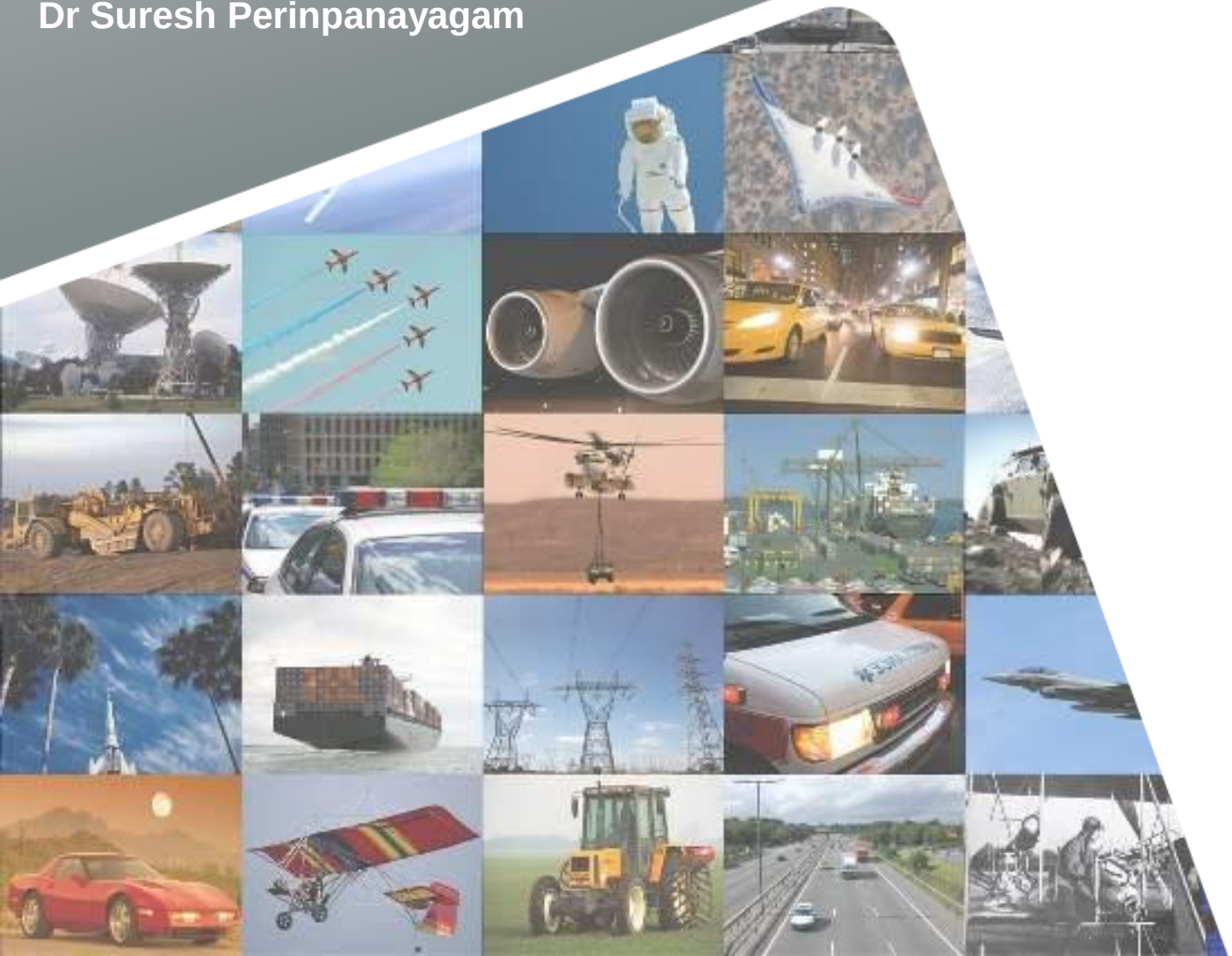
Wide Bandgap for Aerospace Applications

Dr Suresh Perinpanayagam



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EEDA East of England Development Agency

Rolls-Royce

MEGGITT smart engineering for extreme environments

BAE SYSTEMS

THALES

EPSRC Engineering and Physical Sciences Research Council

ALSTOM

http://www.cranfield.ac.uk

Outline

- Overview of Cranfield Power Electronics Capabilities
- Towards All-Electric Aircraft
- SiC MOSFET Case Study
- Developing failure models for Wide Bandgap
- Prognostics development for Wide Bandgap

Welcome to Cranfield

We are an exclusively postgraduate university that is a global leader for education and transformational research in technology and management.

We provide:

- Impact and influence
- Premier learning
- Transformational research.

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Impact and influence

We work with 750+ businesses and governments around the world

Environment:

working with all UK water utility companies and advising major government departments such as Defra

Aerospace:

we have strategic relationships with global companies such as Airbus, BAE Systems, Boeing and Rolls-Royce

Leadership and Management:

we work with major international businesses such as Jaguar Land Rover, L'Oréal and Shell, developing high performance leaders across the world

Defence and Security:

we are one of the world's largest providers of postgraduate defence and security education

Manufacturing:

leading two and key partners in an additional four EPSRC Centres for Innovative Manufacturing.

