Plenary 4:

Reliability in Power Electronics Modules

A Challenge to Define Tools and Methodologies in Phase with the Performances of Power Chips and the Constraints of Use

Introduction

Reliability: A context of complexity

Tools and Methodologies

Experimental approach

Numerical approach

Perspectives

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Introduction

Evaluation of the reliability: A context of complexity

Tools and Methodologies

Experimental approach

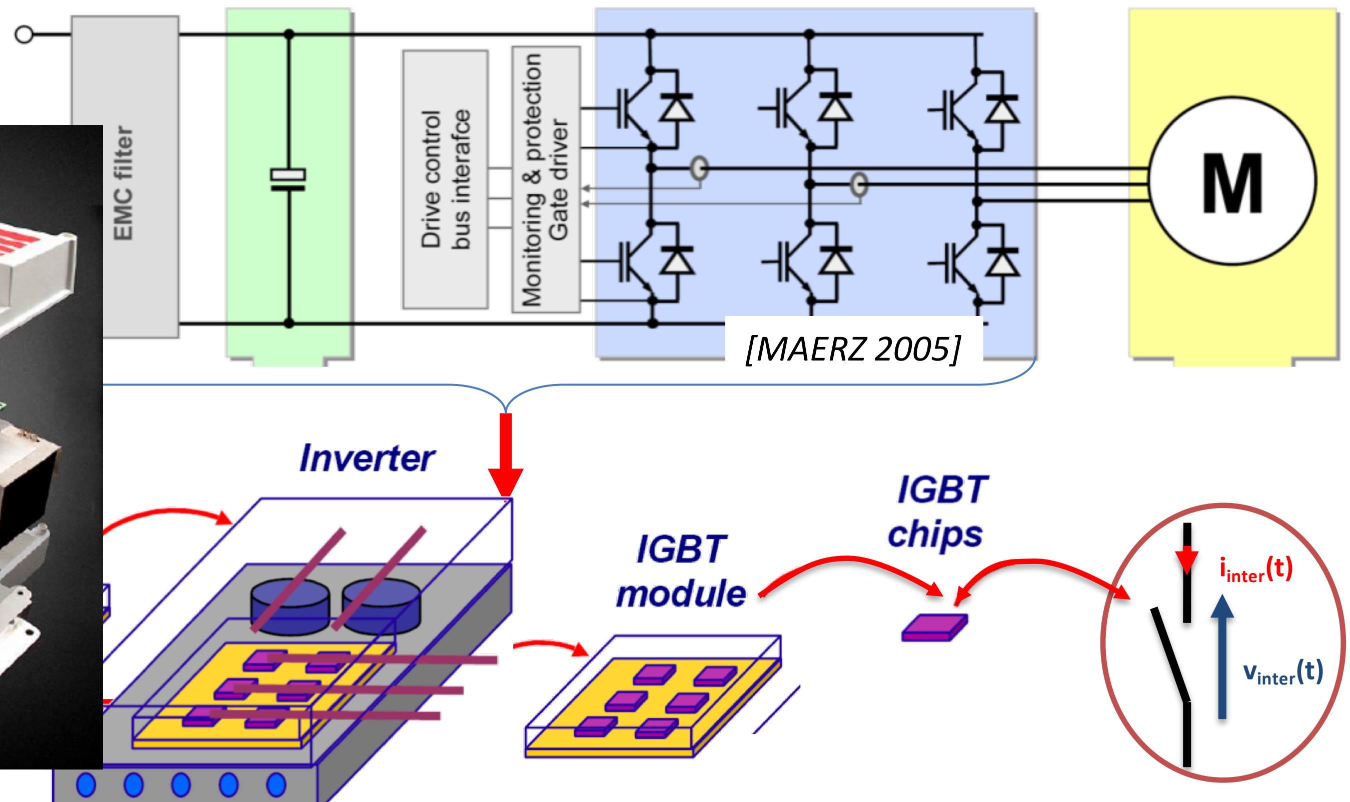
Numerical approach

Perspectives

- Evaluation of the reliability:
  - ➔ A complex design: from nanometer scale to centimeter scale
    from metals to polymer materials through composite ones

<u>For example</u>:

[SEMIKRON]

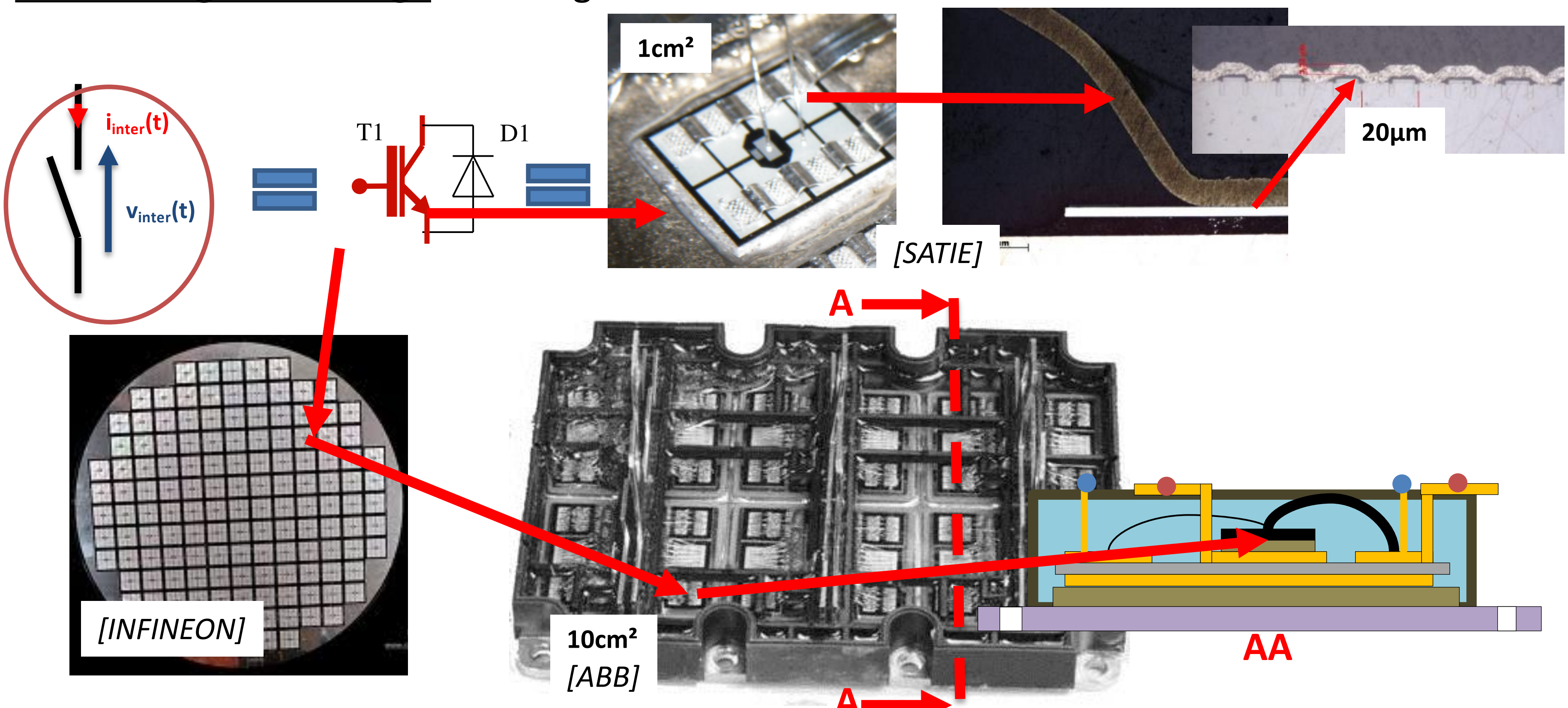


[MAERZ 2005]

RELIABILITY IN POWER ELECTRONICS : INTRODUCTION

- Evaluation of the reliability:
  - ➔ A complex design: from nanometer scale to centimeter scale
    from metals to polymer materials through composite ones

