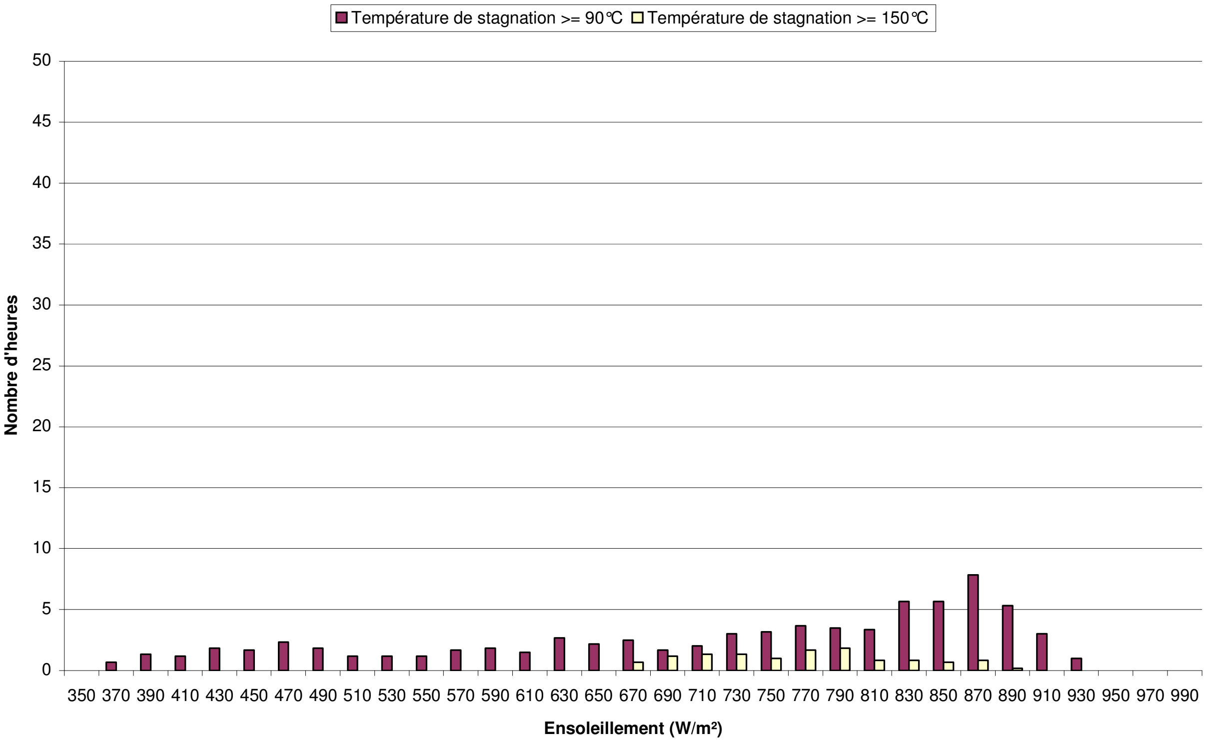


Figure 3 : Irradiance on collectors during stagnation periods for one year without any draw-off in August - SDWH.

Consequently, if we cross the distribution of the number of hours of stagnation with the irradiance, we obtain the following table:

SDWH	T Stag > = 90 °C	T Stag > = 150 °C
< 850 W/m^2	53	11
> = 850 W/m^2	23	2
Total	76	13
	30 %	15 %

Table 7 : Numbers of hours of stagnation according to Irradiance - SDWH.

