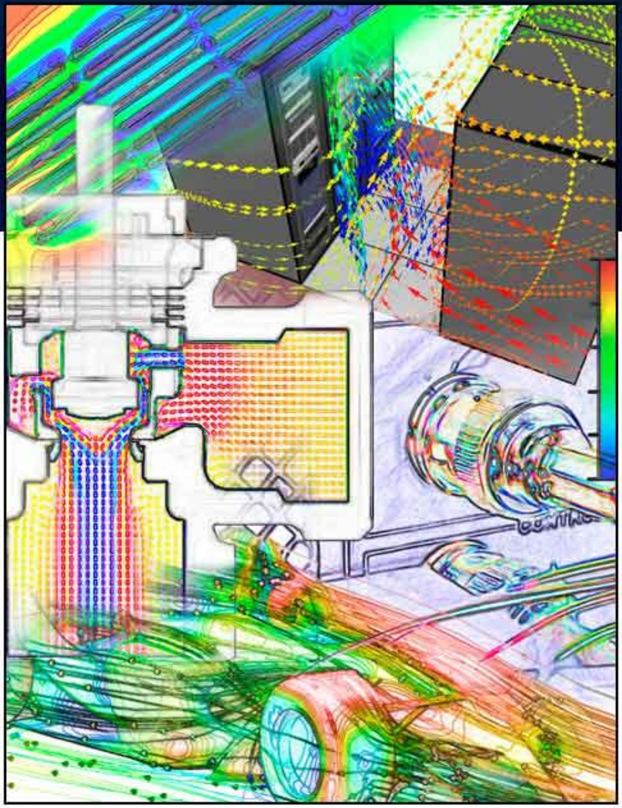

Mission profile based life time estimation of power devices using power cycling testing

Andras Vass-Varnai

Attila Szel, Zoltan Sarkany

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Overview

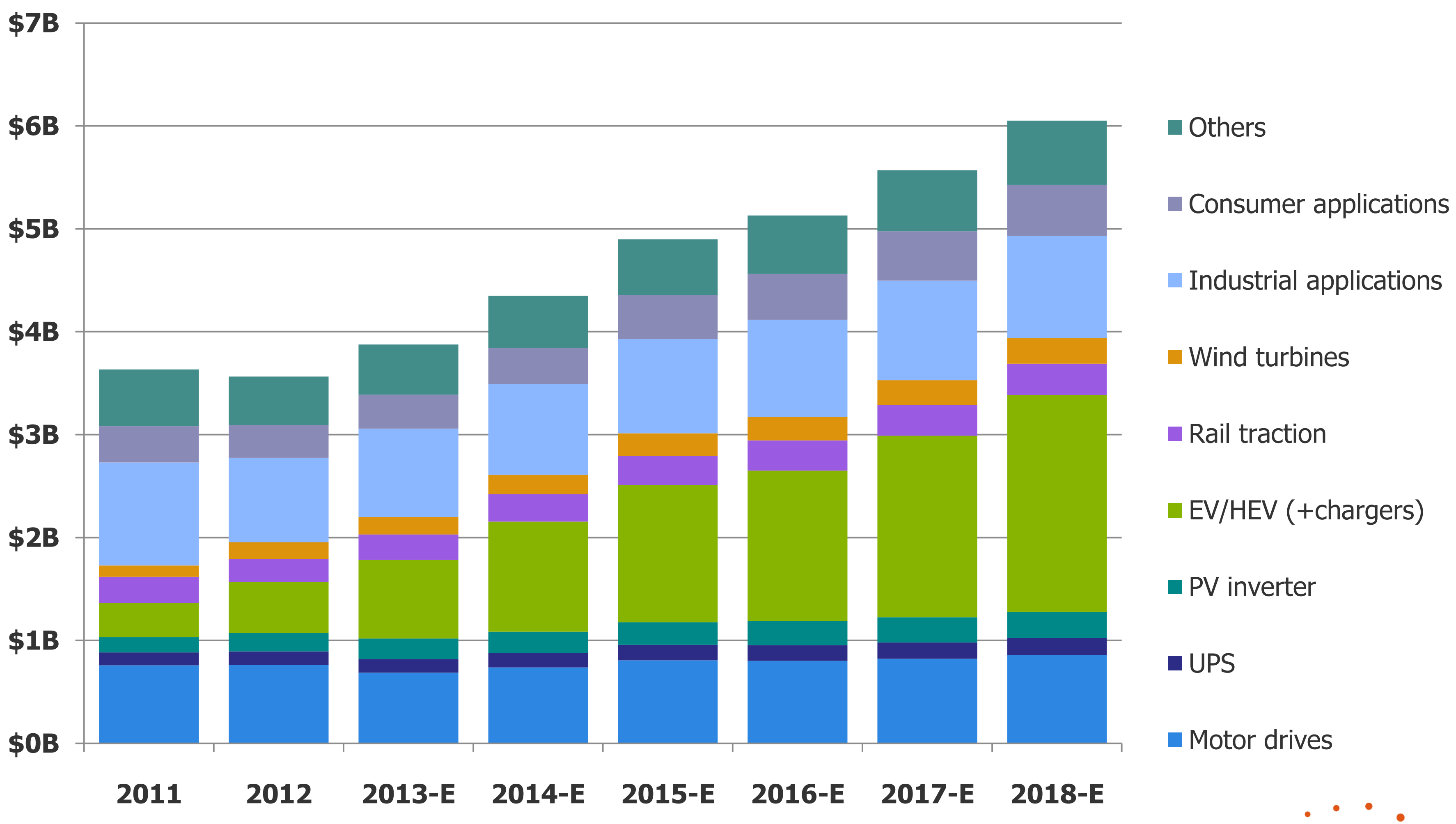
- Short introduction to the industrial challenges in power electronics
- The flow of application based lifetime estimation
  - Simulation model calibration with the structure functions
- Power cycling experimental examples
  - Concurrent failure modes

Insulated Gate Bipolar Transistors (IGBT) / Power Electronics Applications

- Motor drives
  - Commercial motor drives
  - Motor drives discrete
  - Motor drives modules
  - Motor drives IPM
- UPS
  - UPS discrete
  - UPS modules
- PhotoVoltaic inverters
  - Commercial PV
  - Residential PV
  - Solar farms
- Electric Vehicles/Hybrids
  - PHEV/EV
  - Full HEV
  - Mild HEV
  - Micro HEV
  - EV/HEV charging stations
- Railway traction
  - Rail traction inverters
  - Rail auxiliary inverters
- Wind turbines
  - Wind turbine >1MW
  - Residential/commercial wind turbines
- Industrial applications
  - Welding
  - Other industrial
- Consumer applications
  - Induction heating
  - DSC–DSLR camera flash
  - Air conditioner
  - Washing machine
  - Microwave oven
  - Flat panel (LCD/PDP)
  - Lighting supplies
  - Other home appliances
- Others
  - Other power supplies (SMPS)
  - Automotive ignition
  - Marine propulsion
  - Medical applications
  - Defibrillators
  - Avionics converters
  - Heavy duty vehicles
  - Grid –T&D

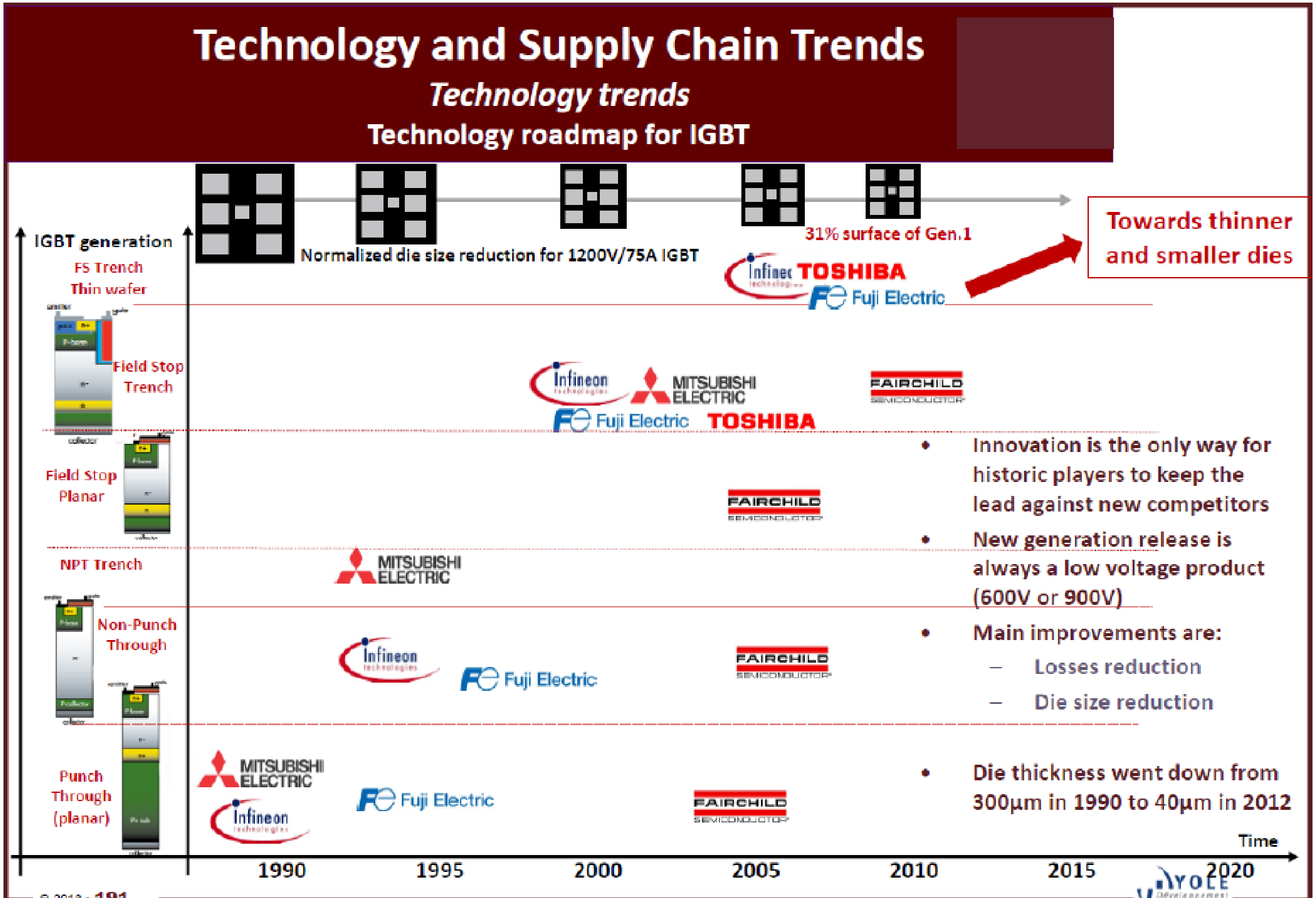
Classification by Yole Développement

IGBT Market Forecast by Segment



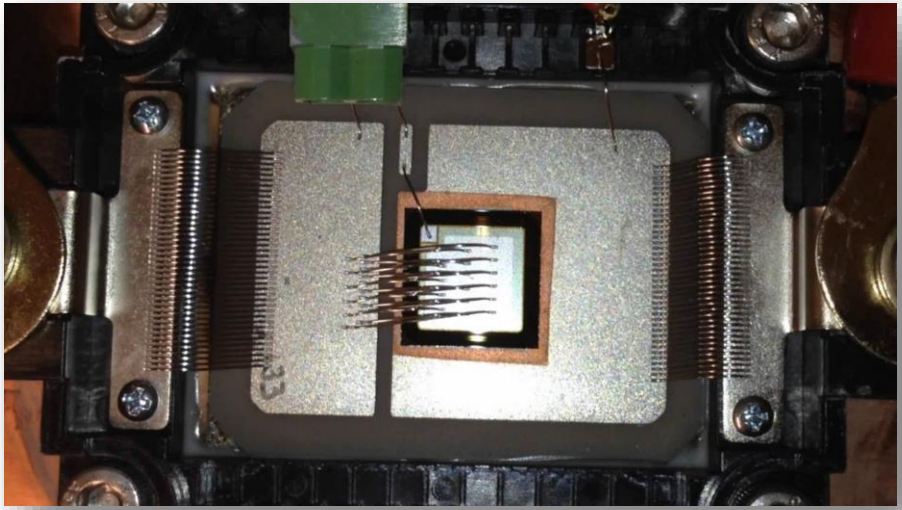
Source: Yole Developpement - IGBT Markets & Application Trends, 2013

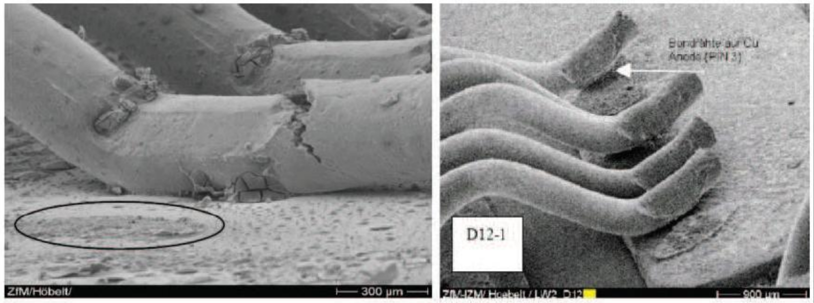
IGBT technology trend – Power densities are increasing



Focus on Power Electronics Module Reliability

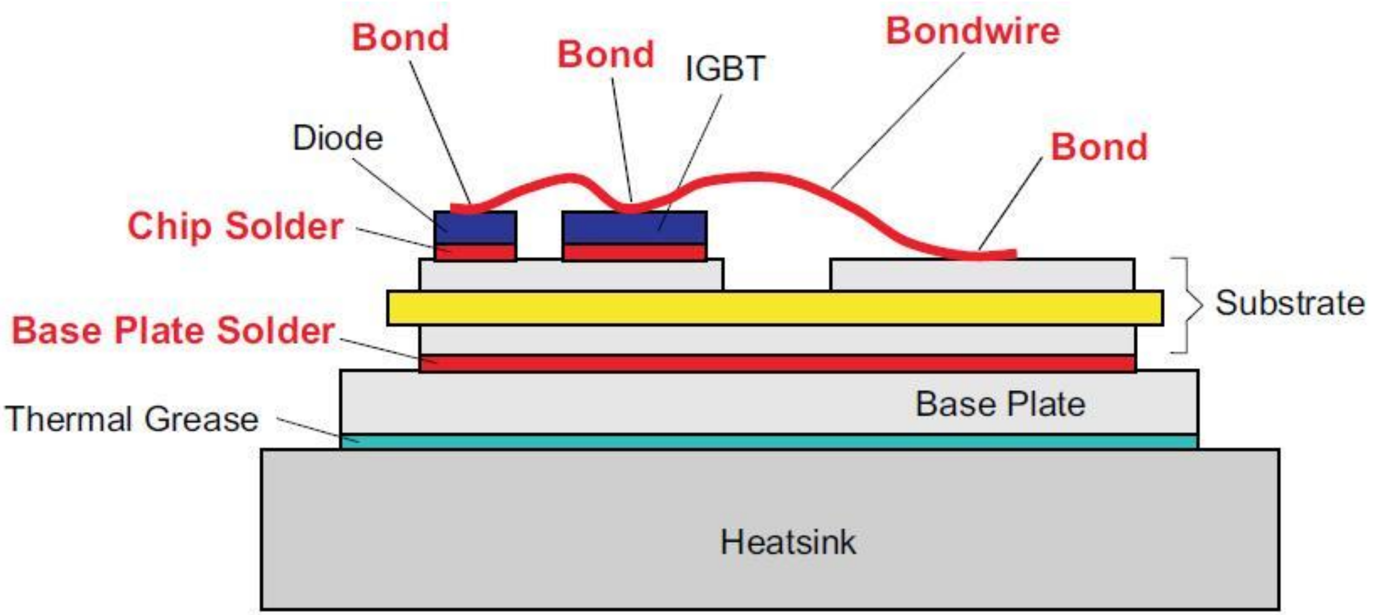
- Examples:
  - Hybrid & electric vehicle (EV)
  - Railway traction applications – 30+ year expected lifetime
  - Reusable energy production, e.g., wind turbines, solar
- 10's of thousands to millions of cycles required
- Issue is thermally induced degradations due to power cycling & heat
  - Wire bond degradation
  - Metallization layer mismatch
  - Solder fatigue
  - Die and substrate cracks





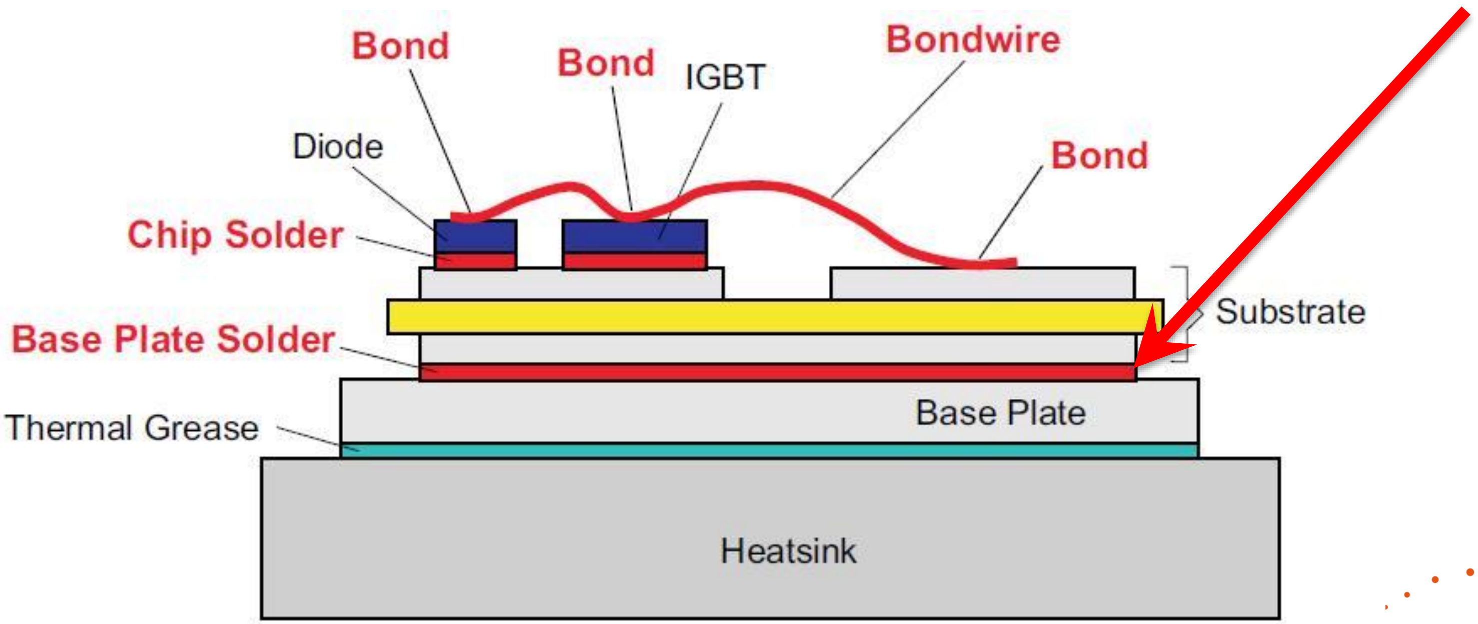
Vulnerable areas of a typical power device

- The thermo-mechanical stress is the largest when the temperature difference between layers is high and the contact surface is large