Power integration design: 2D integration as a standard (active parts on the power assembly)



Reliability in Power Electronics : Introduction

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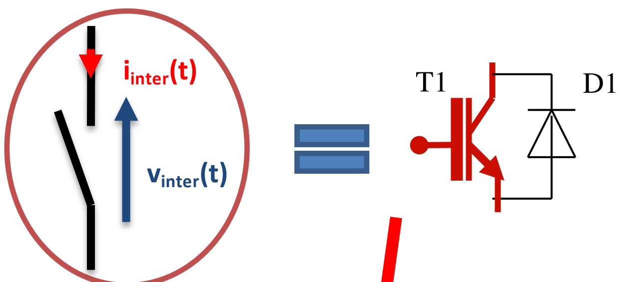
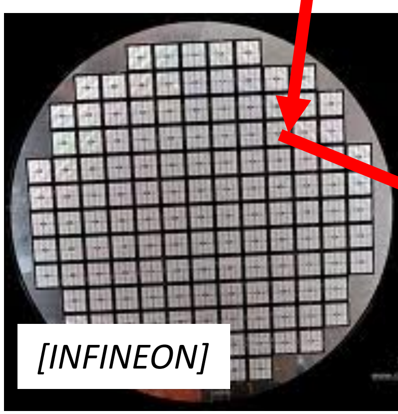
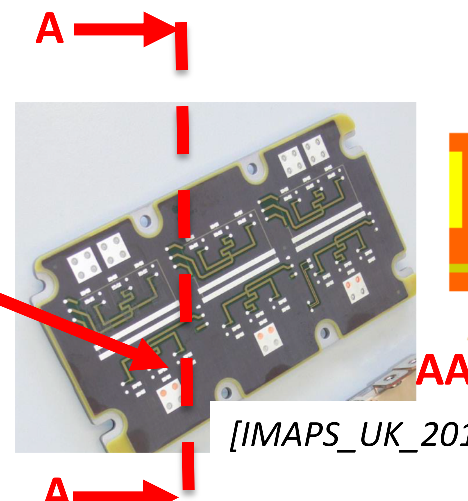
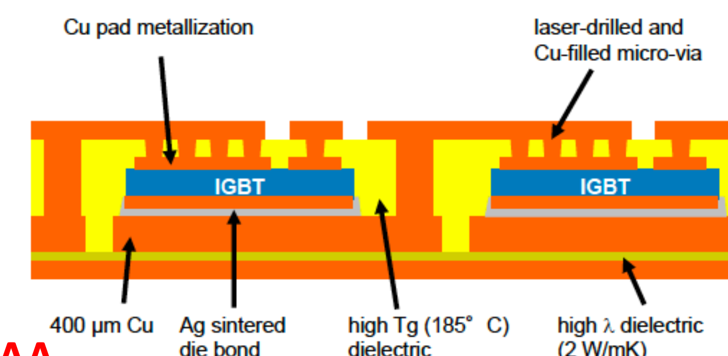
<u>Power integration design</u>: Embedding (active parts in the power assembly)





[INFINEON]





[IMAPS_UK_2016_Ostmann]

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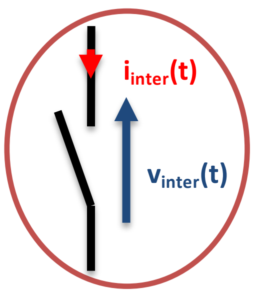
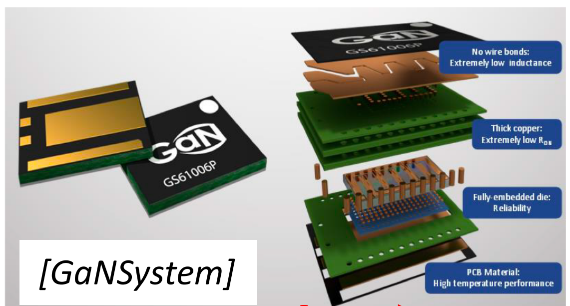
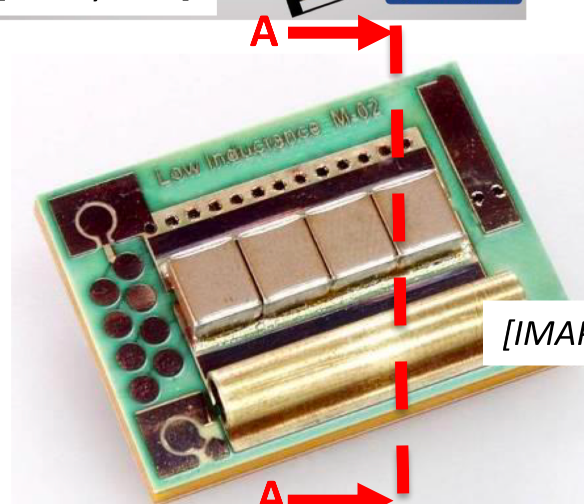
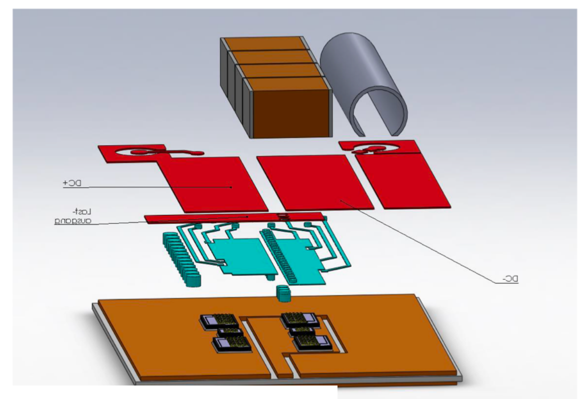
<u>Power integration design</u>: Embedding[2] (active parts and the power assembly)



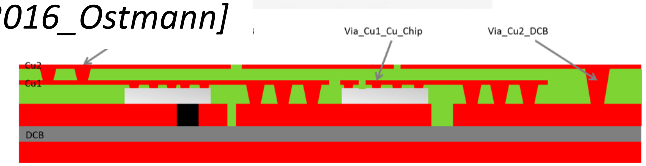


[GaNSystem]





[IMAPS_UK_2016_Ostmann]



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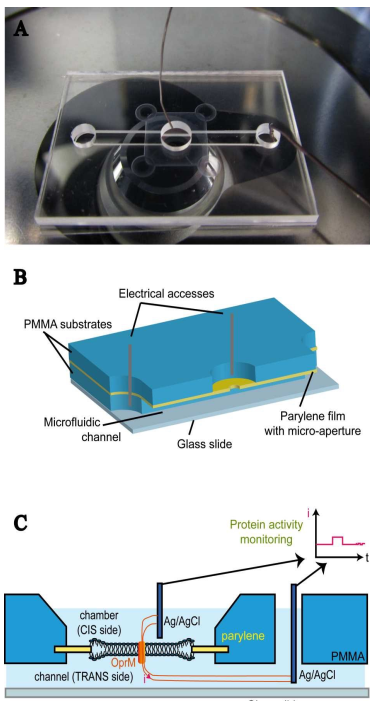
RELIABILITY IN POWER ELECTRONICS : INTRODUCTION

- Evaluation of the reliability:
  - ➔ A complex design
  - ➔ A complex functional environment: everywhere electric energy can be used
    from biology to space environment
    from mission profile to operative conditions



[SATIE]