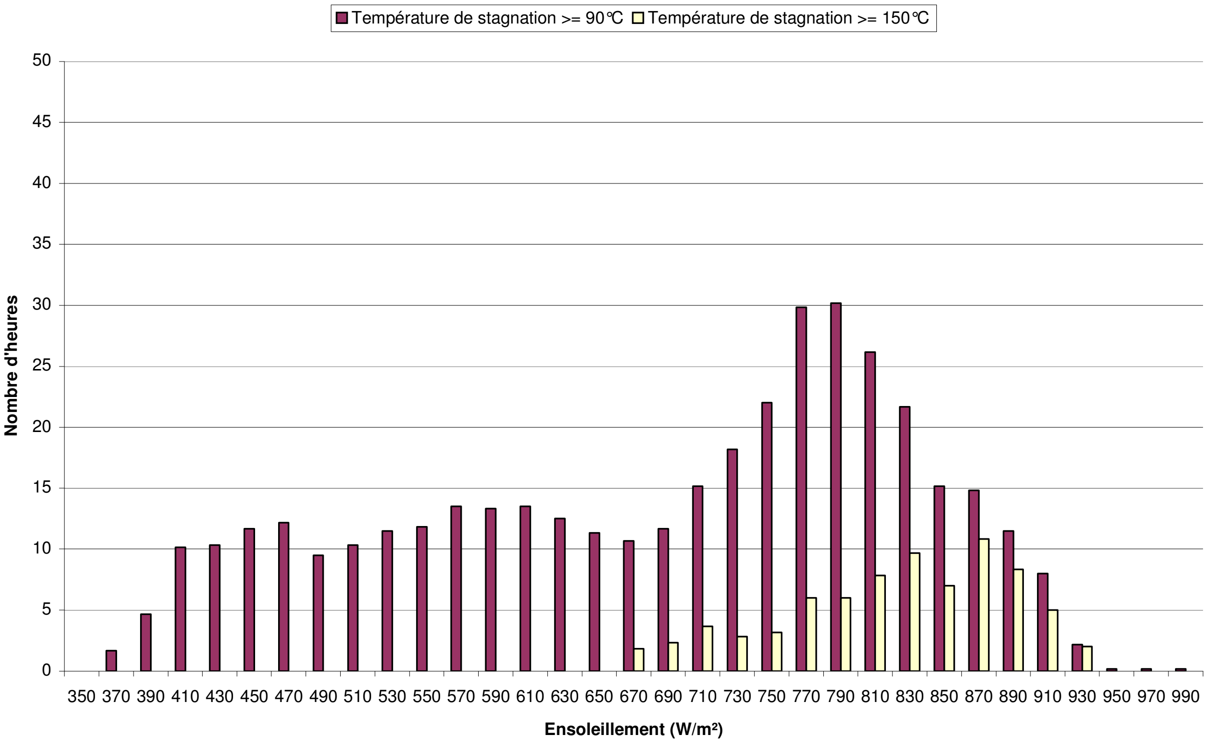


Figure 4 : Irradiance distribution on solar collectors during stagnation periods on one year without any draw-off in August – SCS - 250 l - 90 °C.

Consequently, if we cross the distribution of the number of hours of stagnation with the irradiance, we obtain the following table:

Solar Combined system	T Stag > = 90 °C	T Stag > = 150 °C
< 850 W/m^2	384	43
> = 850 W/m^2	52	34
Total	436	77
	12 %	43 %

Table 8 : Numbers of hours of stagnation according to Irradiance - SCS.

We notice that to obtain temperatures of stagnation higher or equal to 150 °C, the Irradiance received on collector is higher than 850 W/m^2 during 15% of time for the configuration 2 of SDWH and 43 % of time for SCS.

2.1.3 Correspondence with the test of one year ageing of the collector

We propose to study the correspondence of the preceding results with the test of current ageing carried out on a collector only subjected to one year natural exposure.

If we carry out a simulation over the whole year on the same collector tilted to 45° and in stagnation on our site we obtain the following distribution of Irradiance:

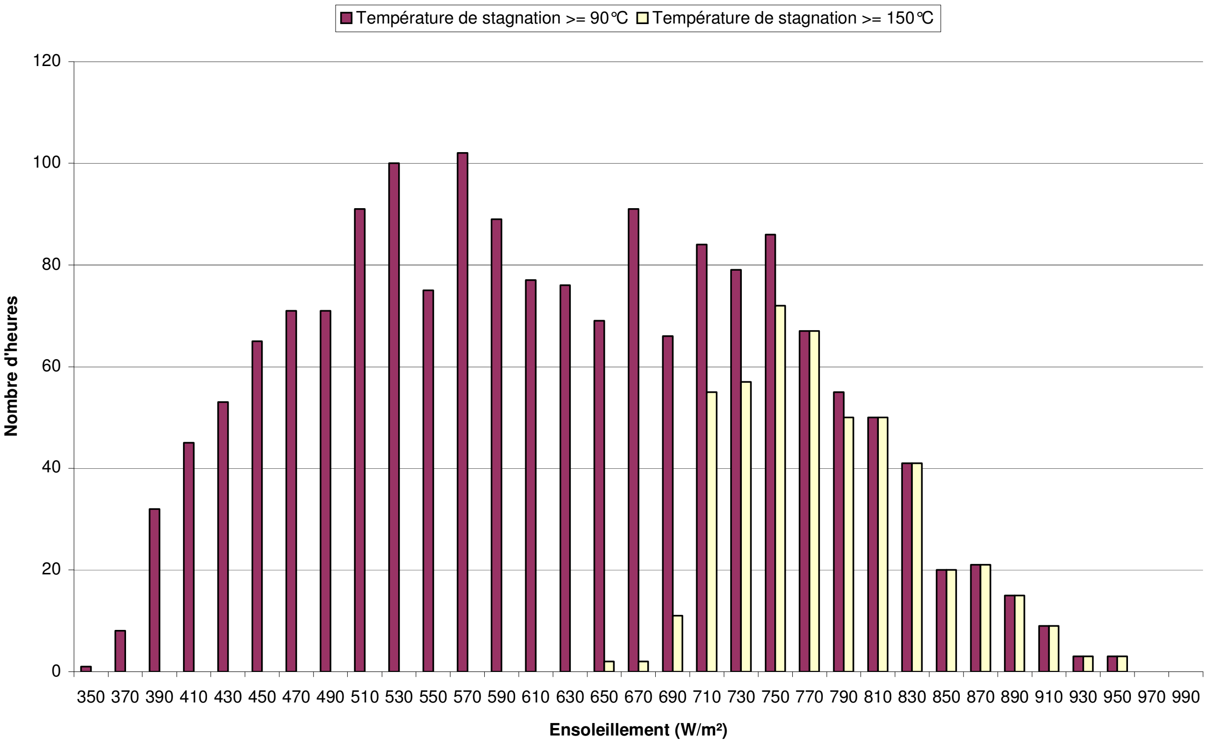


Figure 5 : Irradiance on collector during one year in stagnation and titled to 45°

