

高功率器件的壽命测试

Lifetime testing of power components

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November 2017



USER2USER
MENTOR GRAPHICS USER CONFERENCE

汽車用 IGBT 測試
Automotive IGBT testing

COMMONLY USED TEST METHODOLOGIES

一般測試方式

Insulated Gate Bipolar Transistors (IGBT) / Power Electronics Applications

绝缘栅双极性电晶体(IGBT)/电力电子元件的应用

■ Motor drives 马达驱动

- Commercial motor drives 商用马达驱动
- Motor drives discrete 马达驱动离散
- Motor drives modules 马达驱动模组
- Motor drives IPM 马达驱动智能功率模组

■ UPS

- UPS discrete UPS离散
- UPS modules UPS模组

■ PhotoVoltaic inverters 光伏逆变器

- Commercial PV 商用光伏逆变器
- Residential PV 民用光伏逆变器
- Solar farms 太阳能电站

■ Electric Vehicles/Hybrids 电动/混合动力汽车

- PHEV/EV 插电式混合动力汽车
- Mild HEV 中度混合动力汽车
- Micro HEV 轻度混合动力汽车
- EV/HEV charging stations 电动汽车/混合动力电动汽车充电站

■ Railway traction 铁路牵引

- Rail traction inverters 铁轨牵引逆变器
- Rail auxiliary inverters 铁轨辅助逆变器

■ Wind turbines 风力涡轮机

- Wind turbine >1MW 风力涡轮机>1MW
- Residential/commercial wind turbines 民用/商用 风力涡轮机

■ Industrial applications 工业应用

- Welding 焊接
- Other industrial 其它

■ Consumer applications 消费应用

- Induction heating 感应加热
- DSC-DSLR camera flash DSC-DSLR相机快闪记忆体
- Air conditioner 空调
- Washing machine 洗衣机
- Flat panel (LCD/PDP) 显示器 (LCD/PDP)
- Lighting supplies 照明设备
- Other home appliances 其它家用

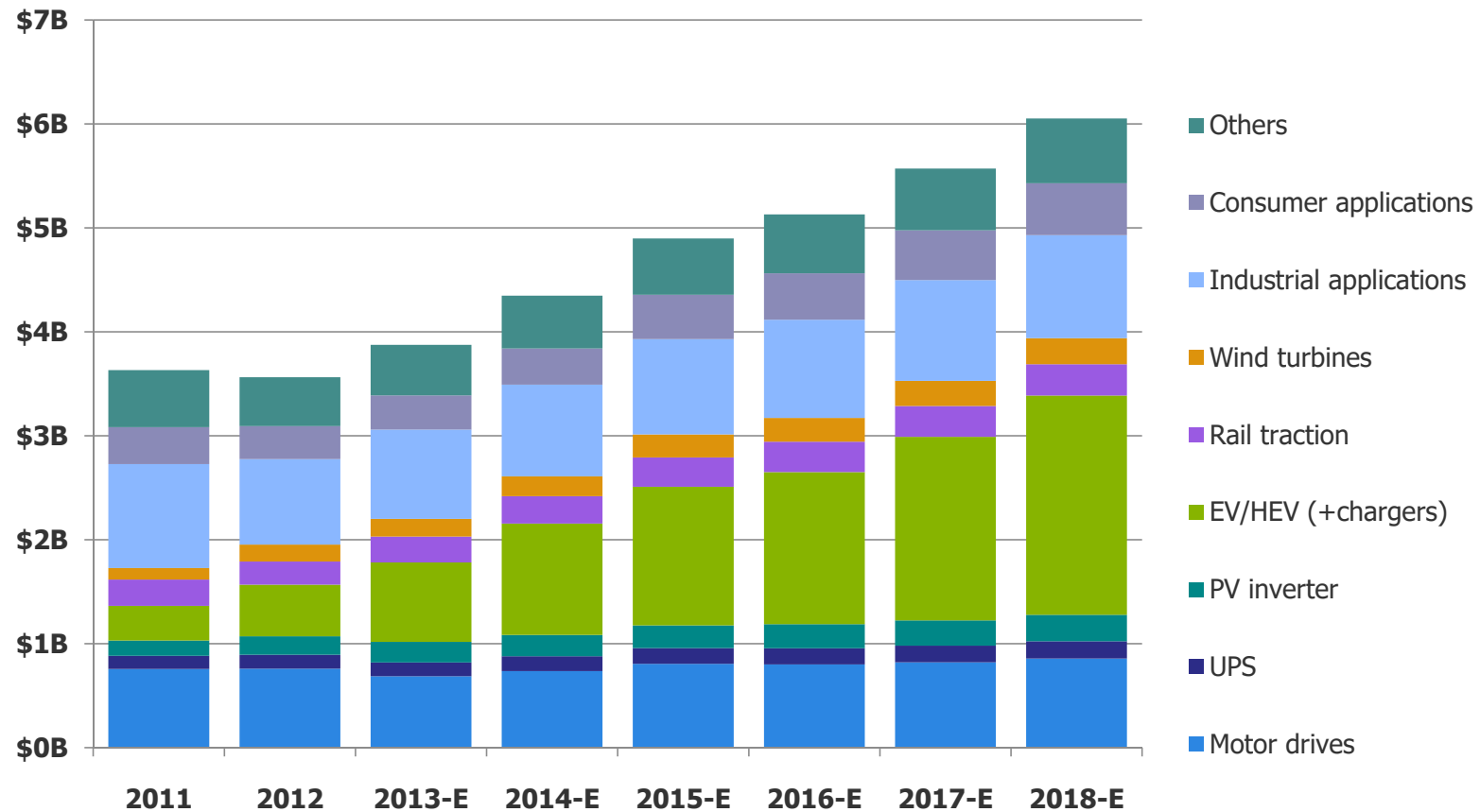
■ Others 其它

- Other power supplies (SMPS) 其它电源供给 (SMPS)
- Automotive ignition 汽车引擎
- Marine propulsion 船舶
- Medical applications 医疗应用
- Defibrillators 医用除颤器
- Avionics converters 航空变流器
- Heavy duty vehicles 重型载重车
- Grid -T&D 智慧型电网

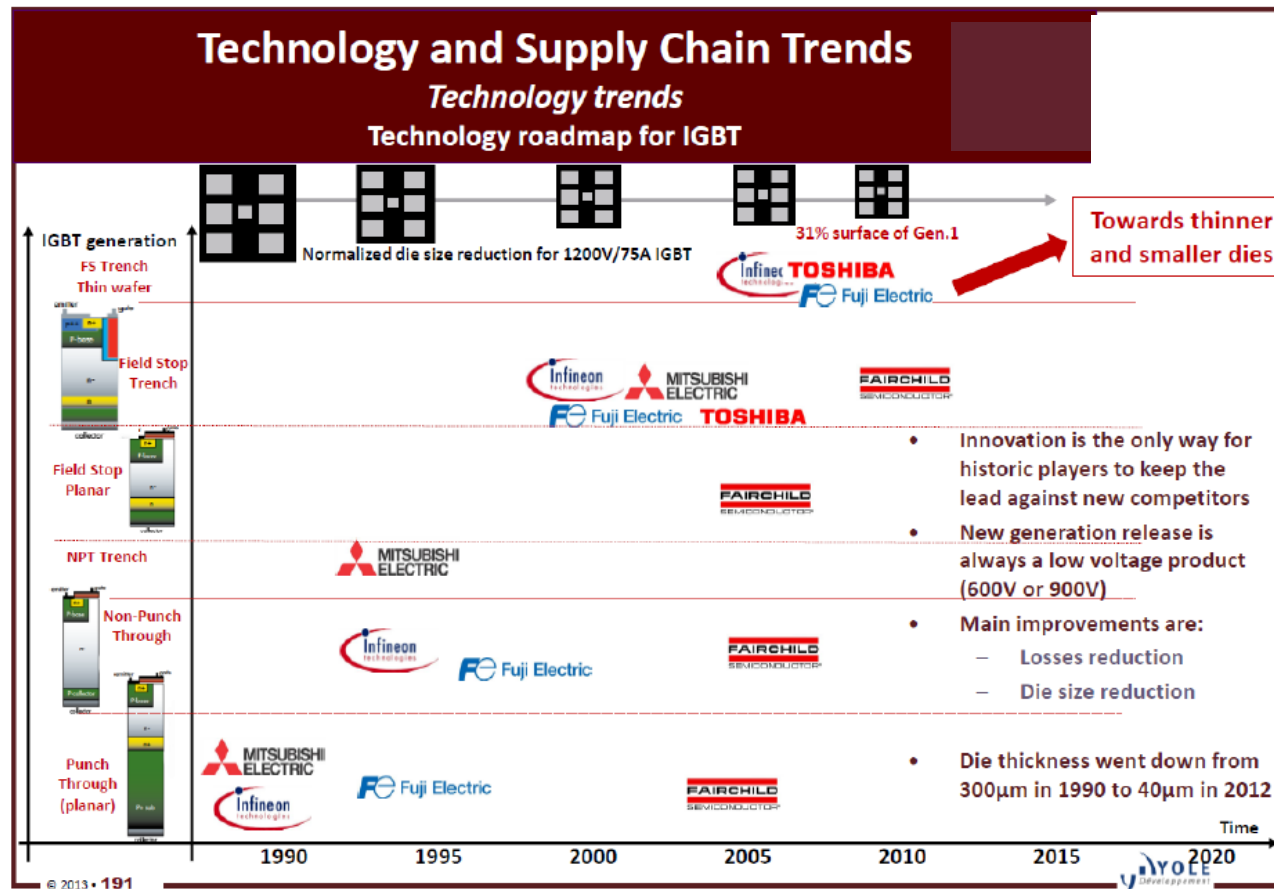


IGBT Market Forecast by Segment

IGBT 于不同应用市场的预测



IGBT technology trend – Power densities are increasing (IGBT 技术发展趋势 – 功率密度的提升)



Commonly used test methods

一般測試方式

- IGBT testing includes some major branches, like
IGBT 主要的測試內容包含
 - Module electrical characterization tests 模組電性測試
 - Environmental tests 環境測試
 - Lifetime tests 壽命測試
 - etc. (mechanical tolerances 機械公差, chemical resistance 耐化學性, ...)
- Mentor Graphics expertise covers an important range of these testing branches,
especially those which are related to **powering solutions** and **thermal effects**
Mentor Graphics 的專家對於功率解決方案和熱效應的部分有特別的涉略

Sources of knowledge in power device testing

功率器件測試的相關技術

There are internal company standards
with poor access to them,
but also some open sources exist

許多客戶有內部自行的規範，很難特別深入了解，但有時也會分享出來

- e.g. AEC - Q101
 - FAILURE MECHANISM BASED STRESS TEST QUALIFICATION FOR DISCRETE SEMICONDUCTORS IN AUTOMOTIVE APPLICATIONS
- Automotive Electronics Council – since 1993, on testing of **automotive components**
- Even though this standard covers discretes, many companies try to re-use the same guidelines for modules
儘管這些標準適用在分離器件，但許多公司也試著用在模塊量測上

Sources of knowledge in power device testing

功率器件測試的相關技術

- Other forum of information exchange: 其他交換訊息的論壇

ECPE European Center for Power Electronics

Some statements in this presentation are inspired by the ideas from the 此報告的內容靈感來自以下概念

ECPE Workshop - Intelligent Reliability Testing

(Nuremberg, 2-3 December 2014)

- and we have our own experience 以及來自於本身的經驗

Tests

■ **Module tests (QM)** 模組測試

- the purpose is ensuring fault free DUTs for the subsequent tests, with parameters met & functional accuracy
目的是為了後續測試先確保無故障的 DUT, 並滿足參數設定和功能準確
- typically short tests, fractions of a second or some seconds
極短的測試, 通常為一秒或數秒鐘
- simple electrical tests, also visual inspection and similar 簡單的電性測試和目視檢查

■ **Characterization tests (QC)** 表徵測試

- Precursor to environmental and lifetime testing 先前的環境和壽命測試
- checks relevant parameters before other tests, can be repeated at defined times and after other tests 確認相關參數在其他測試前能於特定時間內重複獲得

■ **Environmental tests (QE)** 環境測試

■ **Lifetime tests (QL)** 壽命測試

Characterization tests (QC)

表徵測試

Using the terminology suggested at ECPE 相關術語取自於 ECPE

- QC – 01 Determination of parasitic stray inductance (L_p)
— IEC60747-15:2012 Chapter 5.3.2 寄生雜散電感的測定
- **QC – 02 Determination of thermal resistance**
— IEC60747-15:2012 Chapter 5.3.6 熱阻測定
- QC – 03 Determination of short-circuit capability 確定短路能力
- QC – 04 Determination of isolation behavior 確認隔絕狀況
— IEC 60664-1
- QC – 05 Determination of mechanical data 確認機械數據

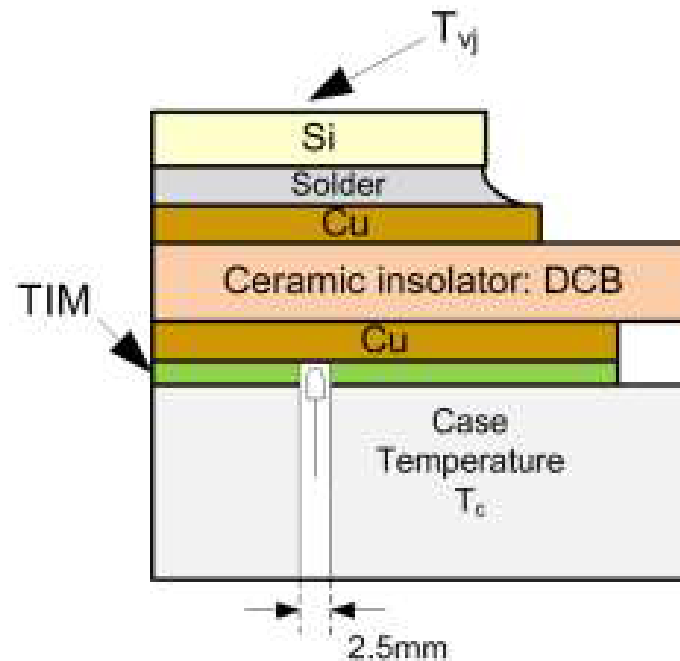
QC – 02

Determination of thermal resistance (R_{th}) 熱阻測定

- Junction to case 結點到殼

(R_{thJ-C} , using Dual interface measurement or aux temp sensor)