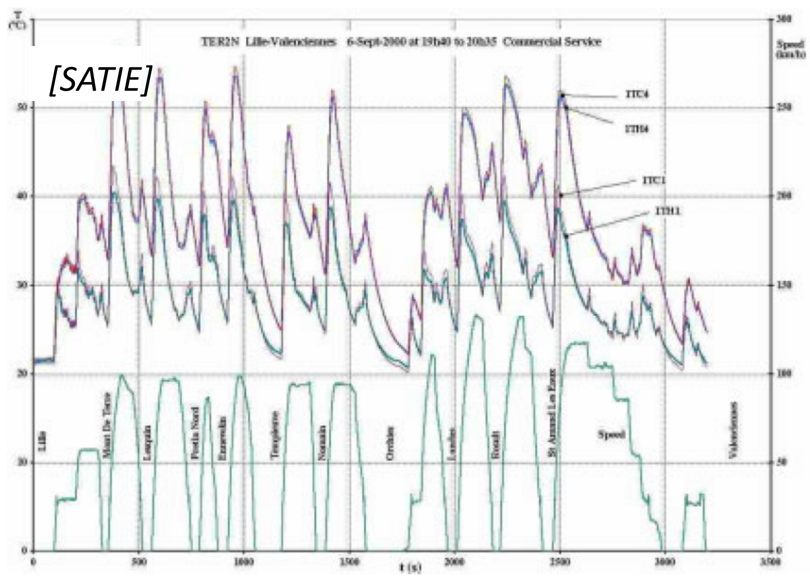
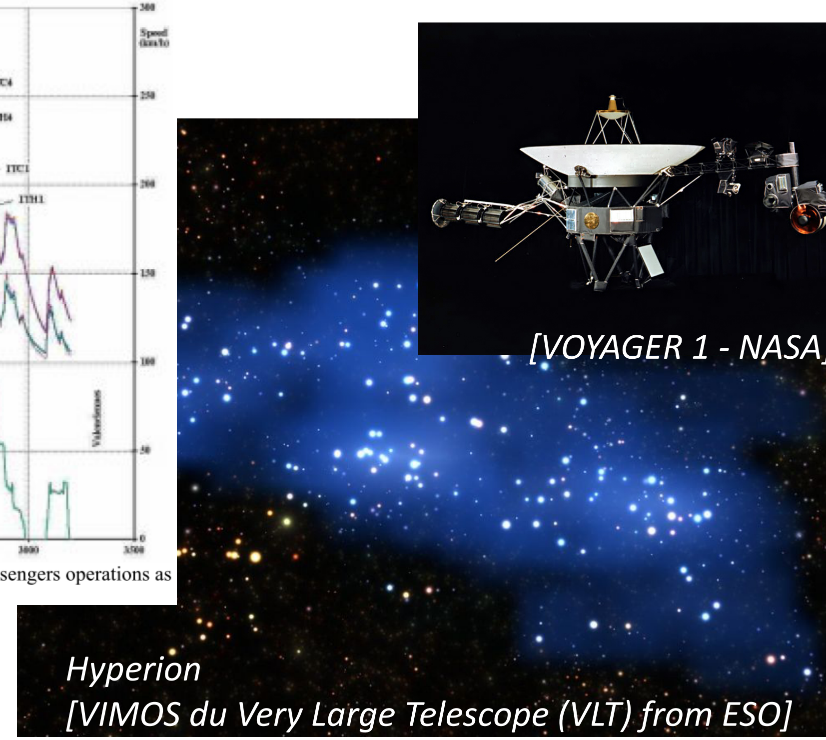


Fig. 6: The dynamic of the thermal stresses are measured during the same passengers operations as figure 4, from Lille to Valenciennes.



Reliability in Power Electronics : Introduction

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  - → A complex functional environment
  - → A complex association of constraints: electrical, thermal , mechanical …chemical

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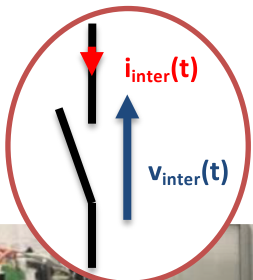
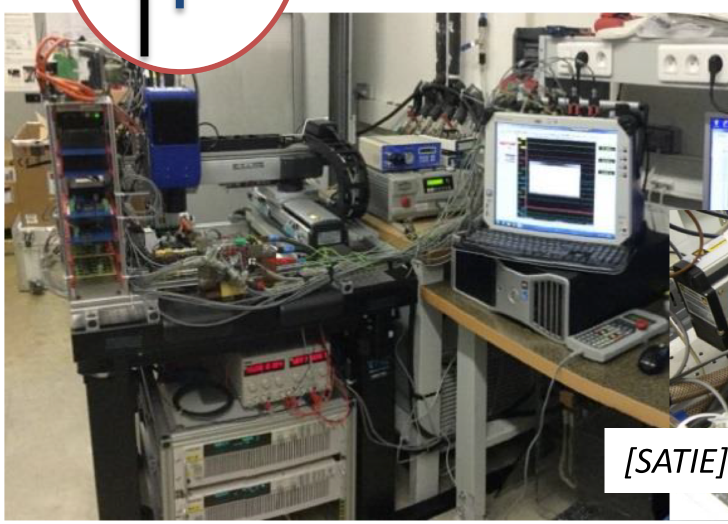
    Power density (Si 100 W/cm² → WBG 1000 W/cm²)

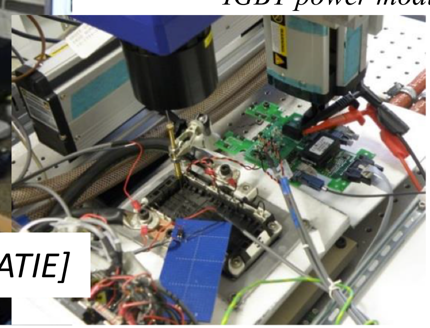
    Current density(Si 100 A /cm² → WBG 300 A/cm²)

    Temperature (Si 175 °C → WBG 250 °C) and large gradients

    δi/ δt, δv/ δt …







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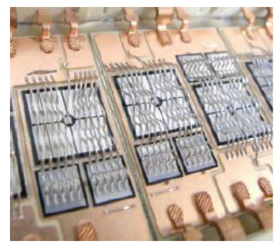
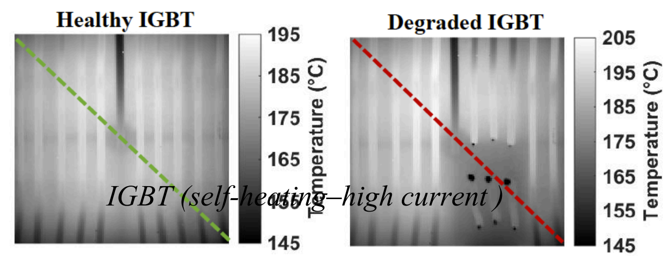
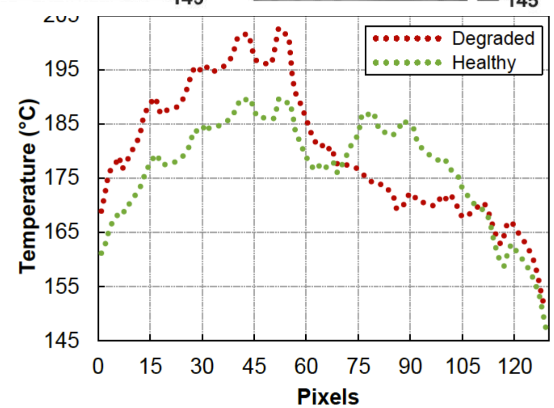


IGBT power module FS200R12PT4



IGBT (self-heating–high current)



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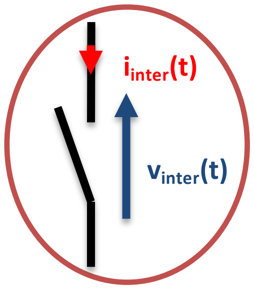