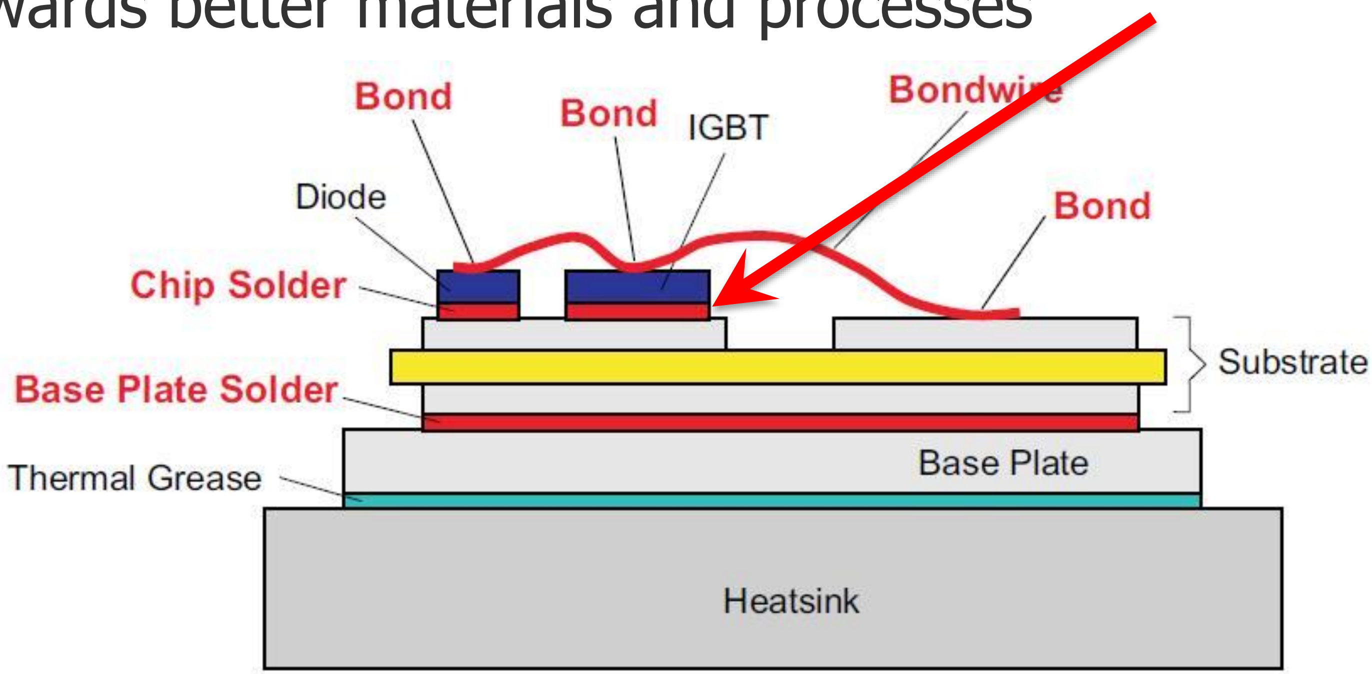
Vulnerable areas of a typical power device

- The thermo-mechanical stress is the largest when the temperature difference between layers is high and the contact surface is large
- Solder joint between the base plate and the back-side metallization of the substrate



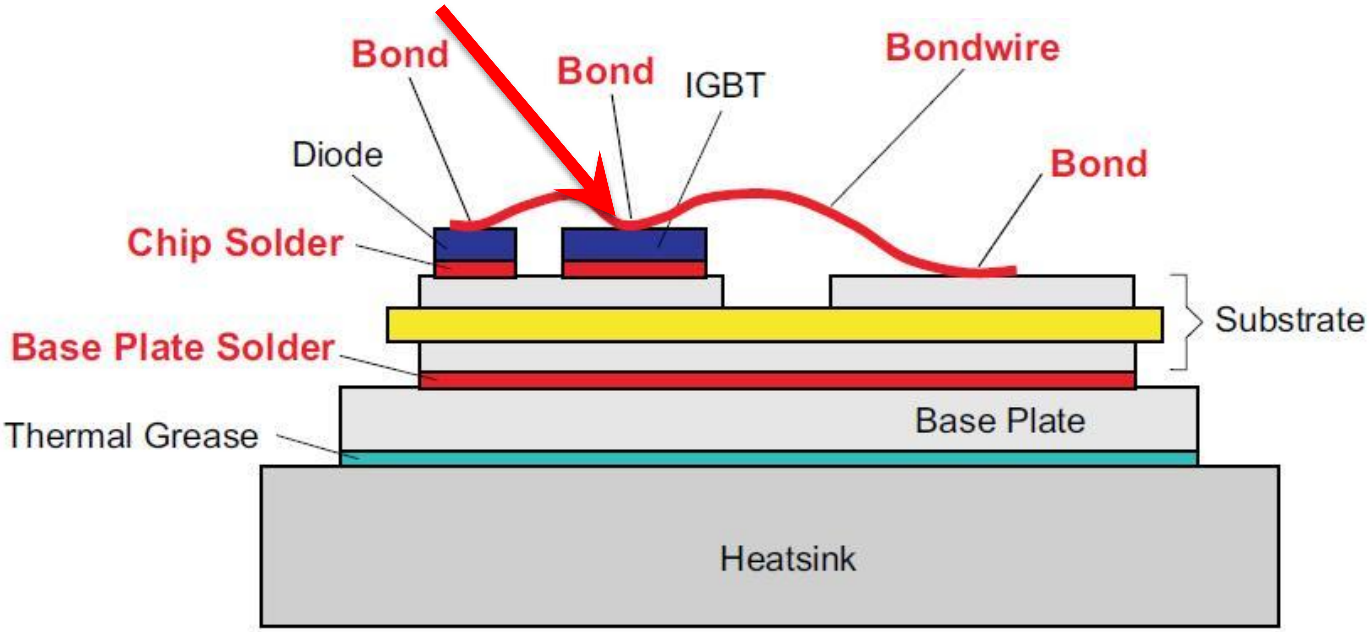
Vulnerable areas of a typical power device

- The thermo-mechanical stress is the largest when the temperature difference between layers is high and the contact surface is large
- Die attach – There was extensive research in this field towards better materials and processes



Vulnerable areas of a typical power device

- The thermo-mechanical stress is the largest when the temperature difference between layers is high and the contact surface is large
- Bond wires - Small area but high temperature swing and CTE mismatch make it vulnerable



Introducing the Industry-Unique MicReD Industrial Power Tester 1500A

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New PWTs: 75% power increase

Going from 12kW to 21kW

New Launches

- PWT 1800A 12C 12V (flagship)
- PWT 3600A 12C 6V (power grid and locomotives)

FY16

- PWT 1500A 3C/12C 8V

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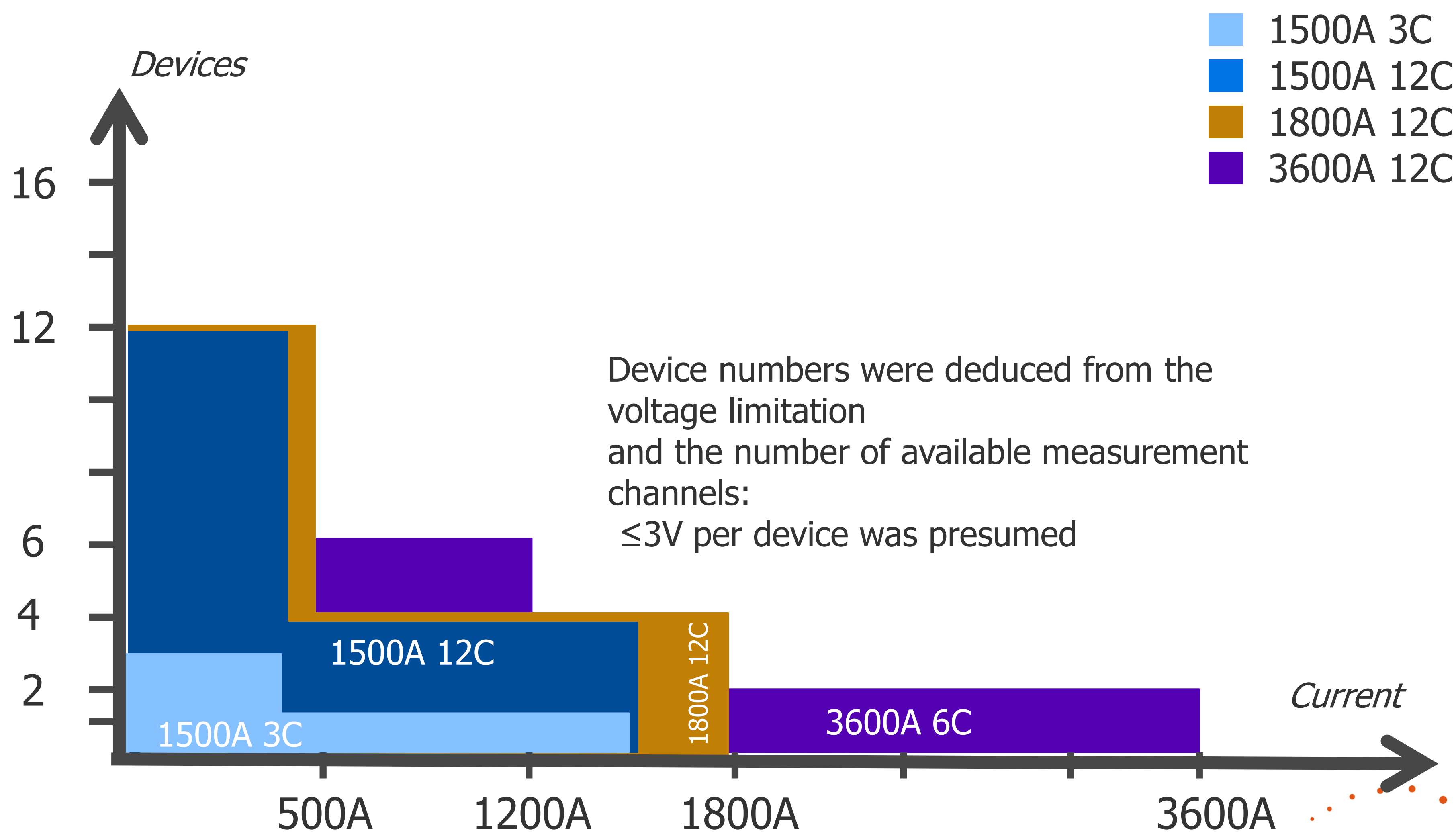
PWT offerings

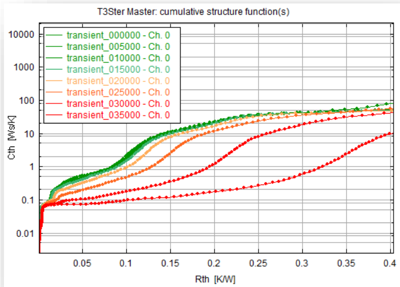


Introducing the Industry-Unique MicReD Industrial Power Tester 1500A

- Industrial implementation of Mentor's industry-unique MicReD T3Ster technology
- Provides fully automated power testing / cycling
- Simple touch-screen user interface
- For MOSFET, IGBT and generic two-pole devices – up to 3x4 simultaneously
- Records diagnostic information during test:
  - Current, voltage and die temperature sensing
  - "Structure Function" identifies changes / failures in package structure
- Supports package development, reliability testing, and batch checking of incoming parts before production

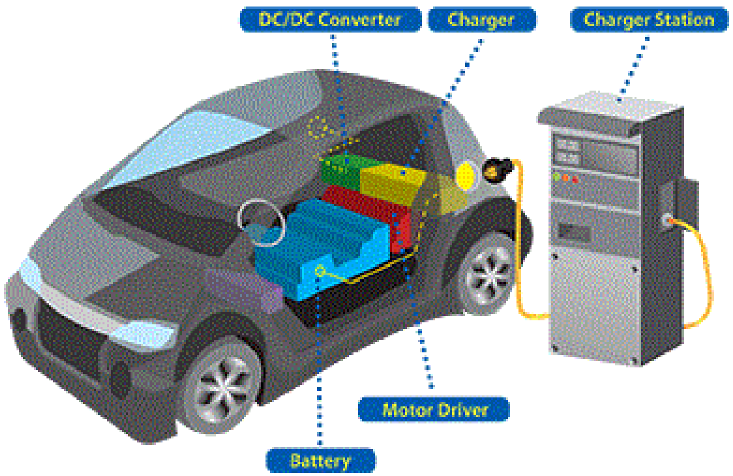
Power Tester 1500A

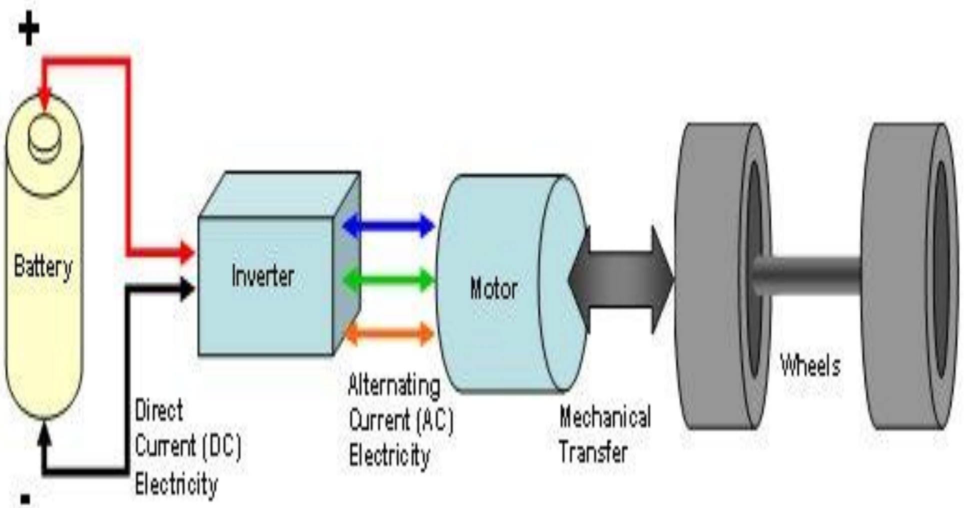

Touch Screen Controls

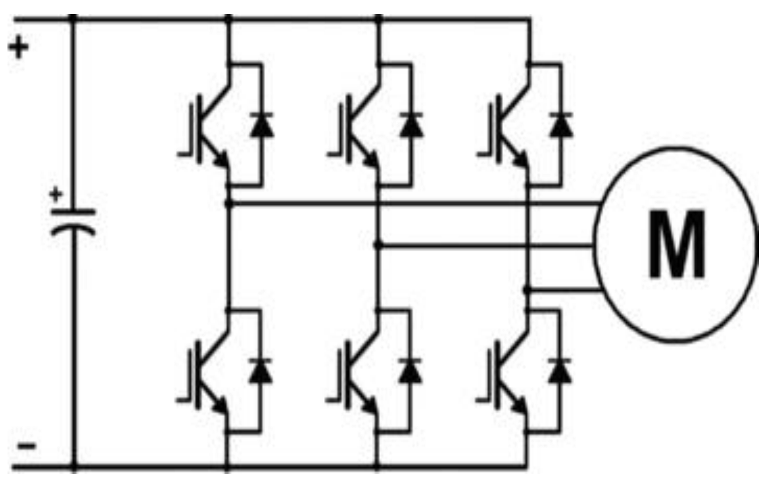


Structure Function

Example: Electric traction in a car

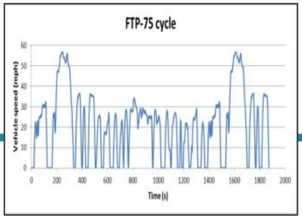


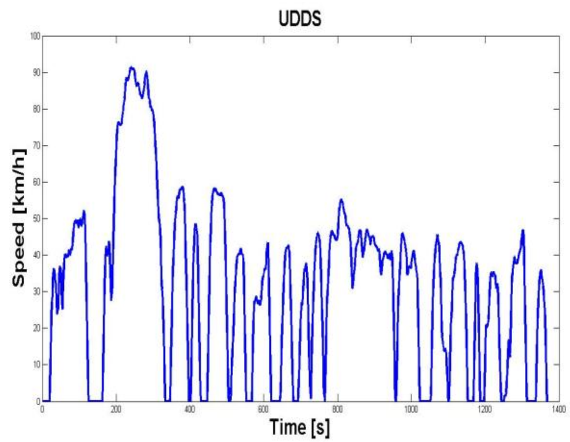


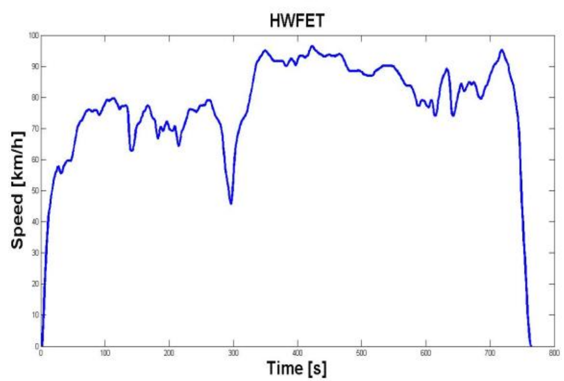


Heating and cooling is determined by the motion of the wheel

Definition of the application – The driving profile







- For the design of the power module the exact definition of the task is necessary
- Possible input data:
  - Electrical data: V, I
  - Velocity v.s. time functions
- Driving profile examples

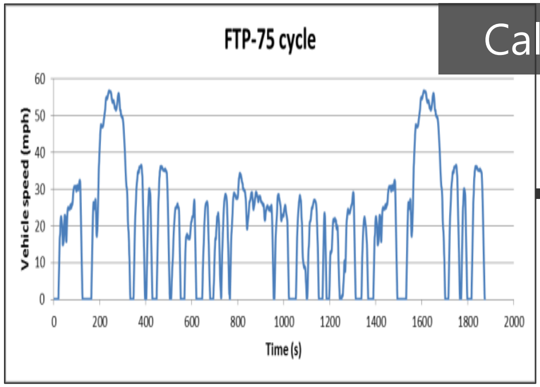
  Test standards defined by the US EPA
  - **FTP-75** for the general city driving
  - UDDS: Inside the city for light vehicles
  - US06: Aggressive driver
  - HWFET: Highway, standard driver

THE FLOW OF LIFETIME ESTIMATION,

BASED ON THE COMBINATION OF SIMULATION AND MEASUREMENT

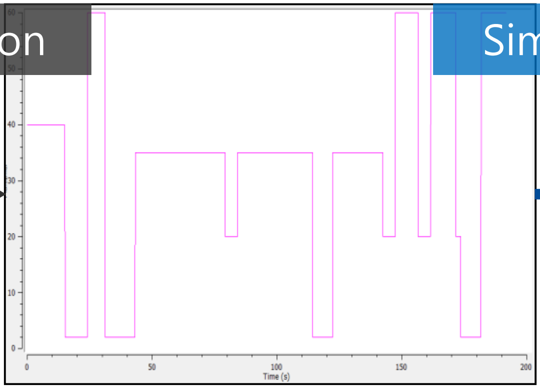
1. Overview of the flow

1. Driving Profile



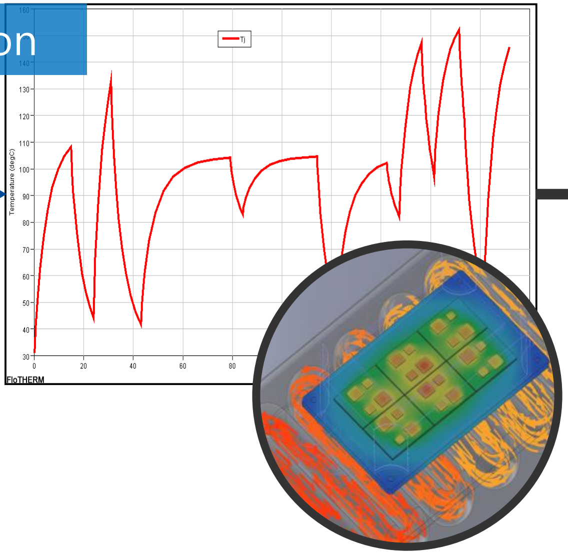
Calculation

2. Power Profile



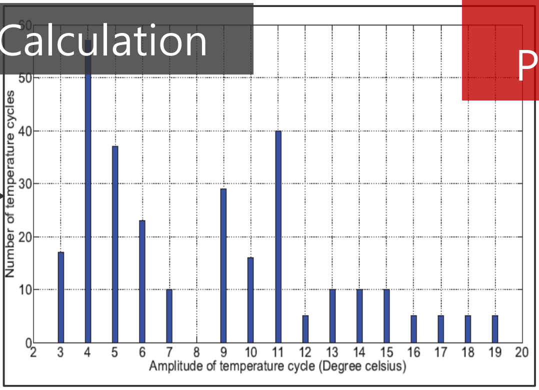
Simulation

3. Temperature Profile



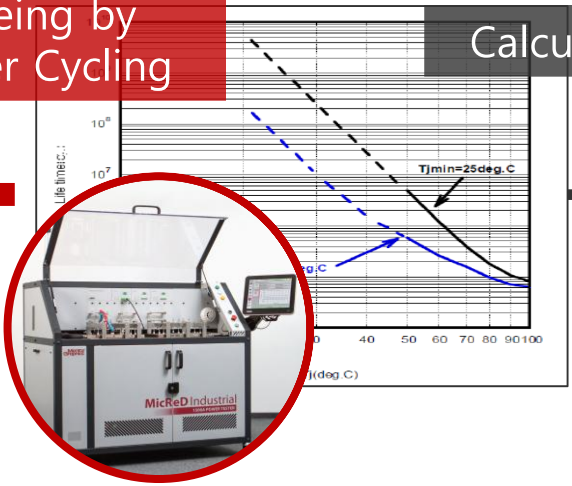
4. Distribution of Temperature Changes

Calculation



5. Lifetime Curves

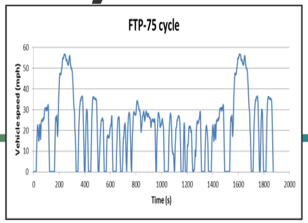
Ageing by Power Cycling

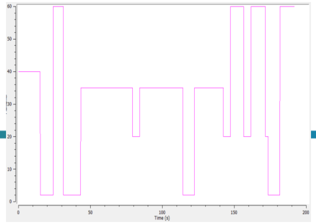


Calculation

Expected Lifetime (e.g12 yrs)