Global reach

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Cranfield's Centres

EPSRC Centre for Innovative Manufacturing

Through-life Engineering Services

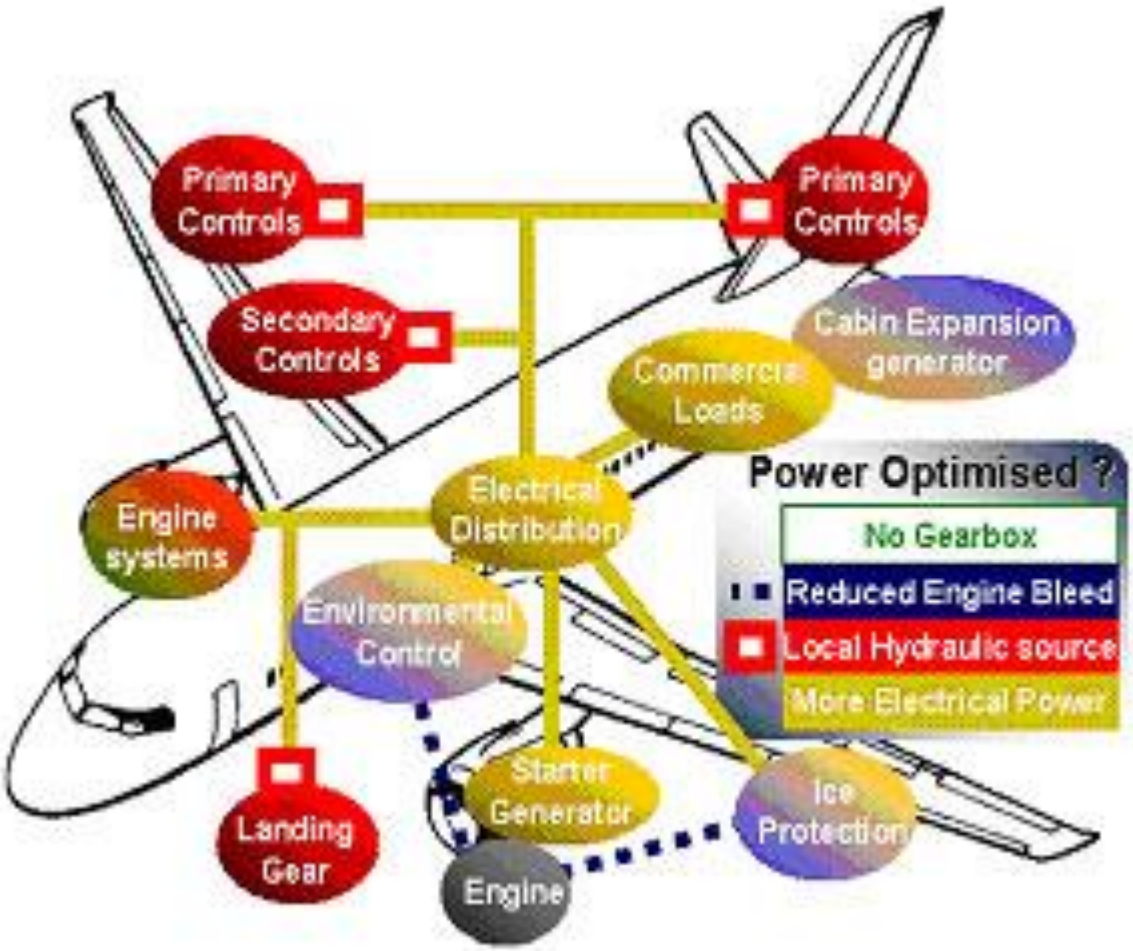
Wide Bandgap Capabilities

Power Electronics Group

Cranfield Nano

The Institute's world-class facilities include clean rooms, laboratories and test/fabrication services through to prototype component manufacture, with extensive analysis, modelling, synthesis and characterisation capability.

Towards All-Electric Aircraft



- Novel architecture for generation and distribution of loads
- Thermal management and thermal exchange
- Flight-proven electrical equipment systems, including environmental conditioning and protection

Electrical Distribution Architecture for Regional Aircrafts

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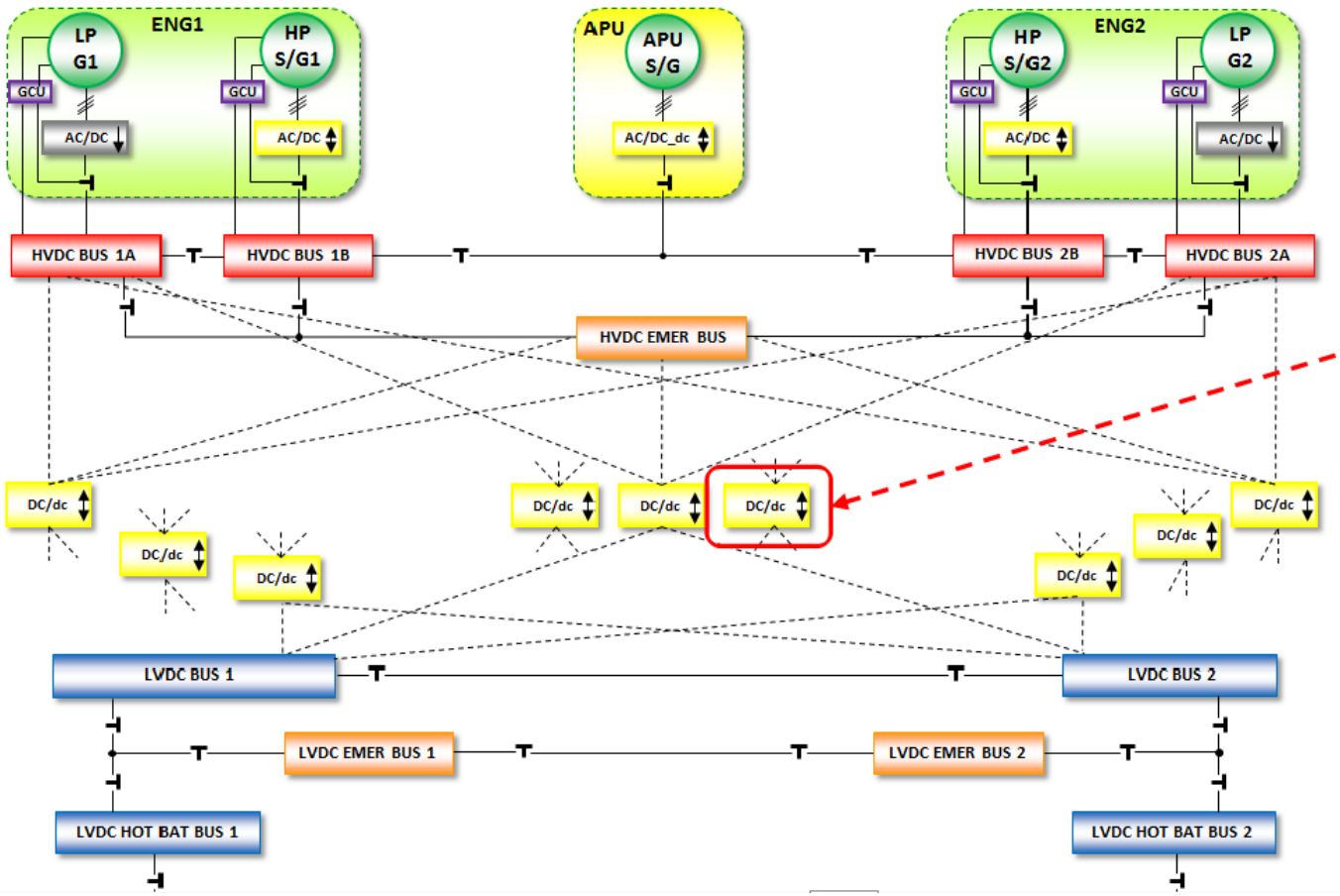
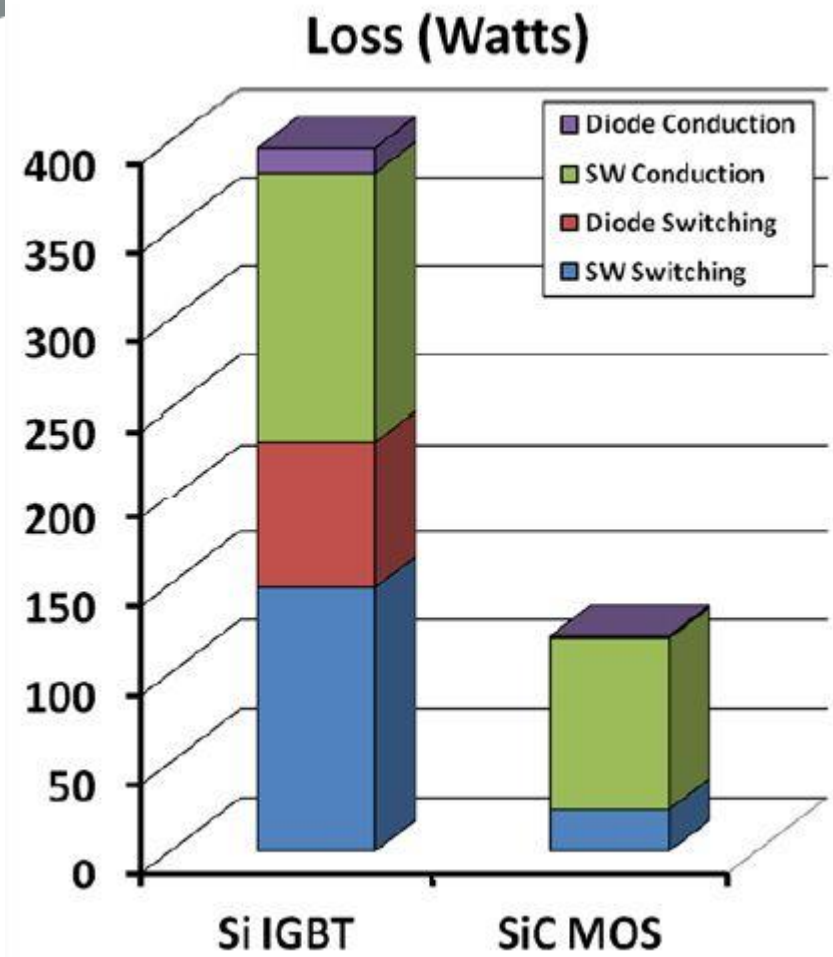