Consequently, if we cross the distribution of the number of hours of stagnation with the irradiance, we obtain the following table:

Ageing exposure test	T Stag > = 90 ℃	T Stag > = 150 ℃
< 850 W/m²	1643	407
> = 850 W/m²	68	68
Total	1711	475
	4 %	14 %

Table 9 : Numbers of hours of stagnation according to Irradiance – ageing exposure test.

2.1.4 Summary of results

Simulation enabled us to show that the current tests of one year ageing in natural exposure of a solar collector largely cover the equivalent duration of 20 years for the normally dimensioned solar water heaters (113 to 244 %). On the other hand, it is not the same for the solar combined systems even when those are dimensioned normally (20 to 41 %).

	SDWH		SCS	
Reached Temperatures of the collector	≥ 90℃	≥ 150℃	≥ 90℃	≥ 150℃
Collector test / numbers of hours per year	1711	475	1711	475
	Normal dimensioned cases			
Numbers of hours per 15 years	1140	195	6540	1155
Cover of the test				
Ratio (1 year/15 years)	150 %	*244 %*	26 %	41 %
Numbers of hours per 20 years	1520	260	8720	1540
Cover of the test				
Ratio (1 year/20 years)	113 %	183 %	20 %	*31 %*
	Most critical cases			
Numbers of hours per 15 years	6930	2880	10410	4830
Cover of the test				
Ratio (1 year/15 years)	*25 %*	16 %	16 %	10 %
Numbers of hours per 20 years	9240	3840	13880	6440
Cover of the test				
Ratio (1 year/20 years)	19 %	12 %	12 %	*7 %*

Table 10 : Comparison of the ageing test of one collector and the collector functioning in its system (SDWH and SCS)

This summary table enables us to show that for the most critical cases, the cover of the test is only very partial (7 to 25 %). Furthermore, we notice that for the temperatures higher than 150℃, the cover of the test for the normal dimensioned systems is relatively good (31 to 244%). On the basis of these results of simulation, we estimate that the one year natural exposure test is relatively representative of the reality and thus that solicitations are closely the same we could await from a normal functioning during 15 to 20 years.

2.2 TESTS TO REALIZE

An often advanced requirement of the user takes 15 years at least use without disorder. To achieve this goal, the CSTB by UEAtc interposed, proposed to distinguish the durability of materials constitutive entering manufacture of the collector, of that of the whole collector.

While taking again this procedure, a simplification can be brought in alarming only of the whole collector, with load of the manufacturers whom they select beforehand constitutive materials to obtain a suitable longevity in connection with the functioning conditions reigning in a collector.

The exposure tests over 30 days according to the standard appear rather relevant in a procedure of operating requirement of the collector but not easily sufficient with the forecast of durability because the test of the collector even under a high total irradiance of 850 W/m² seems for us too short. Indeed, if this exposure test appears necessary to control the behaviour of the collector in severe conditions, it does not make it possible to consider an extrapolation of the long-term behaviour.

Moreover, the constitutive materials undergo during the functioning with the passing of years a chemical evolution which modifies the initial performances. One thirty days duration is too weak to locate a beginning of evolution.

We think that a test of accelerated ageing test moderate recommended to obtain an out-of-date state which corresponds to that of the collector at 10 years for example, should be spread out over 6 to 12 months.

We thus propose to carry out an aptitude test for a use of long duration which will not give a lifespan but which would be reasonable in duration and cost for the manufacturer.

It would consist in laying out the sensor in stagnation outside during one year. The method which seems in first approaches the most adapted, would consist in measuring the evolution of the relevant indicators of performance (average efficiency) in the course of time under requests representative of reality. The acceptable levels of performances for one determined period for the collector could be the measurement of the difference between the initial thermal performances (before ageing) and finales (after ageing) whose threshold could be 10%.

In addition to the determination of the variation of the performances of the thermal solar collectors, we propose to carry out a neat visual inspection of the sensor in order to define the deteriorations undergone by the product (possible degradation of the coating of the absorber, degradation of the cover, degradation of the joints...).

2.2.1 Principal disorders noted on solar collectors

The tests carried out in our laboratory enabled us to know the principal disorders caused on the solar collector:

- concerning the transparent cover:
  - stains on the external face,
  - condensation on the internal face,
  - deposit on the internal face,
  - ageing in the case of a plastic material,
  - breakage in the case of glass

- concerning the absorber:
  - aspect,
  - corrosion,
  - traces of condensation,
  - deformation,
  - escapes of liquid.

- concerning the joints:
  - cracking of material,
  - washing away and bad connection cover case (frame).