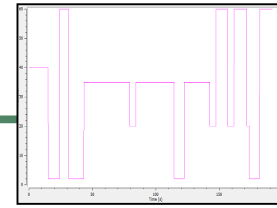
2. Power profile calculation, based on mission profile

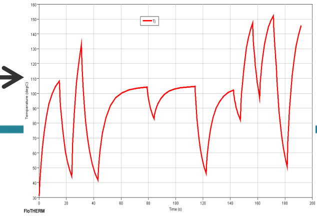


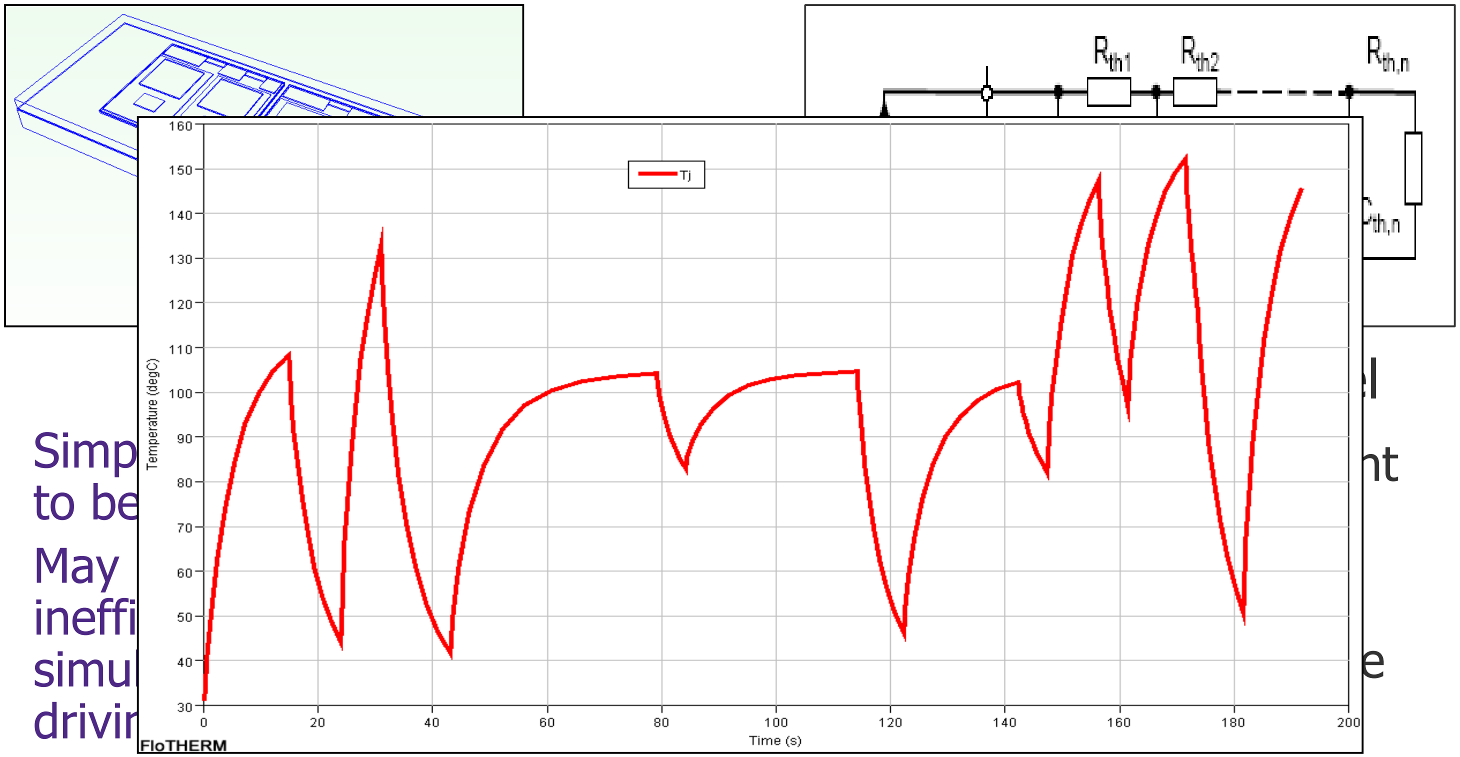


- ► Forces used for modeling the movement of a car
  - Rolling resistance: $F_g = \mu_g mg$
  - Air resistance: $F_{air} = \frac{1}{2}\rho A C_d v^2$
  - Acceleration resistance: $F_{acc} = ma$
  - Elevating resistance: $F_{elev} = mgsin(\varphi)$ *(neglected)*
- ► Engine power: $P_{engine}(t) = \Sigma F v(t)$
- ► Total required power: $P_{total}(t) = \frac{P_m(t)}{\eta}$ *(η – efficiency)*
- ► **Power loss**: $P_v(t) = P_{total}(t) - P_{engine}(t)$
  - $P_v(t)$ is partially the conduction and switching loss of the IGBT

3. Temperature profile simulation







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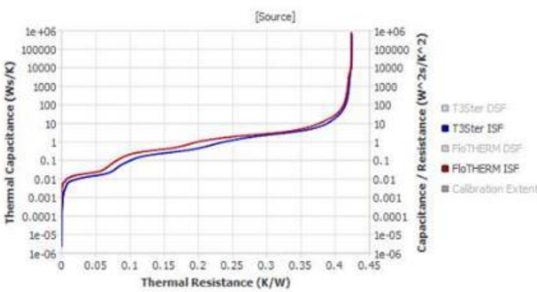
- Issues with modeling multi-heatsource packages

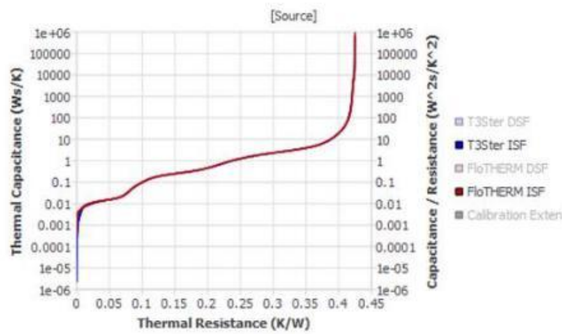
4. Why to calibrate simulation model…

Uncalibrated Model that produces a steady state Tj within 0.5% of the calibrated model. SF comparison is somewhat reasonable looking at first glance:

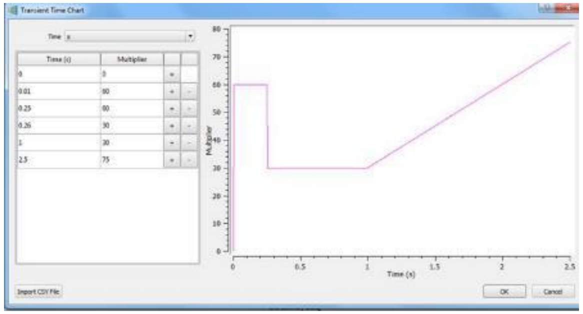
Uncalibrated SF comparison:



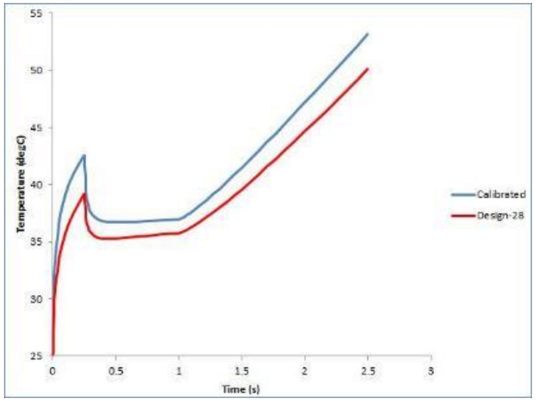
Calibrated model SF comparison:



Simulate both calibrated and uncalibrated model with an arbitrary power profile:



And compare the responses. Design 28 is the uncalibrated model. The peak at 0.25s is off by ~24%.



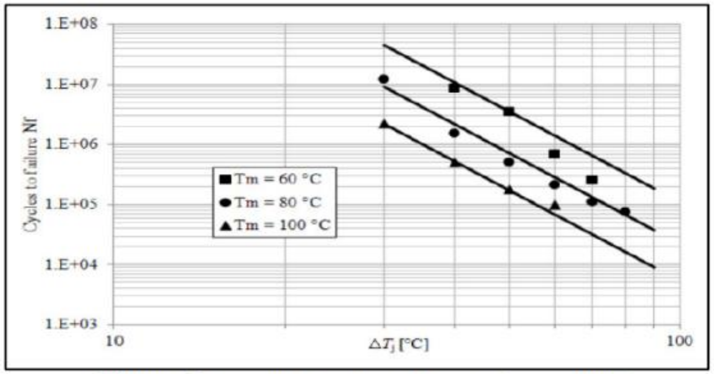
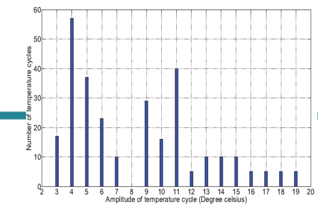
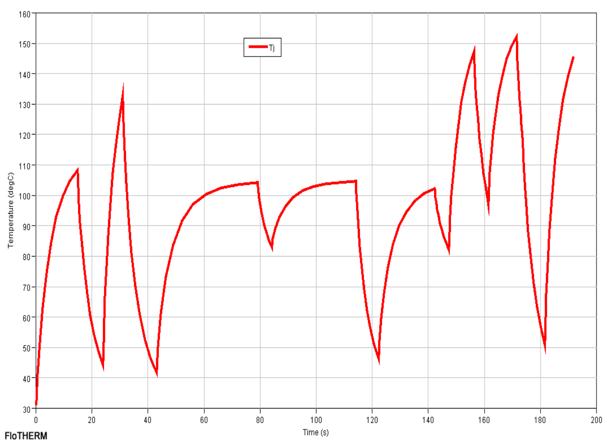


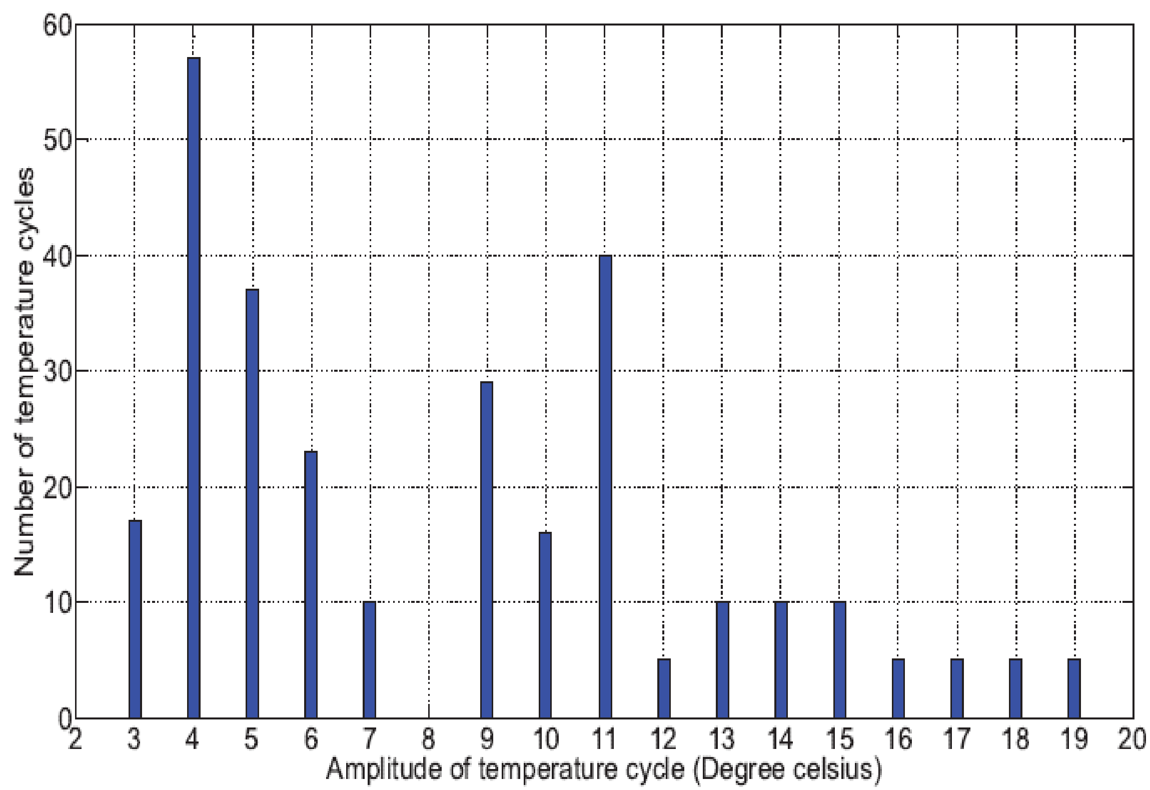
Figure 5: Experimental results (markers) and the analytical model fit on the individual results (solid lines)

5. Temperature histogram calculation



- Count the individual temperature gradient components in the temperature profile – future weighting factor in cycling

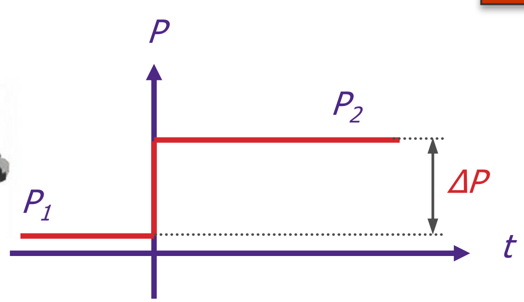


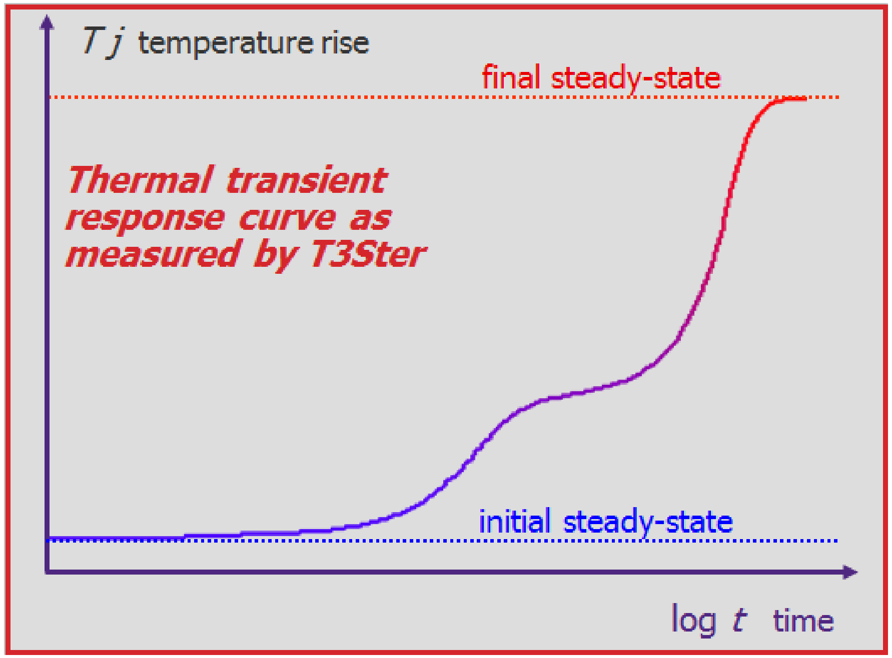


A SHORT DETOUR : SIMULATION MODEL CALIBRATION WITH THE STRUCTURE FUNCTIONS

T3Ster - Transient Response Measurements

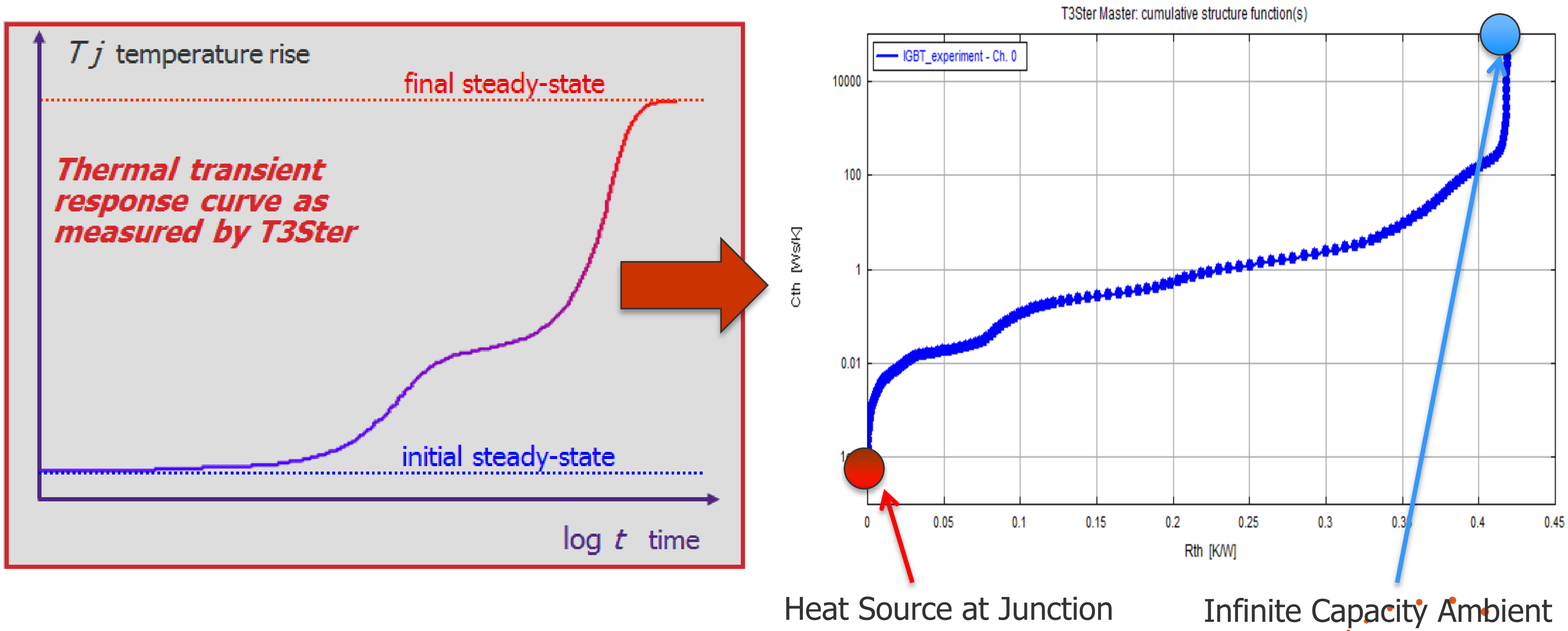
- T3Ster is used to measure the transient thermal response of a package to a change in its power dissipation