DC/DC cellular converter

Comparison between a Si IGBT and a SiC MOSFET

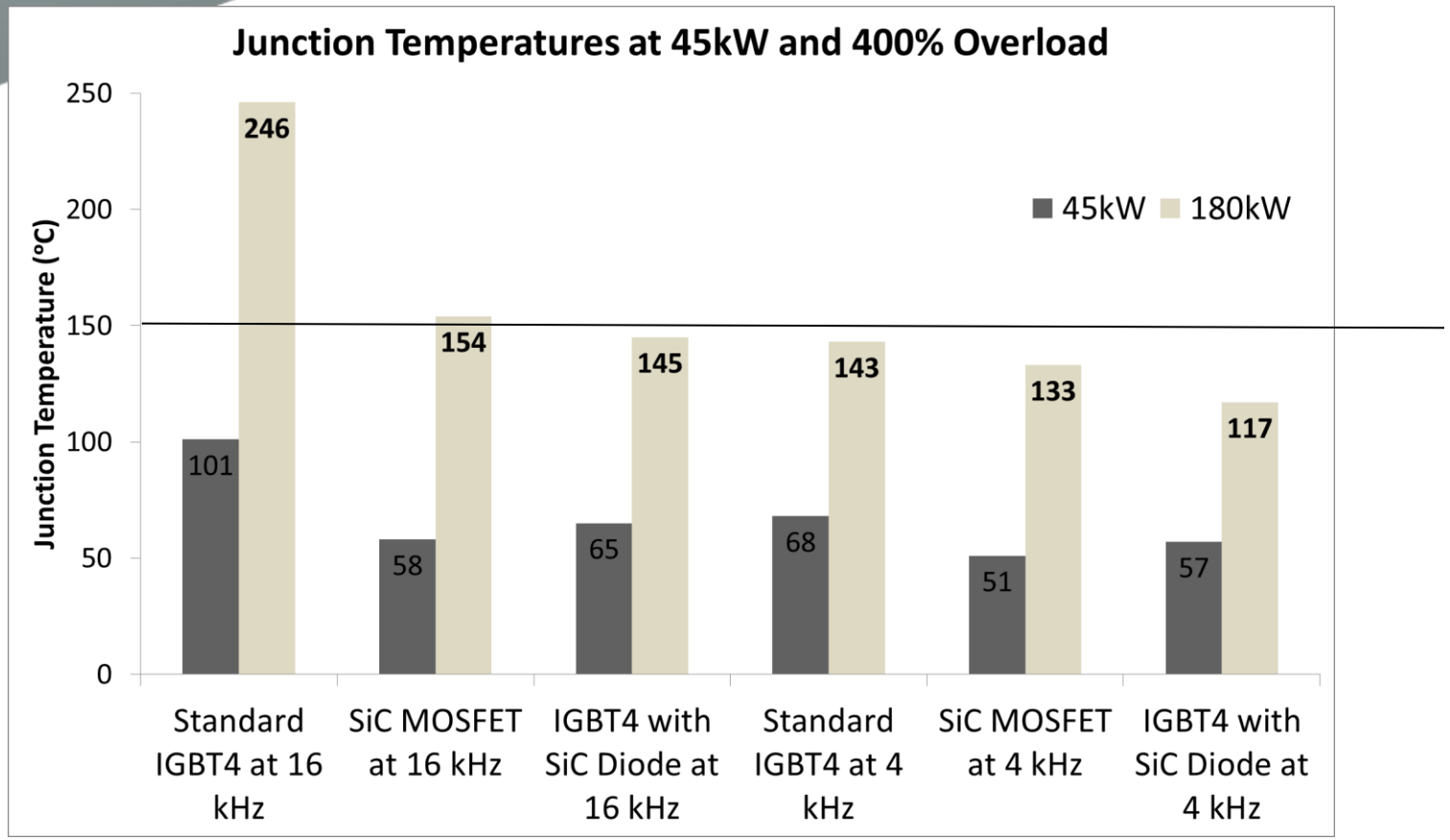


A comparison of the overall losses between a Si IGBT and a SiC MOSFET with similar nominal ratings

