A MULTIPHYSIC APPROACH TO PREDICT THE DEGRADATION OF A COMPOSITE MATERIAL DUE TO CURRENT INJECTION

Jean Rivenc[1], Richard Perraud[2], Gilles Peres[1], Thierry Zink[3], David Andissac[3], Richard Mills[4], Jacques Cinquin[2]

[1]Airbus Group Innovations, 18 rue Marius Terce, 31025 Toulouse Cedex
[2]Airbus Airbus Group Innovations, 12 rue Pasteur, 92150, Suresnes, France Cedex
[3]Airbus Operations SAS, 316 route de Bayonne, 31300 Toulouse, France
[4] Airbus Operations Ldt, 14M Barnwell House, Filton, Bristol BS99 7AR, United Kingdom
Email: firstname.lastname@airbus.com

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Abstract
In aeronautics industry, the use of composite materials made of carbon fibers, embedded into an organic matrix, has significantly increased during the last decade. Many risks assessments have been made in order to address the case of a current injection into the composite structure, due to an inadvertent contact by chaffing of a cable with the material. Nevertheless, a predictive model is useful in order to study the impact of changes like the network voltage, the line impedance, or the composite thermal and electrical characteristics, in the frame of new designs or for optimization purposes. An approach is proposed in this paper, for predicting the material degradation shape and depth as a function of above parameters. A multiphysics software, COMSOL ®, is used for that purpose. The degradation phenomenology, and the link between electrical and thermal behaviors, are explained in details. The role of the thermo-oxidation, the reaction enthalpy and kinetics, and the material mass loss, are presented and analysed. The consequence of the latter on the material electrical conductivity, is discussed, as well as the strategy for modelling these phenomena. The computed degradation shape and depth, is presented in the case of a composite made of 13 plies, for an injected current under 28VDC. The conditions for obtaining a good matching to experimental results, are discussed. At last, forecoming steps are presented in order to assess the model predictability to other cases like 115VAC or 230VAC.

1. Introduction

In the aeronautics industry, the use of composite materials made of carbon fibers, embedded into an organic matrix, has significantly increased during the last decade. These new materials have brought new challenges. Many risks assessments have been made in order to address the case of a current injection into the composite structure, due to an inadvertent contact of a cable with the material. These studies allowed designing safe aircraft installations.

Nevertheless, a predictive model is useful in order to study the impact of parameters changes, such as the network voltage, the line impedance, the composite characteristics (number of carbon plies, plies sequence…), in the frame of new designs or for optimization purposes. When the model predictability is demonstrated, it allows to significantly reduce the number of tests, which are time consuming and very costly. Hence an approach is proposed in this paper for predicting, by numerical means, the material degradation shape and depth as a function of above parameters.

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As a first step, the degradation phenomenology is analyzed during a current injection into the composite. The impact on the electrical conductivity is studied. Once the physical phenomena are understood, the second step is to define a correct way to describe them: a numerical model is proposed, the main assumptions and key input parameters are given. As a third step, the numerical model is used in order to predict the degradation characteristic: the case of a composite material, made of 13 plies, with a DC current injection, is studied and presented. Results are analyzed and compared to experimental results. At last, main conclusions and perspectives for future work are given. In all the study, the material of interest was a composite material made of an epoxy resin with 13 plies of carbon fibers. The plies sequence was [45/90/-45/0/-45/45/90/45/-45/0/-45/90/45].

2. Characterization of the physical phenomena

2.1. Analysis of the material degradation mechanism

When a current is injected into the composite, a heating of the material occurs by Joule effect. The combination of the temperature and of the environment, activates reactions that lead to the material degradation. Both Differential Scanning Calorimetry (DSC) and Thermo Gravimetric Analysis (TGA) are conventional methods for characterizing the material behavior with temperature. In order to understand better the degradation mechanisms, both characterizations were made under two different atmospheres: a neutral atmosphere made of nitrogen, and reconstituted air (20% oxygen and 80% nitrogen, flow rate 40 ml/min) at atmospheric pressure.

Characterizations were made on a STA 449 F3 JUPITER NETZSCH apparatus. After two initial cycles of vacuum for degassing purpose, a temperature rise of 10°C/min was applied up to 500°C. Results are presented in Figure 1.