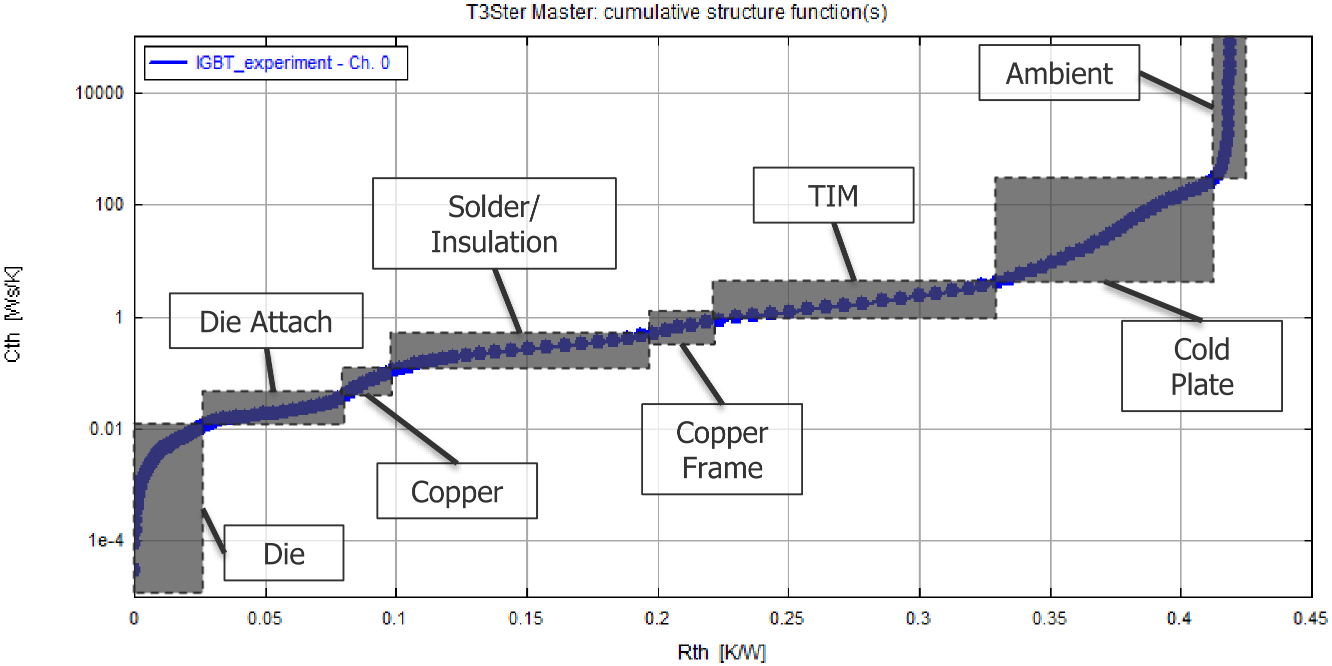
T3Ster - Transient Response Measurements

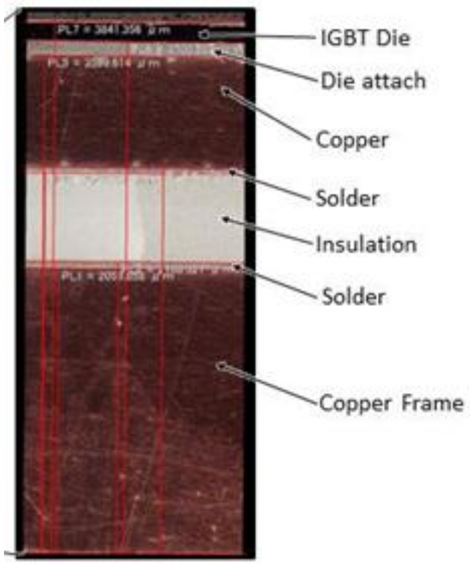
- T3Ster Master software converts the measured thermal response into a Structure Function. One way to interpret this is the RC path that the heat takes from the junction, through the device, and to the ambient.



T3Ster - Transient Response Measurements

- Each section of the Structure Function path represents physical objects the heat encounters. There is a correlation between physical objects and sections of the RC path.





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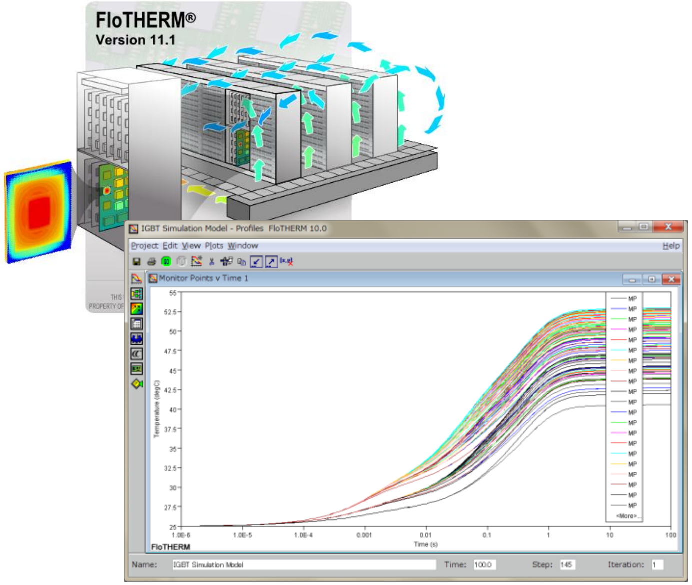
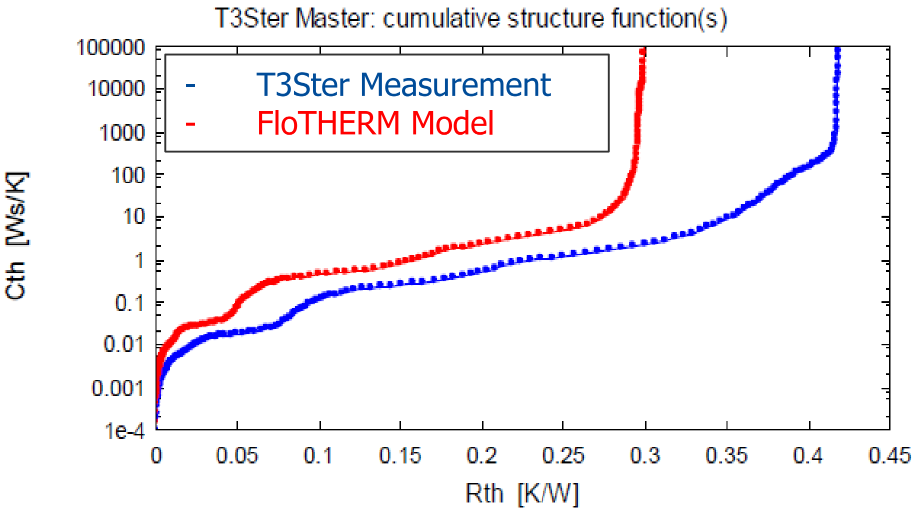
FloTHERM - Transient Response Recording

- A detailed FloTHERM model of the package can be simulated in a virtual test environment to predict a transient response as well.
- New in FloTHERM v11.1, the simulated transient response is converted into Structure Functions using exactly the same methods as T3Ster Master.
- This allows direct comparison of simulation to measurement in a format that correlates to the physical structure of the package.

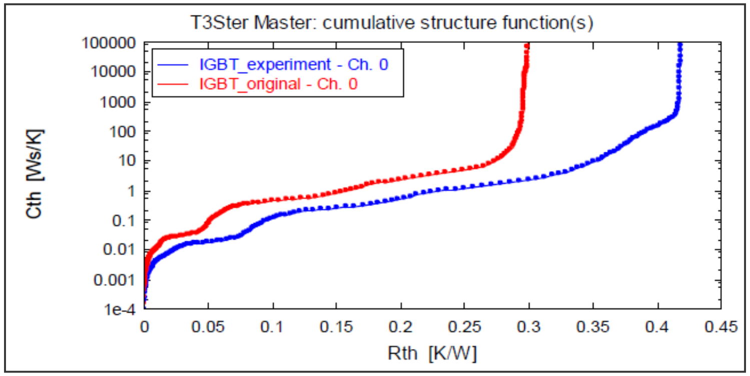




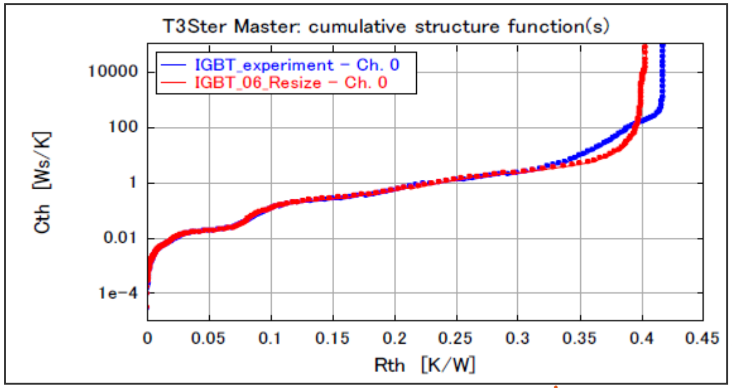
Model Calibration

- To ensure model accuracy the FloTHERM Structure Function <u>**must**</u> match the T3Ster Structure Function across all package elements.
  - **Only then** are we ensured that each object in the package is modelled correctly.
  - **Only then** are we ensured that the 3D temperature field is accurate
  - **Only then** are we ensured the FloTHERM model includes all package time constants and will respond correctly for all driving power profiles.

—Uncalibrated



—Calibrated



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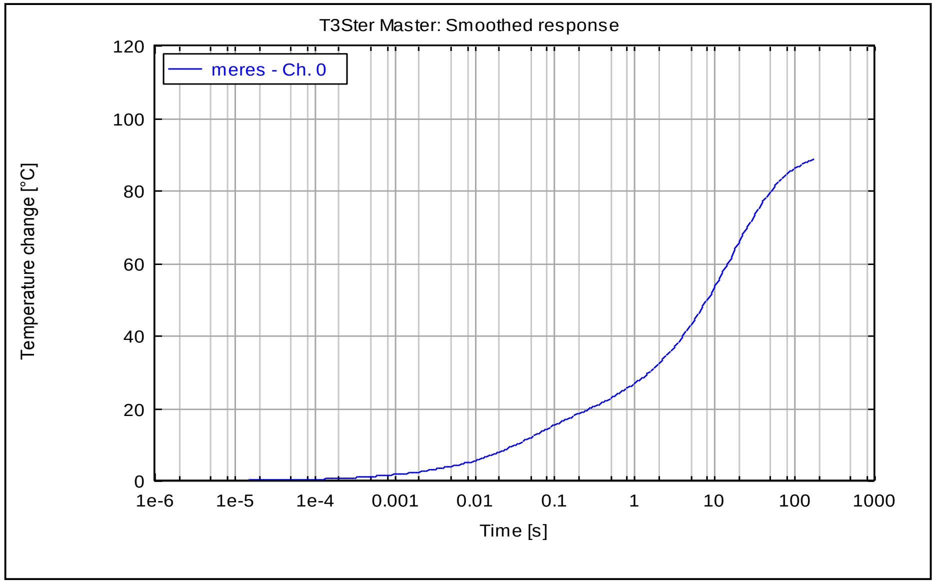
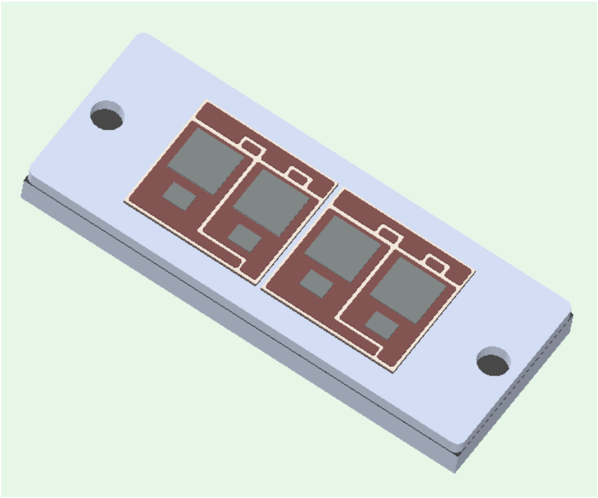
Example : determining the temperature profile of an IGBT by 3D model simulation

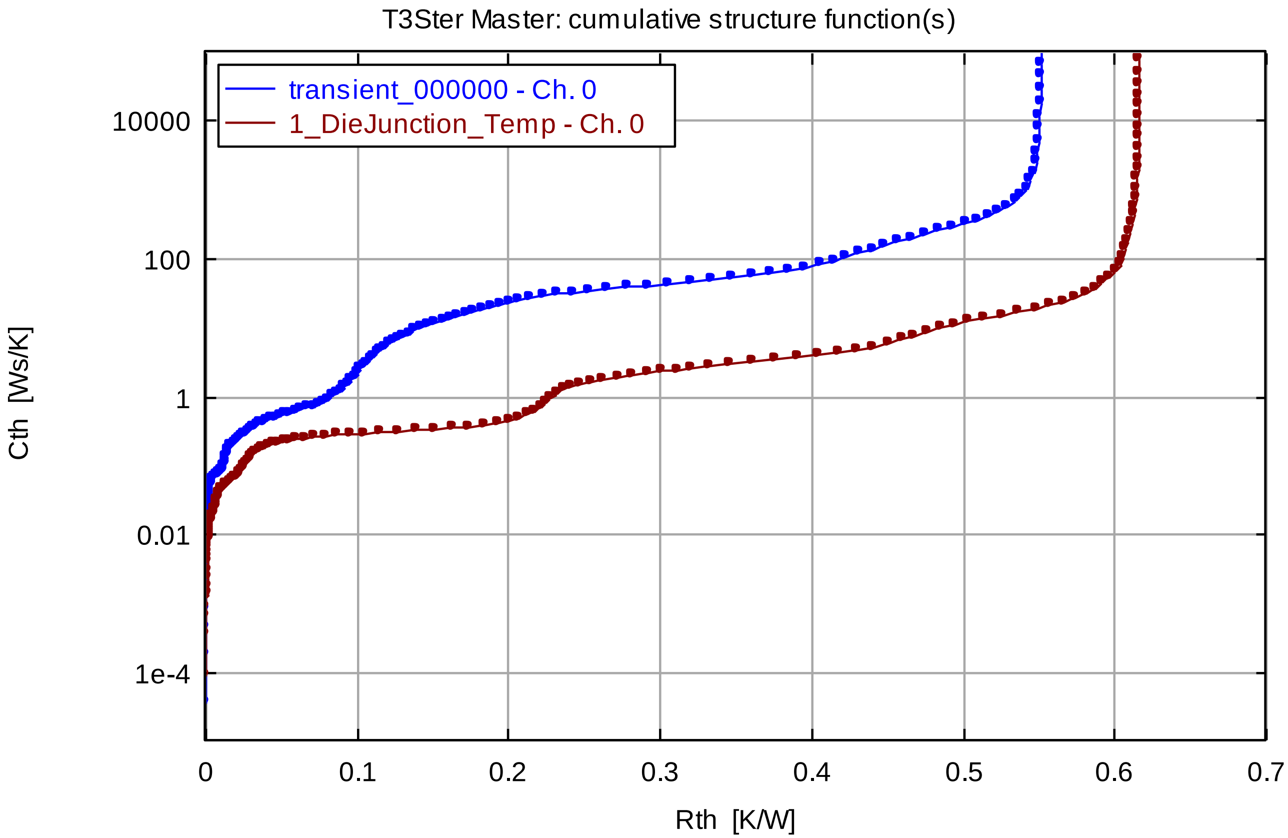
- Create a 3D numerical model of the package
  - Possible problems: Some geometrical or material parameters may be unknown or inaccurate
- Increasing the accuracy by using thermal transient testing: model calibration