利用雙介面量測法或其他溫度傳感器



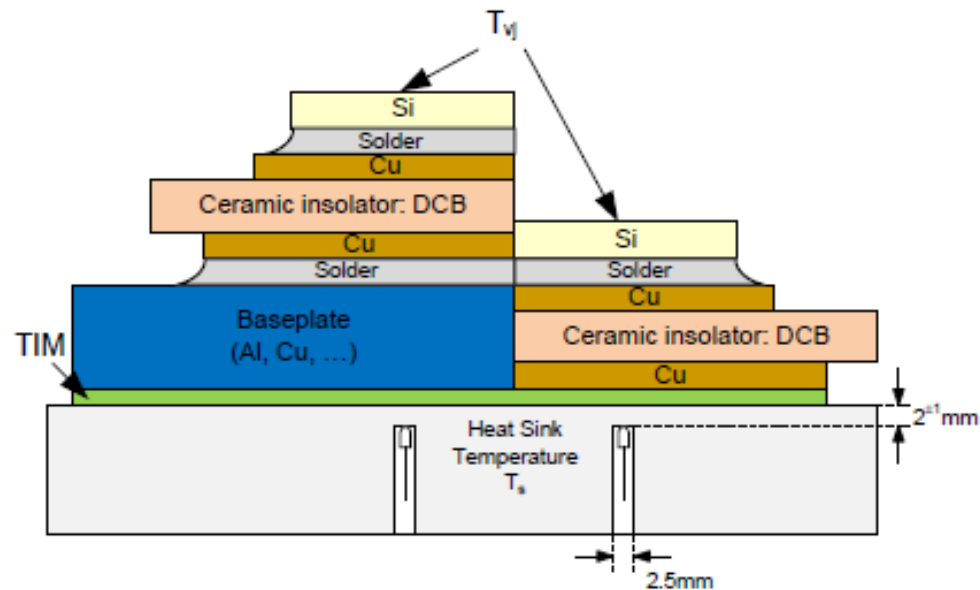
QC – 02

Determination of thermal resistance (R_{th}) 熱阻測定

■ Junction to heat sink 結點到散熱器

(R_{thJ-S} , using embedded Pt100 temperature sensor – where and how many?? customer specific)

利用內置的 Pt100 溫度傳感器, 放置位置和數量由客戶自行定義



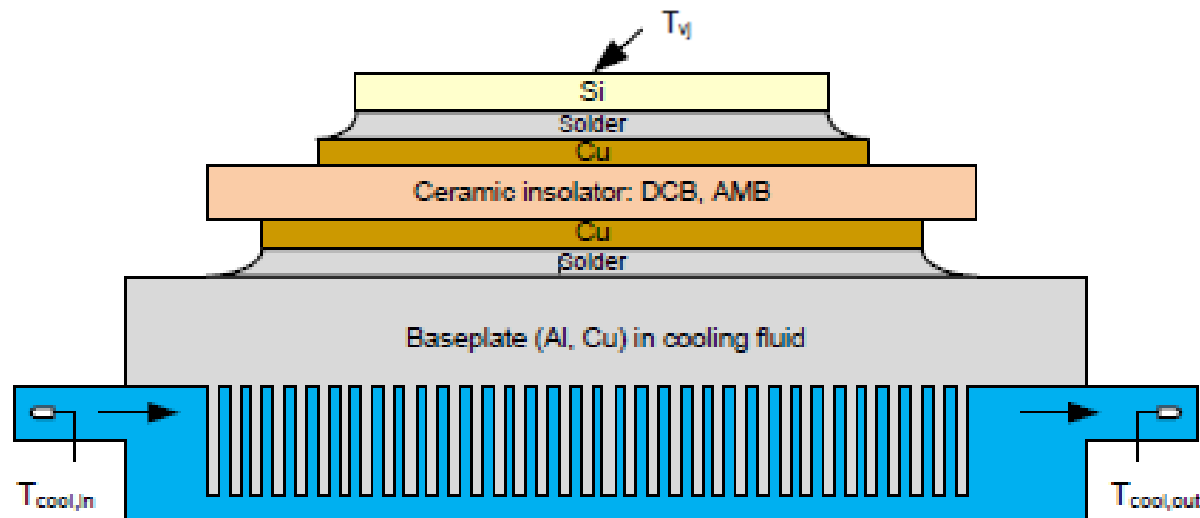
QC – 02

Determination of thermal resistance (R_{th}) 熱阻測定

■ Junction to ambient 結點到環境

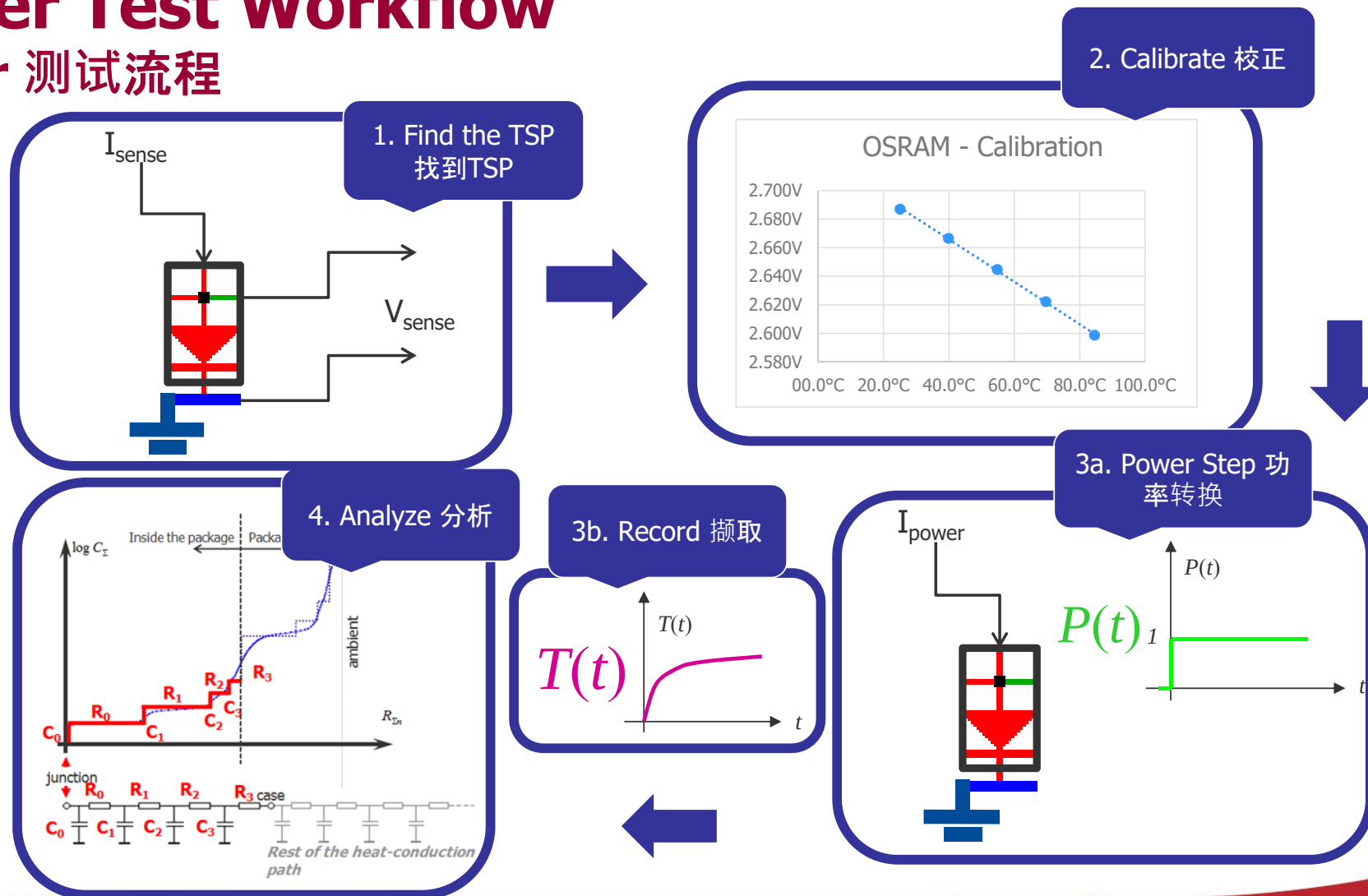
(R_{thJ-A} , its **real effective value** is inherently provided by all other measurements. In case of integrated heat sink; coolant temperatures give additional information for system integration.)

實際有效數值由其他量測所提供，在集成散熱器的情況下，冷卻液的溫度提供額外的訊息



T3Ster Test Workflow

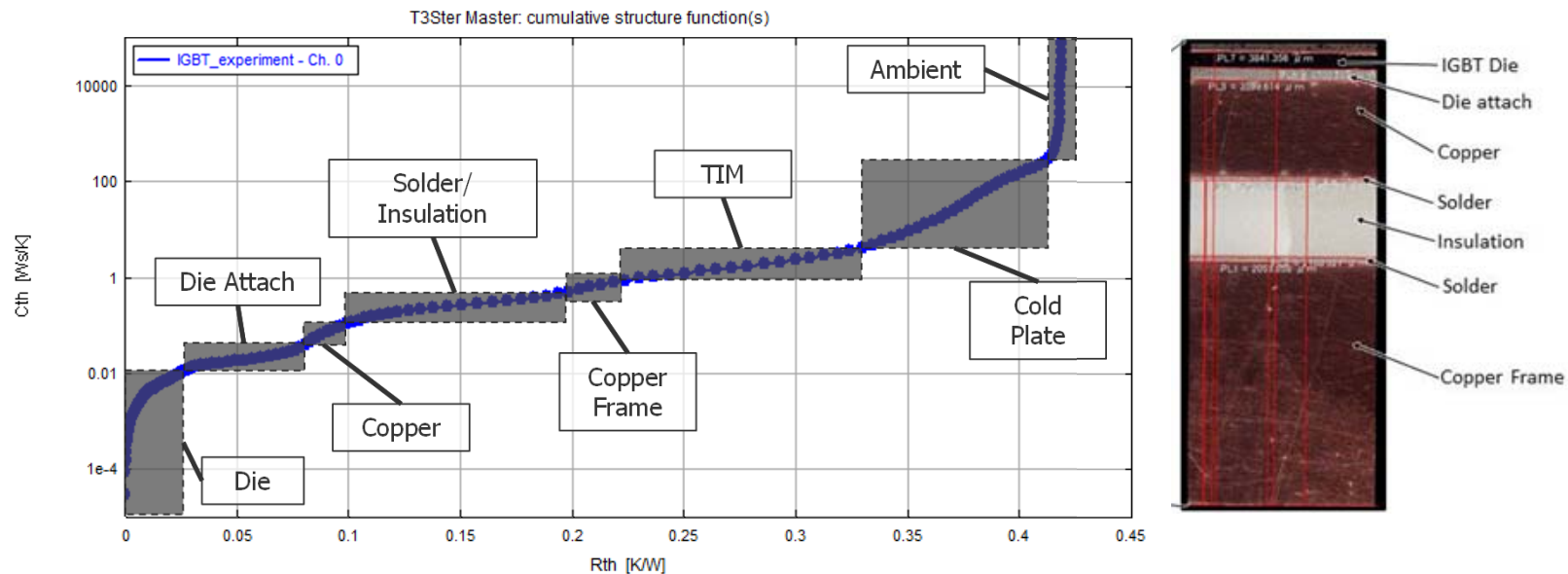
T3Ster 测试流程



T3Ster - Transient Response Measurements

T3Ster – 瞬態響應量測

- 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.
“結構函數”路徑上的每個部分都代表熱所遭遇到的物理對象。
物理對象和部分的 RC 路徑之間存在相關性。



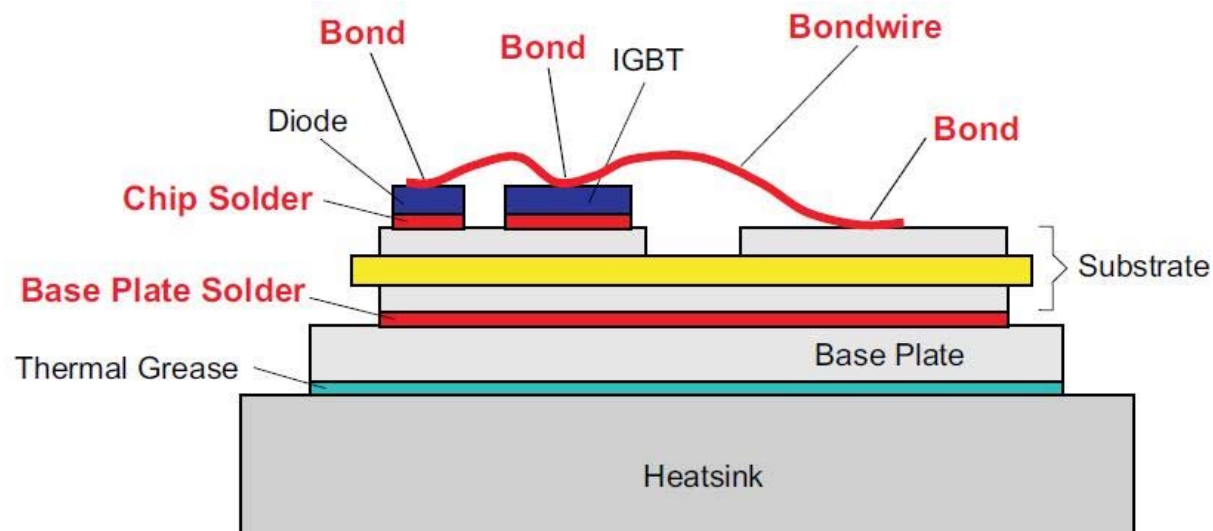
Environmental testing (QE) in automotive

- The environmental tests serve to verify the suitability of power electronics modules for use in motor vehicles.
環境測試主要用於驗證功率電子模塊在機動車輛中的適用性
- Some commonly used environmental test solutions 一些通用的環境測試方式
 - **Temperature shock tests (TST)** 溫度衝擊測試
 - Contactability (CO) 接觸性
 - Vibration (V) 震動
 - Mechanical shock (MS) 機械衝擊
- Out of these we can focus only on those which induce mechanical damage in the heat conduction path of the power module
在這之中我們只能關注在功率模塊的導熱路徑中所引起得機械損傷
 - Combined with structure function evaluation it is a good test method
結合結構函數是很好的測試方式