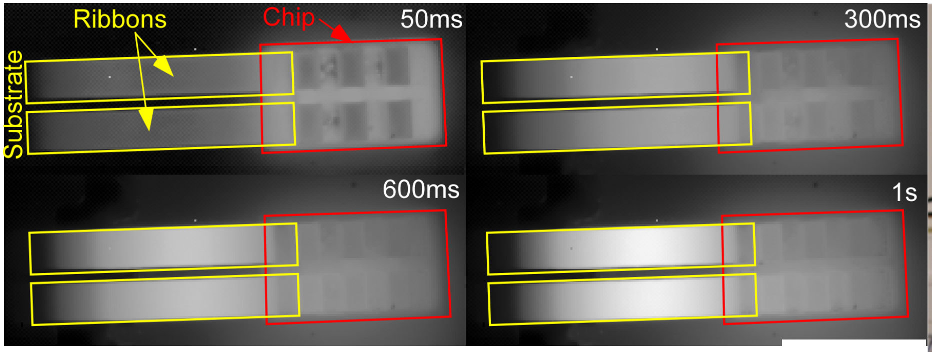

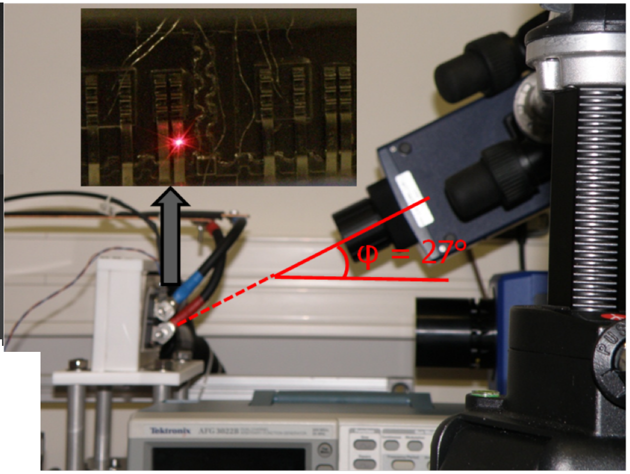

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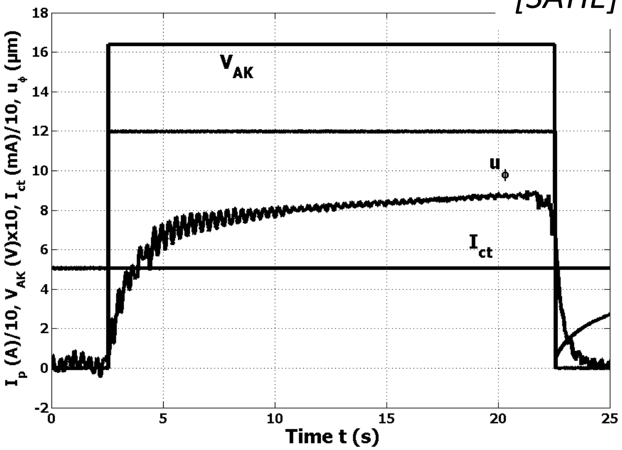

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Completed by:

- ➔ Long expected lifetime
- ➔ Relatively expensive devices

1 year too late,
nevertheless an opportunity to celebrate the 21 years of the first European mission.

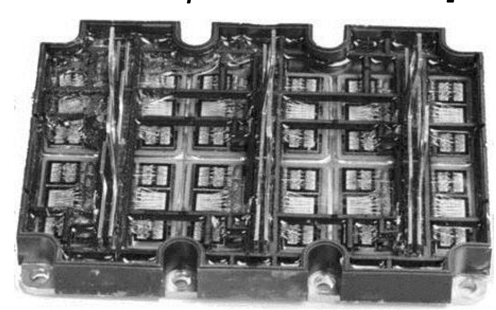
After the Swiss LESIT project (1993-1995), the **RAPSDRA** European project (FP4) (1996-**1998)**:
Reliability of advanced high power semiconductor devices for railway traction applications,

IGBT press pack [ABB]

From 3D electrothermal conception
to 2D standardised solution

From large surface contact
to thousands of wires

IGBT power module [ABB]



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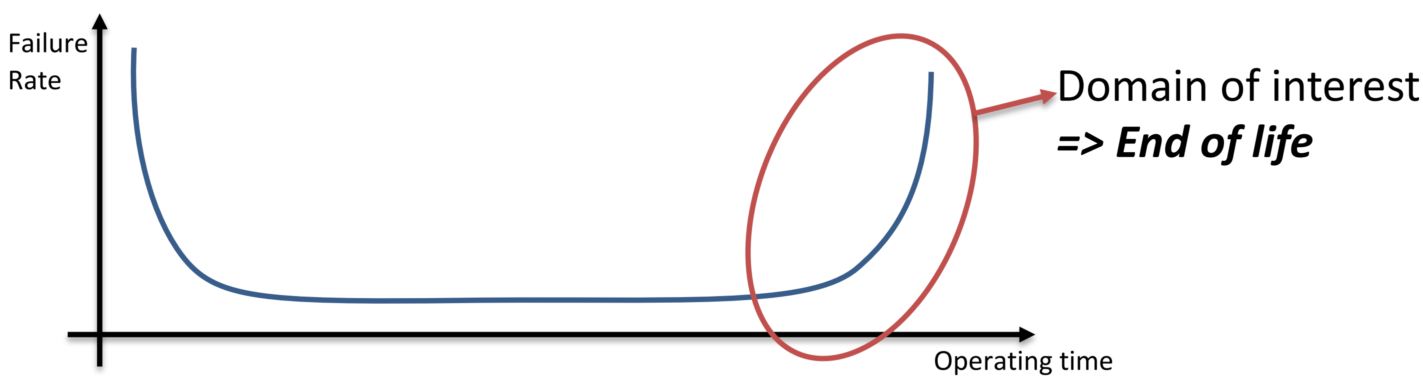
Difficulties to realise an evaluation of the reliability with the statistical approach

➔ Understand the physical mechanisms of the damages in order to improve the availability, reliability and robustness of power modules



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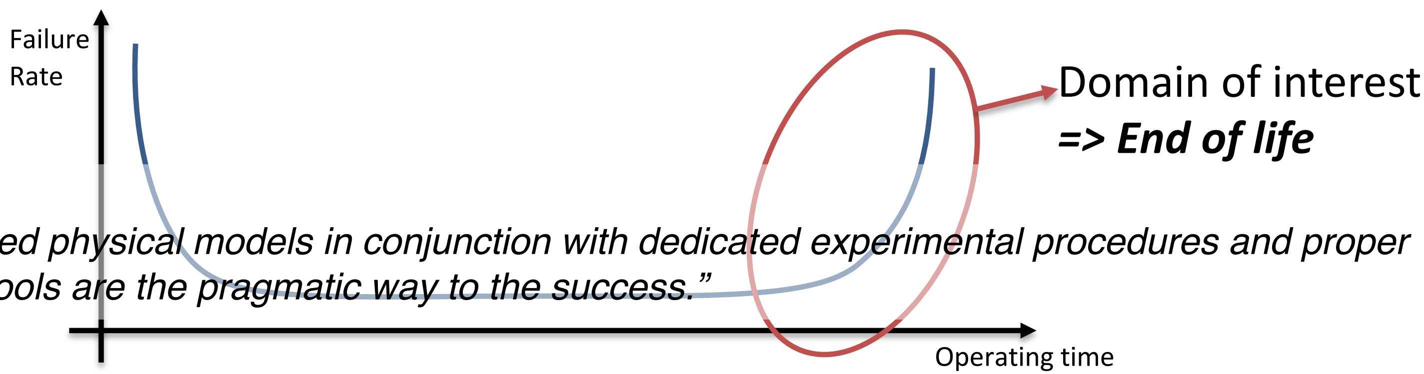

CIAPPA_2005:
"Purpose-oriented physical models in conjunction with dedicated experimental procedures and proper computational tools are the pragmatic way to the success."

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Evaluate the reliability of power electronics: A context of complexity
Industrial and academic actors propose Tools & Methodologies

Introduction

Reliability: A context of complexity

Tools and Methodologies

Experimental approach

Numerical approach

Perspectives

Reliability in Power Electronics : Tools & Methodologies

- Global approach to evaluate the reality of the power module under condition of use

  Evaluate the impacts of constraints on the power electronics technologies:

  - Identification of the main damage mechanisms
  - Identification of the main ageing factors

  Offer a solution to improve the availability, reliability and robustness:

  - Identification of the rules of design
  - Better understanding of the behaviour
  - Representative law for an estimation of the MTBF

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Experimental:

Accelerated Thermal Cycling Tests (ATCT): thermal, mechanical

Accelerated Power Cycling Tests (APCT): electrical, thermal, mechanical

In correlation with

Numerical:

Modelling behaviour under constraints

Modelling the law of lifetime before failure

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- Accelerated Ageing Tests:

  Historically: Railway application (30 years of lifetime expected)

  Relatively low variation of the junction temperature
  Large number of bonding wires
  Low current density
  Low power density

➔ Constraints must be representative from the point of view of the conditions of use.