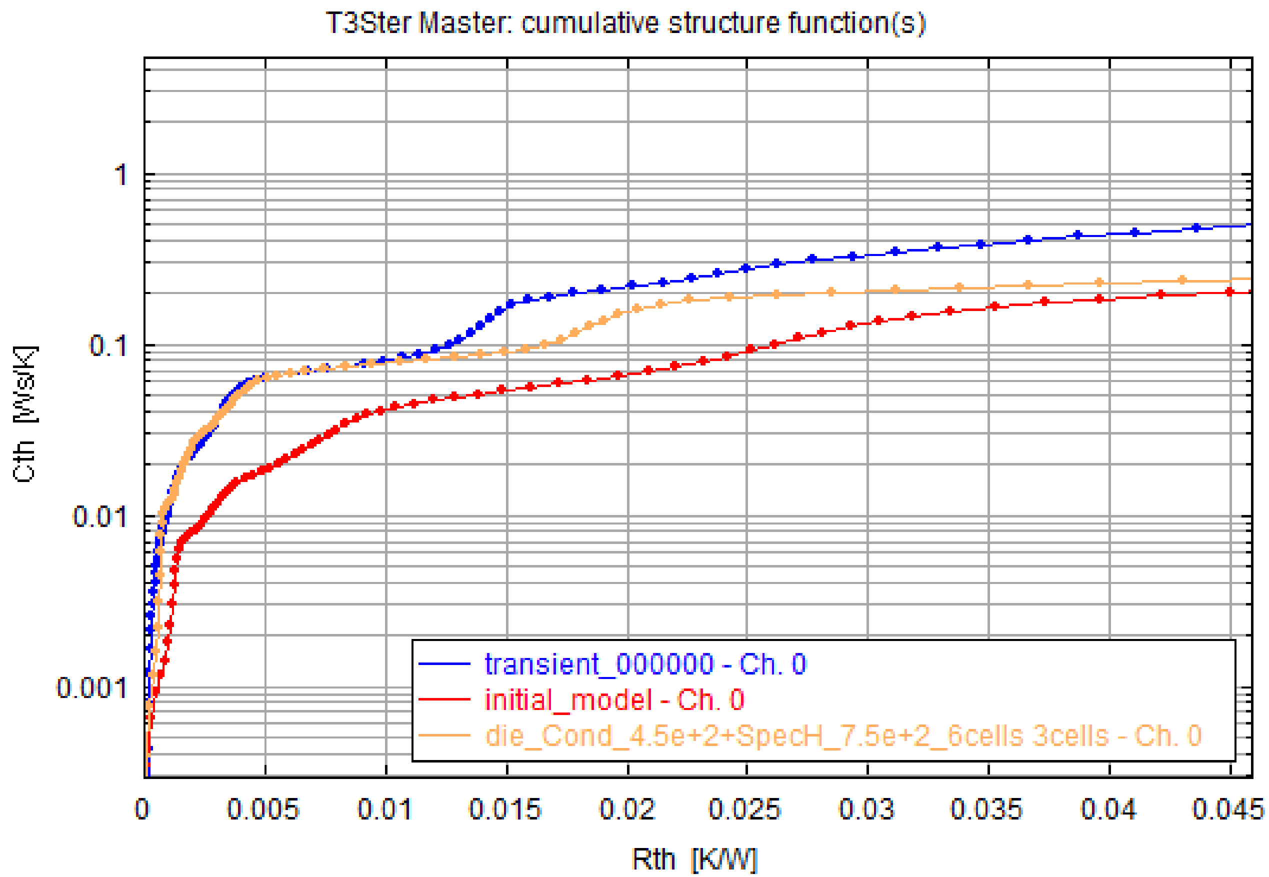


Model calibration with the structure functions

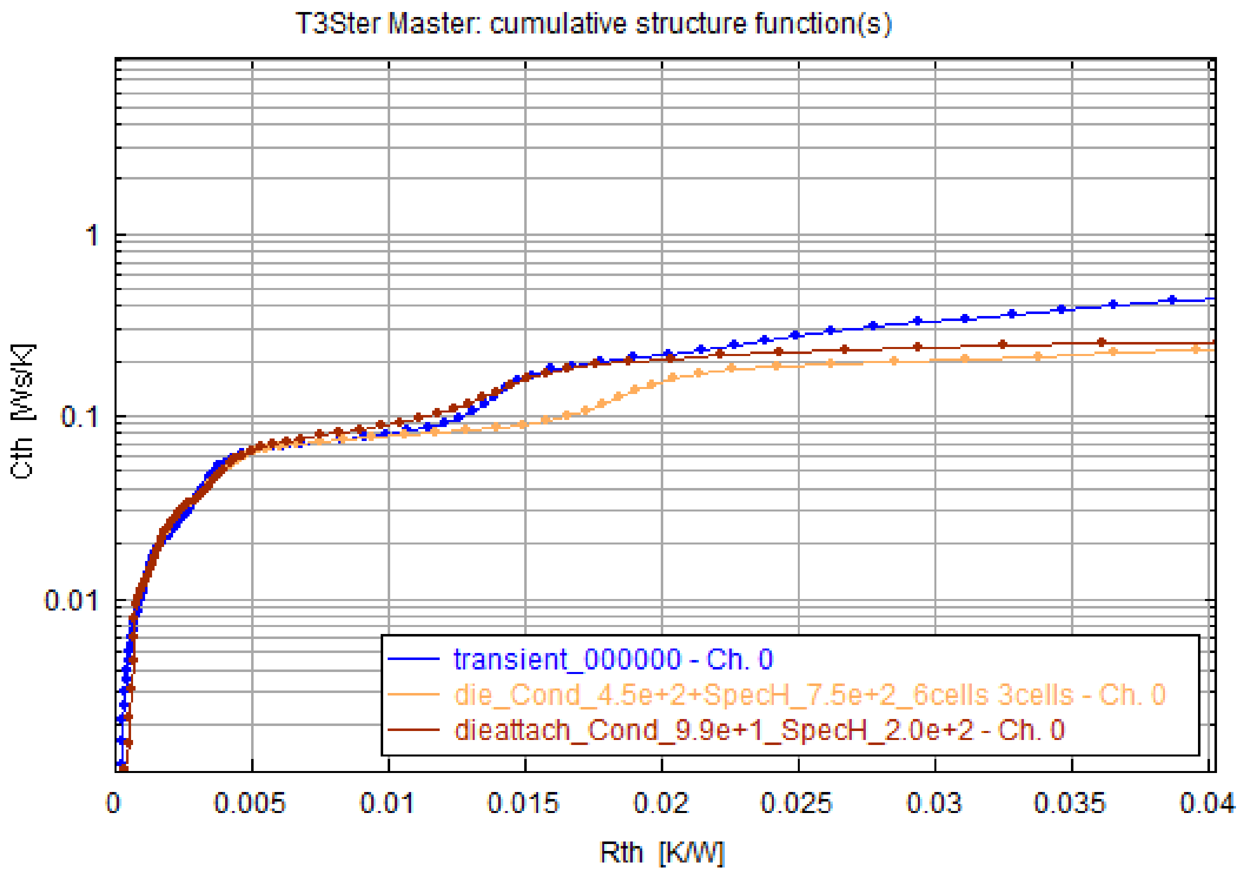
- Initial model vs. Measurement before the cycling started



Calibration of the die region

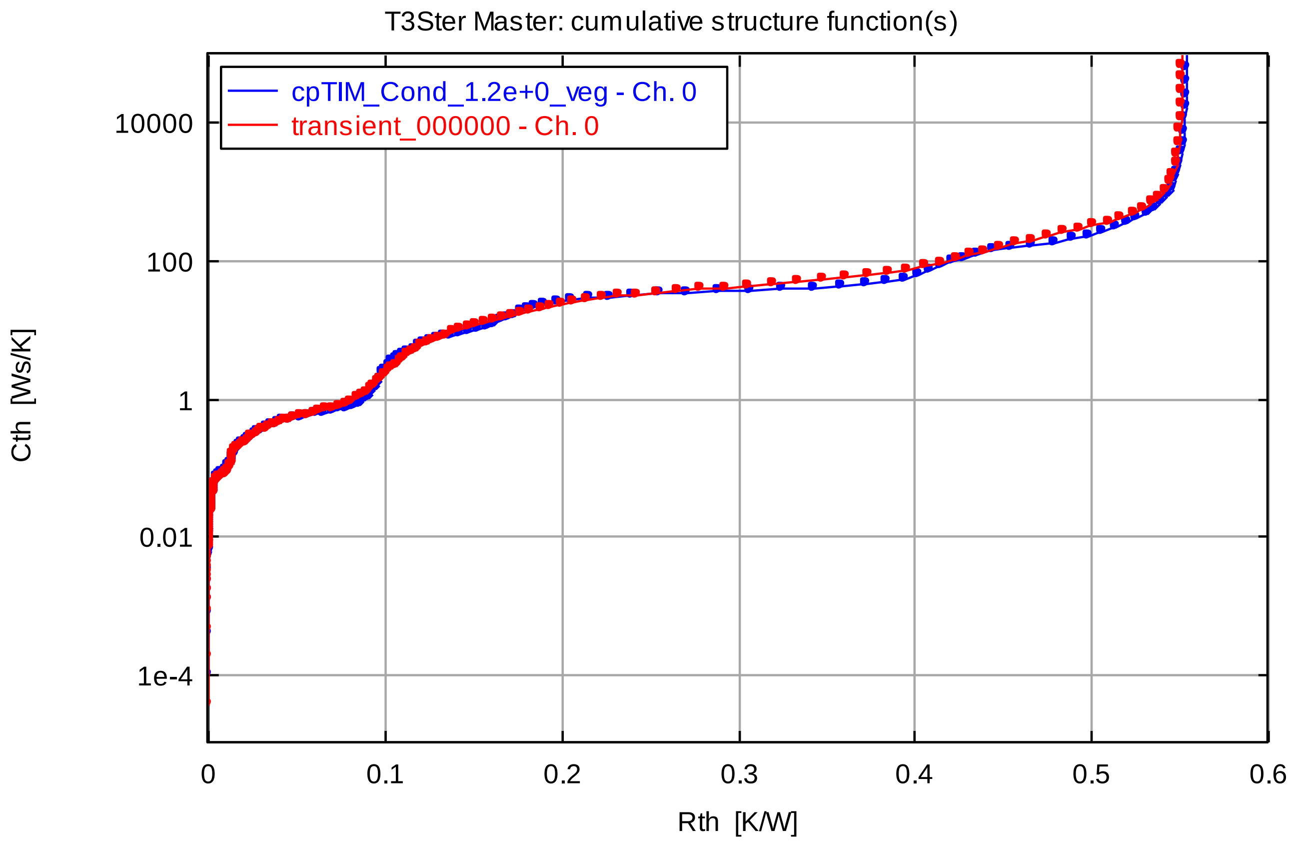


Resistance change of the ceramics



Calibration of the TIM2

- Final, calibrated model



Ready to be used for accurate thermal simulation…

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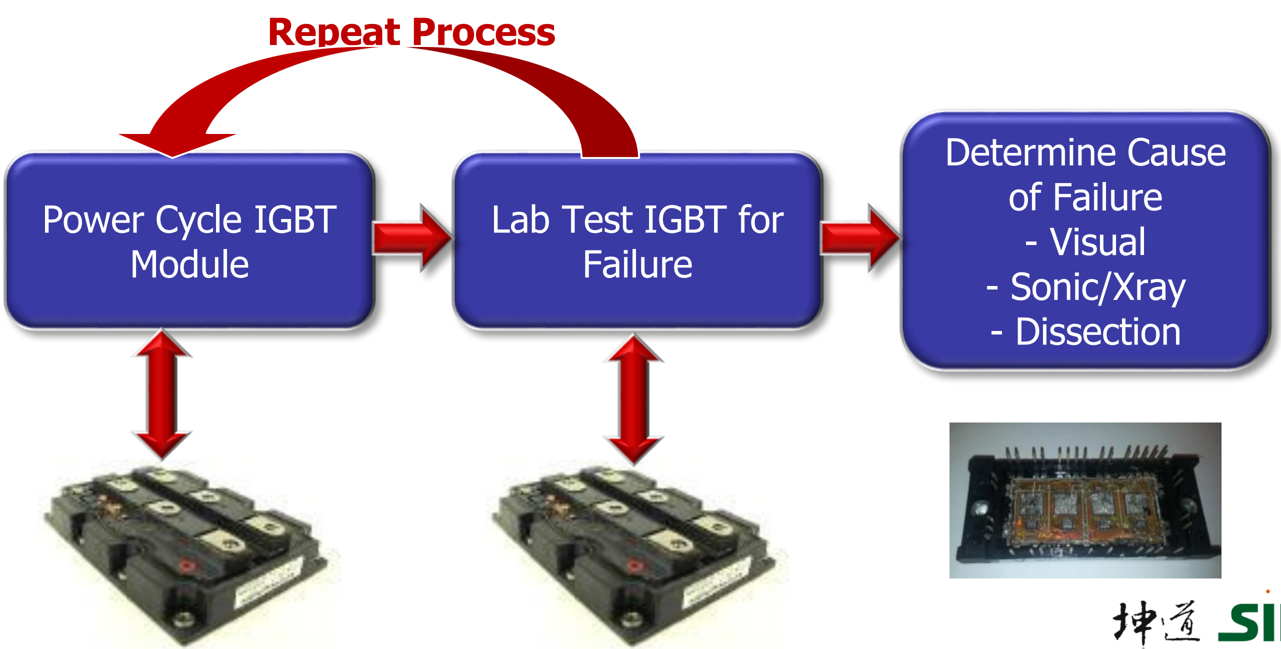
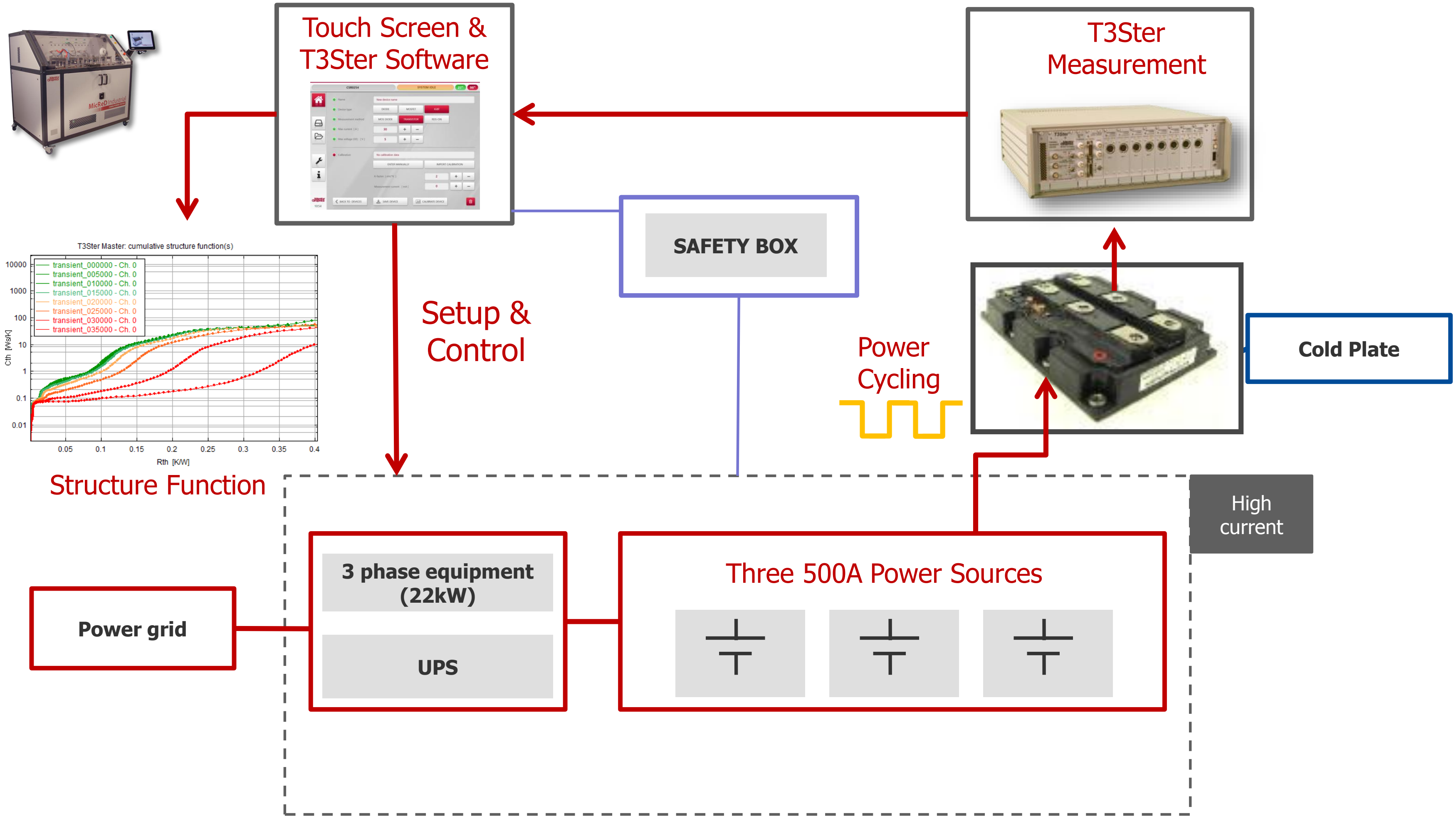
ACCELERATED AGEING
BY MONITORED POWER CYCLING

Traditional Power Cycle Failure Testing

- Traditional Process:
  - Run set number of power cycles
  - Take to lab and test for failure
  - Repeat power cycling/lab testing cycle until failure
  - Take to lab and determine reason for failure
- Issues:
  - Repetitive cycle/lab test process = long times
  - No "real time" indication of failure in progress – only post mortem
  - Failure cause requires lab analysis – typically internal to package

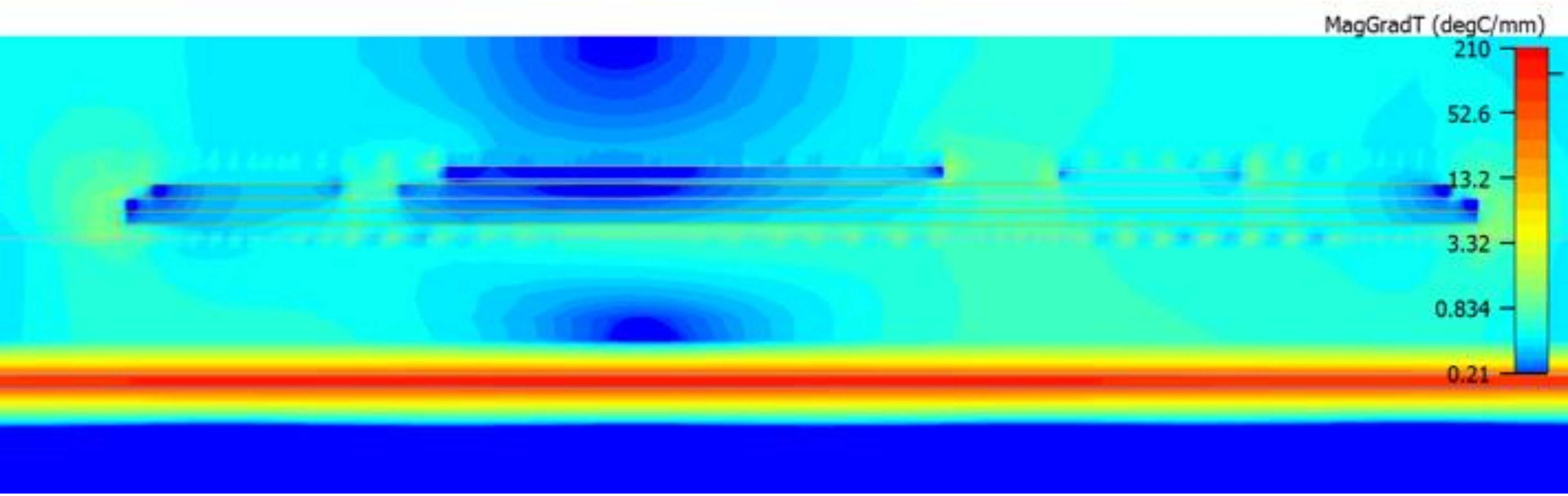


MicRed accelerated ageing: Continuously monitored to understand failure mechanisms

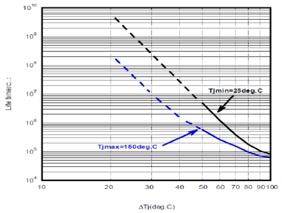


The ageing process (cycling) has to be simulation based

- Temperature gradient development during power cycling



6. Measure points of the lifetime curves and estimate lifetime



- Arrhenius model: $N_f = e^{\left(\frac{E_a}{k_b \cdot T}\right)}$

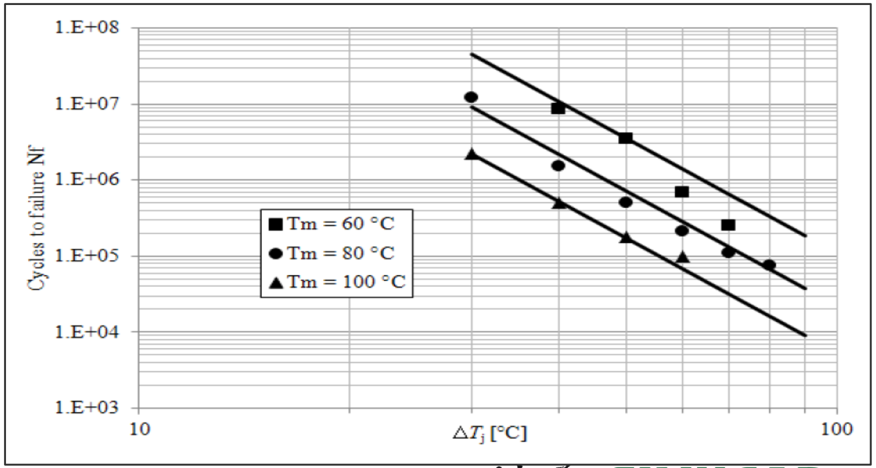
Cycles to failure

- Extended Arrhenius models:
  - $N_f(\Delta T) = A \cdot (\Delta T_j)^{\alpha} \cdot e^{\left(\frac{E_a}{k_b \cdot T}\right)}$ (used by: F* Company)
  - $N_f(\Delta T) = A \cdot f^{\beta} \cdot (\Delta T_j)^{\alpha} \cdot e^{\left(\frac{E_a}{k_b \cdot T}\right)}$ (used by: I* Company)

- **Lifetime estimation**

$$N_{f\_sum} = \frac{1}{\sum_{k=1}^{n} \frac{w_i}{N_{f\_i}}}$$

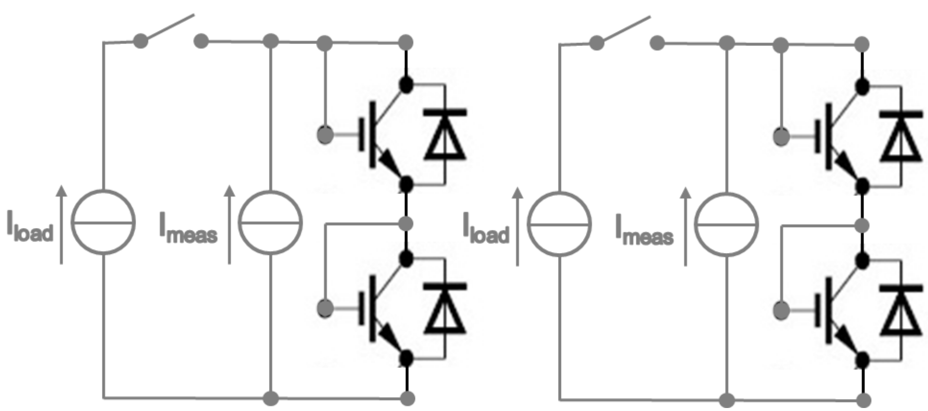
$$t_{operation} = N_{f\_sum} \cdot t_{cycle}$$