Vulnerable areas of a typical power device

典型功率组件的弱点

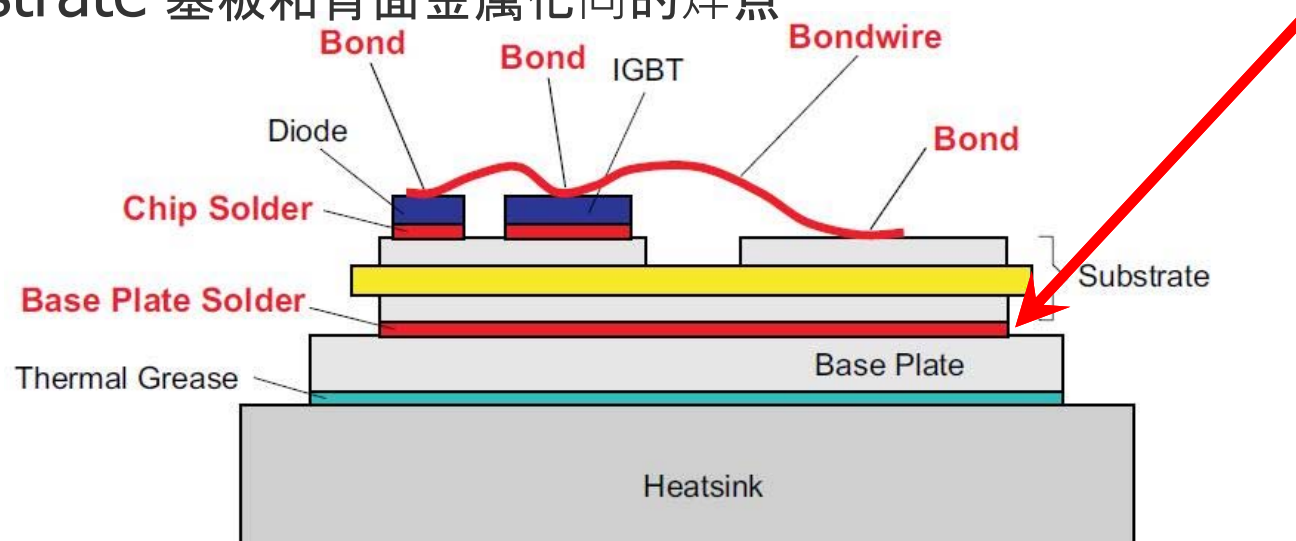
- The thermomechanical stress is the most significant where the temperature change and the contact area between the layers are high 各层接触面和温度变化剧烈处是热机应力最显着的位置



Vulnerable areas of a typical power device

典型功率组件的弱点

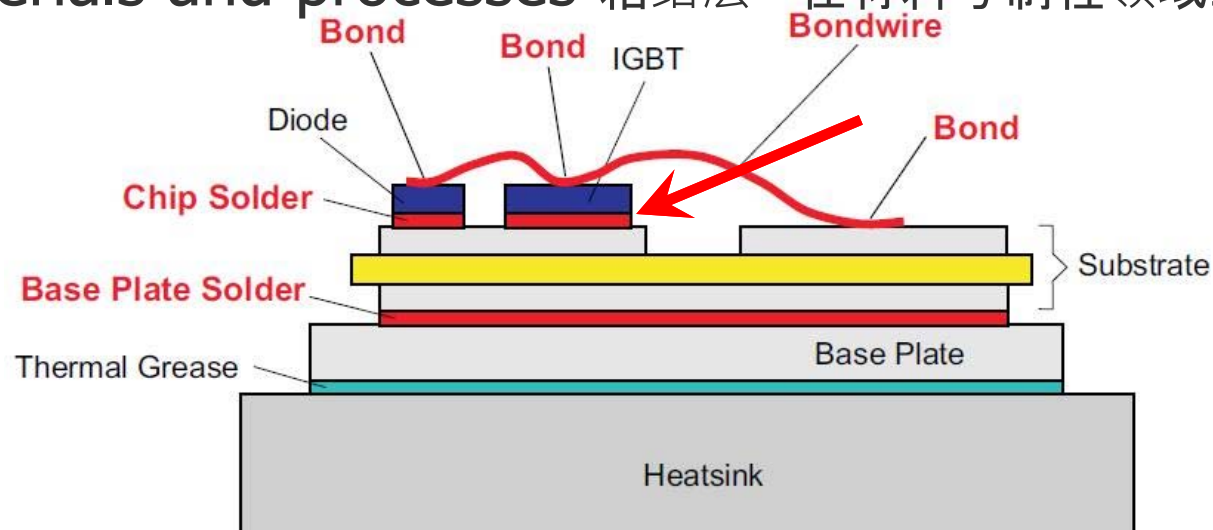
- The thermomechanical stress is the most significant where the temperature change and the contact area between the layers are high 各层接触面和温度变化剧烈处是热机应力最显着的位置
- Solder joint between the base plate and the back-side metallization of the substrate 基板和背面金属化间的焊点



Vulnerable areas of a typical power device

典型功率组件的弱点

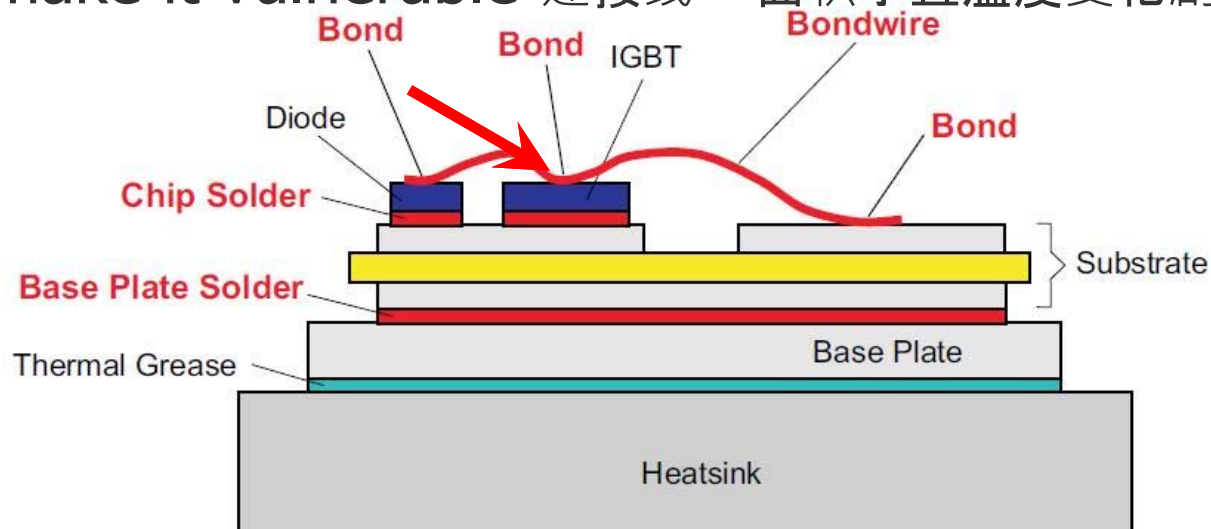
- The thermomechanical stress is the most significant where the temperature change and the contact area between the layers are high 各层接触面和温度变化剧烈处是热机应力最显着的位置
- Die attach – There was extensive research in this field towards better materials and processes 粘结层– 在材料与制程领域上已有广泛研究



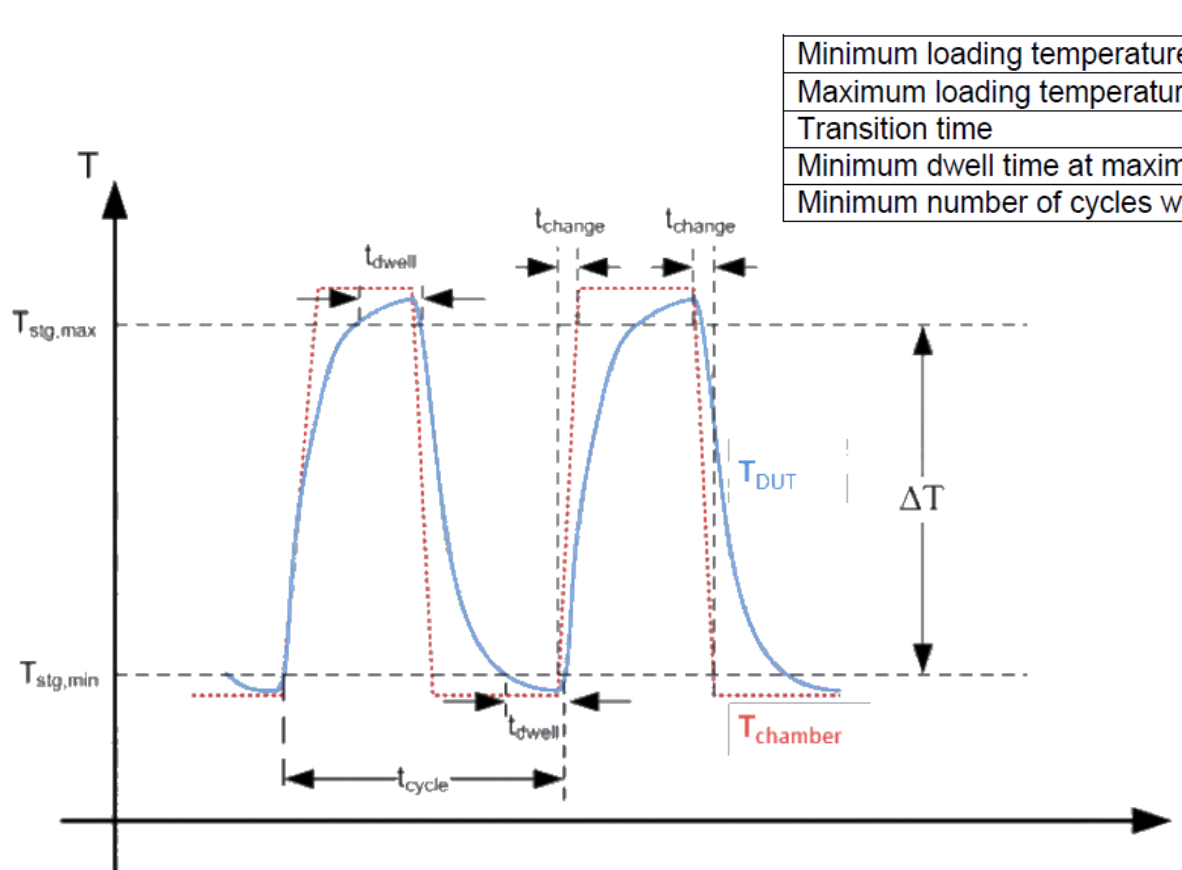
Vulnerable areas of a typical power device

典型功率组件的弱点

- The thermomechanical stress is the most significant where the temperature change and the contact area between the layers are high 各层接触面和温度变化剧烈处是热机应力最显着的位置
- Bond wires - Small area but high temperature swing and CTE mismatch make it vulnerable 连接线 – 面积小且温度变化剧烈、热膨胀系数不同都是其弱点



Thermal Shock Test (QE – 01) 熱衝擊測試



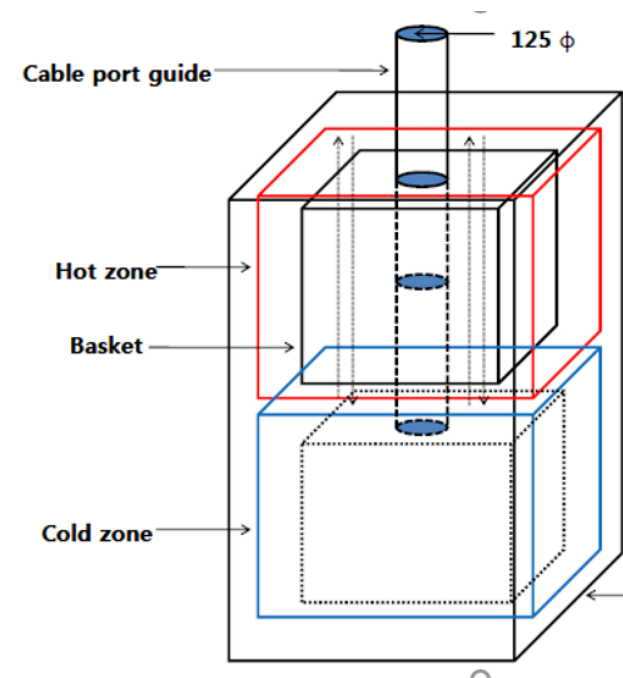
TST test parameters

Minimum loading temperature value	$T_{stg,min}$	$-40\text{ }^{\circ}\text{C}_{-10}^0$
Maximum loading temperature value	$T_{stg,max}$	$+125\text{ }^{\circ}\text{C}_0^{+15}$
Transition time	t_{change}	$< 30\text{ s}$
Minimum dwell time at maximum/minimum temperature	t_{dwell}	$> 15\text{ min}$
Minimum number of cycles without failure	N_C	$> 1\ 000$

Alternative environmental option 2

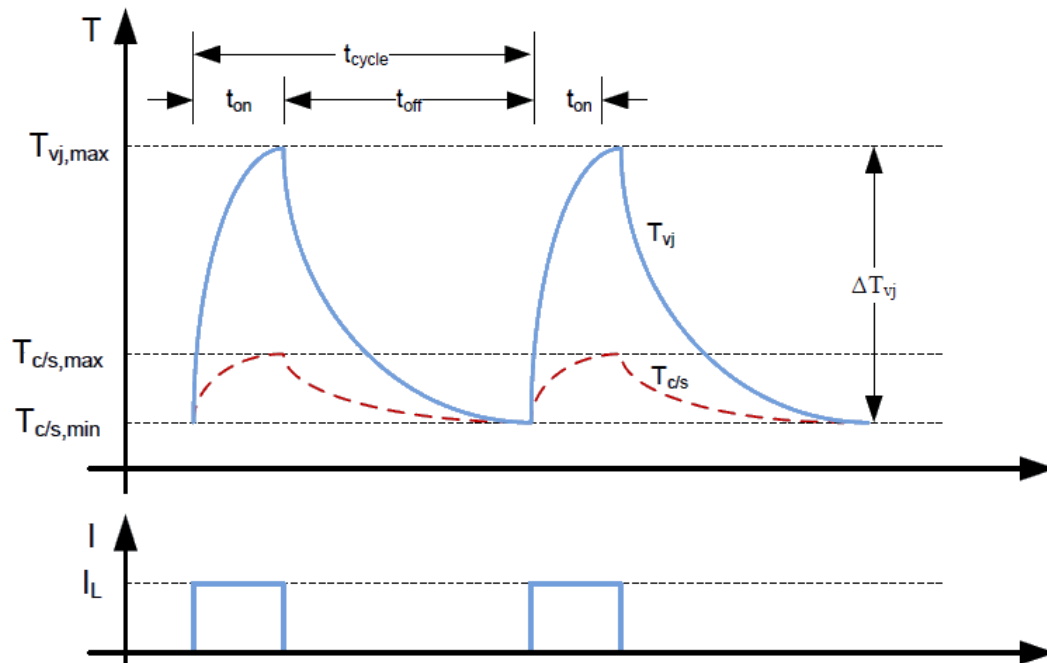
TST test 另一種環境測試方式 TST測試

- The software should be able to drive the thermal shock chamber in the following way:
軟件需要能夠控制熱衝擊腔體
 - Set up the temperatures of the hot and cool zones 設定冷和熱區域的溫度
 - Set up the storage times in the hot and cool zones 設定在冷和熱區域的停留時間
 - Enable TSP calibration in the entire range of the TS-120 chamber 在 TS-120 整個腔體內運行TSP溫度較準
 - Perform thermal transient tests periodically in a selected zone 定期在選定的區域執行熱瞬態測試
- Optionally:
 - Set up the cycle numbers for the individual zones and the cycling parameters 設定各別區域內的循環次數和參數