- concerning insulator:
  - deformation,
  - separation of the absorber

- concerning the frame:
  - corrosion for a metal trunk,
  - degradation of aspect for a plastic trunk.

2.3 CONCLUSION

The tests of ageing which we carry out currently must be supplemented by series of real measurements taken on site throughout test i.e. 1 year. These measurements would make it possible to know the real irradiance on the collector, the temperature of stagnation reached in the collector, but also the distribution of these values during the year. Measurements could thus allow the comparison with simulation made previously.

A question also arises on the harmonization of the tests and the taking into account of the character of ''reproducibility'' of the test, also we propose to make same simulation but for other European climate location. In the second time, it could be interesting to carry out a Round Robin Test on a live test in these same laboratories in order to compare with simulations carried out.

An exposure test in a climatic room of solar simulation under strong irradiation 900 W/m^2 during 4 months at least, collector in stagnation, could be carried out, if it integrates the weather environment bordering the collector (rain, moisture, cold...).

Concerning the visual observation carried out on the collector after ageing, we note that a great difficulty of this evaluation resides on the fixing of thresholds of deteriorations.

3. FAILURE MODE EFFECT AND ANALYSIS

3.1 INTRODUCTION

In order to improve the non-quality or poor quality of the building products, and the part of maintenance and operating stages in the cost of a building, CSTB developed an original tool for the capitalization and use of experience and knowledge on building products degradations.

The aim of the proposed tool is to modelize the potential evolution of the behaviour of a studied product during his exploitation stage. We have a functional approach of the problem. That is to say that we study the performance of a product as regards of his ability to ensure functions for which it was designed.

The originality of our tool is fourfold. Firstly, we capitalize and use the experience and knowledge on building products degradations by developing data bases (for instance impact of climatic factors on materials, incompatibility between materials, list of functions, …) and favouring expert participation (for instance determination of aggressiveness level of climatic factors on materials, classification of failure scenarios by criticality level, …).

Secondly, we integrate all the potential degradations which could occur during the process stages (from the design stage to the beginning of the exploitation stage) in the modelization of the product behaviour during his exploitation stage.

Thirdly we classify the failure scenarios of the product (chaining of degradations or failures of its components drawing to the failure of the product) by criticality level.

Finally, we represent graphically the results of the Failure Modes, Effects and Analysis (FMEA).

In the following paragraphs, we will present the proposed methodology, the graph results and finally the potential exploitations of the event-driven graph.

In the following paragraphs, each step of the methodology will be presented and illustrated with an example of a solar panel system.

3.2 METHODOLOGY

3.2.1 System analysis

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

3.2.1.1 Structural analysis

This first analysis allows us to describe the structure of the product being studied. We identify its morphology (geometrical shape, dimensions, etc), its topology of relations with neighbourhood objects, its physico-chemical composition and the nature of its environment in order to know the nature and the aggressiveness level of the environment for materials of components.

The Figure 1 describes the schematization of the eight components of the solar panel system. The “external components” are outside the spatial limit of the studied product.

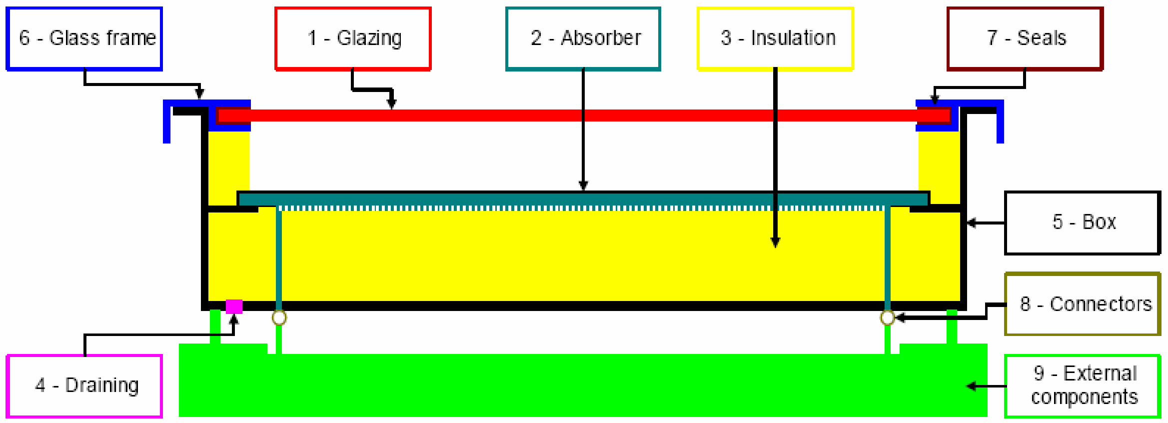


FIGURE 1.
Structural decomposition of a solar panel system

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, 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.