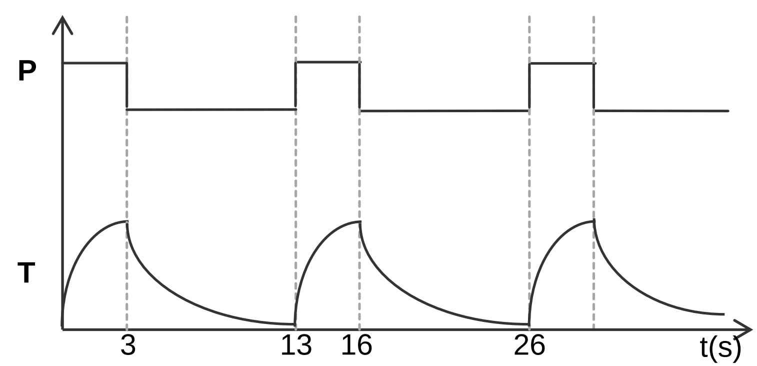


Experiment I. – Setup and parameters

- Devices mounted on temperature controlled cold plate
- Base plate temperature: 25°C
- Targeted junction temperature: 125°C
- Constant current regardless of the voltage change
- Transient test after every 200 power cycles

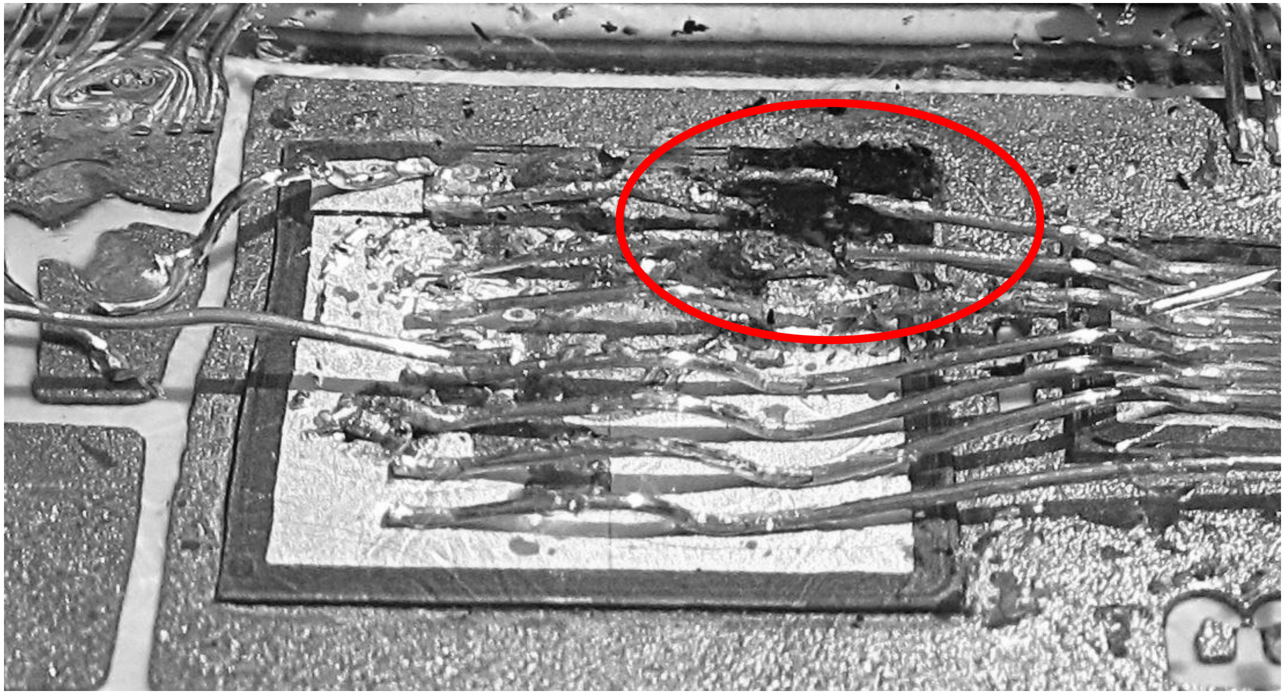
	Sample 0-3
I_{load}	25 A
P	~200 W
ΔT	~100 ℃
Control Mode	const. I
$T_{Heating}$	3 s
$T_{Cooling}$	10 s



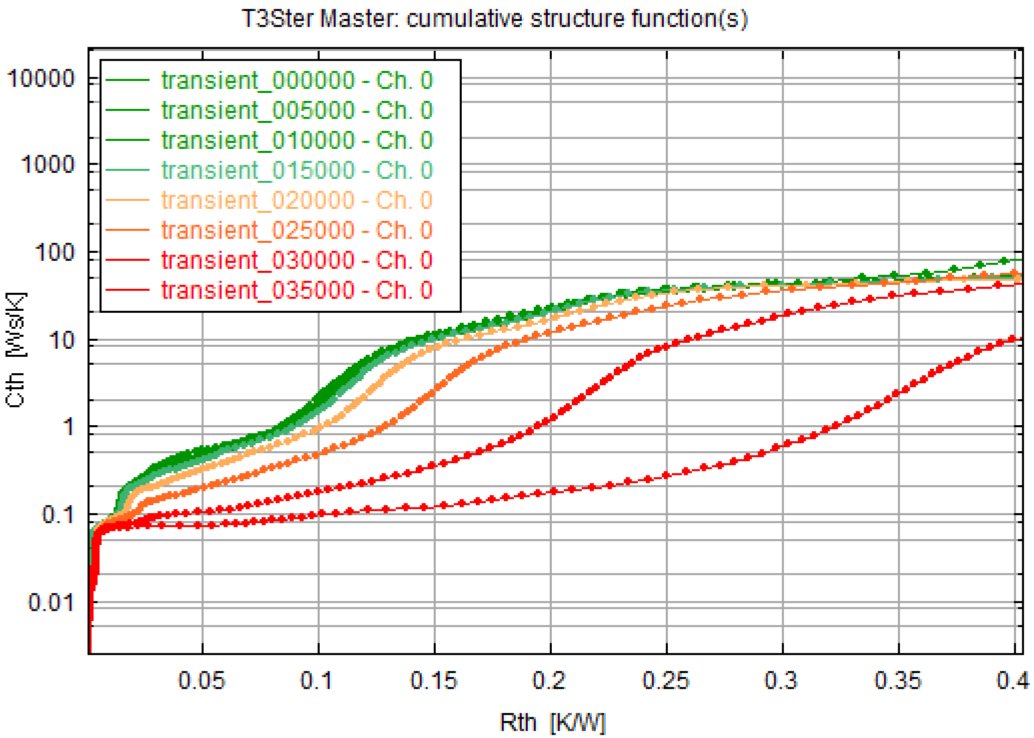


Experiment I. – Results 1.

- All devices failed after approx. 40,000 power cycles
- Broken bond-wires and burnt areas on the chip surface observed
- In fact all IGBTs ultimately failed due to the overheating and damage of the gate-oxide:

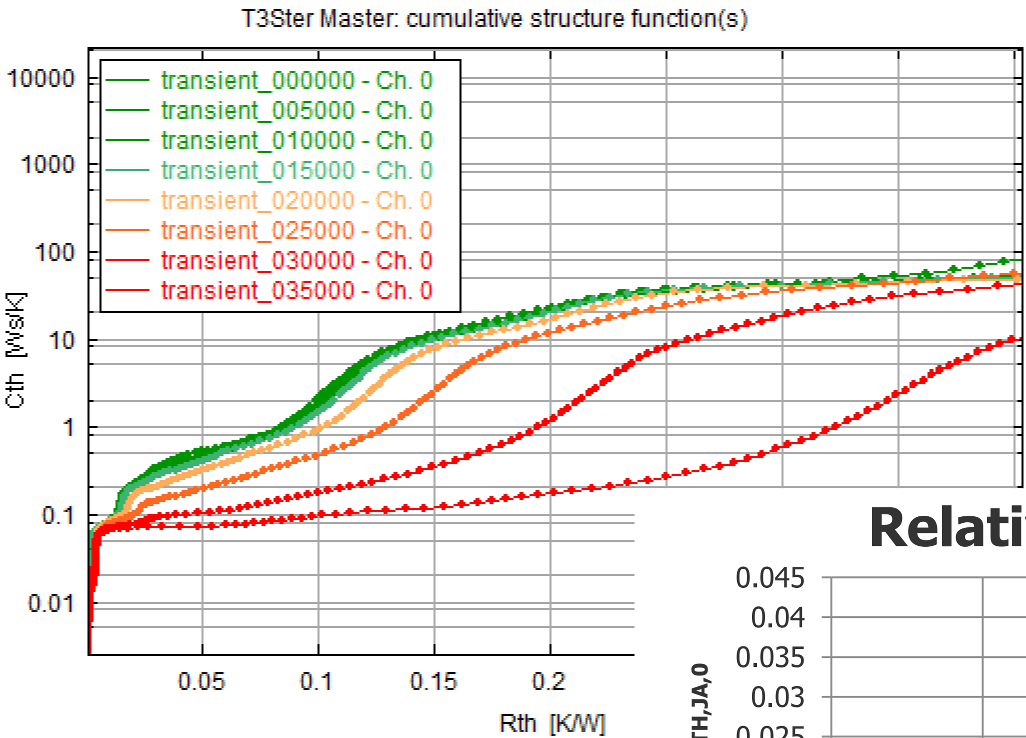


Experiment I. – Results 2.

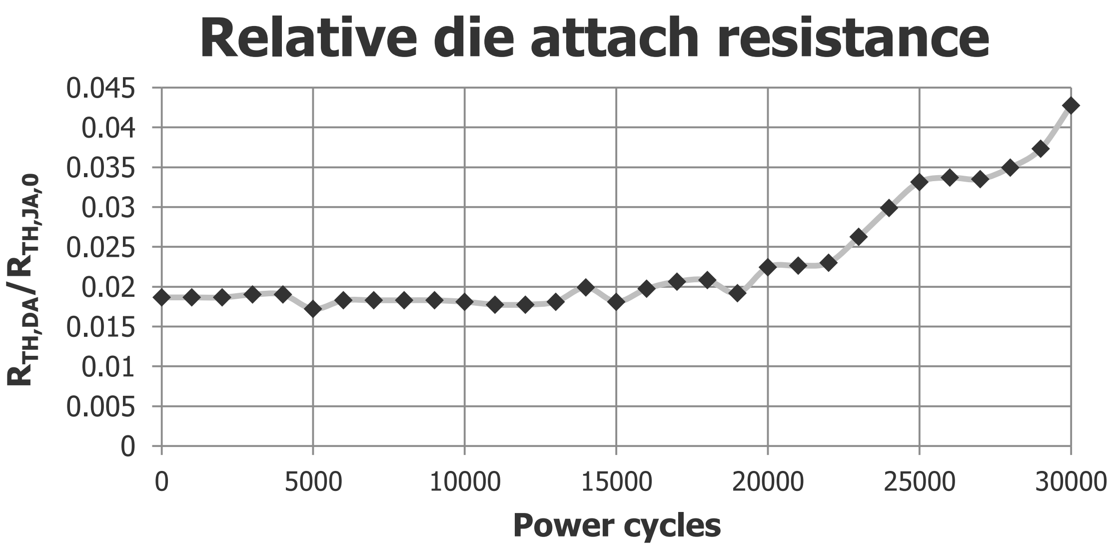


Continuous degradation of the die-attach layer can be observed after ~10,000 to 15,000 cycles

Experiment I. – Results 2.



Continuous degradation of the die-attach layer can be observed after ~10,000 to 15,000 cycles



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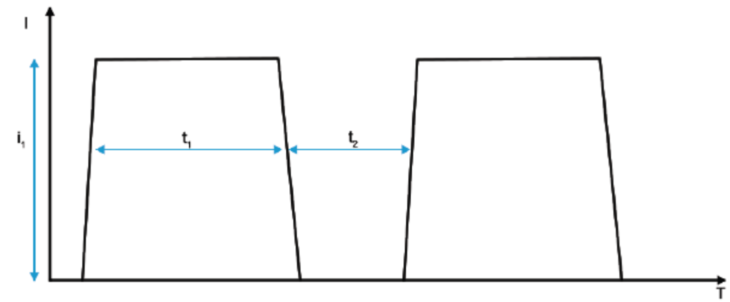
Various control strategies

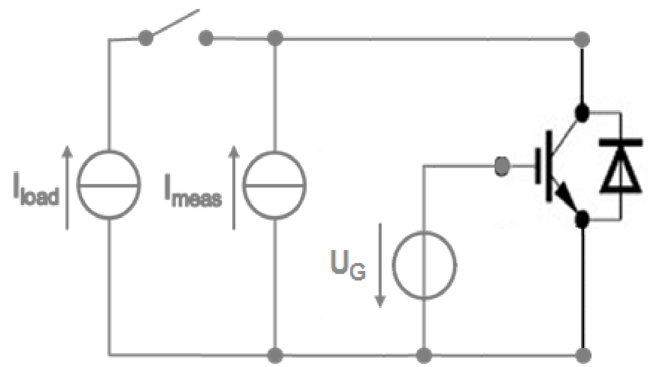
- Constant current
  - Degradation has immediate impact on resulting temperature swing, no compensation
  - Most severe strategy



- Constant current, change of the cold-plate’s HTC
  - Changes the flow rate of the coolant liquid in sync with the cycles
  - Helps to create a temperature swing at the case to induce failures in the base plate solder
  - For longer cycle times
- Constant power, P_V
  - Constant t_{on} and t_{off}
  - Power losses are held constant by controlling the driving current
- Constant ΔT_J=Const
  - Driving current control

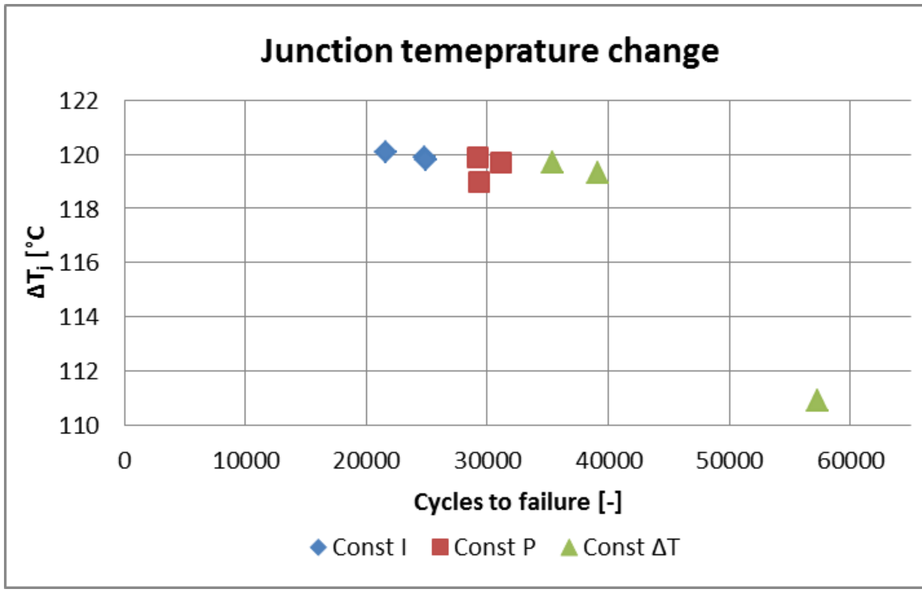
Experiment II. – Setup and parameters

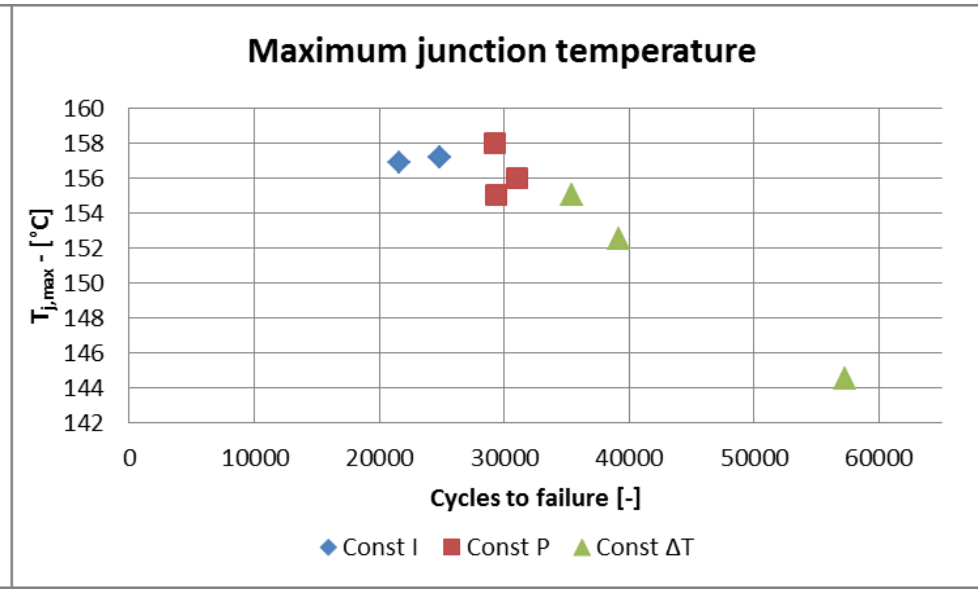
- Devices mounted on temperature controlled cold plate
- Base plate temperature: 25 °C
- Various control strategies*
- Transient test after every 250 power cycles



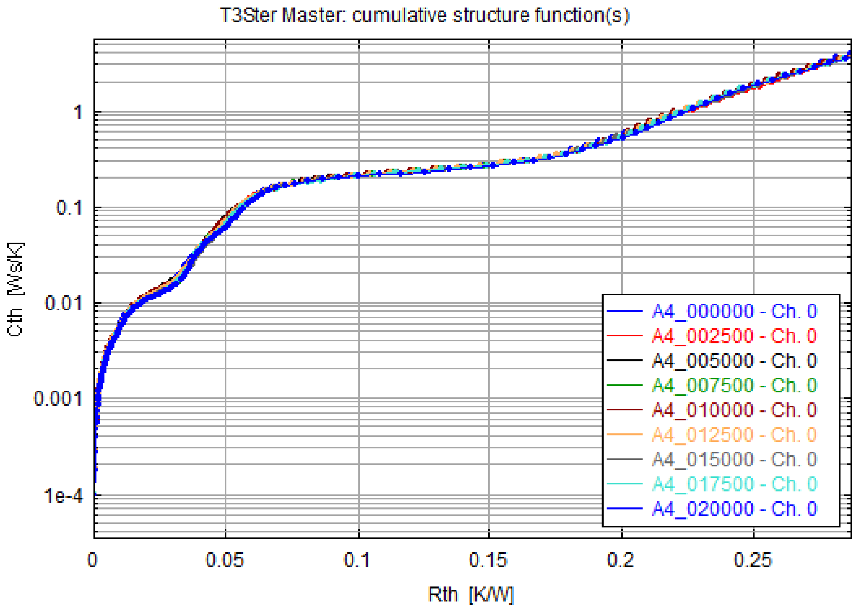
Power cycling strategy	Device	Initial parameters (avg(1..1000 cyc))				Cycles-to-failure
		I [A]	P [W]	DT [°C]	$T_{j,max}$ [°C]	
Const. I	A4	**90.0**	389.6	120.1	156.9	21570
	B4	**87.2**	379.1	119.9	157.2	24837
	C4	**89.1**	388.2	119.8	157.2	24892
Const. P	A3	93.7	**399.1**	119.9	158	29226
	B3	90.4	**399.1**	119.7	156	31081
	C3	90.3	**399.1**	118.9	155	29340
Const. ΔT	A2	91.2	411.1	**119.9**	155	35406
	B2	90.5	396.8	**110.9**	144.5	57329
	C2	91.1	382.1	**119.3**	152.5	39149