Inverter for Ground Power Units

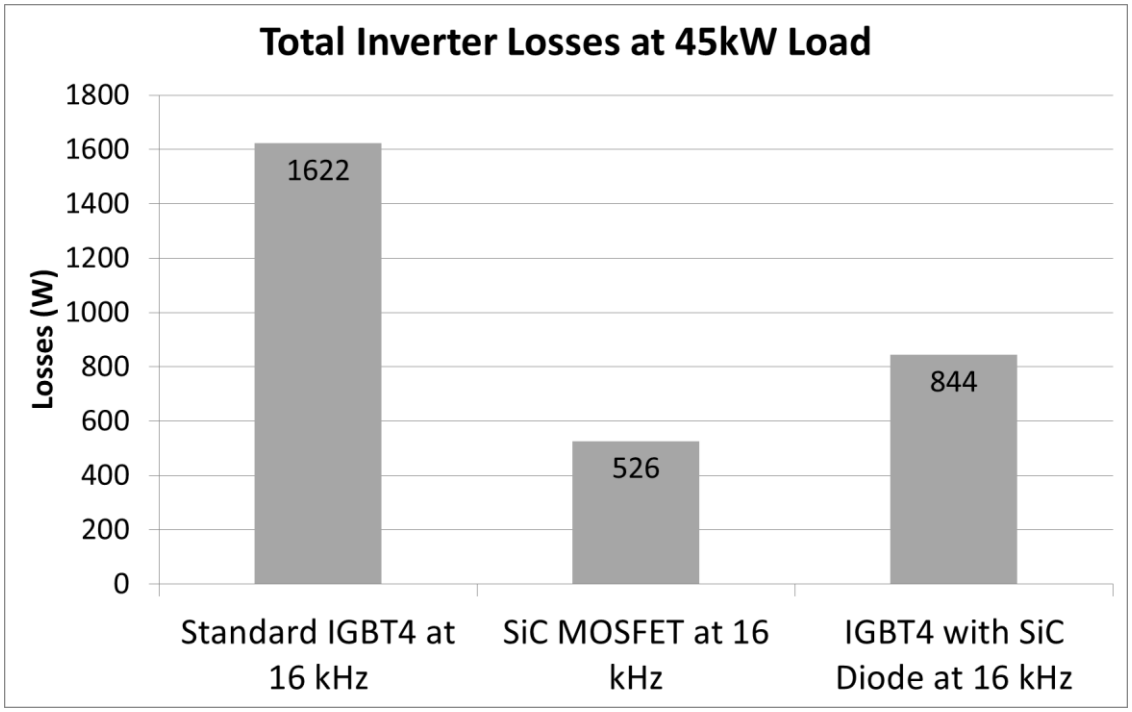
45 KW Inverter Design Parameters		
Parameter	Value	Unit
DC Link Voltage	500	VDC
Output Voltage - Line to Line	232	VAC
Output Frequency	400	Hz
Power Factor	0.85	
Nominal Output Power	45	kW
400% Overload value	180	kW
Switching Frequency at Nominal Load	16	kHz
Switching Frequency at Overload	4	kHz
Heatsink Thermal Resistance	0.017	K/W
Maximum Junction Temperature	150	^{o}C
Ambient Temperature	40	^{o}C

Effect of Junction Temperature



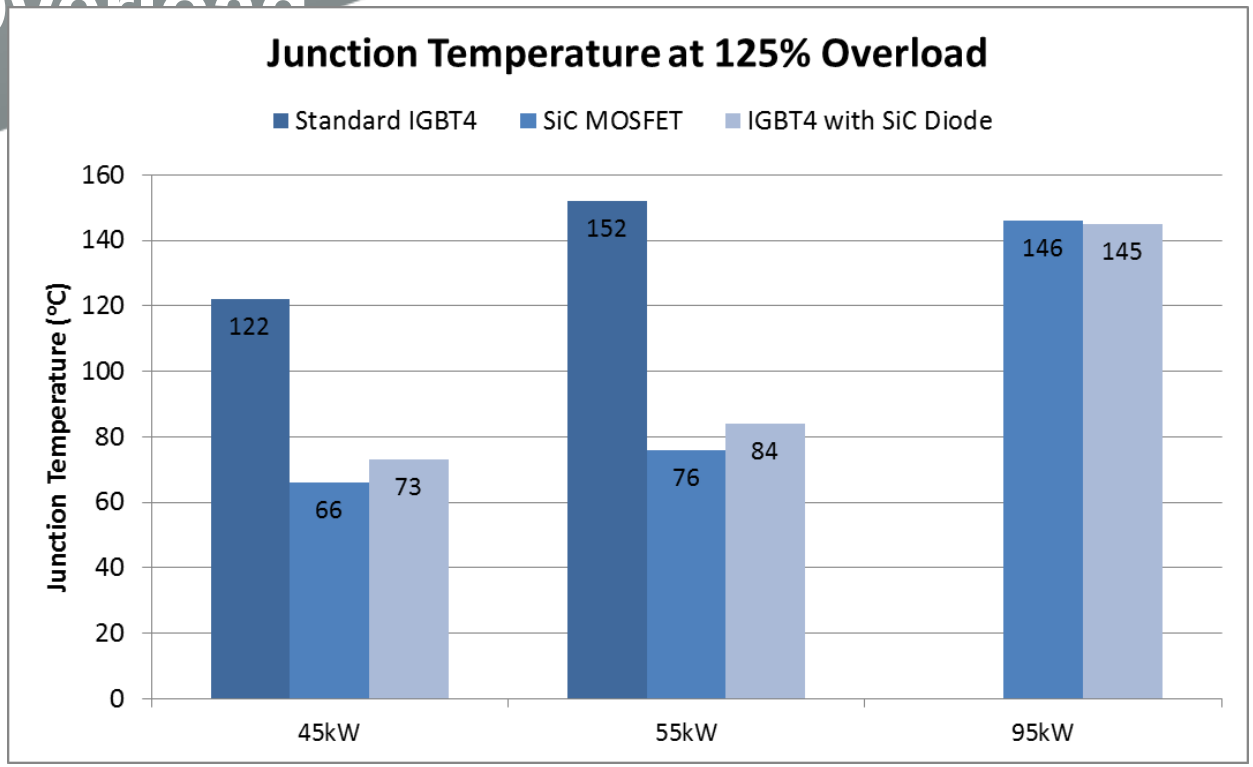
Junction temperatures of switching devices under nominal load and overload conditions. Note the reduction in temperature which corresponds with the reduction in switching frequency.