  ➔ Electro-thermomechanical constraints as the main failure mechanisms

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<u>Experimental:</u>
Accelerated Thermal Cycling Tests (ATCT): thermal, mechanical
Accelerated Power Cycling Tests (APCT): electrical, thermal, mechanical

"…focused on reliability and identified failure modes and failure indicators due to thermal cycling generated by the urban traction working conditions".
*[*G. Coquery*, M.Piton**, R.Lallemand*, S Pagiusco**, A.Jeunesse, Thermal stresses on railways traction inverter IGBT modules : concept, methodology, results on sub-urban mass transit Application to predictive maintenance, EPE, 2003]

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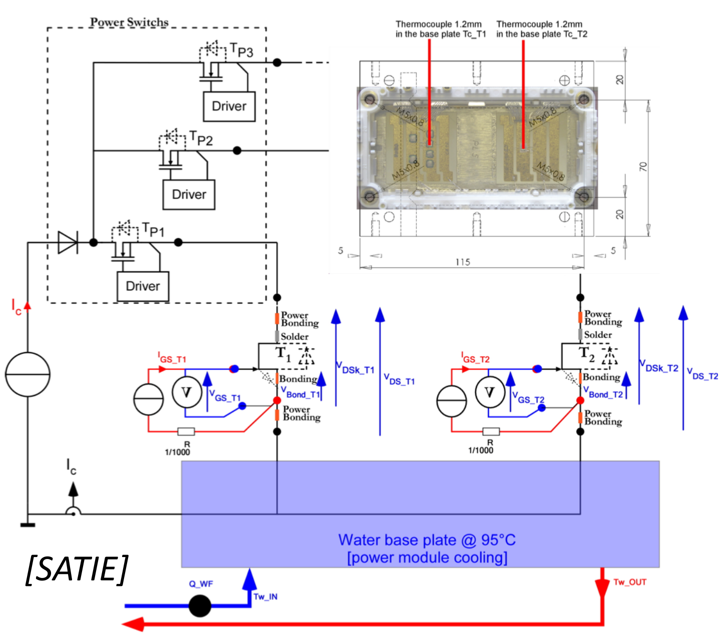
=> Tools and Methodologies

Reliability in Power Electronics : Tools & Methodologies

- Accelerated Power Cycling Tests (APCT)

Conditions for conventional DC power cycling test:

- Periodic power dissipation and cooling phase:
  - Low voltage, direct on-bias operating condition (without switching)
    - Control $Ton_{Dissipation}$ versus $Toff_{Cooling}$
    - Control electrothermal conditions for a specific technology



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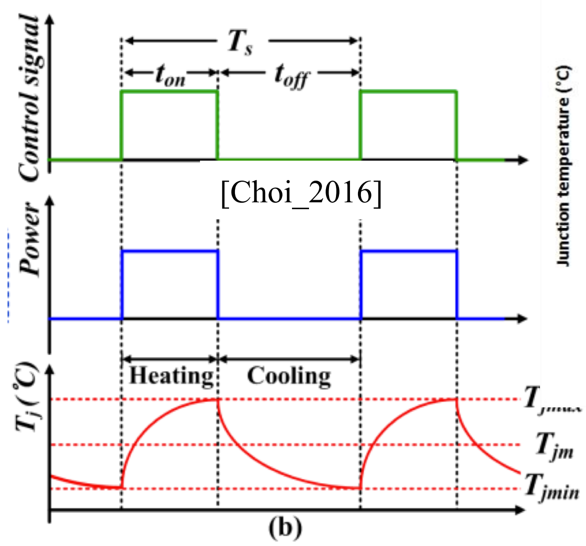
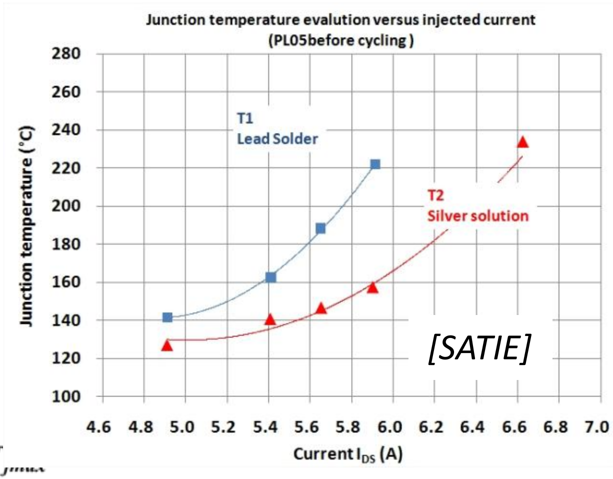
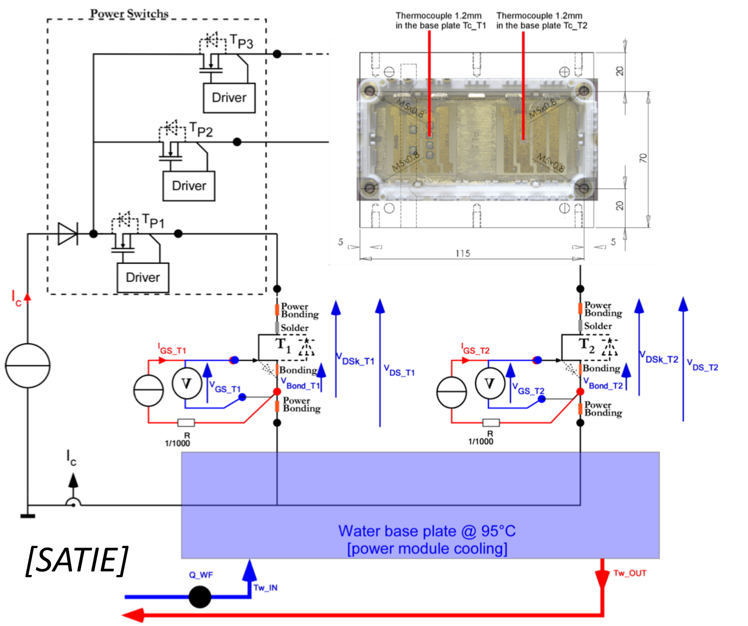


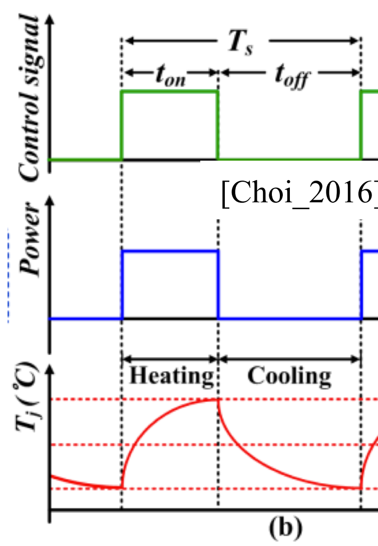


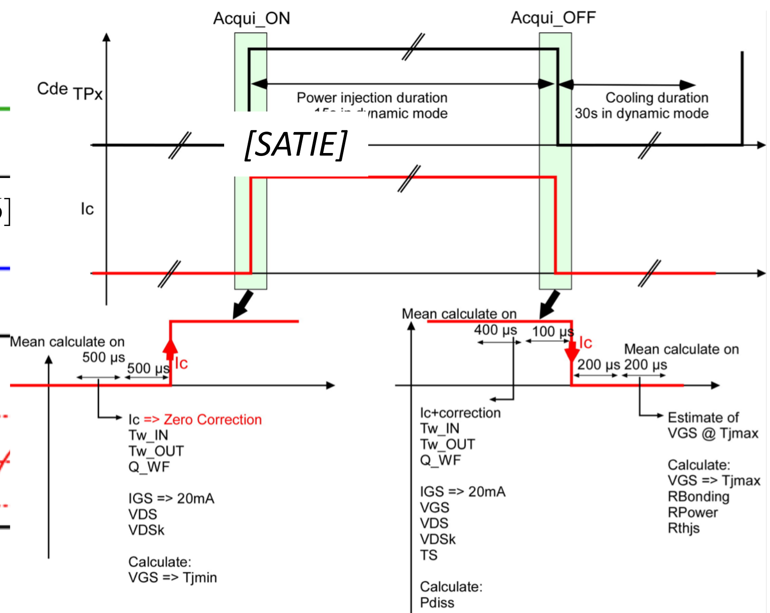
- Accelerated Power Cycling Tests (APCT)