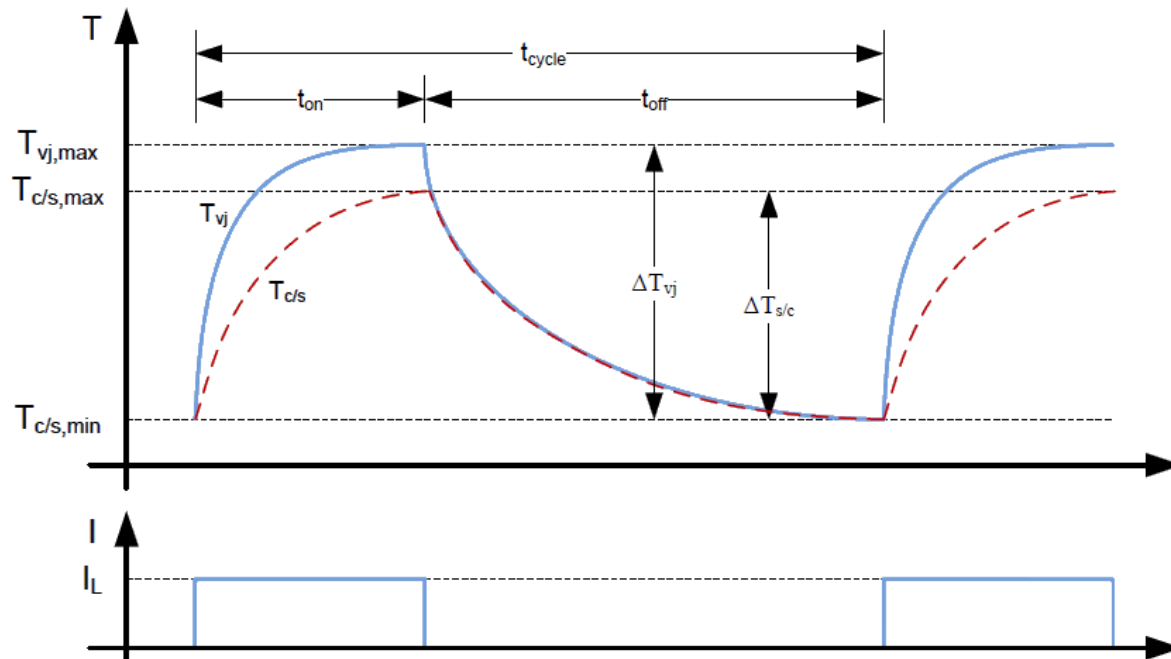
Lifetime test (QL – 01), PC_{sec} 壽命測試

- Checks failure mechanisms near the die (die attach, bond wire) with on-time $t_{ON} < 5s$
確認接近結點附近的失效機制 (附著層, 接合線), 導通時間 $< 5s$
- EOL criteria based on specific voltages (V_{CE}, V_F) or T_j increase, related to R_{th}
EOL 的標準是基於與 R_{th} 有關的特定的電壓 (V_{CE}, V_F) 或增加的 T_j



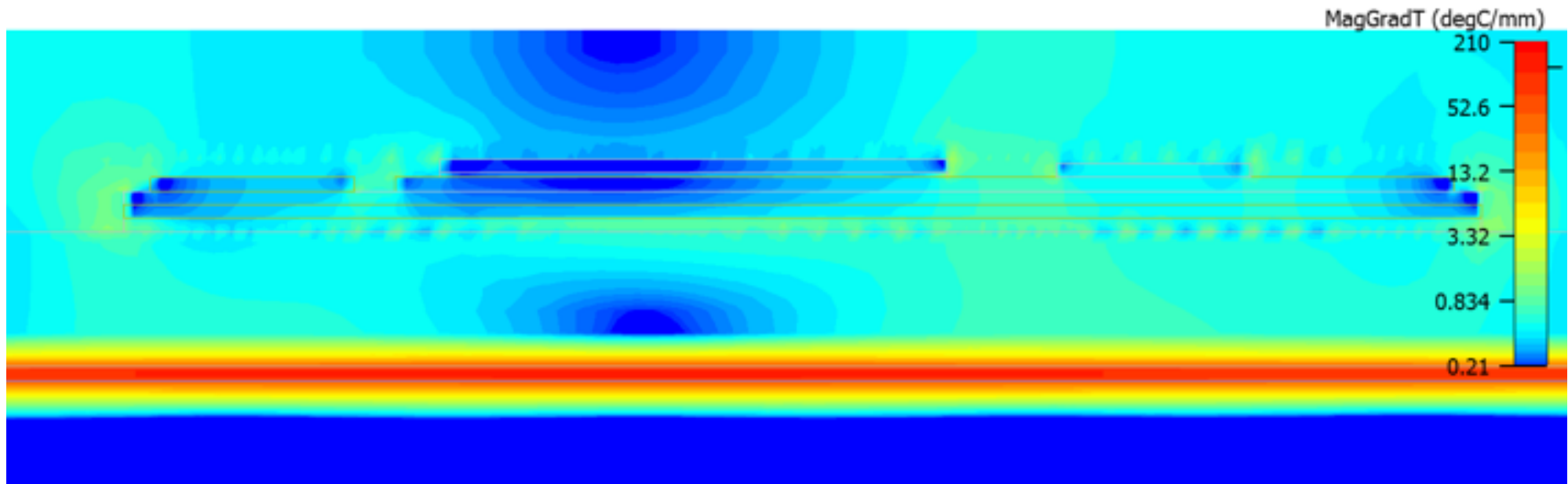
Lifetime test (QL – 02), PC_{min} 壽命測試

- Checks failure mechanisms farther from the die, like baseplate solder with on-time $t_{ON} > 15s$
確認遠離結點的失效機制, 例如底版焊點, 導通時間 $> 15s$
- EOL criteria based on specific voltages (V_{CE}, V_F) or T_j increase, related to R_{th}
EOL 的標準是基於與 R_{th} 有關的特定的電壓 (V_{CE}, V_F) 或增加的 T_j



The ageing process (cycling) has to be simulation based 老化過程 (循環) 必須依據仿真結果

- Temperature gradient development during power cycling
在功率循環期間的溫度梯度



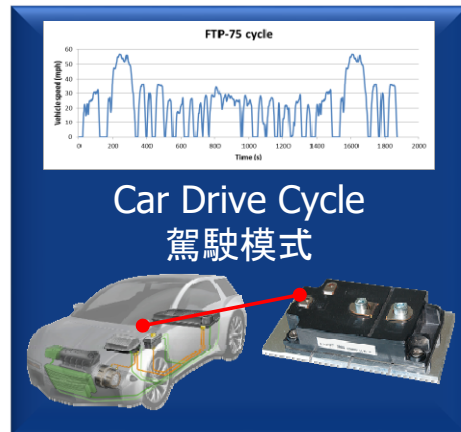
Automotive IGBT testing
汽車 IGBT 測試

MISSION PROFILE BASED LIFETIME TESTING

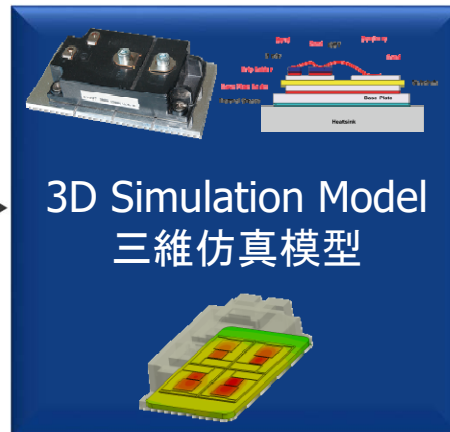
基於任務型態的壽命測試

Calculating the lifetime of E-cars

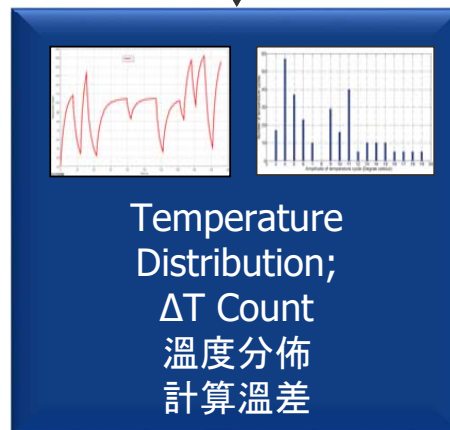
計算電動車的壽命



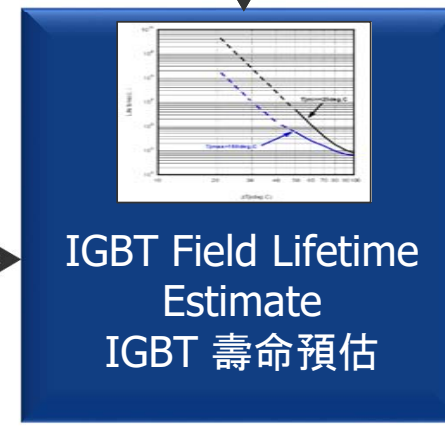
功率
Power
VS.
Time
時間



FTP75: "Federal Test Procedure"
IM240: "Out of city limits"
UDDS: "Inside the city for lite vehicles"
NYCC: "New York City profile"
NEDC: "New European Driver Cycle"
JC015: "Japanese Drive Cycle"
WLTP: "Chinese Drive Cycle"
K-WHVC: "Korean World Harmonic Drive Cycle"



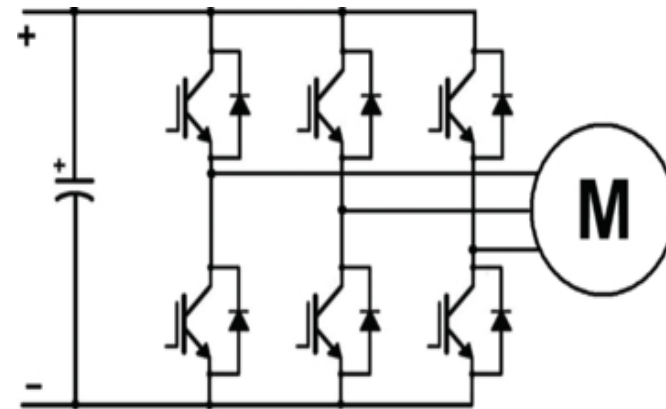
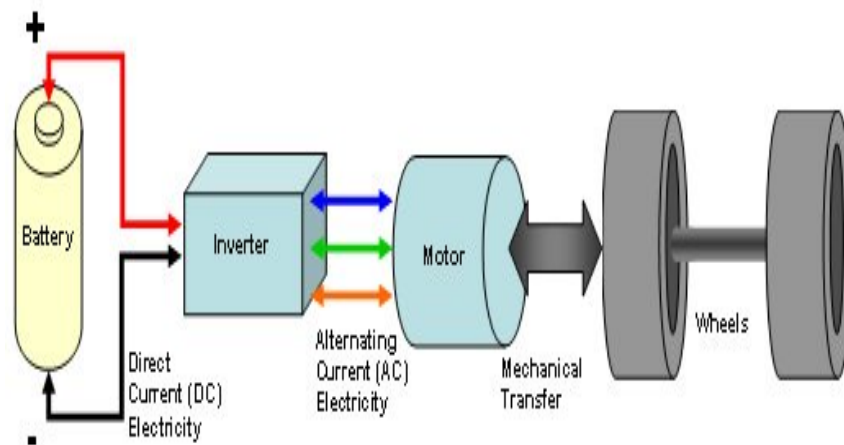
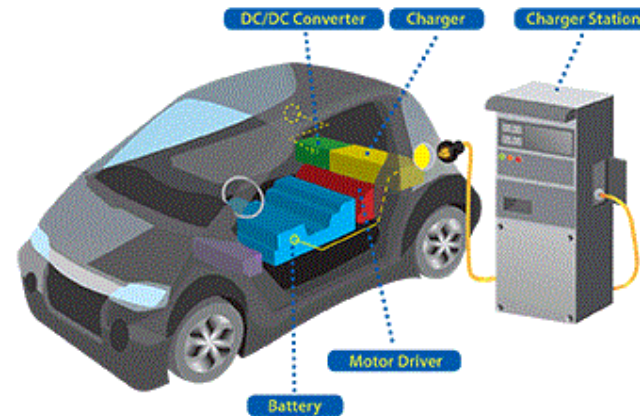
ΔT
Count
計算溫
差



The real need is to
predict an IGBT
lifetime estimate
upfront (e.g. 12 yrs)
實際需求是預先預估
IGBT 的壽命 (例如: 12
年)