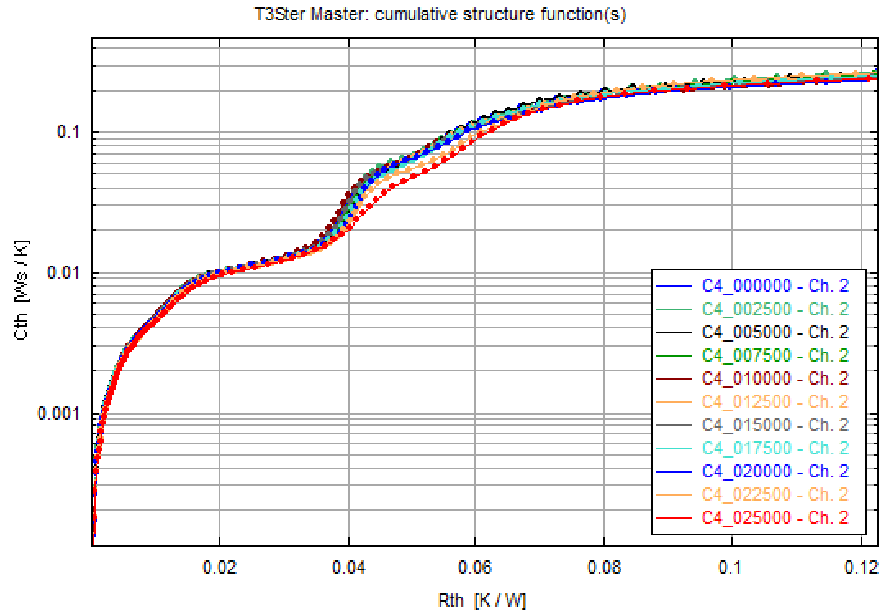
Cycle numbers to failure using different control strategies



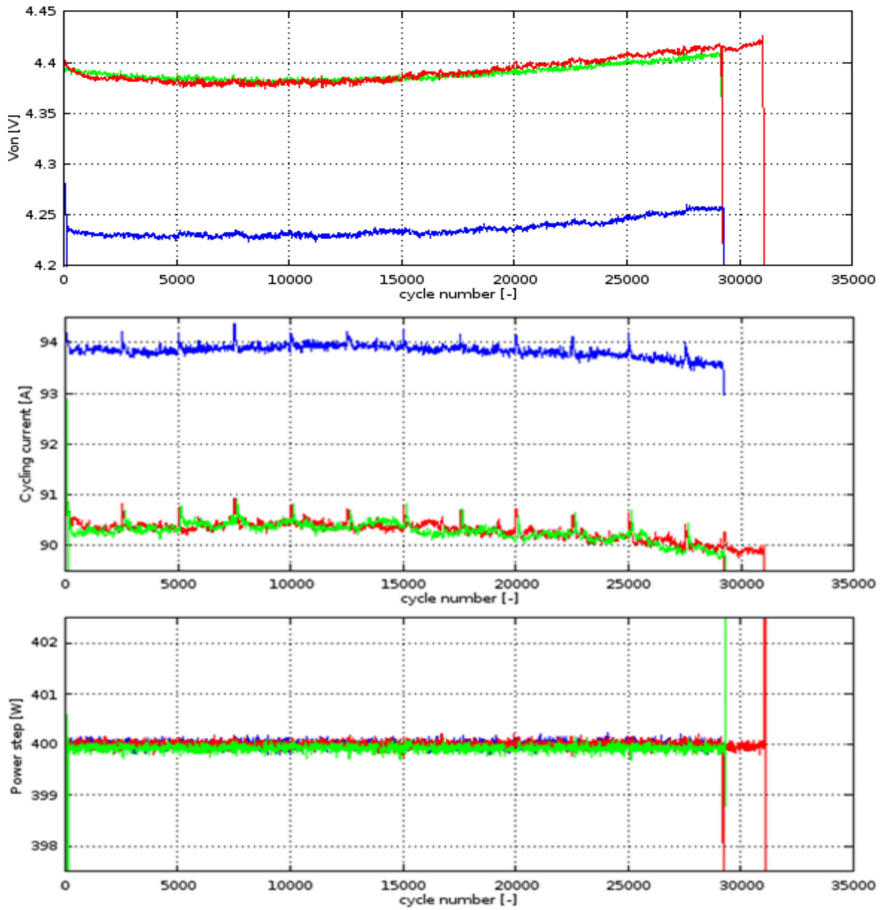


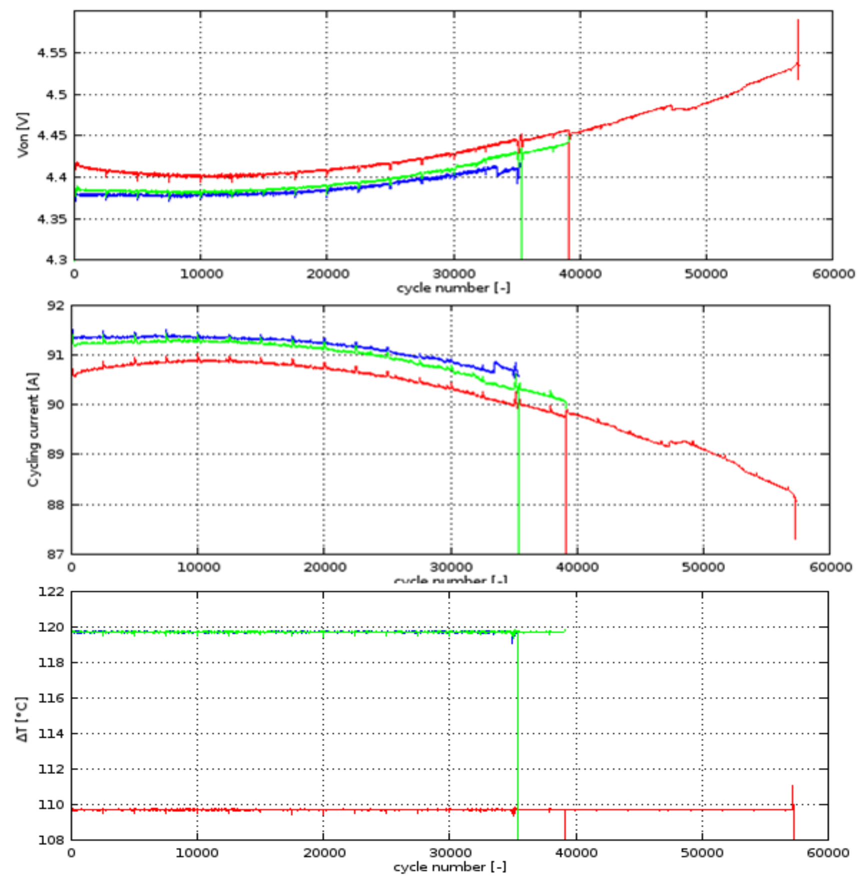
Structure functions to identify die attach degradation





Cycling number vs. electric parameters for constant ΔP (left) and constant ΔT (right)



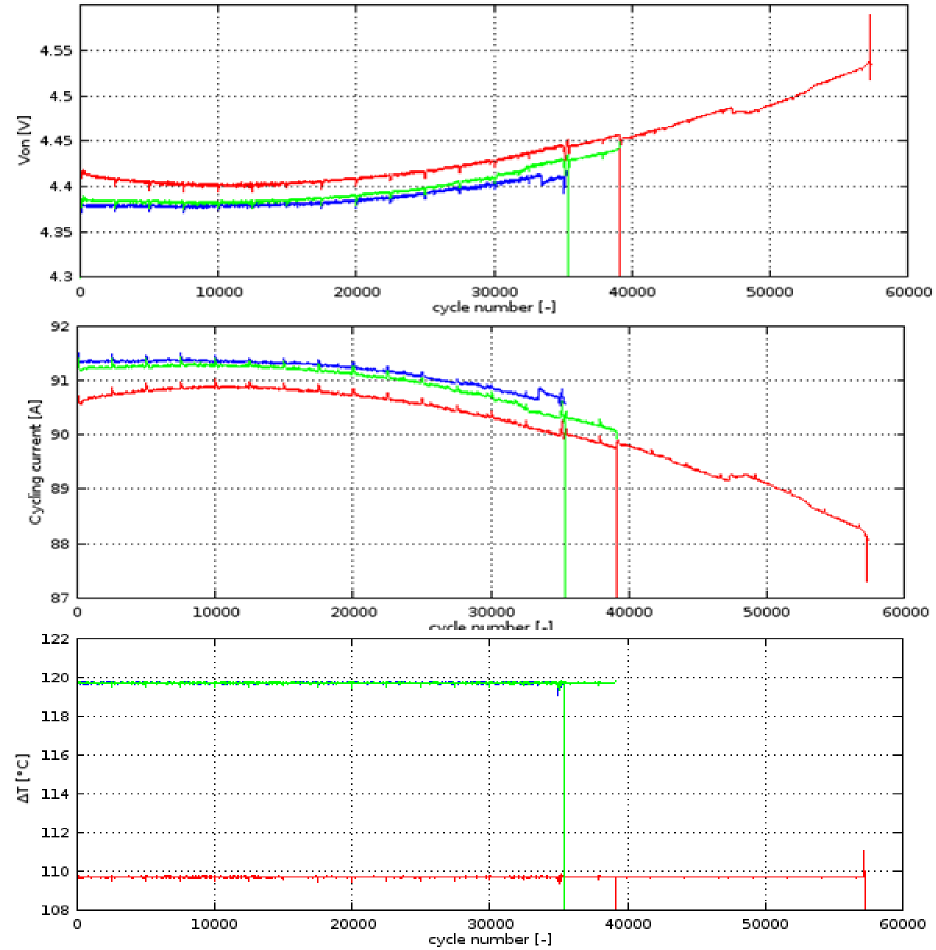


Example: Effect of temperature differences on lifetime

- The same parameters used for IGBT cycling
- ΔTj is kept constant, but 10°C difference between two cases

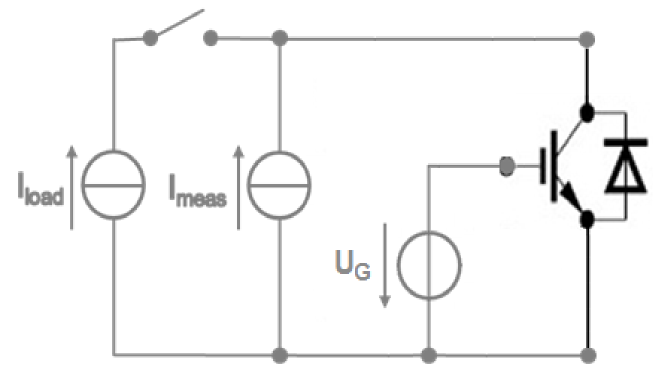
Significant difference in the lifetime
- 120°C: ~36000 cycles
- 110°C: ~58000 cycles

- 2 points of the lifetime curve are available



Experiment III. – Setup and parameters

- Devices mounted on temperature controlled cold plate
- Base plate temperature: 25 ^{o}C
- Targeted junction temperature change : 105 ^{o}C
- Various control strategies*
- Transient test after every 250 power cycles

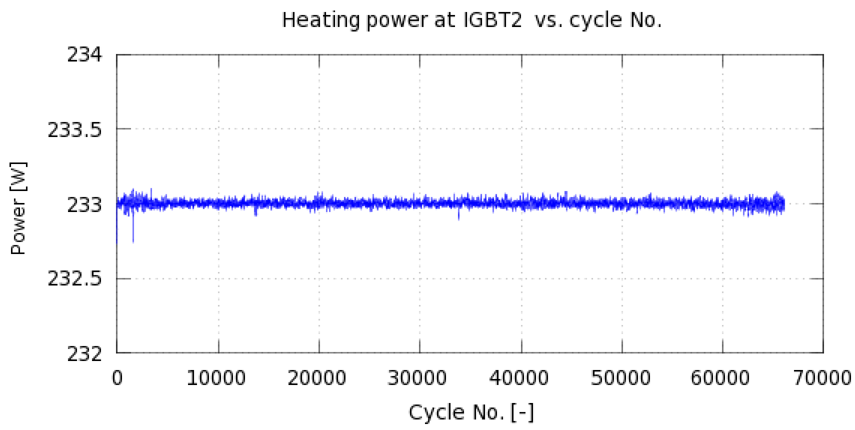


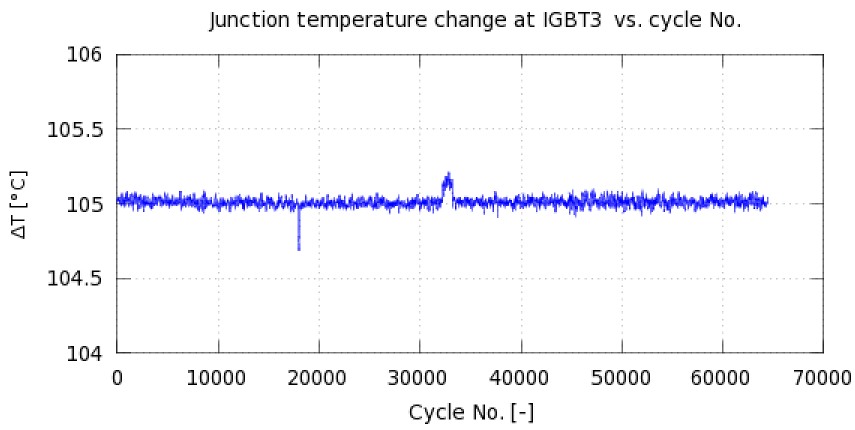
- Number of additional parameters monitored continuously: I_{cycle}, P, V_{on}, V_{hot}, V_{cold}, T_{hot}, T_{cold}, ΔT_J, $\Delta T_J/P$

	IGBT1	**IGBT2**	**IGBT3**
$\mathbf{I_{load}}$	**68 A**	64.4 A	65 A
P	240 W	**233 W**	246 W
$\mathbf{\Delta T_J}$	**105 ℃**	**105 ℃**	**105 ℃**
***Control Mode**	const. I	const. P	const. ΔT_J
$\mathbf{T_{Heating}}$	3 s		
$\mathbf{T_{Cooling}}$	17 s		

Experiment III. – Results 1.

- Well controlled test parameters
  - Variance of the controlled parameter is less than 0.1% (0.1W, 0.1 °C)



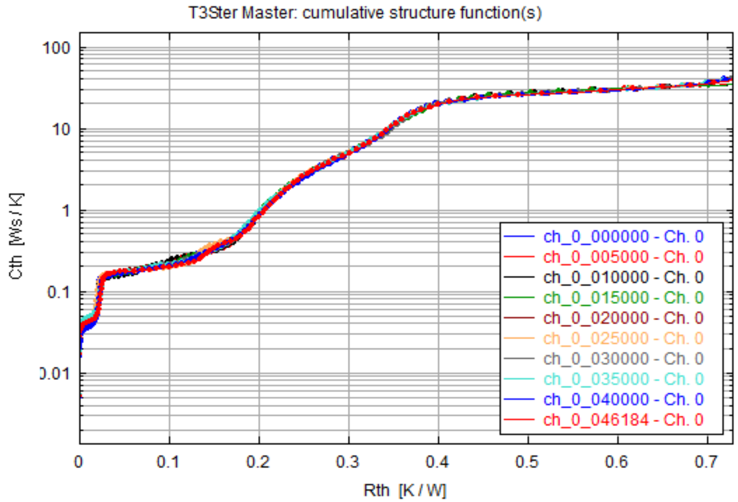


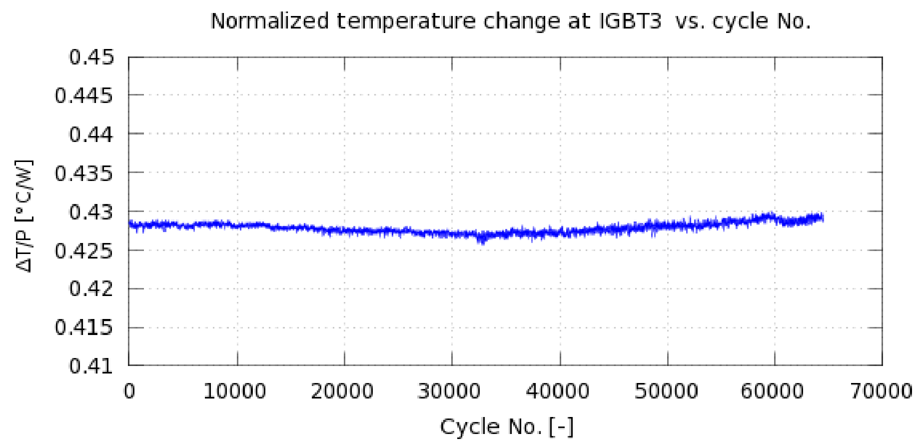
- Although number of investigated samples was too low to draw any quantitative conclusions, a significant difference can be observed in the cycles to failure for the devices:

	Cycles until total failure of the device
Constant heating current (I)	~45 000
Constant heating power (P)	~65 000
Constant junction temperature change (ΔT_J)	~70 000

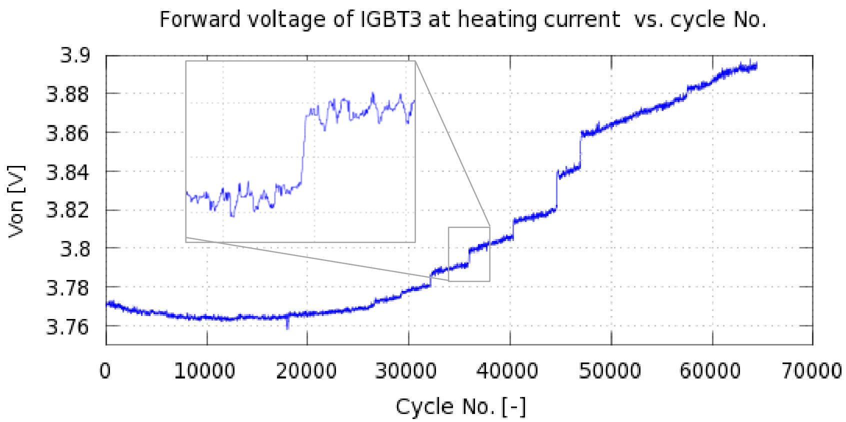
Experiment III. – Results 2.