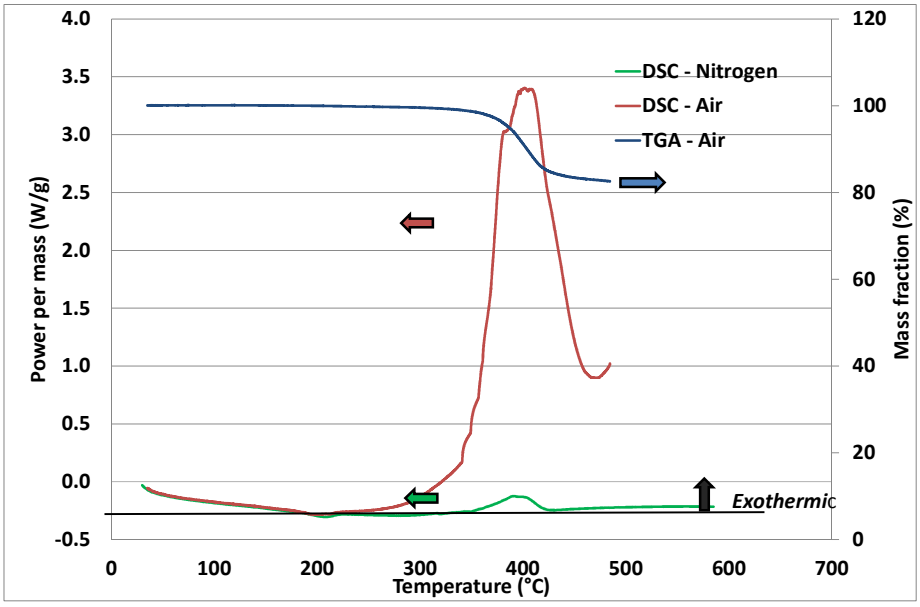

Figure 1. DSC and TGA analysis performed on the composite coupons under nitrogen and air reconstituted (20 % oxygen and 80% nitrogen).

A high peak, starting around 300°C and ending around 470°C, with a maximum around 420°C, was observed under oxygen (air ambient). For the test under nitrogen ambient, a very small peak was observed instead. The exothemic high peak was attributed to a reaction activated by the presence of oxygen in the ambient and made idle under neutral ambient, i.e. to a thermo-oxidation of the composite resin.

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From the TGA signal, it could be observed that this reaction lead to a mass loss of the coupon, which reached 80% of the initial mass at the end of the peak. The explanation was that the thermo-oxidation started from the coupon sides, i.e. the interface between the material and the ambient oxygen, led to a vaporization of the resin, and provoked the coupon mass loss. The observed final loss was lower than the initial resin proportion introduced in the material. A probable explanation was that, only a part of the resin had been degraded by thermo-oxidation, leading to the observed mass loss. The other part had been degraded by carbonization, it had stayed inside the coupon and did not lead to a mass loss.

2.2. Impact of material degradation on the composite coupon electrical conductivity

The impact of material degradation on the electrical conductivity of the composite was studied when a current was injected in a transverse direction into coupons of 40x40mm surface and 3.5mm thickness. The dissipated power in the coupon ranged between 50 and 150W. Observations of the coupon after current injection were made with two microscopes: an Olympus GX71 with analysis auto software, and an Olympus DSX100 with DSX software. An example of observation is presented in Figure 2.

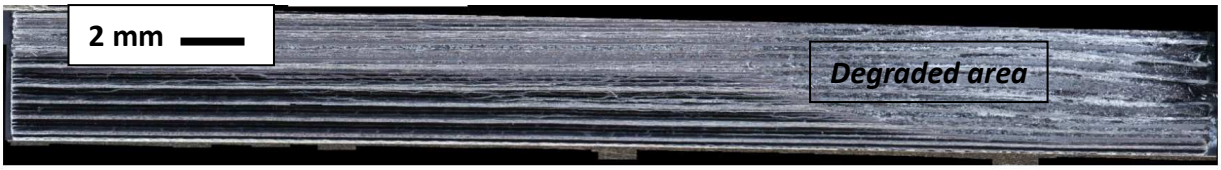

Figure 2. Observation with optical binocular of coupon degradation after current injection.