Comparison of Losses



- **67% reduction in losses can be expected.**
- **1.6% increase in efficiency if the IGBT4 module with SiC diodes is used.**
- **2.3% increase if the SiC MOSFET module is used.**

Junction Temperature at 125% Overload



Standard IGBT4 technology reaches its limit at a 55kW nominal load.

SiC-based devices would be able to increase the nominal rating of the power assembly to 95kW, which represents a 72% increase in power density.

SiC-based devices have the potential to double the power density of typical 3-phase inverters.

Power Electronics Reliability Studies

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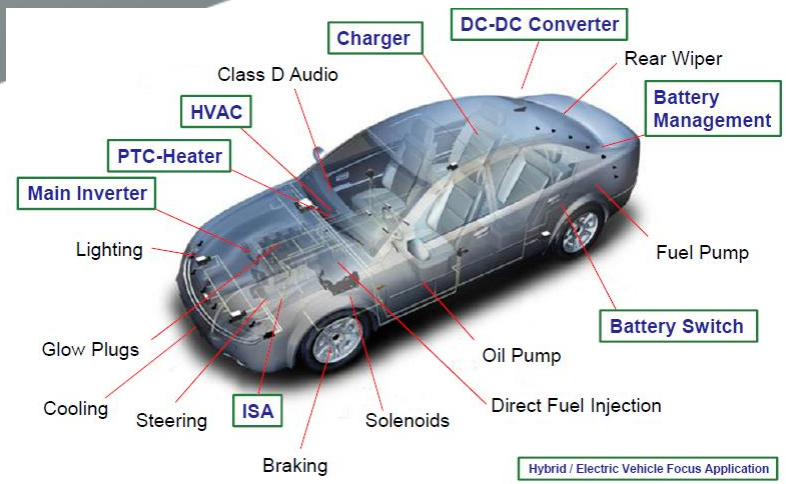
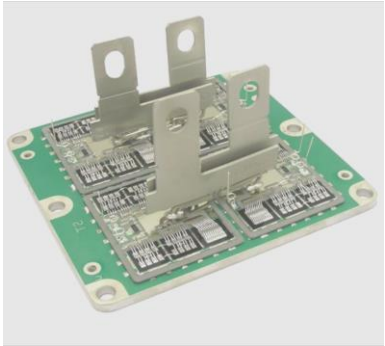
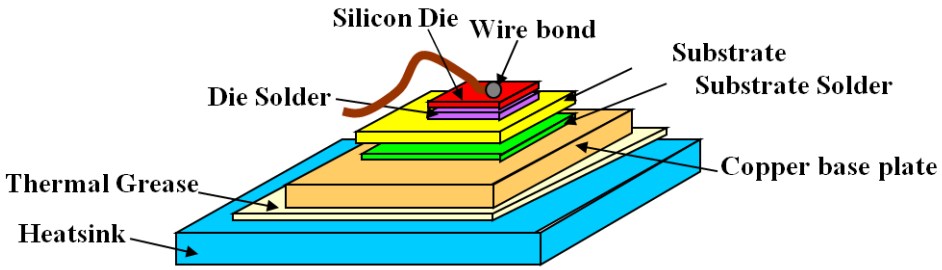




- **Repeated heating and cooling leads to repetitive mechanical stress and eventual failure.**
- **Exposure to sustained high temperatures drives diffusion-related mechanisms (creep, intermetallic growth, annealing).**
- **Mismatch in CTE causes fatigue failure (de-bonding) of bond wires and soldered interfaces.**



Elements of the heat transfer path of the power electronic module

Physics-of-Failure Applied in Design

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Mission Profile

I(t)

(1)Thermal Profile Generator

$T_{interface}(t)$

(2) Rain-Flow Analysis

$\Delta T_{interface}$ vs No. of Cycles

(3) Damage Profile Generator
and
Lifetime Prediction

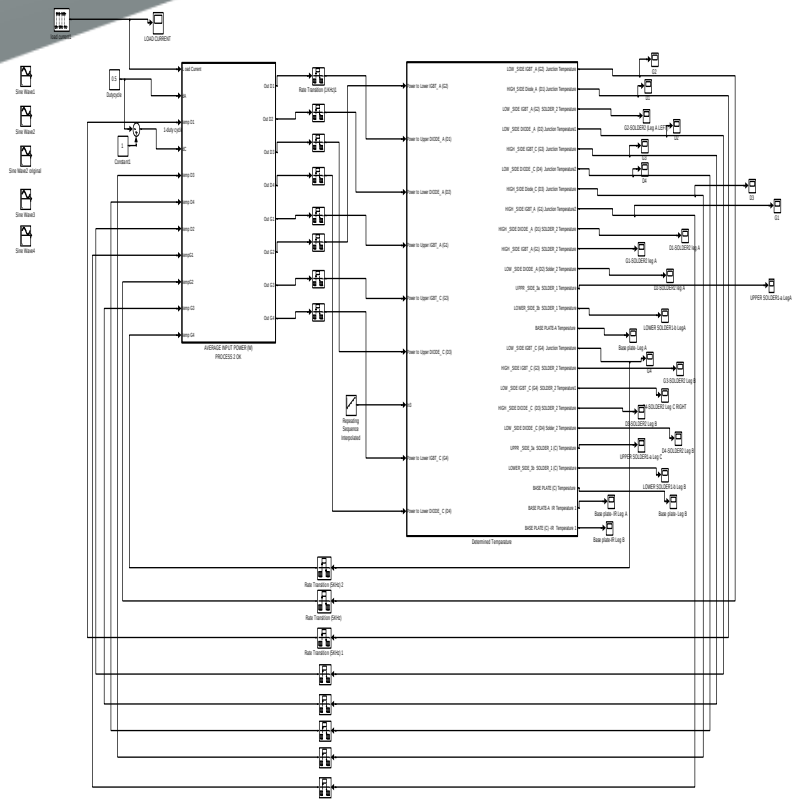
Electrical systems:
- **Trains, Planes & Automobiles**
- **Renewable power sources**
- **Power generation & distribution**
- **Industrial processes**

- **Power-electronics process**
- **Switching strategy**
- **Device electrical models**
- **Device thermal models**