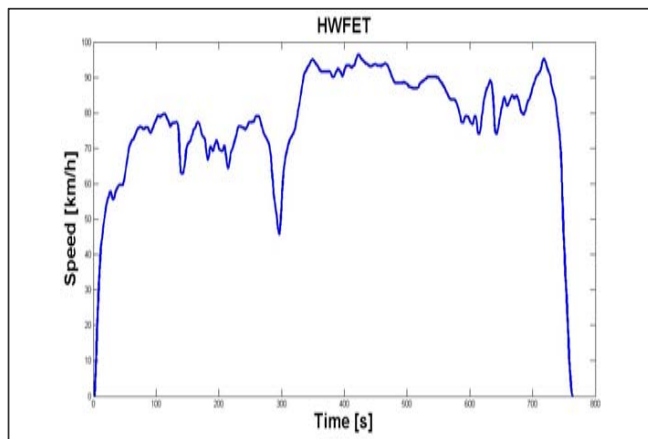
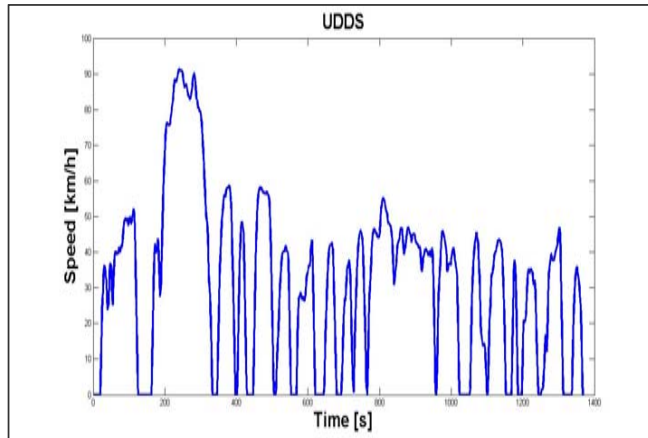
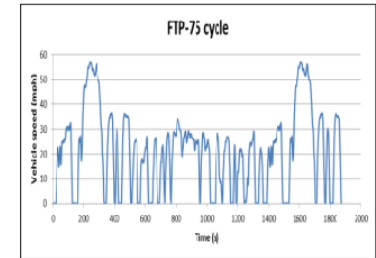
Electric traction in a car

電動牽引汽車



1. Definition of the application – The driving profile

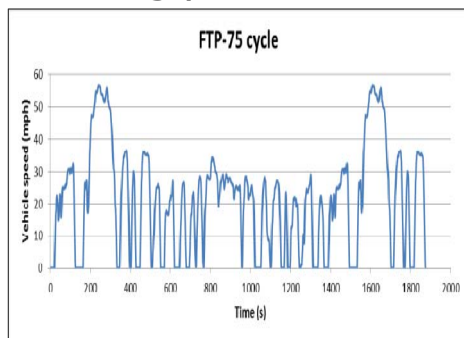
定義應用 – 操控模式



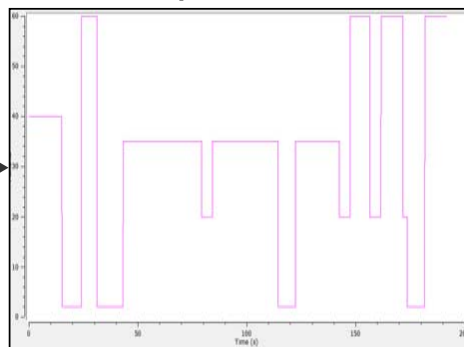
- For the design of the power module the exact definition of the task is necessary
對於功率模組的設計需要考量操作任務
- Possible input data: 可能輸入的數據
 - Electrical data: V, I 電性數據
 - Velocity v.s. time functions 速度 vs. 時間功能
- Driving profile examples 操作模式範例
 - IM240: Out of city limits 超出城市限制
 - UDDS: Inside the city for light vehicles 輕型車輛在城市中駕駛
 - NYCC: New York city profile 在紐約的模式
 - US06: Aggressive driver 積極型的司機

How can the driving profile help?

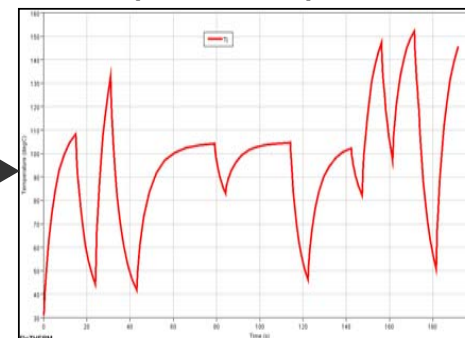
1. Driving profile 操控模式



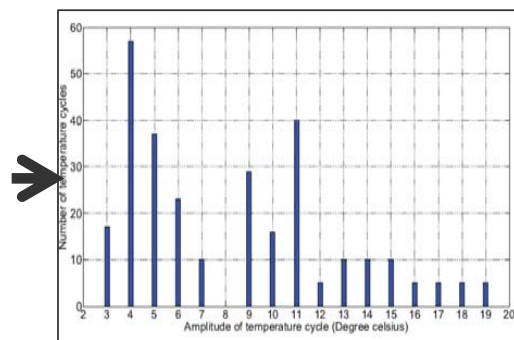
2. Power profile 功率分佈



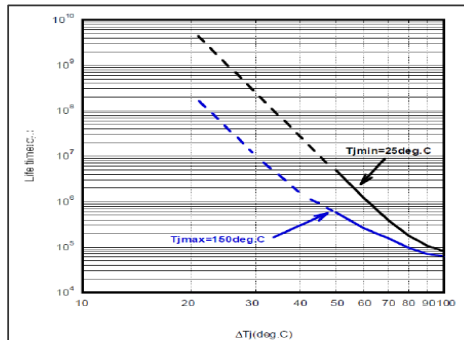
3. Temperature profile 溫度分佈



4. Distribution of peak temperatures
峰值溫度分佈

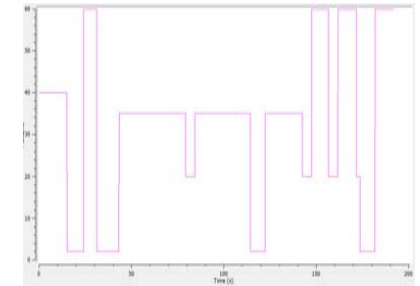


5. Lifetime curves
壽命曲線



**Expected
Lifetime 壽命預測
(e.g 12 yrs)**

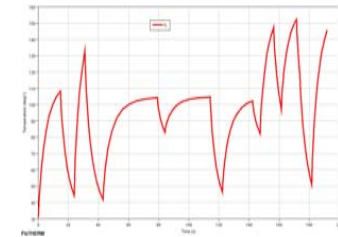
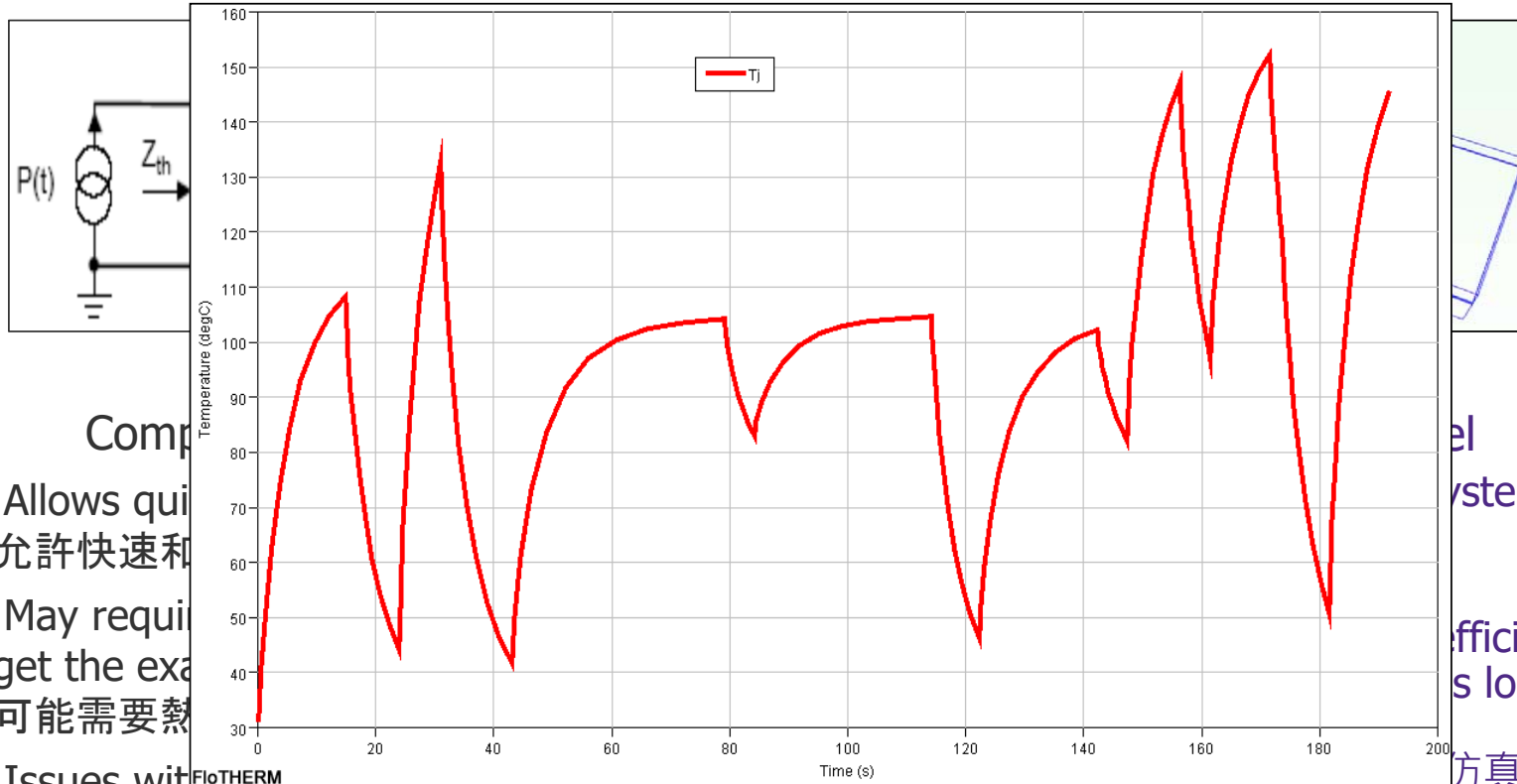
2. Power profile based on mission profile 基於不同任務下的功率分佈



- ▶ Forces used for modeling the movement of a car
汽車運動主要的外力
 - Rolling resistance: $F_g = \mu_g mg$ 滾動阻力
 - Air resistance: $F_{air} = \frac{1}{2} \rho A C_d v^2$ 空氣阻力
 - Acceleration resistance: $F_{acc} = ma$ 加速阻力
 - Elevating resistance: $F_{elev} = mg \sin(\varphi)$ 提升阻力 (*neglected*) 忽略
- ▶ Engine power: $P_{engine}(t) = \Sigma F v(t)$ 發動機功率
- ▶ Total required power: $P_{total}(t) = \frac{P_m(t)}{\eta}$ 總需求功率 (η – efficiency)
- ▶ Power loss: $P_v(t) = P_{total}(t) - P_{engine}(t)$ 功率損耗
 - $P_v(t)$ is partially the conduction and switching loss of the IGBT
是部分 IGBT 的導通和開關損耗

3. To obtain temperature profile

獲取溫度輪廓



- Allows quick simulation
- May require a long simulation time to get the exact temperature profile

- Issues with modeling multiple heat sources in packages

效率

Model system to be

efficient if a transient simulation with a long driving profile

仿真所需時間長且低

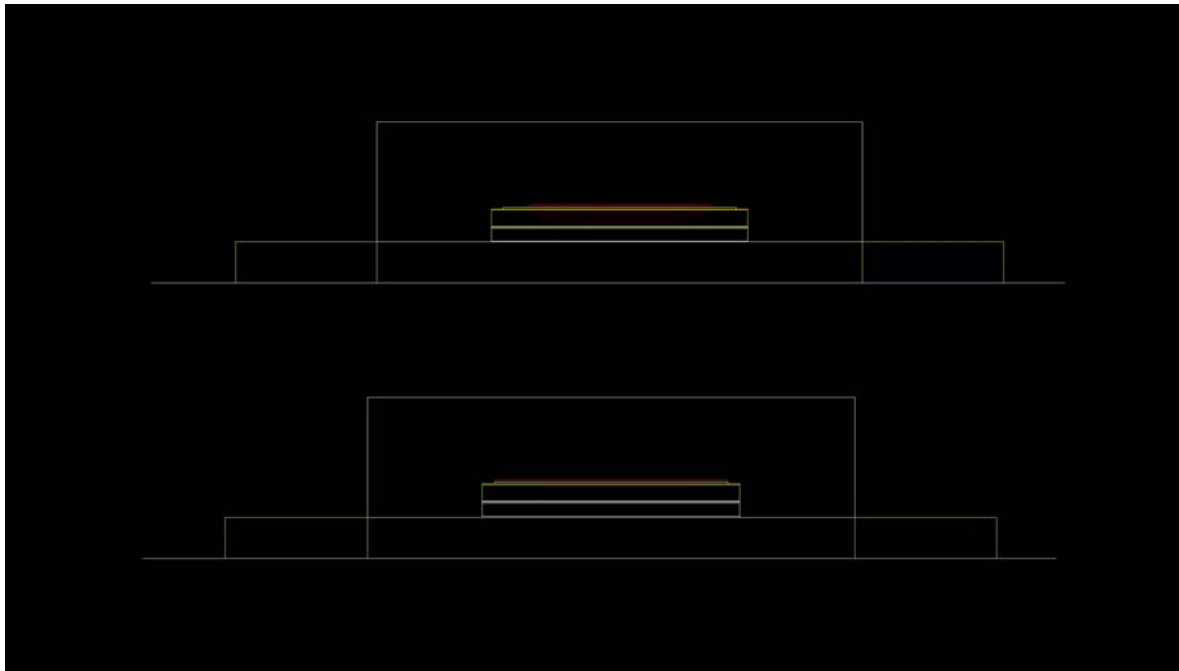
Current Process has many Issues: 1. Accuracy:

目前流程有許多問題 1. 準確性

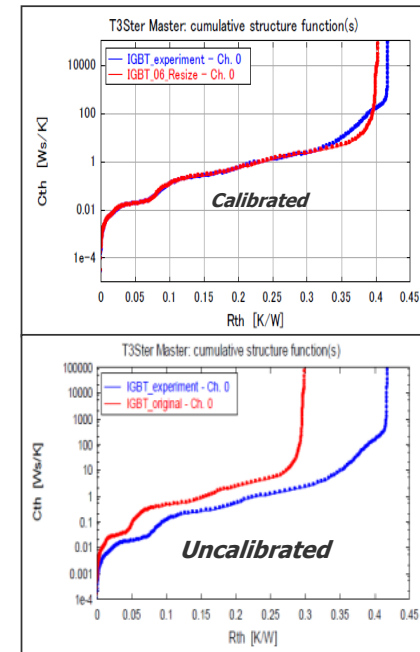
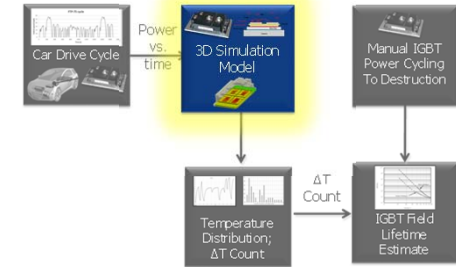
Simulation Error Reduced from $\sim 20\%$ to $\sim 0.5\%$