Two areas in the material bulk, could be identified: one un-degraded area (bottom left in the picture) where plies and inter-plies were clearly visible, and a degraded area. In the latter, carbon plies were not separated by interplies of resin anymore. Bridges of entangled carbon fibers, connecting two adjacent plies, were visible. This suggested that the material conductivity locally increased. Indeed, the carbon fibers conductivity is higher than the interplies conductivity: typically 200S/m between adjacent fibers within a ply, compared to less than 1S/m for interplies [1]. The increase of electrical conductivity could also be explained by resin carbonization, which also created conducting bridges between plies.

The conductivity increase was confirmed by electrical measurements. In some tests, coupon resistance had decreased from 600 mΩ (at initial state) to 150 mΩ (at final state), which indicated that all interplies had been short-circuited by the degradation. Results have been published in [2].

3. Modelling of the electro-thermal degradation

From the previous results, the general frame of the phenomena to be modelled, can be given: the current generates a material heating which, due to the presence of oxygen, generates a thermo-oxidation. The thermo-oxidation generates a mass loss and a re-distribution of carbon fibers in the material, which in turn provokes a change of electrical conductivity. Hence a change in both the current and the dissipated power occurs, and therefore on the temperature. This closed-loop behavior requires to use a tool in which a strong coupling between electrical and thermal effects, is taken into account. For this reason, we decided to use a multiphysics tool, namely COMSOL v5.0 ®, to describe the phenomena. Two modules were used: “Heat transfer in solids” for the thermal part, “Electrical Currents” for the electrical part. The time-dependent solver PARDISO was used. The calculation requested around 50 GB of RAM and the duration ranged between 24h and 48h on a workstation with OS Windows 7, 64 bits, 128 GB RAM and a multicores processor Intel ® Xeon ® CPU E5-1650 v3@3.5 GHz.

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3.1. Modelling of the resin thermo-oxidation and the impact on the electrical conductivity

In the "Heat transfer in solids" module, the sub-module "heat transfer with phase change" was evaluated. After several trials and discussions with the solver editor, we found out that modelled transformations with this sub-module were endothermic. Results from DSC measurements, presented in § 2.1, had shown that the reaction to be modelled was exothermic (thermo-oxidation), which made the sub-module unsuitable to our case.

An alternative method was therefore built:

- the material mass loss due to the thermo-oxidation was described with a conventional equation for a reaction progression [3].

$$dm/dt = -k \times m \times b, \quad (1)$$

where m is the relative mass of the coupon (i.e. the mass divided by the initial mass of the sample, such that $0<m<1$), k is the reciprocal of the reaction kinetics and b is a boolean such as b shifts from 0 to 1 when the temperature becomes greater than 320°C (see § 2.1). The initial conditions were: $m(t=0)=1$.

- the exothermic characteristic of the reaction was described by introducing a local source of heat in the material. The heat power density Q, i.e. the power per elementary volume V, dissipated in the resin due to its thermo-oxidation, is given by:

$$Q(t) = k \times m(t) \times d \times \Delta H \times b, \quad (2)$$

where d is the resin density and ΔH is the thermo-oxidation enthalpy.

Regarding the impact of thermo-oxidation on the interplies electrical conductivity σ_i, it has been proven in § 2.2 that σ_i shifted from the conductivity σ_1 of undegraded interplies to the conductivity σ_2 of adjacent carbon fibers. The shifting occurred for a critical mass fraction m_c, which corresponds to the resin mass loss for which, in the interply, the carbon fibers locally touch each other. For $\sigma_i(m)$, we assumed a linear variation between σ_1 and σ_2. This can be expressed by:

$$\begin{aligned} \sigma_i(m) &= \sigma_2 && \text{for } 0 < m < m_c \\ \sigma_i(m) &= a \times m + b && \text{for } m_c < m < 1 \end{aligned} \quad (3)$$

where a and b are coefficients in order to ensure both the function continuity, and the condition: $\sigma_i(m=1)=\sigma_1$.