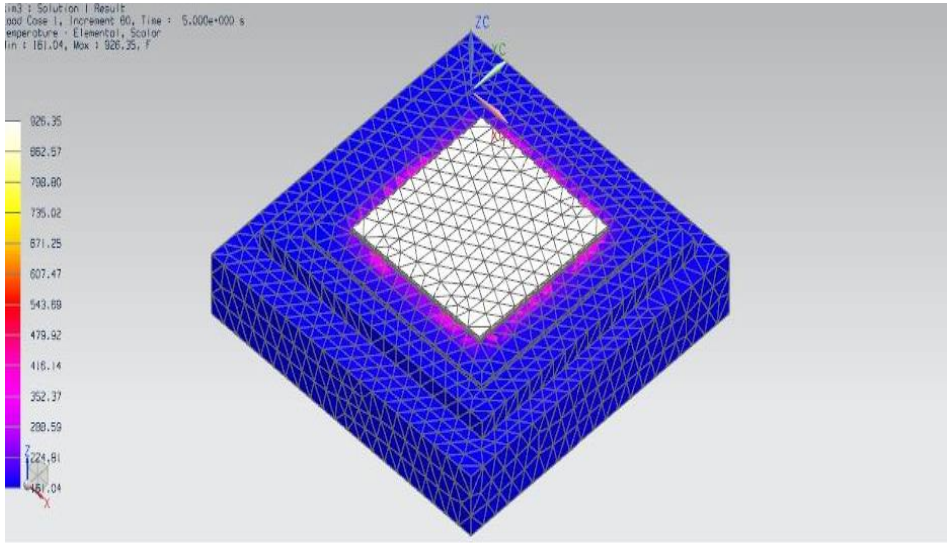
Interfaces:
- **Wire-bonds**
- **Chip solder**
- **Substrate solder**

- **Failure models**
- **POF/Empirical**
- **Statistical models**
- **Weibull**

and Thermo – Mechanical M



Electro-Thermal Model



Thermo-Mechanical Model

Life-Time Models

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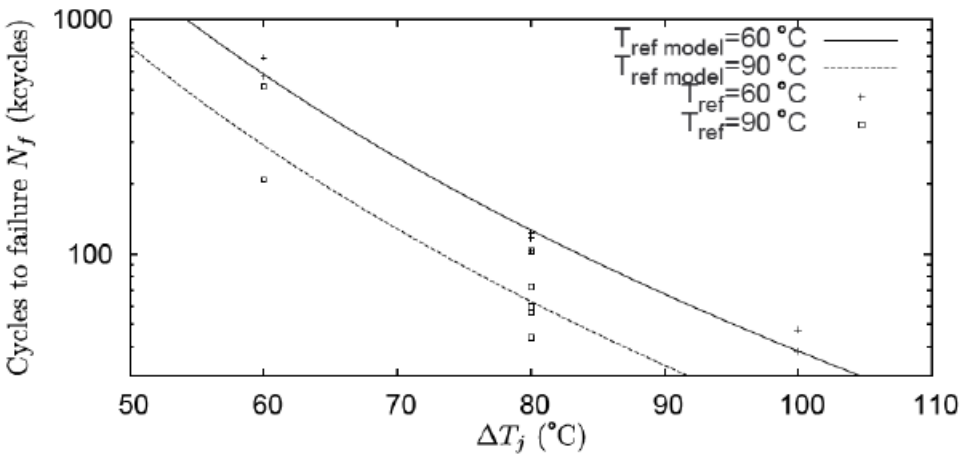
CHOICE OF THE EMPIRIC HELD MODEL (ΔT_J, T_{ref})

$$N_f = \frac{K}{\Delta T_J^{\,v}} \exp\left(\frac{T_a}{T_{ref}}\right)$$

$K = 2.13\ 10^{14}$
$n = 5.33$
$T_a = 126\ ^\circ C$



- **Wire bond wear-out models**

$$N_f = (1.4 * 10^{11}) \Delta T^{-3.597}$$

N_f is the material number of cycles to failure
ΔT is temperature variation.

Reliability life-time models for IGBT bond wire interconnect.

IGBT Reliability

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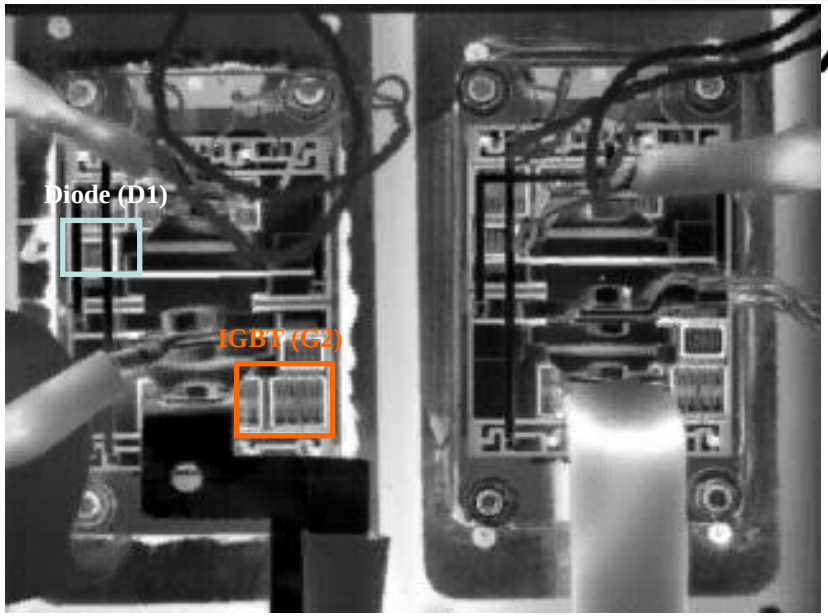