  Conditions for conventional DC power cycling test:

  - Periodic power dissipation and cooling phase:
    - Low voltage, direct on-bias operating condition (without switching)
  - Periodic evaluation of constraints and damage indicators:
    - Specific protocol used to extract indicators
    - Specific threshold levels of damage indicators







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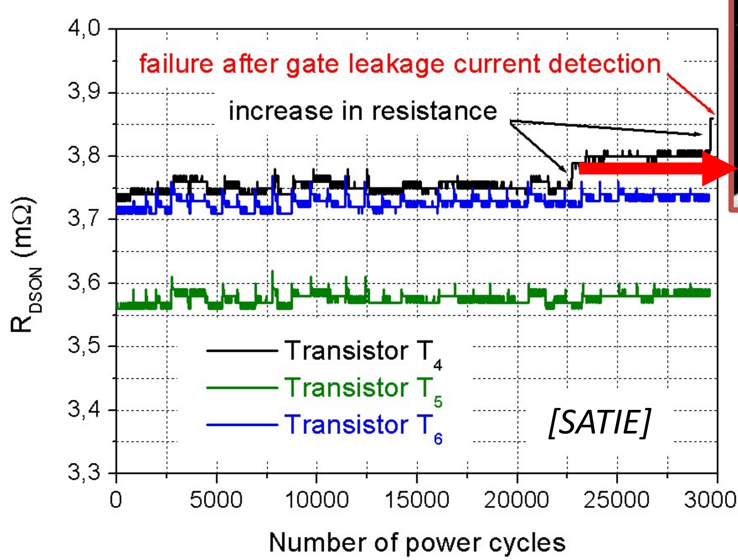

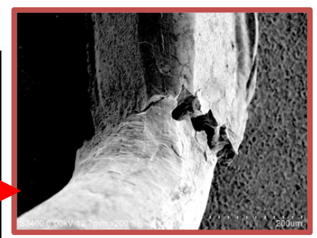

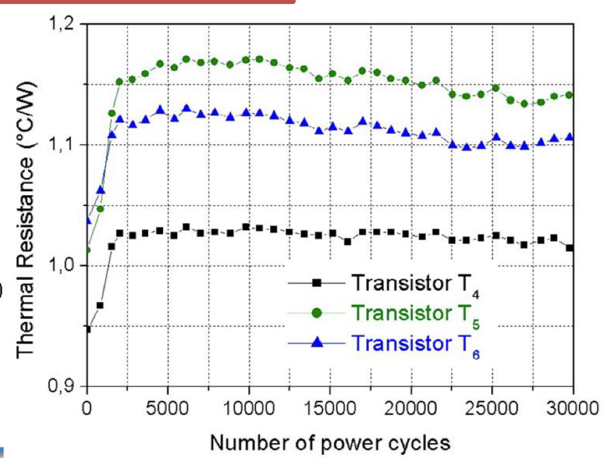

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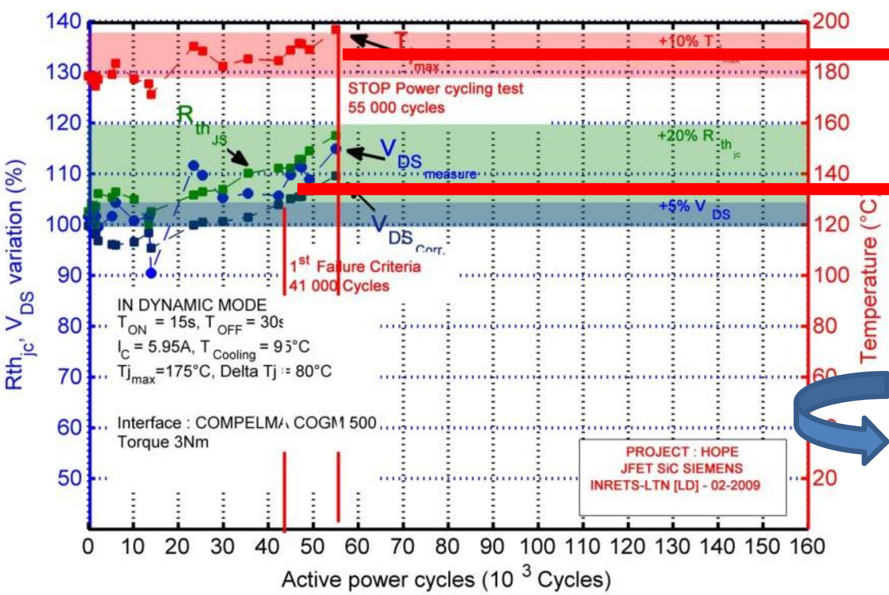
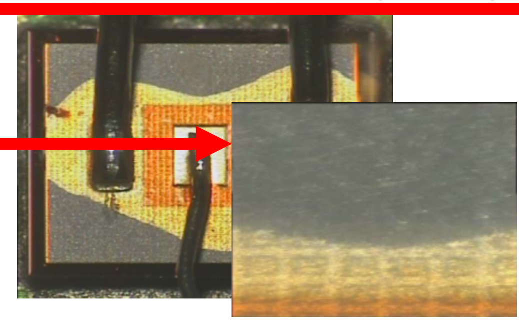
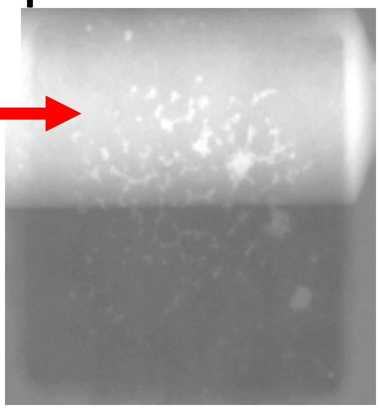
  - Low voltage, direct on-bias operating condition (without switching)
- Periodic evaluation of constraints and damage indicators:
  - Specific protocol used to extract indicators
  - Specific threshold levels of damage indicators **+ adapted criteria**

~150 A/cm² *54 A/cm² (IGBT Si)*

~1000 W/cm² *100 W/cm² (IGBT Si)*







Damages of standard technologies

- Metallization: aluminium reconstruction
- Solder: not a conventional delamination as expected

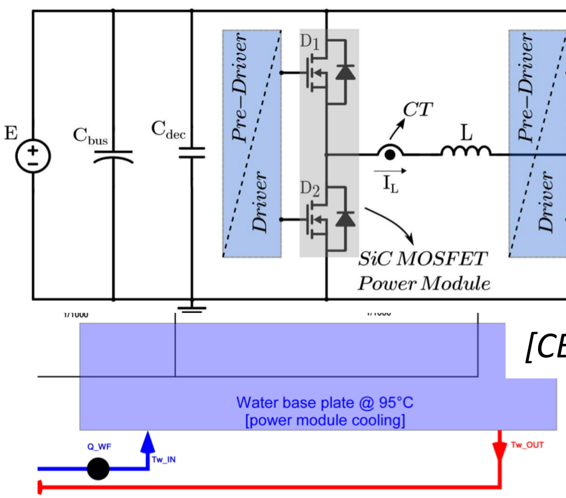
- Accelerated Power Cycling Tests (APCT)