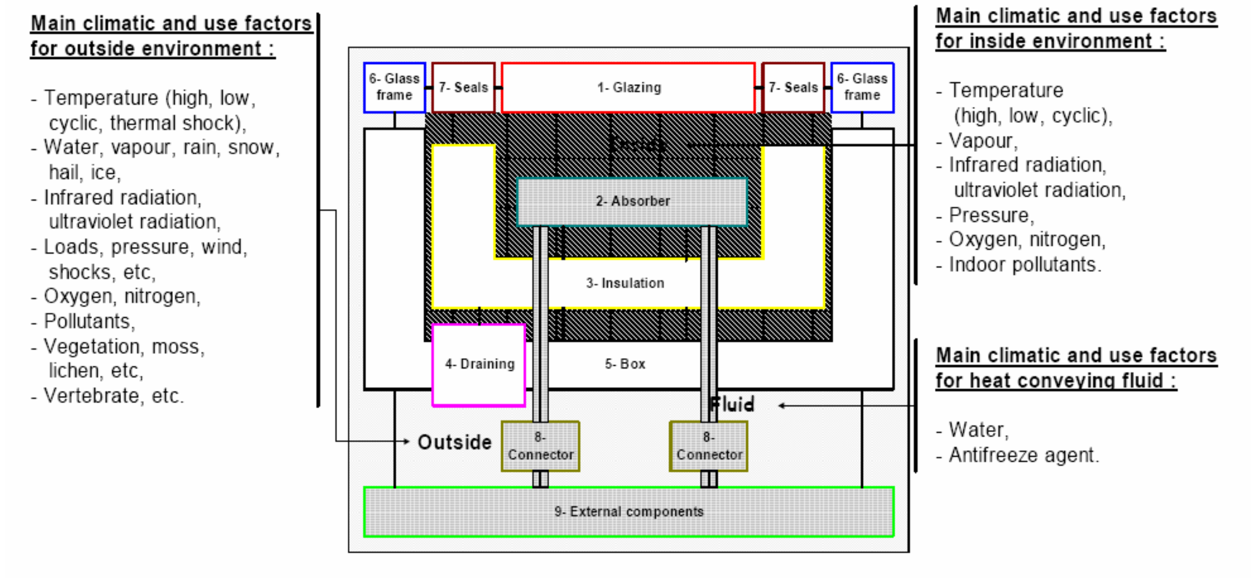


FIGURE 2.
Structural analysis result representation of the components and links of a solar panel system and environmental composition of the three mediums

3.2.1.2 Functional analysis

We have a functional approach of the problem, indeed we consider that the product had failed when it is not anymore able to ensure the functions for which it was designed. 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.
(Ex : a solar panel system has to absorb the solar heat source, to transform it into heat fluid and to convey this fluid). The functional analysis is facilitated by the function data base in which the user can select the principal and technical functions of his product and components.

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 and the evolution of the heat flow by red arrows. For instance, one of the functions of the glazing is to transmit the infrared radiation, so we plot the heat flow through the glazing by an arrow crossing the element “1- Glazing”. The insulation keeps the heat, so the heat flow is held by the element “3- Insulation”, what is diagrammed by a “closed symbol”. 5

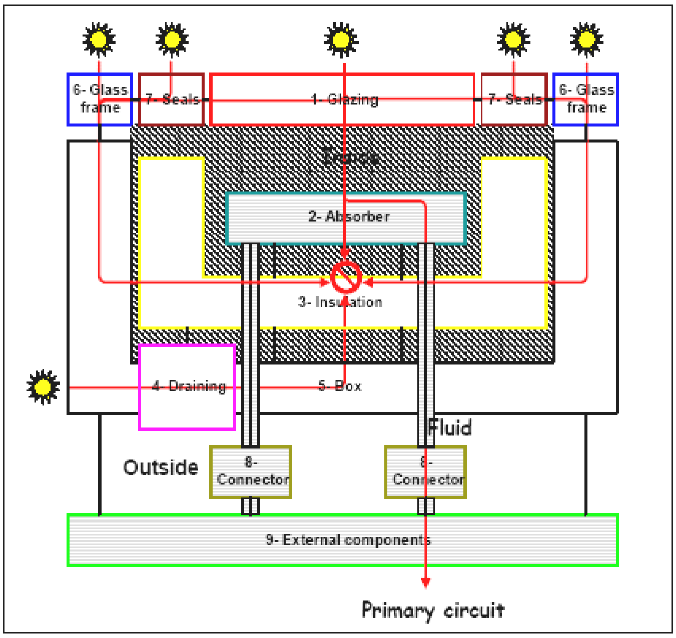


FIGURE 3.
Functional diagram corresponding to the representation of the heat flow evolution through the solar panel system

3.2.1.3 *Process analysis*

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 behaviour of the product in service.

3.2.2 Quantitative analysis

3.2.2.1 *Preliminary analysis of hazards*

The structural, functional and process analysis allows us to describe the structure, the operation and the state of the product at the beginning of its life, once installed in the building.
Then, we search all the potential causes and modes of degradations of the product and his components.

The principle of the preliminary analysis of hazards is that for each function of the product, we search for each component playing a role to ensure this function, then search for failure modes, the causes, and finally the direct (consequences of degradation on the studied component) and indirect effects (consequence of degradation or failure on neighbourhood components).