仿真錯誤導致 $\sim 20\%$ 到 $\sim 0.5\%$ 的差異

- Mentor's recent release of FloTHERM 11.1 allows for unique automated MicReD T3Ster calibrations of material properties for 3D CFD simulations:
FloTHERM 11.1開始有自動校正的功能



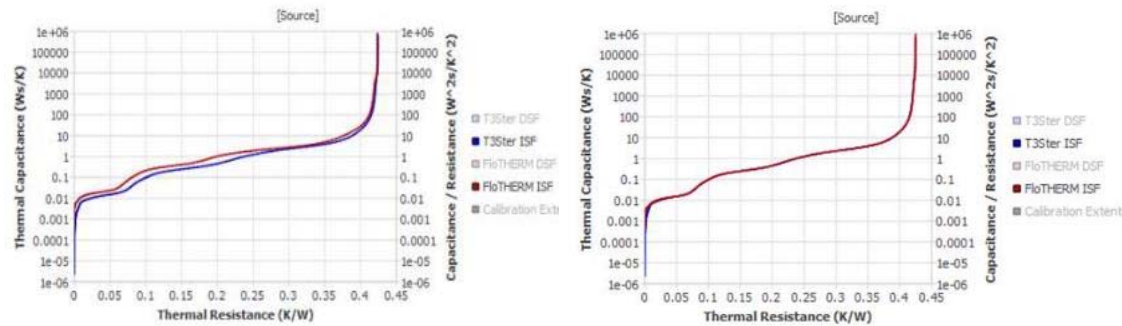
- For IGBTs this results in much lower errors 對 IGBT 可降低誤差



Why to calibrate simulation model...

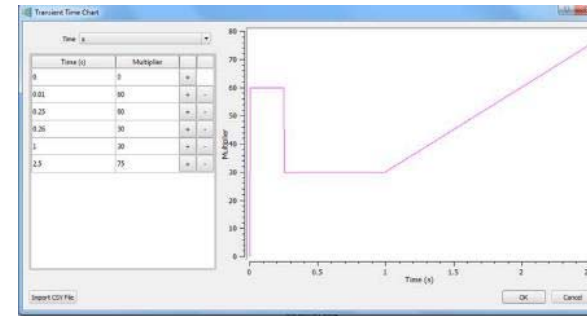
為何校正仿真模型

Uncalibrated SF:
未校準的結構函數

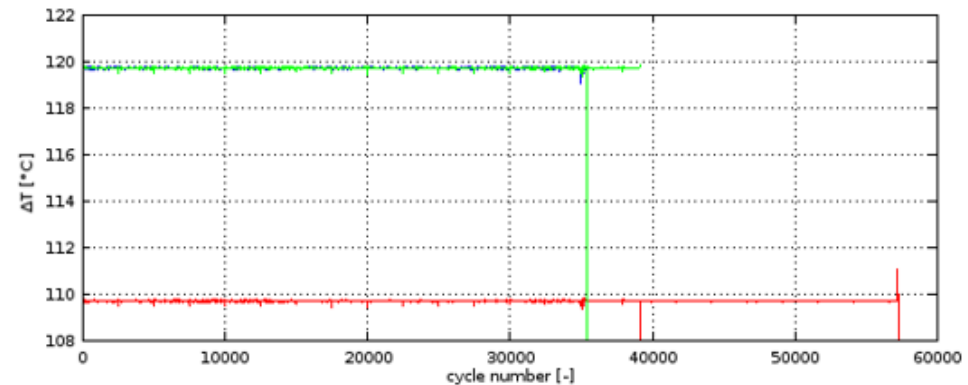
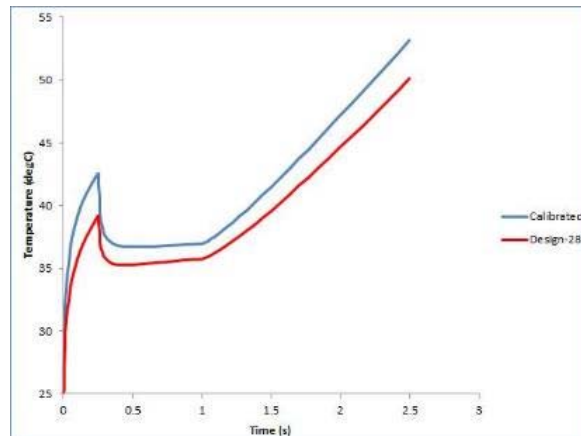


Calibrated SF
校準後的結構函數

Simulate both calibrated and uncalibrated model with an arbitrary power profile:
用任意功率曲線模擬校準和未校準的模型



And compare the responses. Design 28 is the uncalibrated model. The peak at 0.25s is off by ~24%.
比較結果，校準與未校準的模型在峰值 (0.25s) 的差異達到 24%



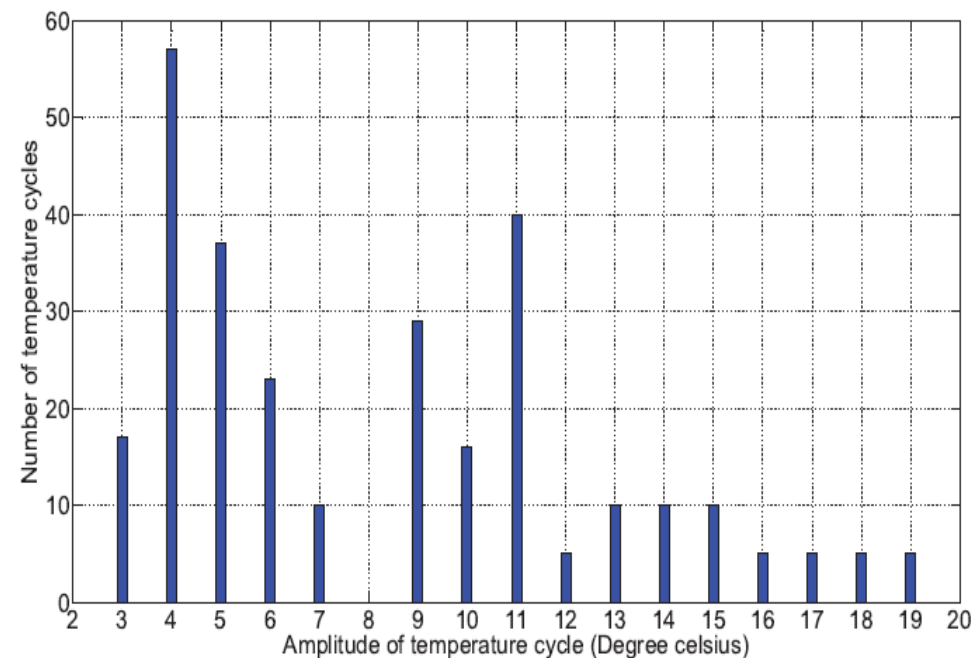
Accuracy is important! 10 °C difference in junction temperature may result in over 30% in lifetime in real cycling conditions.
準確性很重要！在實際循環測試時，10度的結點溫差會導致30%的壽命差異

4. Temperature histogram

溫度直方圖

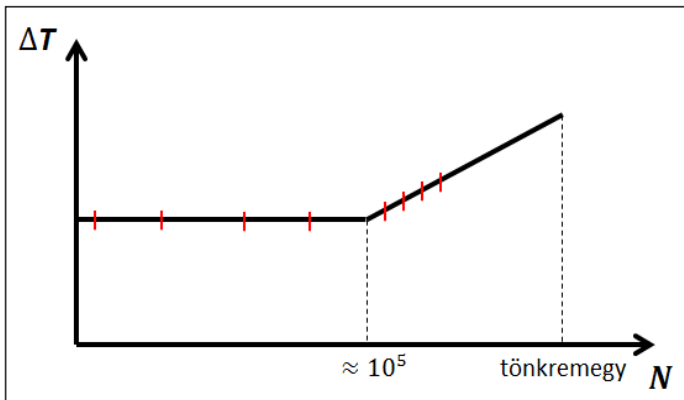
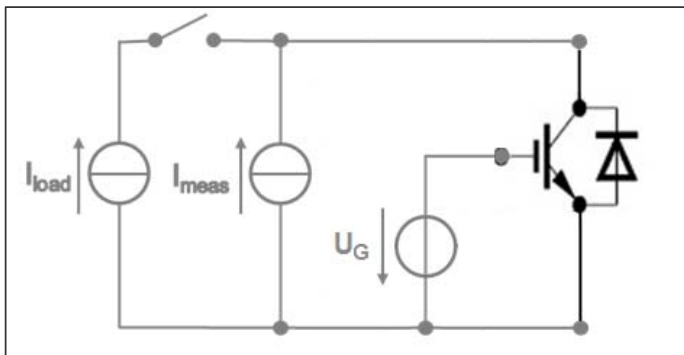
- Counts the individual temperature components in the temperature profile – future weighting factor in cycling

計算溫度分佈圖中的各個溫度分量 – 在循環中的未來加權因子



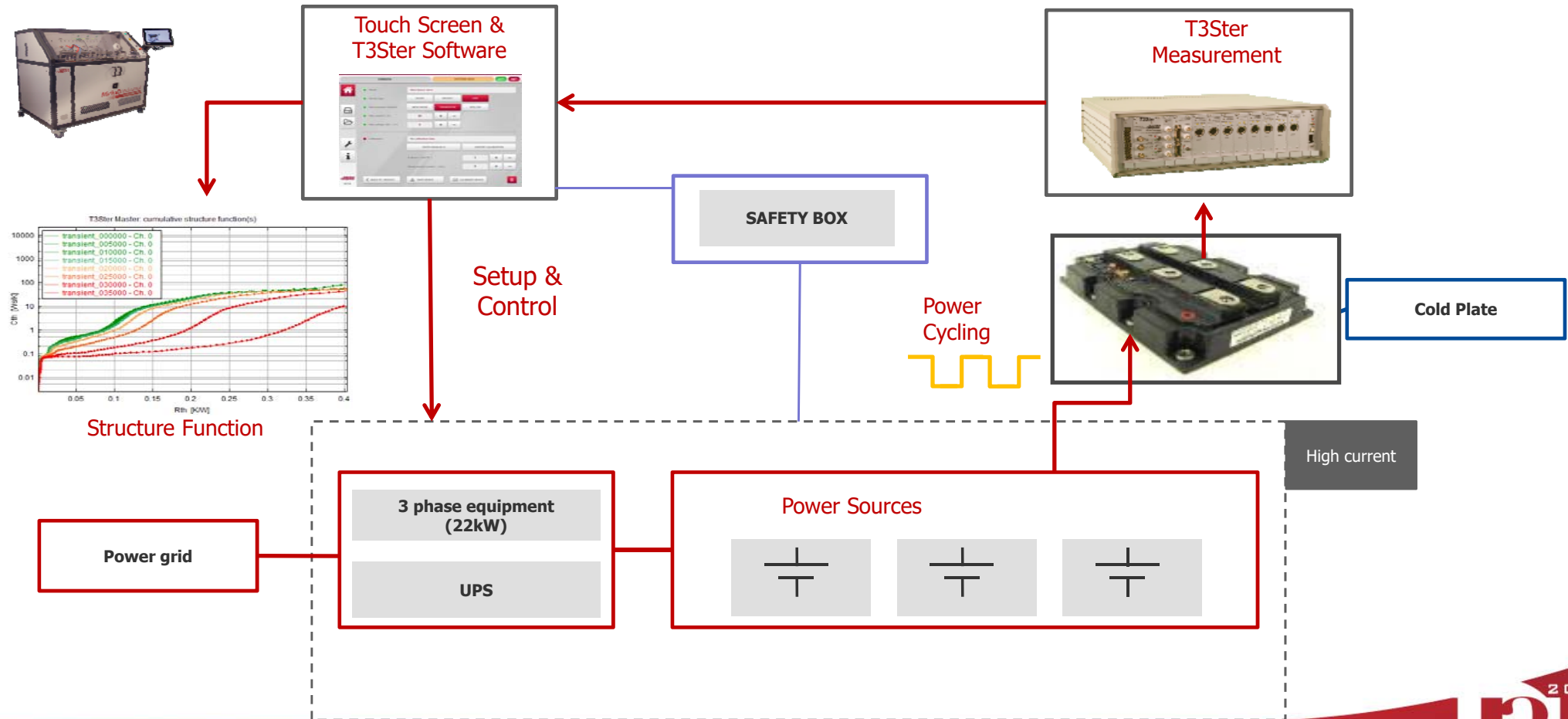
5. Power cycling 功率循環

► Reliability / lifetime test 可靠性 / 壽命測試

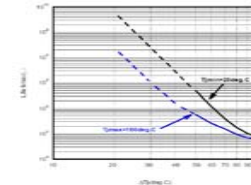


- Switching the power between two defined states
在兩種預定的模式下切換
 - Inducing mechanical stress 引發機械應力
 - Which will lead to failure 何種會導致失效
-
- Monitoring the phenomenon with optical/thermal tests
用光學/熱測試來監控現象
 - Checking the maximum temperature change of the sample in each cycle
確認樣品在每次循環時的最高溫度變化

Continuously monitored process to understand failure mechanisms 持續監控來了解失效機制



6. Lifetime curves 壽命曲線



- Arrhenius model: $N_f = e^{\left(\frac{E_a}{k_b \cdot T}\right)}$ 阿瑞尼斯模型 Cycles to failure 循環至失效

- Extended Arrhenius models: 擴展阿瑞尼斯模型

$$N_f(\Delta T) = A \cdot (\Delta T_j)^\alpha \cdot e^{\left(\frac{E_a}{k_b \cdot T}\right)}$$

(used by: Fuji Electric)