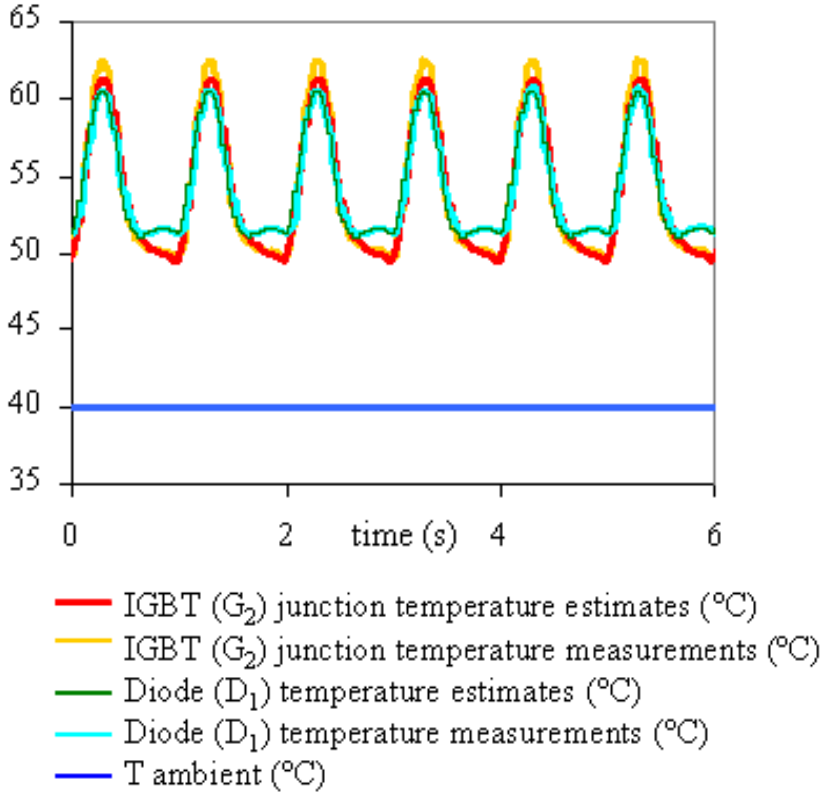

Comparisons between Junction Temperature Estimates and Measurements

- **Infra-Red Measurements**

CEDIP Titanium high frame rate camera

Integrated Vehicle Health Management

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Vehicle Maturation/New Product

Design
Engineering
Manufacturing

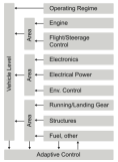
- Production, certification & testing
- Total ownership costs
- System & life cycle
- Requirements
- FMECAs
- Design models
- Failure modes/models
- System test data

Sense

Asset

Act

Acquire



Transfer

Health Status
- Current
- Predicted

Operational Control

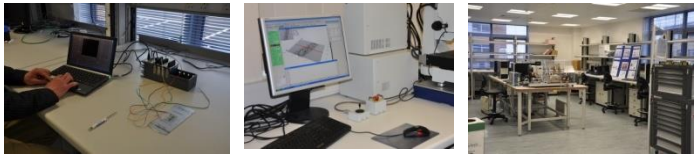
- Operational Demand
- Fleet Availability
- MR & O leading

- Operational Schedule
- Operational Effectiveness

Maintenance & Logistics

- Maintenance Scheduling
- Spares Supply
- Asset Tracking
- Maintenance Execution

Health Status



Analyse

Data Repository
& Ground Processing

Power Module IGBT

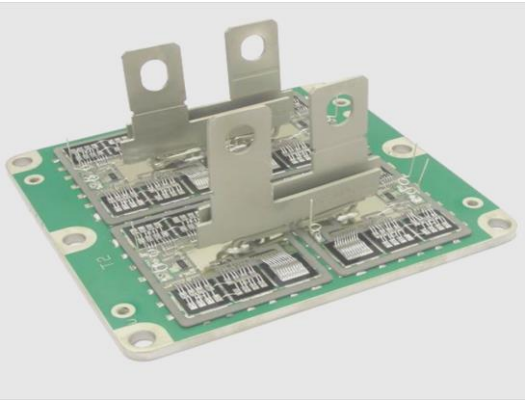
Repeated heating and cooling leads to repetitive mechanical stress and eventual failure.

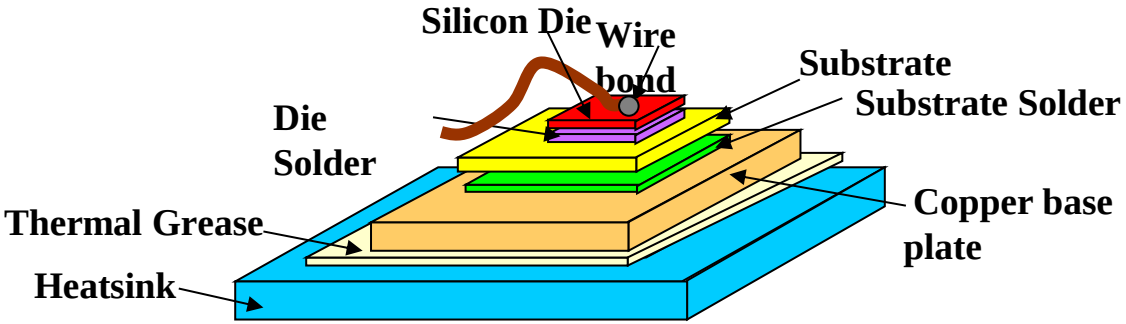
Exposure to sustained high temperatures drives diffusion-related mechanisms (creep, intermetallic growth, annealing).

Failure Mechanism	Precursor Parameters
Time-dependent dielectric breakdown	$V_{GE(th)}$, I_{ge}
Latch-up	$V_{CE(ON)}$, I_{CES}
Wire bond flexure fatigue, solder die attach fatigue, die attach voiding	$V_{CE(ON)}$

Mismatch in CTE causes fatigue failure (de-bonding) of bond wires.

CTE mismatch causes fatigue failure at soldered interfaces.