Improve representativeness: Power cycling test close to operating conditions:

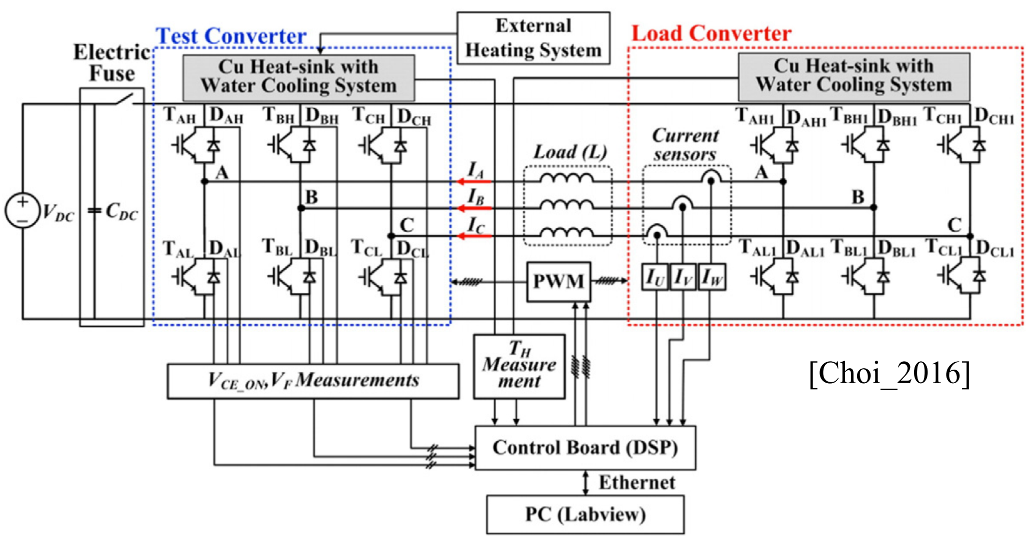
- Periodic power dissipation and cooling phase:
  - Power module and drivers are under test
  - Switching on power dissipation and current density (cf. WbG)
  - Cooling system contribution with thermal coupling effects

A lot of parameters and contributors

- Can demonstrate realistic damages (not the power module only)



[CEA-G2Elab-SATIE]



[Choi_2016]

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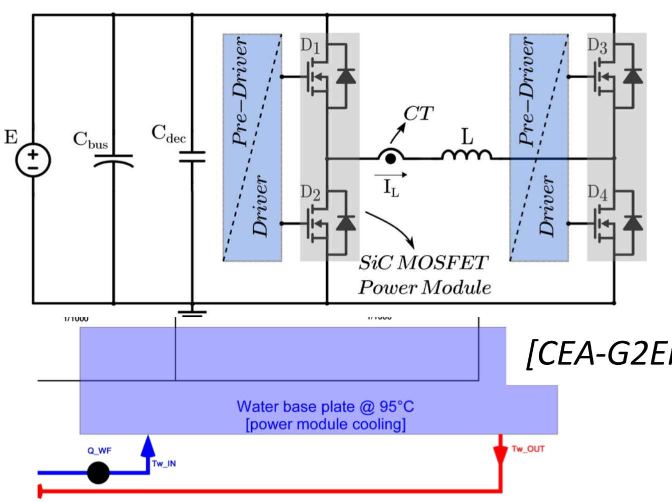
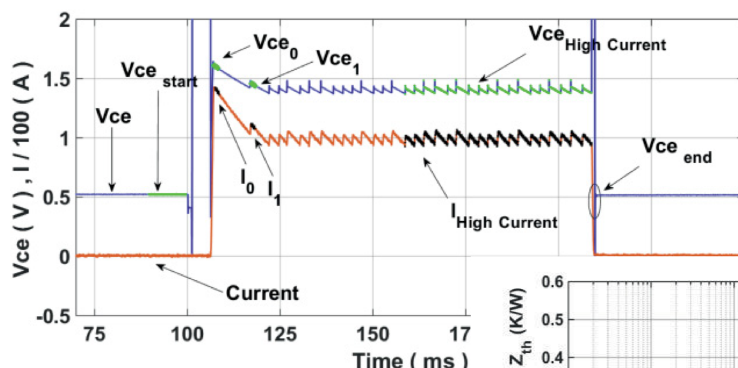
A lot of parameters and contributors:

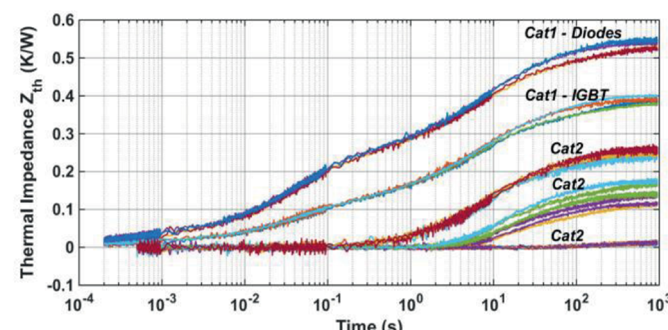
- Can demonstrate realistic damages (not the power module only)
- Indicators of constraints and damages adapted to operating environment

  + Criteria



[CEA-G2Elab-SATIE]





Reliability in Power Electronics : Tools & Methodologies

- Global approach to evaluate the reality of the power module under conditions of use

Evaluate the impacts of constraints on the power electronics technologies:

Identification of the main damage mechanisms

Identification of the main ageing factors

Propose solution to improve the availability, reliability and robustness:

Identification of the rules of design

Better understanding of the behaviour

Representative law for an estimation of the MTBF

Experimental

Accelerated Thermal Cycling Tests (ATCT): thermal, mechanical

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In correlation with

Numerical:

Modelling behaviour under constraints

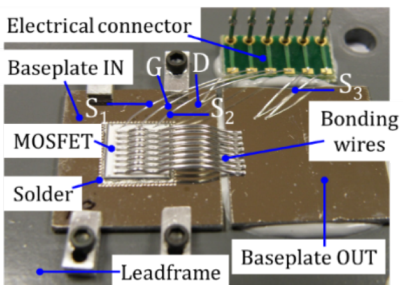
Modelling the law of lifetime before failure

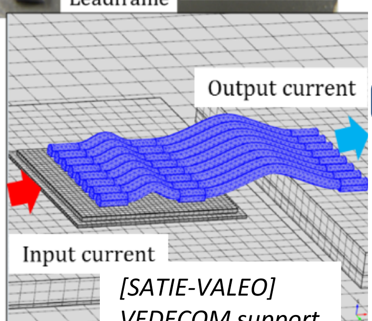
- Modelling behaviour of power module under constraints:
  - → Large scale factor from square micrometers to square centimeters
  - → Complex association of the multiphysics constraints
  - → Complex association of semiconductor physics and the classic one

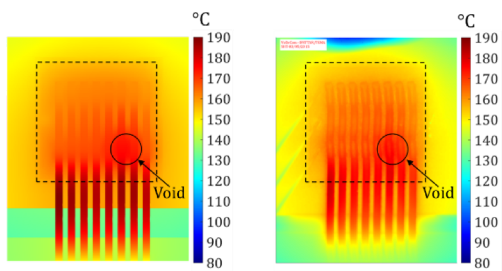
[SATIE-VALEO]
VEDECOM support

- Modelling behaviour of power module under constraints:
  - → Large scale factor from square micrometers to square centimeters
  - → Complex association of the multiphysics constraints
  - → Complex association of semiconductor physics and the classic one

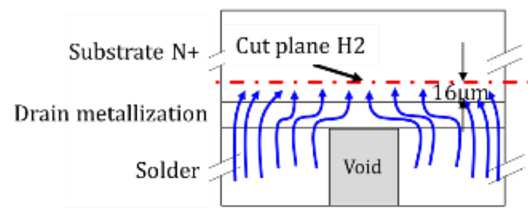
Modelling and simulation conditions have to be representative:
- → Multiphysics coupling in accordance with the objectives of the study
- → Details of the modelling in accordance with the objectives of the study
- → Cooling system modelled with the respect of his static and transient performances