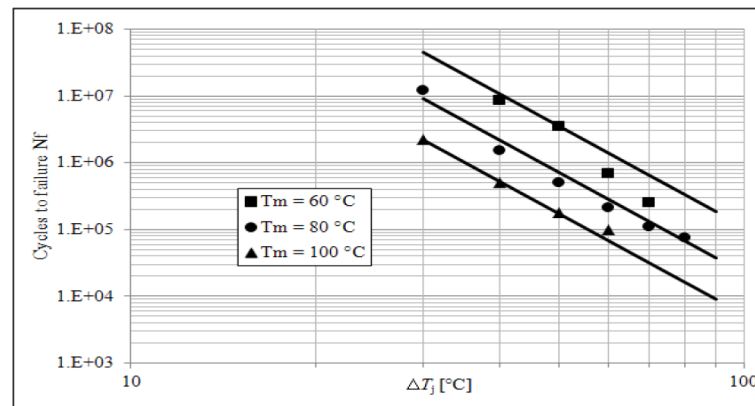
$$N_f(\Delta T) = A \cdot f^\beta \cdot (\Delta T_j)^\alpha \cdot e^{\left(\frac{E_a}{k_b \cdot T}\right)}$$

(used by: Infineon)

- Lifetime estimation 壽命估算

$$N_{f_sum} = \frac{1}{\sum_{k=1}^n \frac{w_i}{N_{f_i}}}$$

$$t_{operation} = N_{f_sum} \cdot t_{cycle}$$



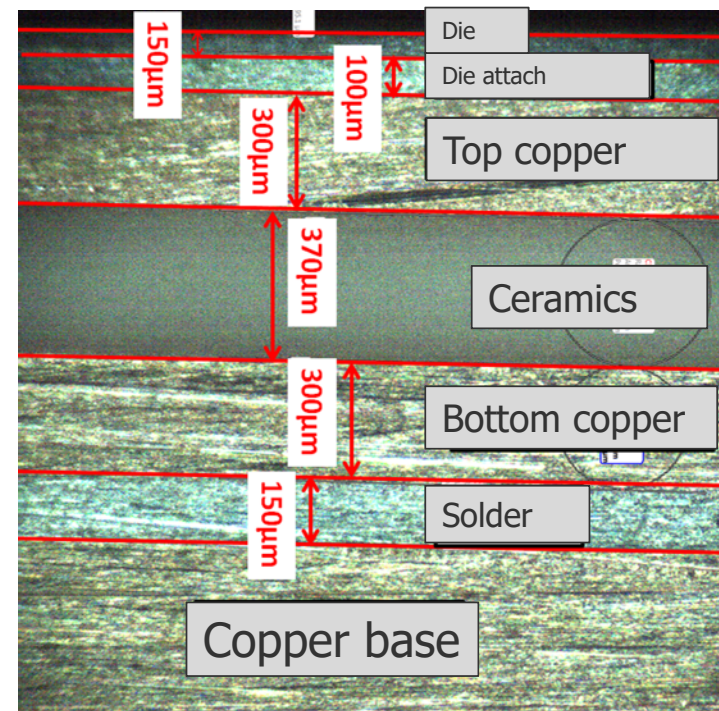
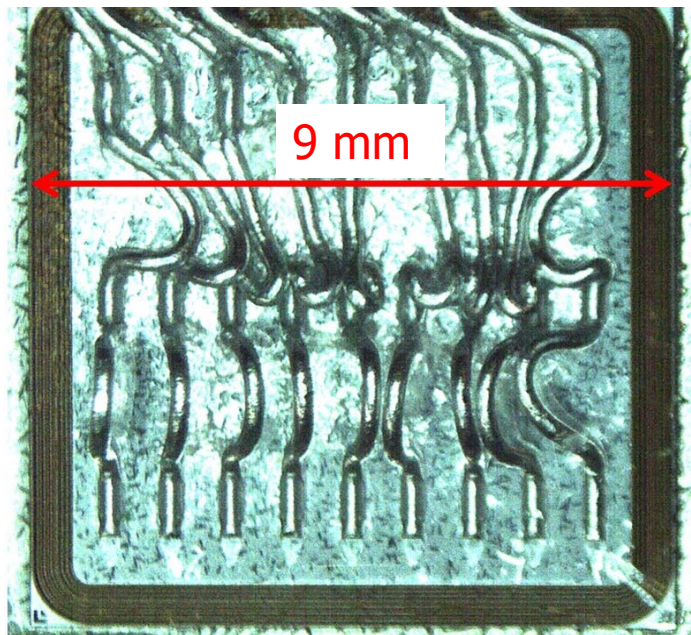
CASE STUDY

案例分享

IGBT 3D model

IGBT 三維模型

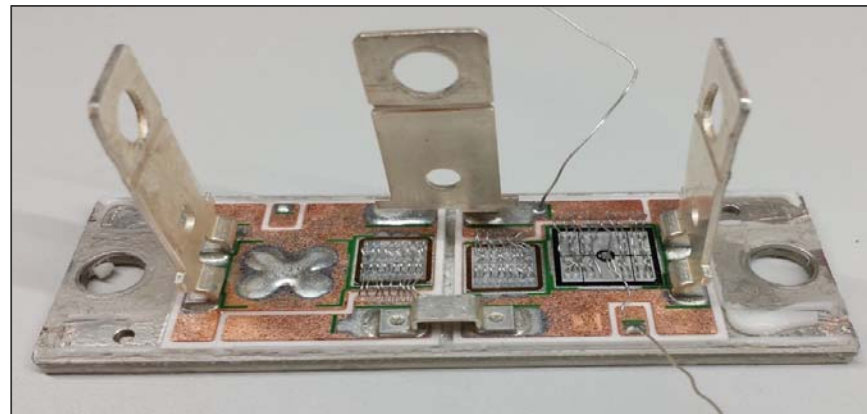
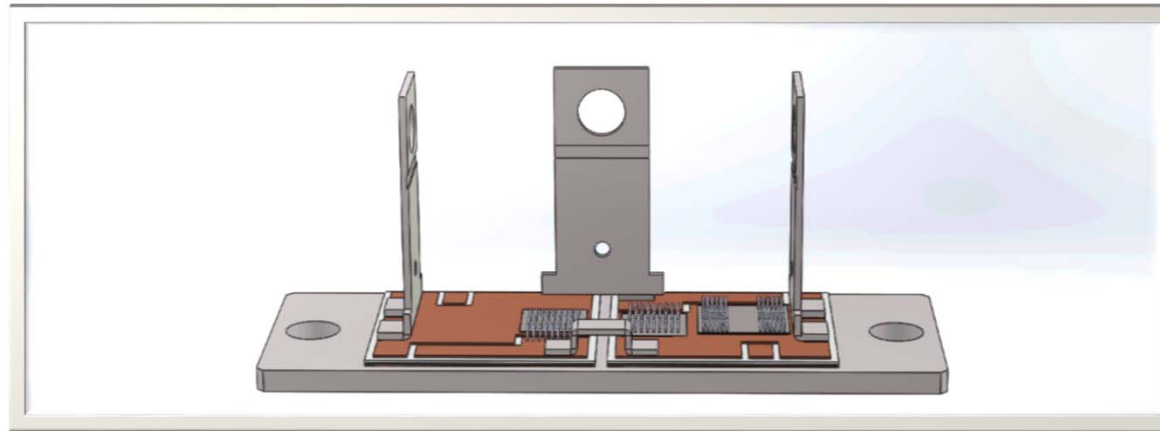
- We opened up and measured a sample's geometry 打開並量測樣品的幾何外型



IGBT 3D model

IGBT 三維模型

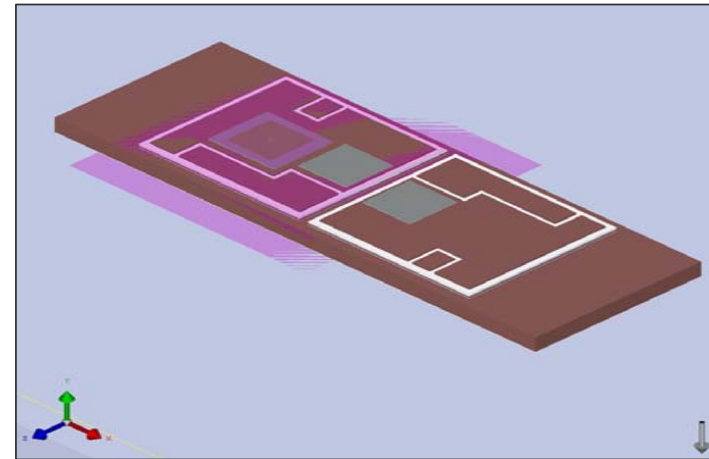
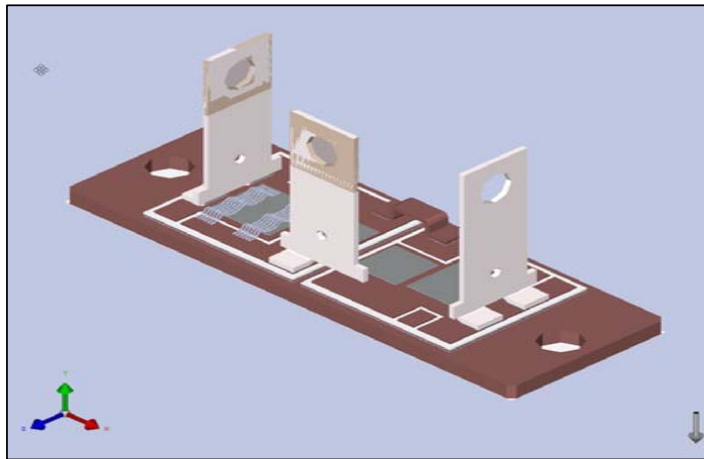
- 3D representation built in SolidWorks 在 Solidworks 建立三維模型



IGBT 3D model

IGBT 三維模型

— Then imported to FloTHERM 匯入至 FloTHERM



— Assign material parameters to layers 定義各層材料參數

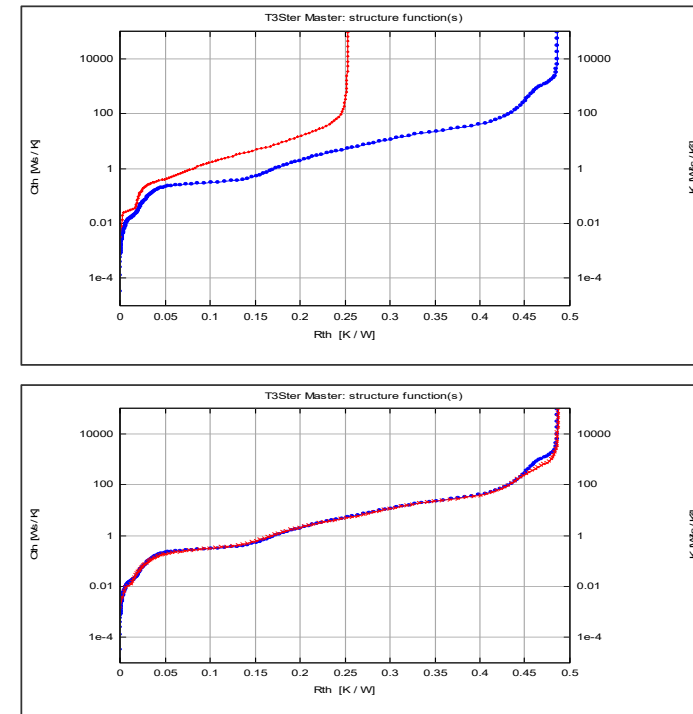
- Specific heat 比熱
- Thermal conductivity 熱傳導係數
- Density 密度

Model calibration

模型校正

- Adjustment of material properties until a perfect match is achieved between structure functions

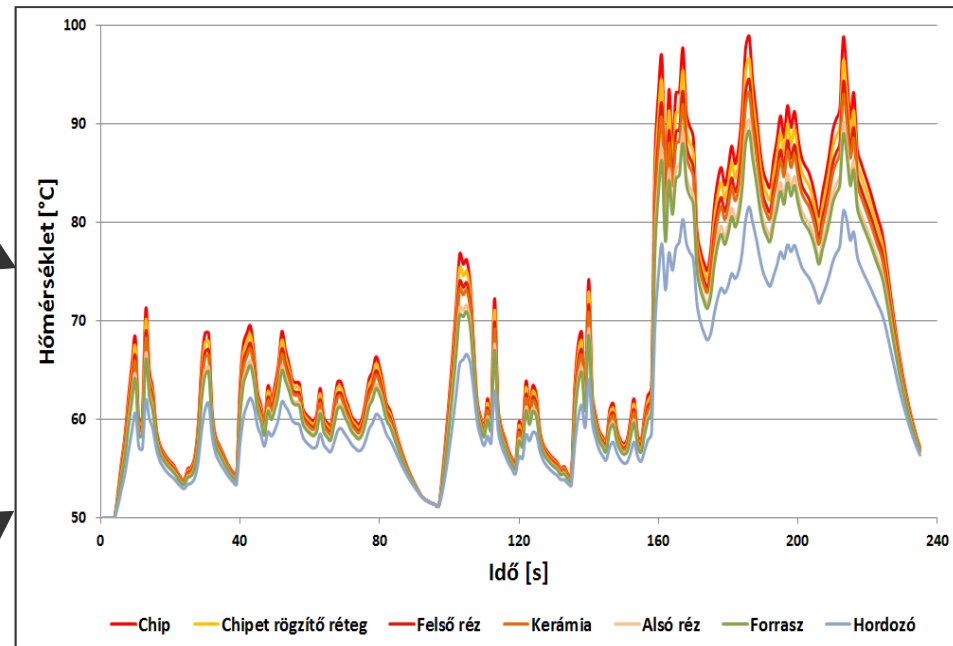
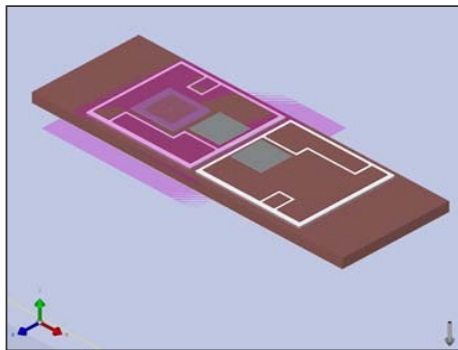
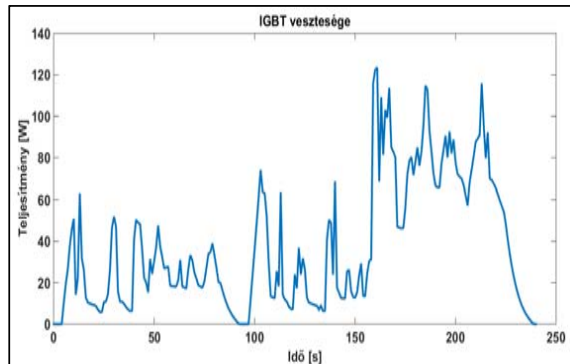
調整材料參數讓結構函數能完全重疊