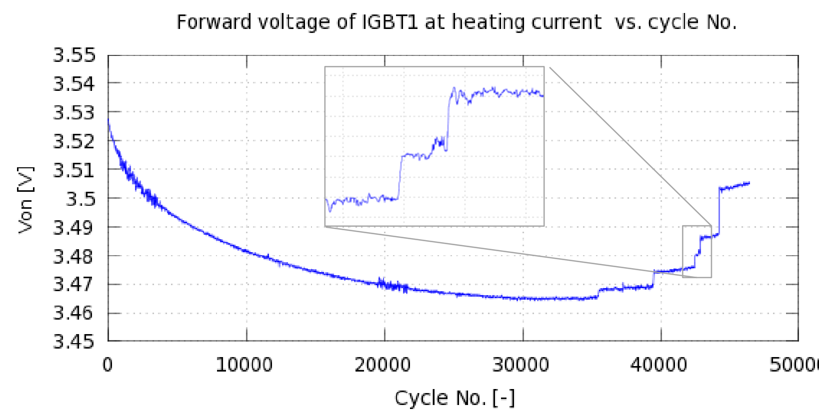
- No sign of degradation in the heat flow path – variation of R_{th} is below 0.5%





- Steep sections can be seen in the CE Voltage of the transistor at high current level - these steps are indicative of bond wire damage/breakage

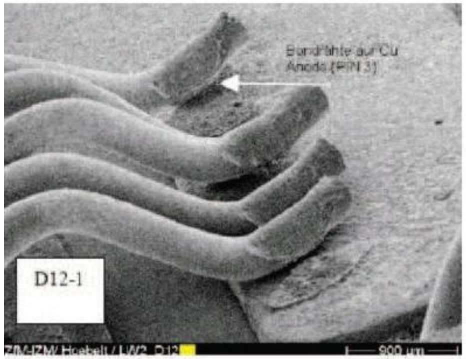


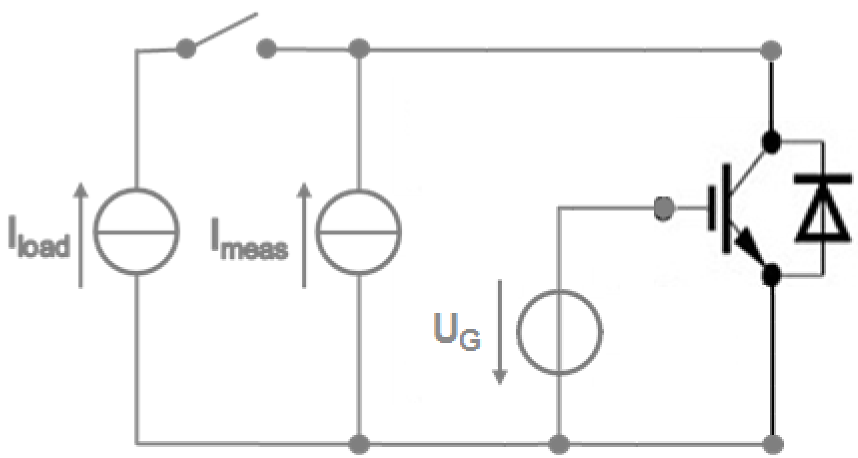


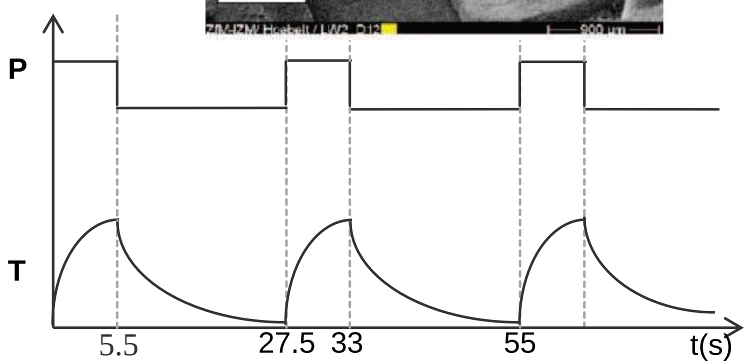
Experiment IV. – Bond wire degradation

- $I_{D\ max}$=160A
- Device driven is saturation mode, V_{GS}=15V
- Target ΔT = 100° C
- Constant timing and current regardless of the voltage change

I_{load}	160 A
P	~530 W
ΔT	~100 ℃
$T_{Heating}$	5.5 s
$T_{Cooling}$	22 s
Tmax	135 ℃

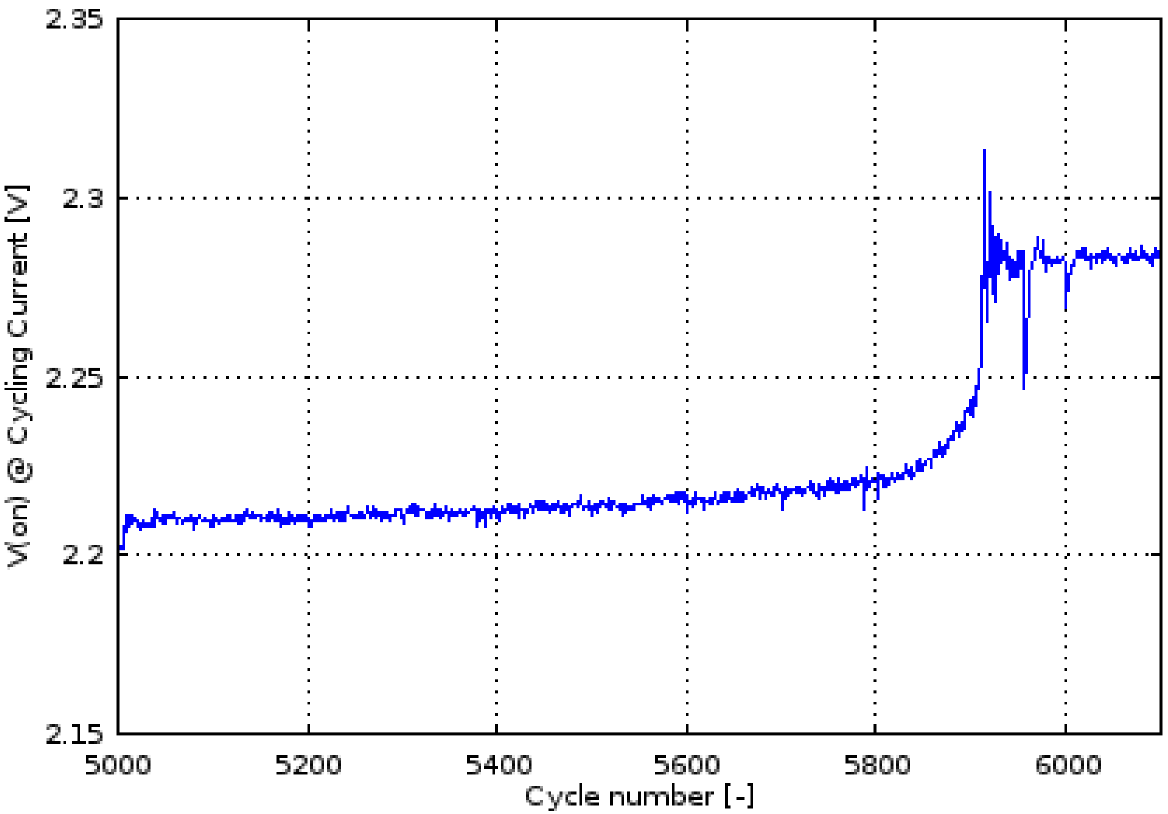






Experiment IV. – Bond wire degradation

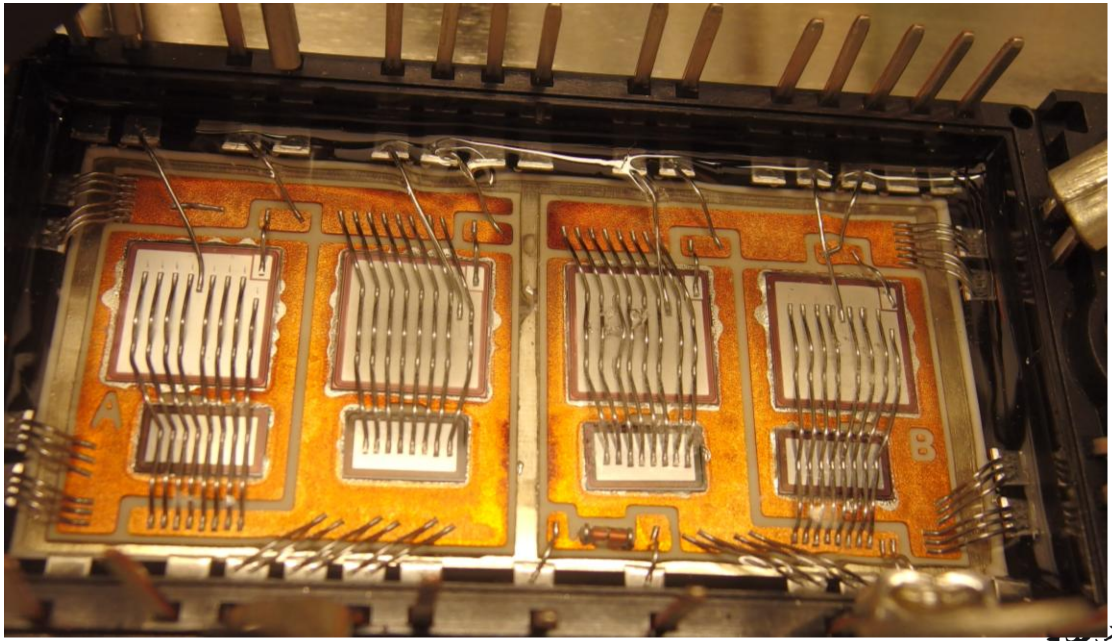
- Firs voltage drop increasing gradually
- Then stepwise voltage elevation can be observed



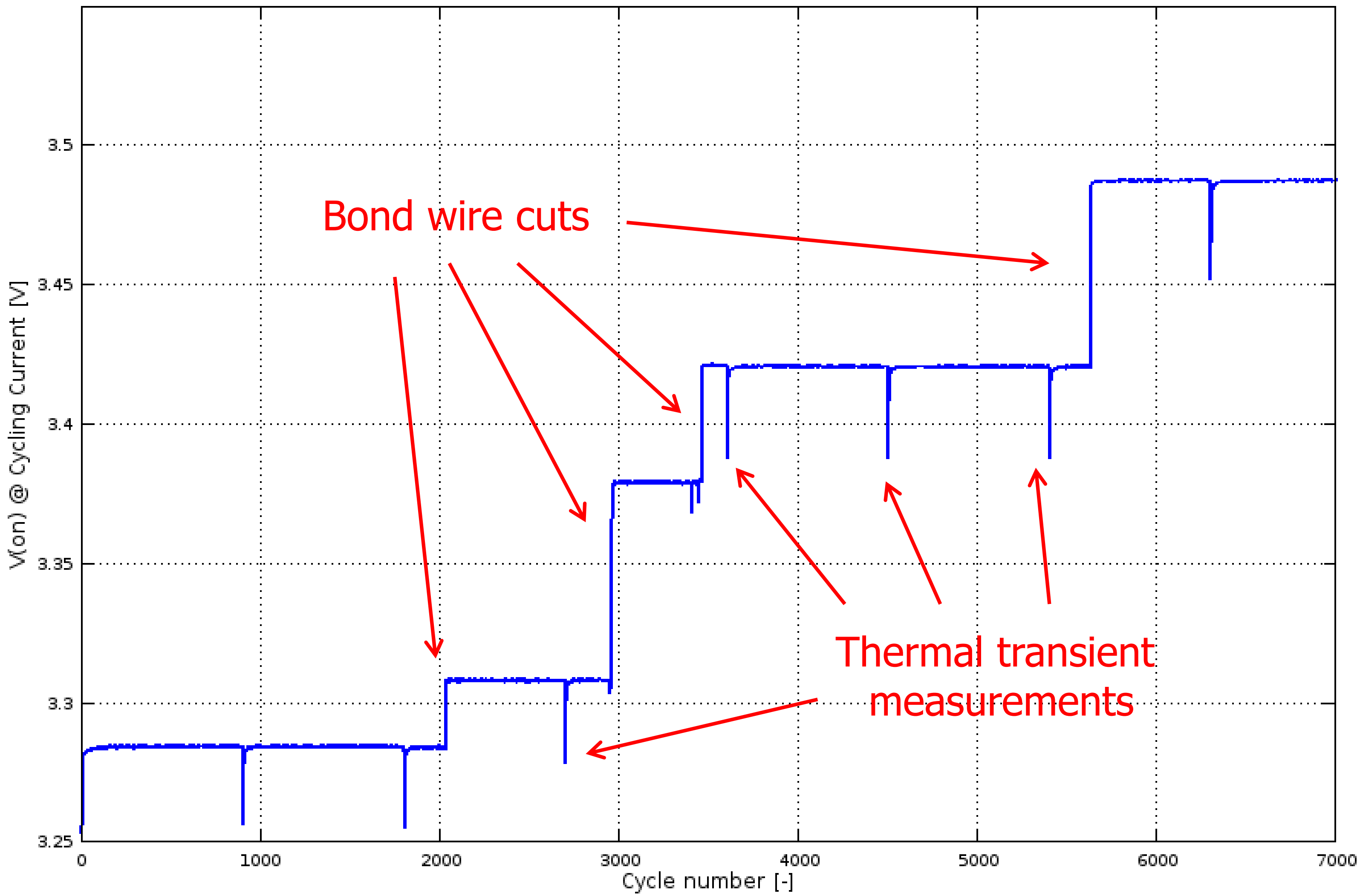
Experiment IV.b – Bond wire cut test

- $I_{D\ max}$=80A
- Device driven is saturation mode, V_{GS}=15V
- Limited heating current was used to ensure there is no degradation during the test
- Transient test after every 900 power cycles

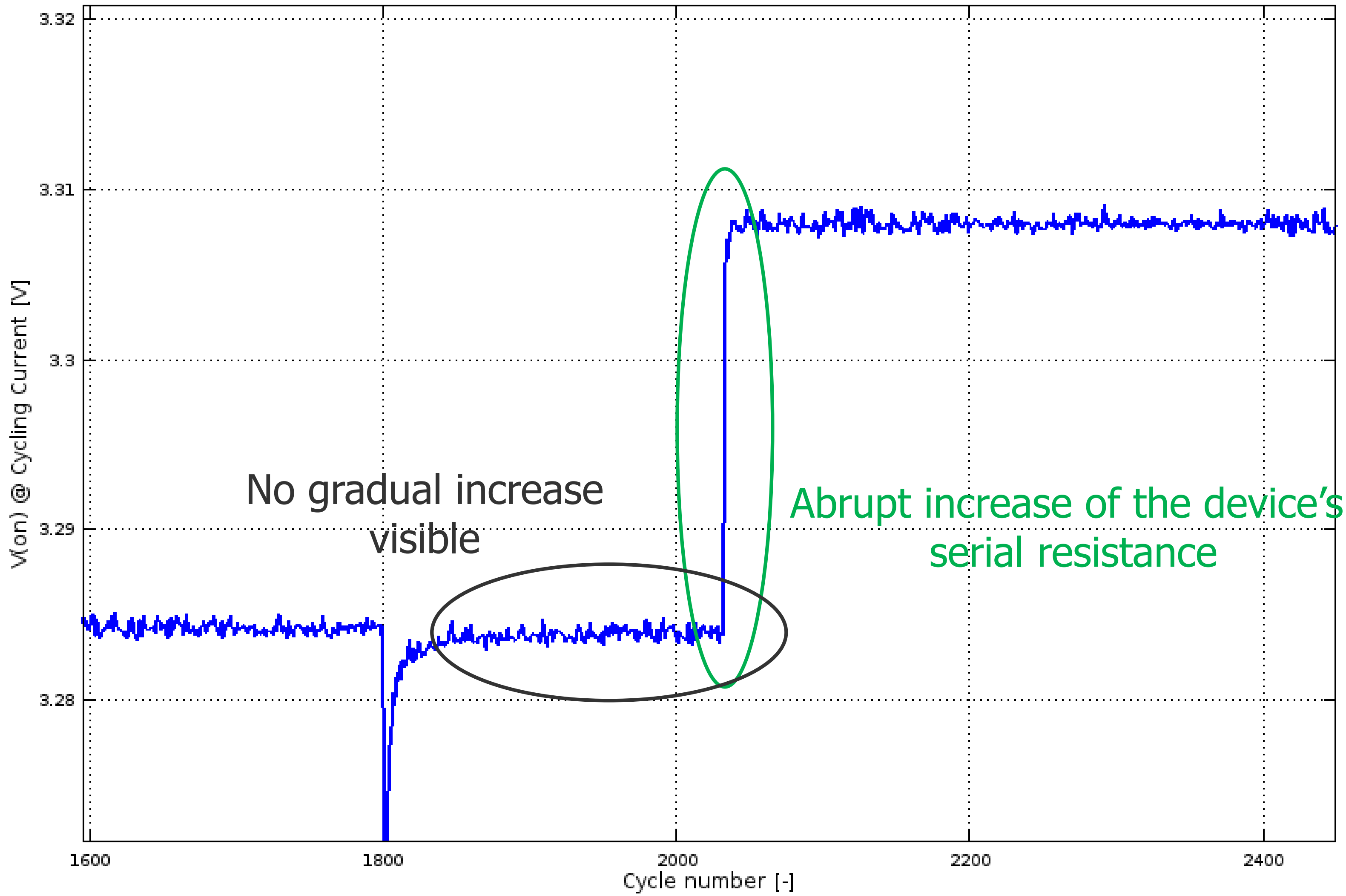
I_{load}	50 A
P	~65 W
ΔT	~35 ℃
$T_{Heating}$	0.5 s
$T_{Cooling}$	1.5 s



Experiment IV.b – Bond wire cut test



Experiment IV.b – Bond wire cut test

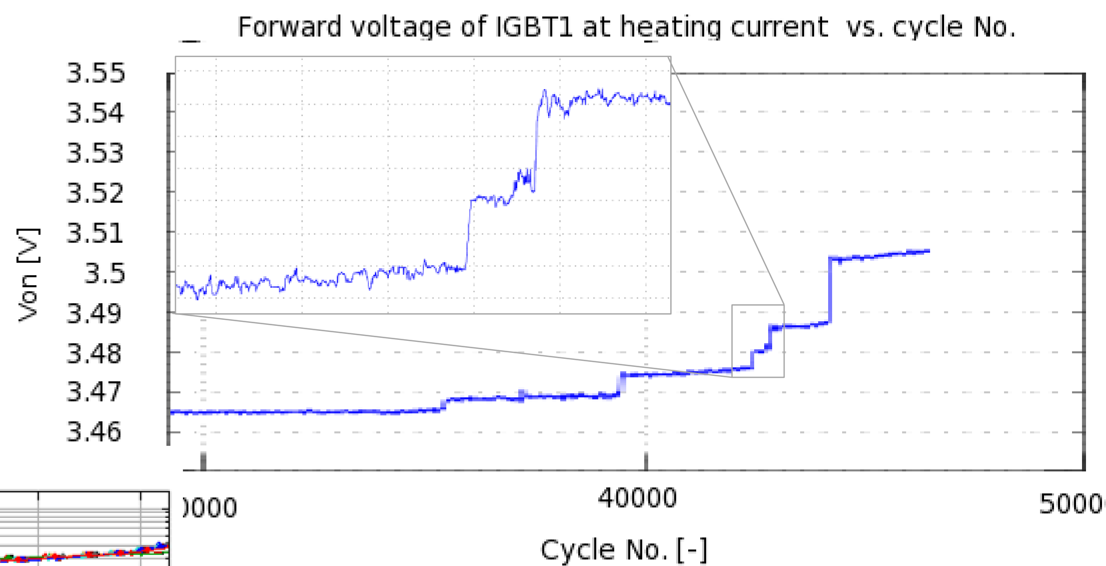


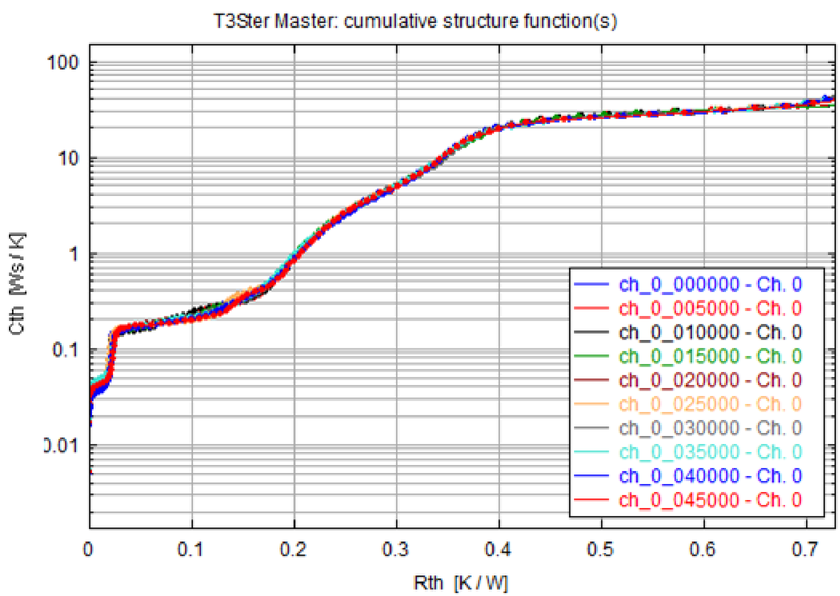
Concurrent failure modes

- In real applications it is likely that the two effects discussed above arise in parallel

- Problem:
  - The increasing bond resistance can be recognized on the voltage drop curve
  - The change of the Rth indirectly affects the voltage drop at load current level
  - In case of IGBTs due to the typically positive TCO at high current levels the direction of the change is identical
  - Hard to separate the two effects

Concurrent failure modes – Experimental results





We could verify that there was no structural change

Conclusions

- The lifetime of a power device significantly depends on the intended application.
  - Mission profiles/driving profiles described
- Mentor Graphics' CFD simulation tools such as FloTHERM, FloTHERM XT or FloEFD allow users to understand the temperature changes during operation
  - Calibrated by physical tests
- The Power tester helps to create lifetime curves
  - Provide relationship between the device temperature change during power cycles and the cycle number to failure.
- Finally, we demonstrated an example workflow on how to calculate the expected lifetime
- Precise temperature calculations/measurements needed for accurate prediction