3.2. Model presentation and input data

The numerical model of the tested panel is shown in Figure 3, and its main characteristics in Table 1. Current injection was modelled with a cylindrical metallic electrode, in contact with the first carbon ply only (simulation of chaffing). The area (a few mm^2) was representative of the cable in contact with the panel. Current exit was through 8 grounded fasteners (at the right of the panel in Figure 3), modelled by cylindrical metallic electrodes, that completely crossed the panel thickness.

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Table 1. Main input parameters into the numerical model.

Parameter	Value (USI)	Justification
Panel dimensions (m)	0.4 x 0.4 x 210^{-3}	Size of tested panels
Plies conductivity (S/m)	σ_{11}=40 000, σ_{22}=σ_{33} =200	Carbon fibers conductivity [1]
Interplies conductivity (S/m)	Equ () with σ_1=1, σ_2=200 and m_c=0.999	Cf. § 3.1
Voltage (V)	25.8	Same value as test bench
Installation resistance (Ω)	0.07	Same value as test bench
Thermo-oxidation enthalpy (J/g)	3970	DSC processing, sigmoid method
Reaction kinetics k (s^{-1})	0.018	TGA with first-order approximation
Current duration (s)	0.6	Breakers tripping time

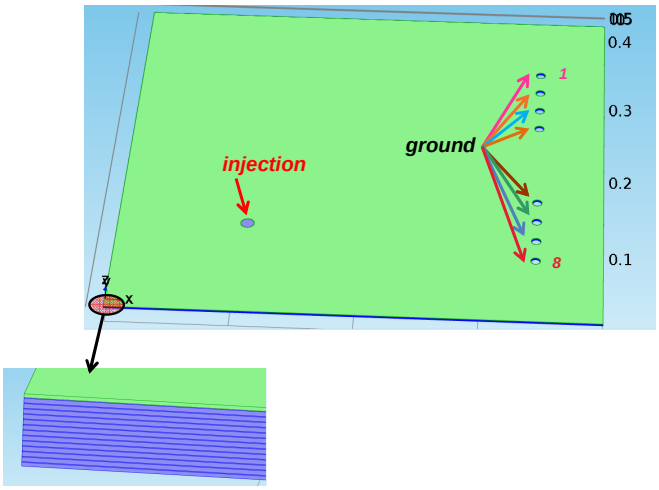

Figure 3. Presentation of the composite panel modelled with the multiphysics software COMSOL.

4. Results and analysis

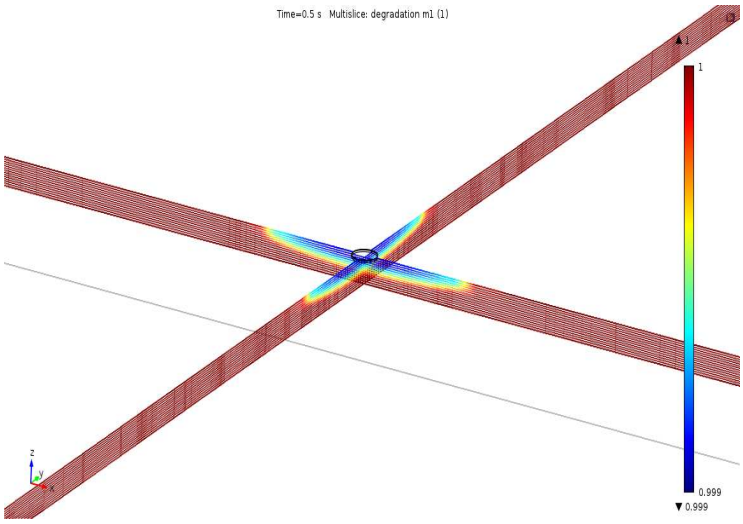

Figure 4. Mapping of the degradation progress (parameter *m*) at t=500 ms.

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The variation of the current and the coupon voltage are presented in Figure 5. The observed voltage decrease and current increase are self-consistent to a decrease of the panel resistance (i.e. an increase of the equivalent conductivity), while the installation resistance is constant. Indeed, the value starts from 440 mΩ (22V/50A) and ends at 120 mΩ (16V/130A).