Layers	Original			Modified		
	Density [kg/m³]	Specific heat [J/kgK]	Thermal conductivity [W/mK]	Density [kg/m³]	Specific heat [J/kgK]	Thermal conductivity [W/mK]
Chip	2330	700	117,5	2330	700	100
DA	14520	151	59	14000	1000	67
Copper	8930	385	385	8930	385	385
Ceramics	3300	725	170	3300	725	170
Solder	1	1	57	1	1	57
Copper base	8930	385	385	8930	385	385

Simulation of the IGBT's temperature profile

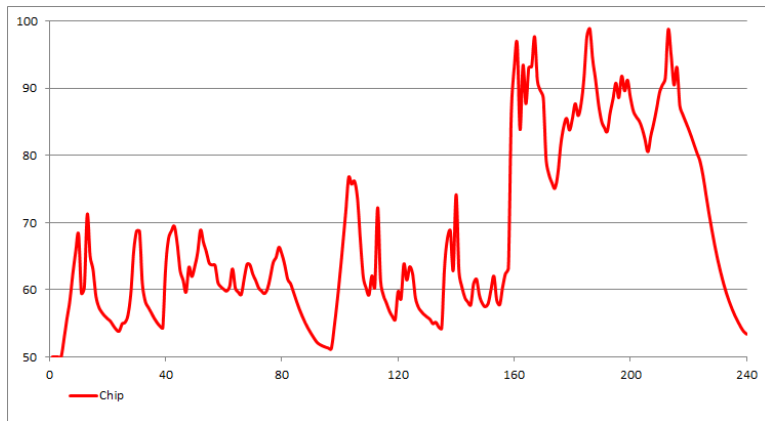
IGBT 溫度分佈仿真結果



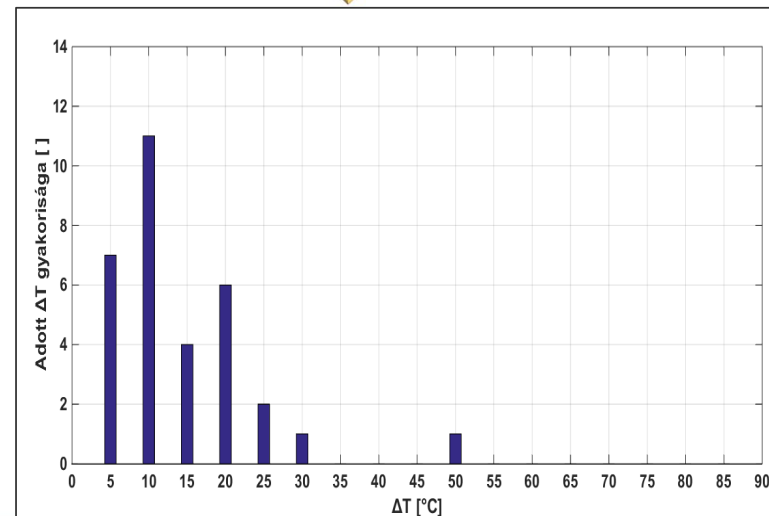
— Simulate the effect of transient power on the structure 利用仿真了解結構在瞬態功率下的影響

Obtaining the histogram 獲得直方圖

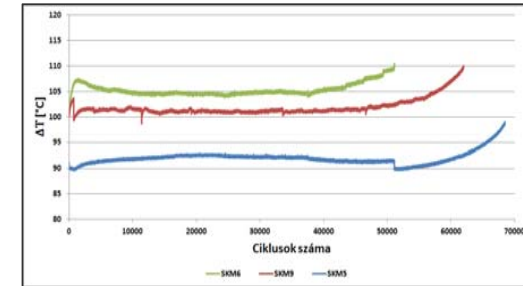
- Calculate the distribution of the ΔT components 計算器件的溫差分佈



Rainflow algorithm
雨流算法



Accelerated lifetime tests 加速壽命測試

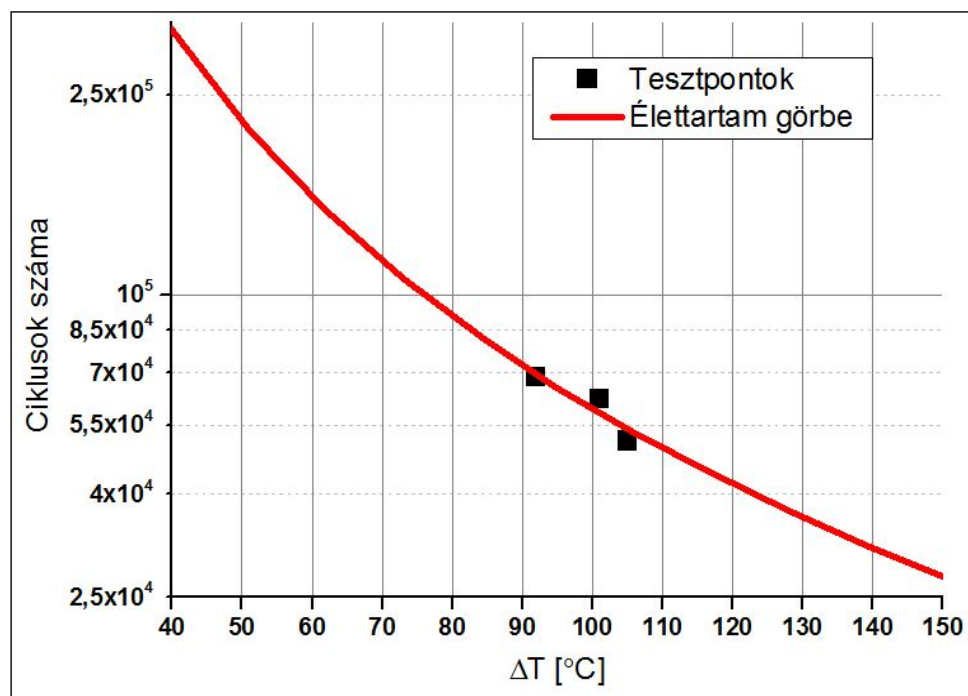


	Average ΔT [°C]	Cycle number to failure [-]
SKM6	105	51104
SKM9	101	61969
SKM5	92	68465

- 3 samples were cycled at pre-set boundary conditions:
110°C, 100°C, 90°C 3 個樣品以不同的條件進行循環測試

Lifetime curve

壽命曲線



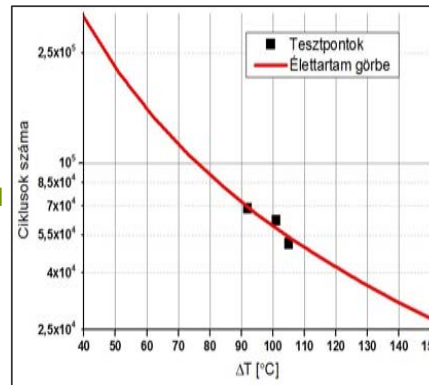
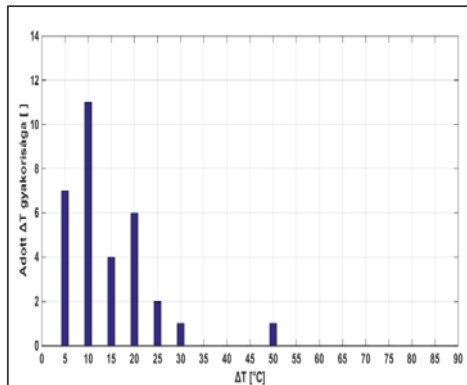
A	a
3,69448·10 ⁸	-1,89743

- Curve fitting following the Coffin-Manson model
依照 Coffin-Manson 模型進行曲線擬合

$$N_f = A \cdot (\Delta T_j)^\alpha$$

Lifetime prediction

壽命預測



ΔT [°C]	Count (w_i)	Cycle number (N_i)
5	7	17430372
10	11	4678680
15	4	2167716
20	6	1255856
25	2	822356
30	1	581860
50	1	220737

$$N_{f_sum} = \frac{1}{\sum_{k=1}^n \frac{w_i}{N_{f_i}}}$$

$$t_{operation} = N_{f_sum} \cdot t_{cycles}$$

N_{f_sum}	t_{ciklus} [s]	$t_{operation}$ [h]
55382	240	3692

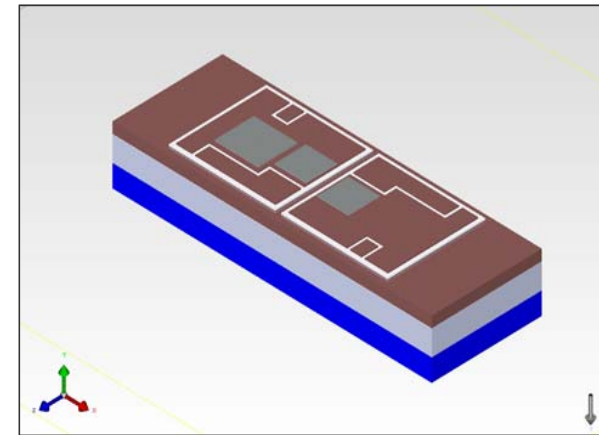
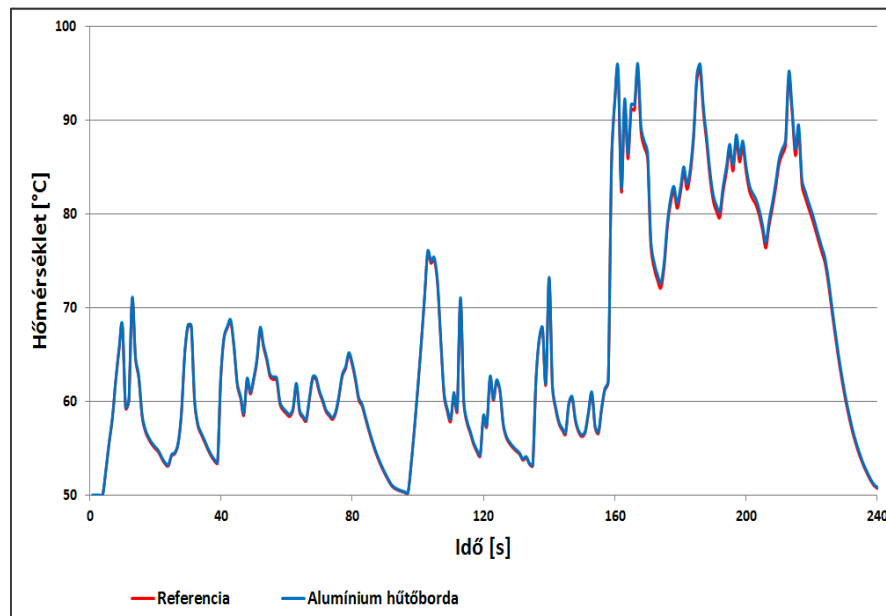
OPTIMIZING THE COOLING SYSTEM

優化冷卻系統

Different cold-plates

不同的冷板

- Copper vs. Aluminum 銅 vs. 鋁
- Difference < 2% 差異 < 2%

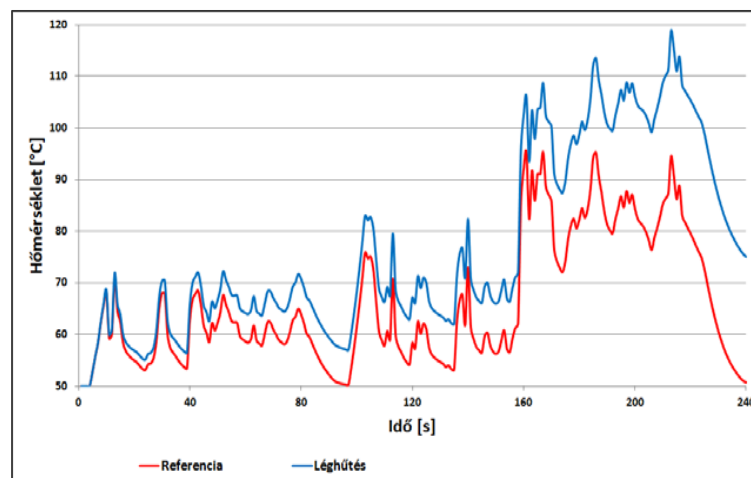


	N_{f_sum}	t_{cycle} [s]	$t_{operation}$ [h]
Copper	54171	240	3611
Aluminum	53128	240	3541

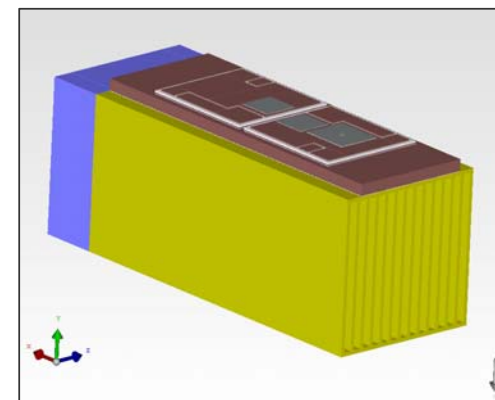
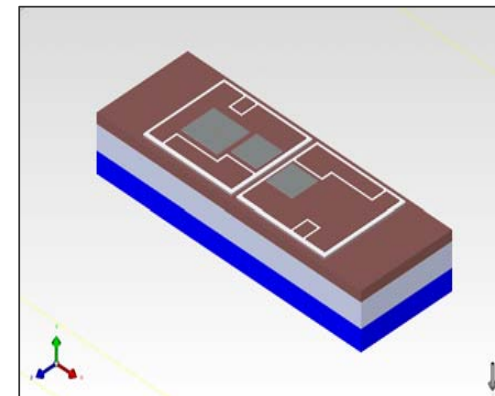
Different cooling systems

不同的冷卻系統

- Liquid vs. air cooling 液體 vs. 空氣冷卻
- Copper cold-plate 銅製冷板
- Difference ~ 12% 差異 ~ 12%



	N_{f_sum}	$t_{cycle}[s]$	$t_{operation}[h]$
Liquid	54171	240	3611
Air cooling	47986	240	3199





USER2USER