We distinguish two types of degradation or failure causes: action of climatic factors on a component and unexpected behaviour due to building process. We deduct the first type of causes of the studied product from a data base which defined for each material all the potential climatic factors that present an aggressiveness character.

Nominal behaviour (t=0)

From this graph (figure 3), 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. For each element, we know the environment(s) “in contact” with this element and the environmental agents included in these environments. Knowing the materials of the elements, for each element and each environment, we identify the aggressive environmental agents which could degrade at short or long term the elements and so the product. The stress conditions are summarised in the following table.

	Outside								Inside						Fluid	
	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	Temperature (high, low, cyclic, thermal shock)	Vapour	Infrared radiation, ultraviolet radiation	Pressure	Oxygen, nitrogen	Indoor pollutants	Water	Antifreeze agent
1- Glazing	X	X	X	X			X	X	X		X	X		X		
2- Absorber									X	X	X	X			X	X
3- Insulation	X	X	X						X	X	X					
4- Draining																
5- Box	X	X	X	X			X	X	X	X	X	X				
6- Glass frame	X	X	X	X			X	X	X	X	X	X				
7- Seals	X	X	X	X			X	X	X	X	X					
8- Connectors	X	X	X	X											X	X
9- External elements	X	X	X	X											X	X

Figure 4: Environmental stresses – Initial conditions

Degradation and failure analysis – Failure modes (t > 0)

Knowing the “nominal” functioning of the product, we can now analyse potential degradations and failures. We study the behaviour of the product when a material or element deviates from its normal behaviour.

3.2.2.2 Failure modes and effects analysis

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).

Step 1: Preliminary analysis of degradation - 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 glazing towards high, low and cyclic temperatures, thermal shock, water, rain, snow, hail, ice, infrared radiation, loads, pressure, wind, shocks, vegetation (including moss, lichens, etc) and vertebrate (bird, small mammals, etc). With this methodology, we are able to identify degradations and failures not only due to these "single" factors, but also due to a 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).

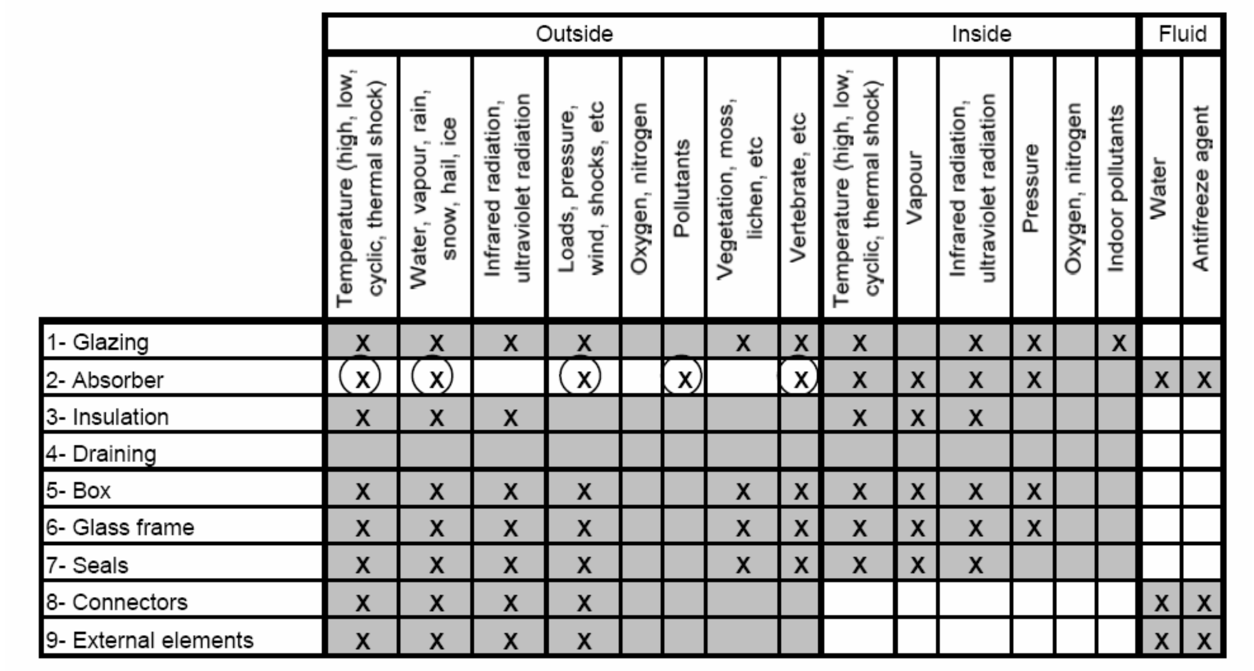
Knowing the element (and its constituent material) as well as the potential stress factors, we identify the potential behaviours, for instance:

- pressure inside the solar panel can lead to the cracking of the glazing,
- infrared radiation can lead to the swell of the coating (one part of the absorber),
- high temperature can lead to the gassing of the insulation,
- vertebrate can provoke the break of the seals,
- …

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

The behaviour or the degradation identified during the first step leads to potential modifications of the environment or the structure. As examples to degradation and failure, the following was observed :

- the dilatation of coil (one part of the absorber) on effect of pressure due to the coolant liquid draw to the loss of solidity of the absorber, but it still fulfils its main functions ("to absorb infrared radiation", "to transmit liquids" and "to diffuse heat"),
- if the glazing has broken, i.e. non ability or partial ability to ensure the "to be watertight" function, the absorber is no more protected against aggressive environmental agents of the outside environment (temperature, water, rain, snow, hail, ice, vertebrate, loads, wind, …). The initial state is updated and becomes a "State 2" condition for which we have to study the effect of temperature, water, rain, snow, hail, ice, vertebrate, loads, wind… on the absorber (Figure 5).