(a) Simulation (b) Measurement



Thickness (µm)	Resistivity (Ωm)
228	1.E-4
1	1E-8
246	1.3E-7

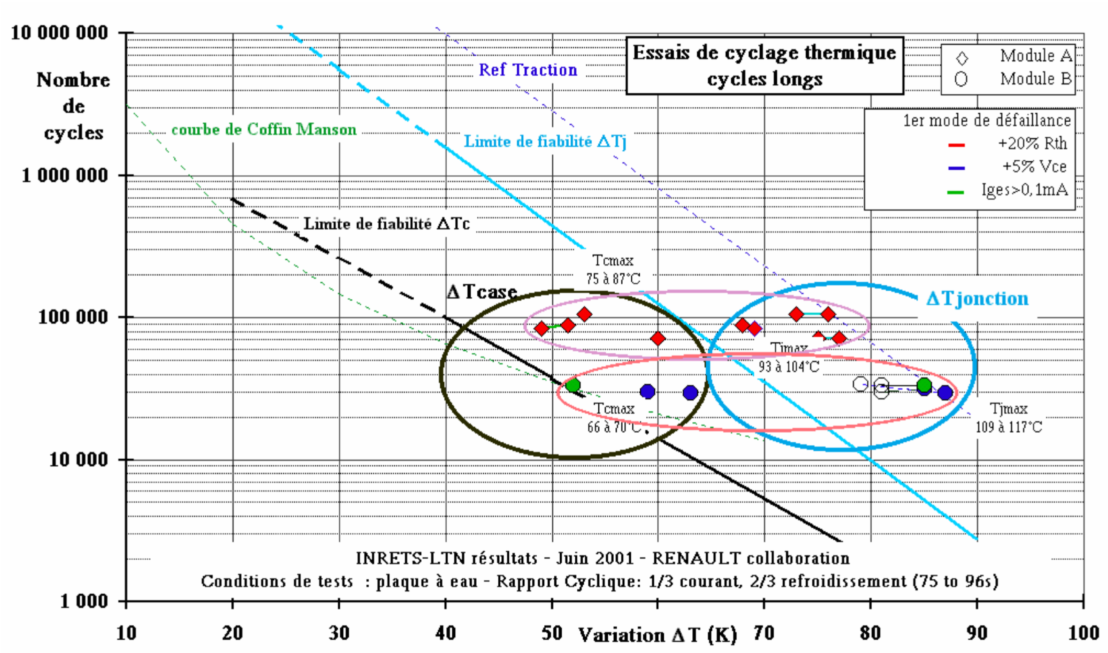
Optimization of the electrothermal coupling simulation

Discretisation:

Distribution of the power dissipated in the model used

Layer of 1µm thickness in a square centimetres 3D model

- Model of ageing and lifetime before failure:
  → Long time to propose a law of lifetime prediction from experimental campaigns
  → Large dependences with the technological choices that define the damage mechanisms
  → Experimental campaigns still useful to propose a model adapted to the field of use



- Model of ageing and lifetime before failure:
  - → Long time to propose a law of lifetime prediction from experimental campaigns
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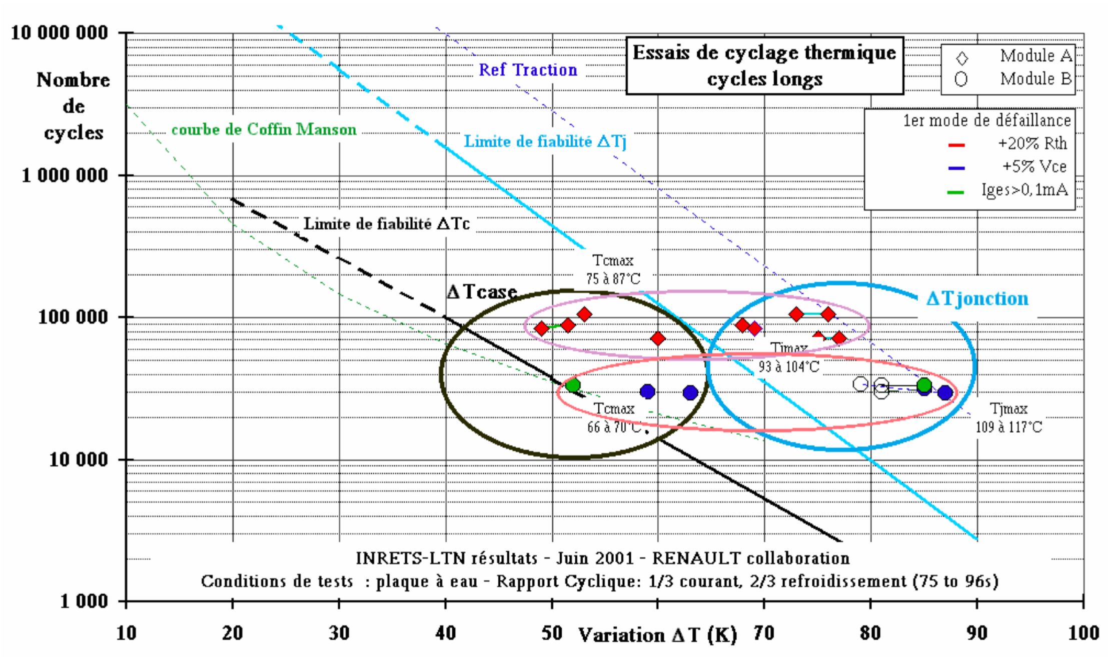
Experimental methodologies are not standardized
Simulation could be used more to extend experimental results
The sensitivity of the test parameters to the results must be evaluated!



Introduction

Reliability: A context of complexity

Tools and Methodologies

Experimental approach

Numerical approach

Perspectives

Reliability in Power Electronics : Perspectives

<u>*Experimental aspects*</u>*: not exhaustive*

- Are ageing tests always adapted for new technologies and mission profiles?
  - *Smaller, lighter, faster, hotter converters*
  - *Higher current and dissipated power densities*
  - *Operating conditions close to maximum acceleration criteria*

Reliability in Power Electronics : Perspectives

Experimental aspects: not exhaustive

- Are ageing tests always adapted for new technologies and mission profiles?
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- Power cycling tests have to be able to:
  - *Evaluate new indicators of constraints and damages with revised threshold*
  - *Evaluate the realistic damage mechanisms*
  - *Evaluate the acceleration factors of damage mechanisms*
  - *Evaluate laws of cumulative damage mechanisms*
  - *Evaluate law of lifetime before failure*

- New robust and sensitive indicators used with innovative analysis tools to develop:
  - *New ageing tests with continuous control of conditions and damages*
  - *A diagnostic toolbox able to evaluate the power module integrity*
  - *A prognostic toolbox able to quantify the lifetime before failure*

Reliability in Power Electronics : Perspectives

<u>Numerical aspects</u>: not exhaustive

- Simulation of the power electronics behaviour under constraints
  - A representative model

    Multiphysics coupling as a standard (electro-thermal or electro-thermomechanical)

    Adjust the discretisation level for a representative model

    Define a standardized database of materials properties for EP

  - Correlate numerical simulations with experimental results for:

    A better understanding of constrains

    A validation of electrothermal and electro-thermomechanical coupling

Reliability in Power Electronics : Perspectives

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  - Explore identification and analysis tools to be more robust (classification, recognition…)

Reliability in Power Electronics : Perspectives

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Merge experimental and numerical approaches

- Diagnostic and prognostic help to deploy innovative solutions

PLENARY 4:

RELIABILITY IN POWER ELECTRONICS MODULES

A Challenge to Define Tools and Methodologies in Phase with the Performances of Power Chips and the Constraints of Use

Introduction

Reliability: A context of complexity

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Numerical approach

Perspectives

Thank you for your attention

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