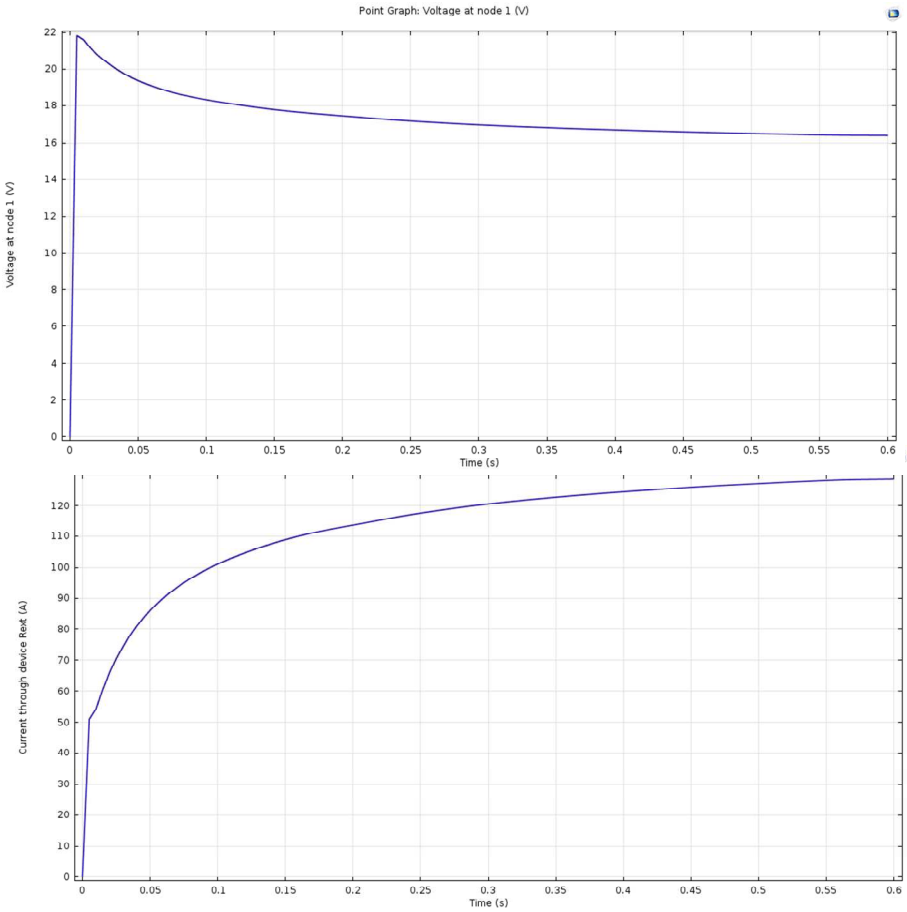

Figure 5. Numerical calculation of the coupon voltage (top) and current (bottom) during degradation.

4.2. Comparison to experimental results

Experimental results, obtained for the same composite panel and electrical conditions, are shown in Figure 6.

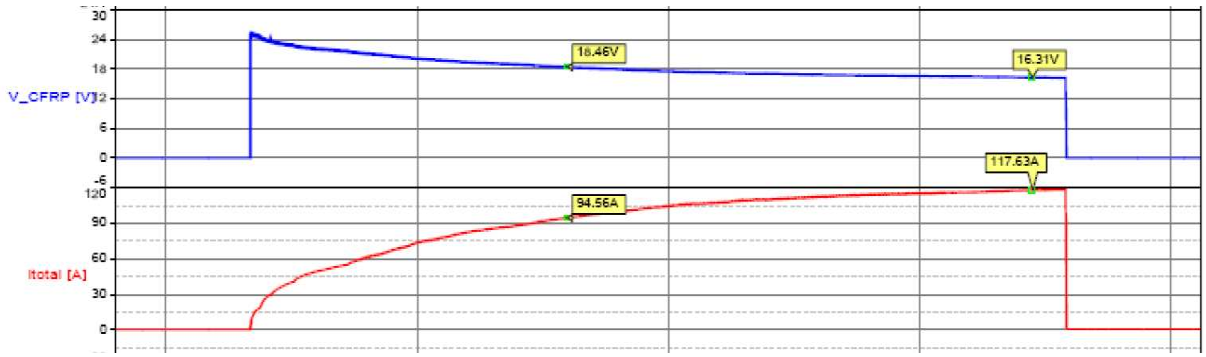

Figure 6. Measurement of the coupon voltage (top) and current (bottom) during degradation.