	Outside								Inside						Fluid	
	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	Temperature (high, low, cyclic, thermal shock)	Vapour	Infrared radiation, ultraviolet radiation	Pressure	Oxygen, nitrogen	Indoor pollutants	Water	Antifreeze agent
1- Glazing	X	X	X	X			X	X	X		X	X		X		
2- Absorber	ⓧ	ⓧ		ⓧ		ⓧ		ⓧ	X	X	X	X			X	X
3- Insulation	X	X	X						X	X	X					
4- Draining																
5- Box	X	X	X	X			X	X	X	X	X	X				
6- Glass frame	X	X	X	X			X	X	X	X	X	X				
7- Seals	X	X	X	X			X	X	X	X	X					
8- Connectors	X	X	X	X											X	X
9- External elements	X	X	X	X											X	X

Figure 5: Environmental stresses – State 2

This table summarises the new environmental conditions stressing the product when the glazing had failed (State 2). The new environmental agents to take into account are bordered.
Steps 3 and following ones: Degradation of elements due to updated climatic or use factors
Given the modification of structural or environmental conditions (step 2), the behaviour under new environmental conditions is then studied (action of environmental factors on elements due to structural modifications, mainly loss of protection):

- corrosion of the coating due to water stresses,
- …

Again we iteratively identify the modification of both structure and environment (step 2), then step 3, and so on…
For instance, once the glazing has failed (due to pressure inside stresses) the coating of the absorber is stressed by temperature, water, rain, snow, hail, ice, vertebrate, loads, wind … (step 2). It will fail by corrosion, holing or breaking and then will not fulfil or fulfil partially its "to absorb infrared radiation" function anymore. The infrared radiation will not be absorbed, not be changed into heat source, not be transmitted to the liquid coolant and then to the primary circuit. Consequently the solar panel no fulfil its "to absorb and transmit the heat" function, it will break down.

The second type of causes is stated by experts. They include potential defects, negligence, errors due to materials (quality, chemical reaction between seals and glass frame) mean (unsuitable fixing means), method (surface cleanness …), middle (temperature, organic deposit for absorber), and manpower.

3.3 RESULTS

We thus obtain:
- information about the “Nominal behaviour” of the product in a given environment,
- information on the degradation and failures, expressed as a list of degradation and failures (FMEA table) or a failure tree (with scenarios)

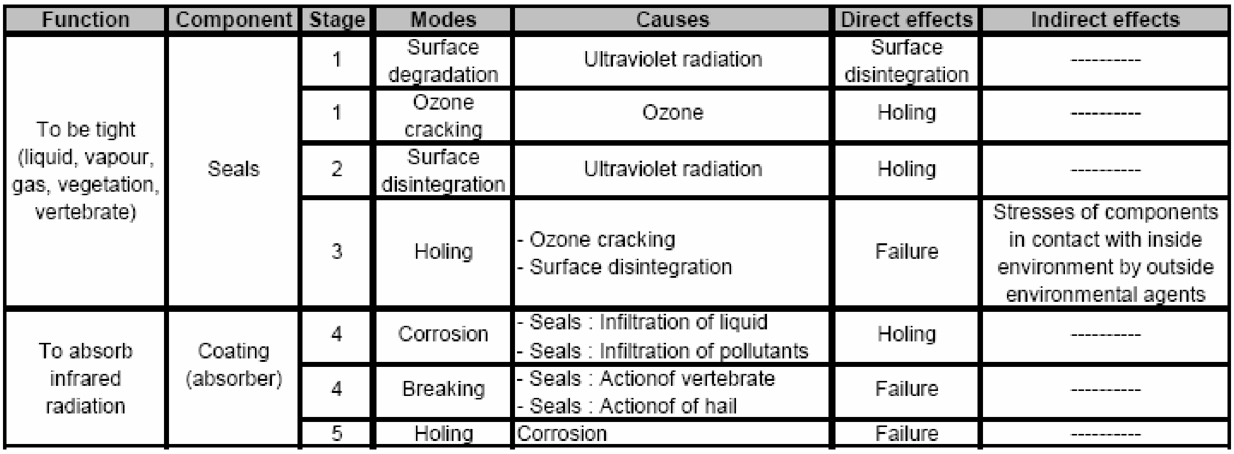
We capitalize the results of the qualitative analysis in a Failure Mode and Effects Analysis (FMEA) table, presented on Table 1.

Functions	Components	Stage	Modes	Causes	Directs effects	Indirect effects

Table 1
Propose 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

In this table are listed for each element, the modes, causes and effects.
In column “Stage”, we distinguish the “single” failures (stage = 1) and the “complex” failures (stage =i, i>1). The “single” failures are directly due to the aggression of the product by its environment, and the “complex” failures result to the order of degradations.

The below table 2 is an extract of a failure modes and effects analysis of a solar panel system. This example aims to highlight the iterative principle of the failure modes and effects analysis. Indeed the stresses of ultraviolet radiation on the seals create a disintegration of the seals surface (step1) which draws to the holing of the seals (step 2). The step 3 is the failure of seals due to holing and that generates the corrosion of coating (step 4) and its failure (step 5).



Function	Component	Stage	Modes	Causes	Direct effects	Indirect effects
To be tight (liquid, vapour, gas, vegetation, vertebrate)	Seals	1	Surface degradation	Ultraviolet radiation	Surface disintegration	----------
		1	Ozone cracking	Ozone	Holing	----------
		2	Surface disintegration	Ultraviolet radiation	Holing	----------
		3	Holing	- Ozone cracking - Surface disintegration	Failure	Stresses of components in contact with inside environment by outside environmental agents
To absorb infrared radiation	Coating (absorber)	4	Corrosion	- Seals : Infiltration of liquid - Seals : Infiltration of pollutants	Holing	----------
		4	Breaking	- Seals : Actionof vertebrate - Seals : Actionof of hail	Failure	----------
		5	Holing	Corrosion	Failure	----------

Table 2
Propose 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

3.3.1 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).

3.3.1.1 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 6 is an extract of an event-driven graph of a solar collector. This graph represents the failure scenario defined below (cf. Table 2).

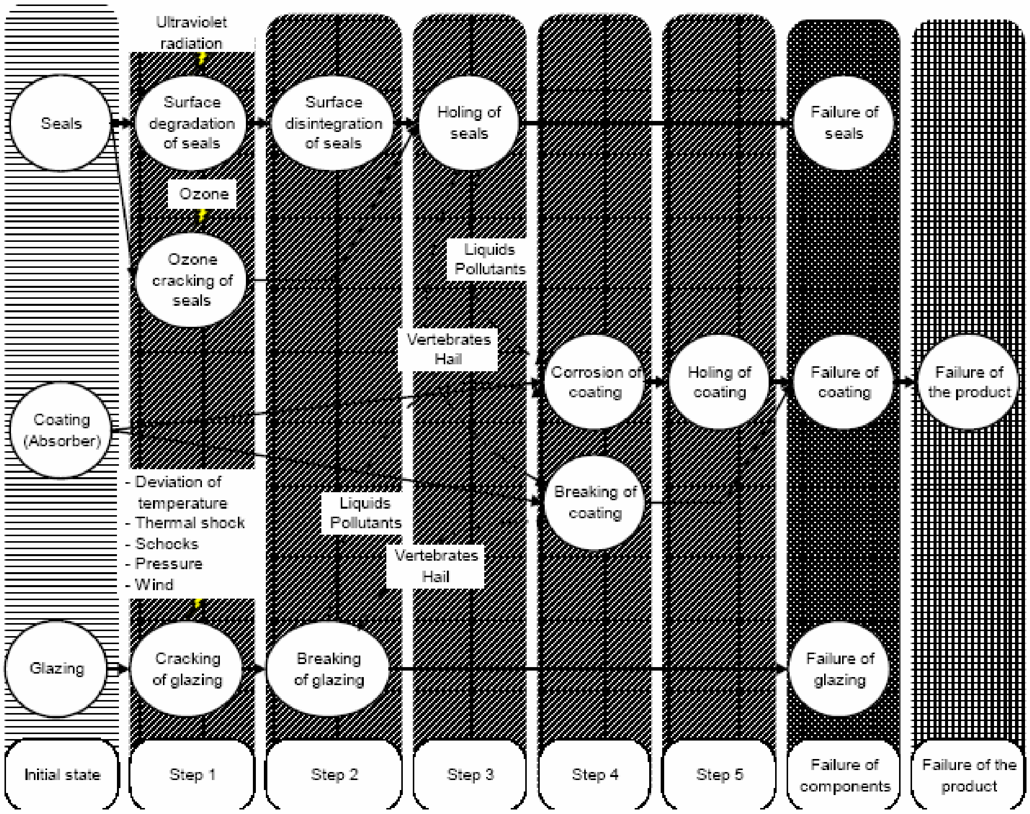


Figure 6 : extract of an event-driven graph of a solar collector

3.3.1.2 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 eventdriven 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.

3.3.2 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 6. 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. For each failure scenario we determinate a criticality level measured by means of three risk indicators: the occurrence probability P (probability to observe the degradation or the failure due to the identified causes), the detection probability D (chance to detect the failure by means of diagnosis, quality control) and the severity of consequences S (consequences of the failure in terms of economic, human … aspects).

The product of these three risk indicators, for each failure scenario, gives us a criticality level. Consequently we can order the different failure scenarios according this criticality level.

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