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It can be noticed that currents and voltages, computed by the model, are similar to experimental ones. Results are not strictly identical, because the source voltage decreased during the experiments, due to the generator regulation. This point had not been taken into account in the simulations. Another interesting point is that the obtained degradations, from an experimental point of view, had a conic shape around the injection point, which was in accordance to the numerical results.

4.3. Results analysis and discussion

It is observed, both from experimental and numerical results, that the panel resistance tends to stabilize during the test. This means that, at any given instant, the degradation does not progress anymore. This fact can be explained by considering an elementary volume of undamaged resin, close to the growing degraded area. In this volume, the temperature at steady-state is a function of the local dissipated power. As explained, the damaged area is more conducting than the undegraded interplies. Therefore, as the degradation progresses, it locally creates a conducting bridge between the two adjacent plies. Near this bridge, the voltage supported by the resin volume collapses, which means that the local dissipated power also collapses. When this power collapse is such that the temperature at steady-state becomes lower than the actual temperature, the temperature starts to decrease. When the quantitative value becomes lower than the temperature of thermo-oxidation activation, the reaction aborts and the damage can not progress anymore. This physical phenomenon is reproduced in our mathematical modelling. When the local temperature becomes lower than the reaction activation, the boolean *b* goes back to 0. According to Equ (1), *dm/dt* cancels, which means that $m(t)$ becomes constant and is "latched" to its last computed value.

As shown in § 2.1, processing of TGA measurements led to a thermo-oxidation kinetics of: $1/k$=541 s, i.e. much slower than the experiment duration (0.6s). This result means that the resin mass loss is expected to be negligible during the experiment. Nevertheless, experimental results show that a degradation indeed occurs within 600ms, which can be seen both from the resistance variation, and from the panel inspection after the test. This tends to confirm that a very small loss of resin is sufficient to create the effect of conductivity increase. Whether the chosen value of 0.1% is realistic or low, is questionable. However, this result is consistent to the fact that a very low mass fraction provokes a conductivity change, which is experimentall observed. This also suggests that there is a strong link between the reaction kinetics and the critical mass loss. For instance, if the reaction kinetics was of the same order as the experiment duration (100 ms for instance), then a critical mass loss of 0.1% would not explain the experimental results; a value of 50% would make more sense.

5. Conclusions and future work

The mechanism of composite degradation during a current injection has been understood and confirmed by experiments. The current injection provokes a temperature rise by Joule effect. When the resin temperature reaches 320°C, the presence of oxygen in the environment initiates a thermo-degradation, from the coupon surface, and a loss of resin. In the areas where degradation occurs, the electrical conductivity locally increases. This mechanism can be explained by the removal of the resin enabling more contacts between conducting carbon fibers, and / or by the carbonization of the resin, which creates conducting bridges between two adjacent carbon plies. In our case, the conductivity increase provoked a decrease of the local dissipated power and a spontaneous abortion of the degradation mechanism.

With the use of a multiphysics numerical model, and a strong coupling of electrical and thermal effects, the shape and the depth of the degradation has been computed as a function of the composite morphology (number of plies and interplies, plies sequence, etc…), the current injection points, and the aircraft installation (network voltage, installation resistance and breakers tripping time).

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The variation law of the interplies conductivity as a function of the resin mass loss, had to be adjusted to one experimental result, because this parameter was not accessible by measurement. In order to assess the model predictability, the next step will be to compute the degradation on different cases (e.g. 28VDC with other plies sequences, 115VAC, 230VAC…), and to compare results to experimental ones.

Some phenomena, neglected so far, might have to be taken into account in the future. The network voltage has been assumed to be constant. The actual decrease, due to the generator limitation, may be significant in AC, as well as the inductance loop of the external circuit. Also, the reaction kinetics *k* has been assumed to be constant. In reality, TGA measurements showed that the mass loss was not a first order (exponential) shape. In order to take the reaction activation energy into account, the value of *k* has to be a function of temperature, with a maximum at the temperature of the DSC peak.

If the model predictability is demonstrated, it will allow to assess, for new materials, voltages or installations, whether the damage resulting from a short circuit is still acceptable, and has no consequence on the installation.

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