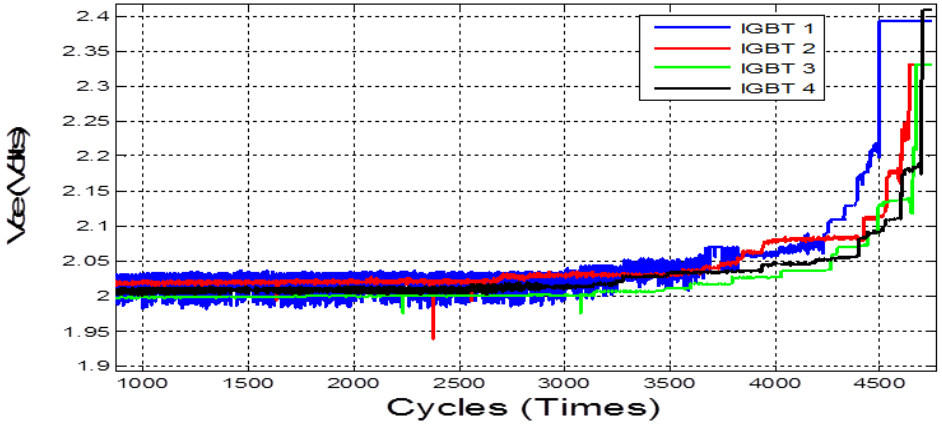


Elements of the heat transfer path of the power electronic module

Power Cycling Ageing Test

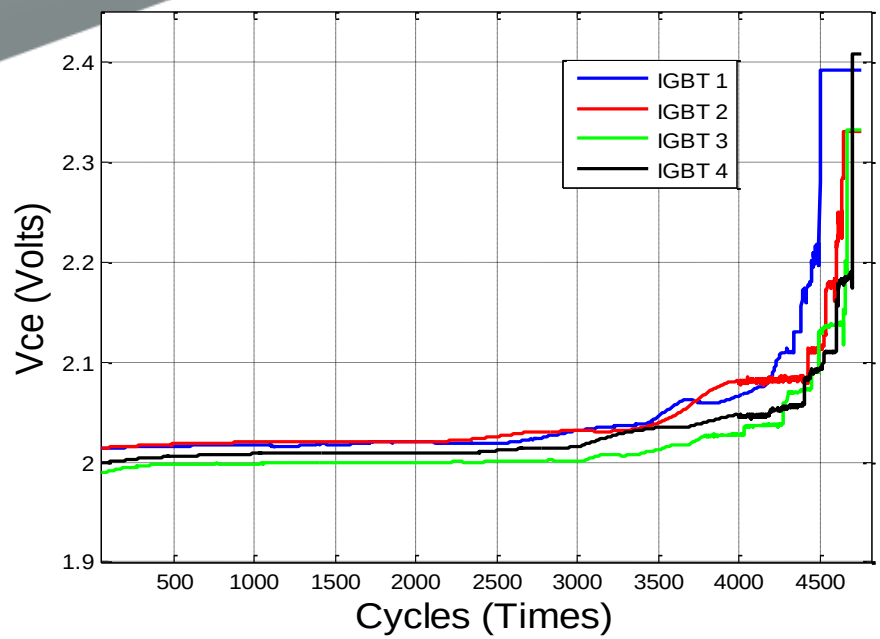
The power cycling ageing test provides monitoring and measurements of temperature and electrics.

- On-state collector emitter voltage (Vce) changes with different power cyclings.
- The junction temperature and the collector-emitter are measured and recorded constantly until the IGBT fails in accelerated ageing experiments.
- The failure mode involves wire bond lifting off and progressively ending before reaching the open circuit.

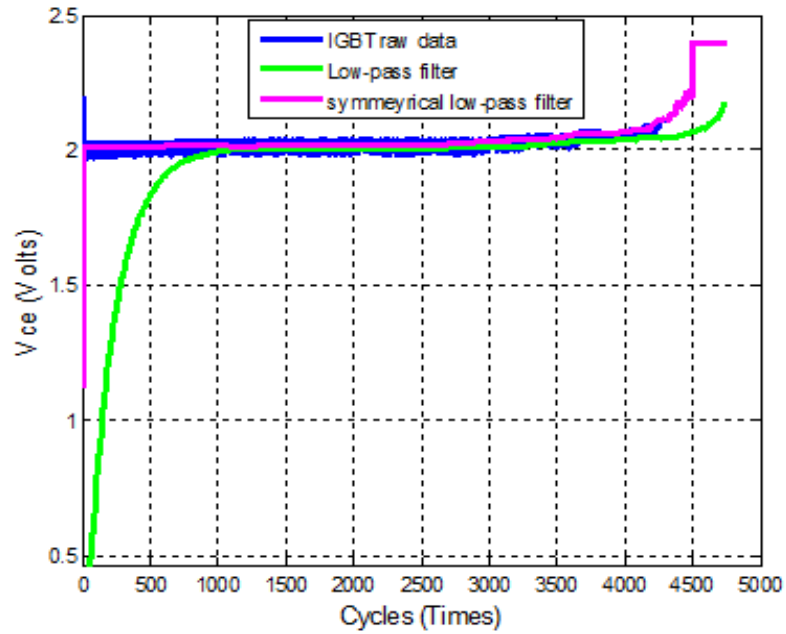


- The Vce (on-state) parameter indicates any increases in a non-monotone fashion and shows discrete steps with noise invasion until the IGBT fails.
- The Vce (on-state) voltage precursor indicates a sudden fall at the end of the ageing process when the IGBT fails after more than 4,500 time units.

Noise Filtering



All IGBT run-to-failure data sets after filtering



First IGBT data set after filtering

Data Clustering

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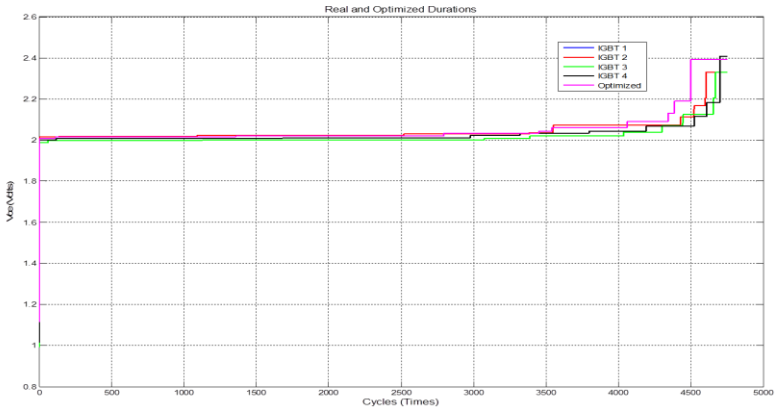
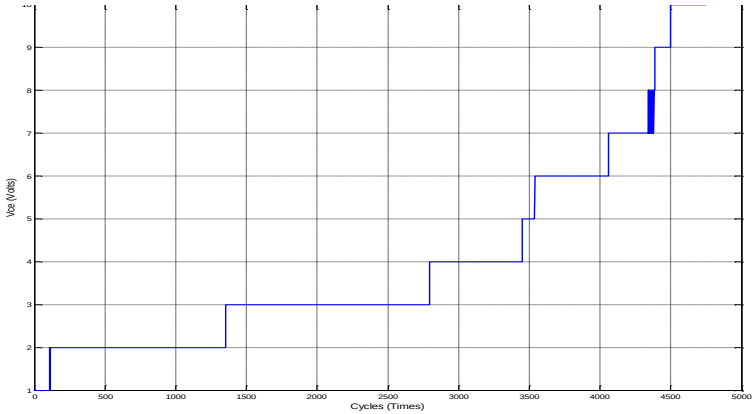
TABLE III: IGBT Degradation Phase Duration

	IGBT No	1	2	3	4
Duration of Each Degradation Phase	1st Phase	1	2	2	2
	2nd Phase	109	132	61	117
	3rd phase	1245	955	1069	1561
	4th phase	1440	1429	1940	1296
	5th phase	656	866	317	341
	6th phase	88	164	645	480
	7th phase	521	879	266	394
	8th phase	282	94	145	331
	9th phase	45	78	209	85
	10th phase	111	6	17	91
	IGBT Life	4498	4605	4671	4698





Parameter Optimization

Using analytical maximum likelihood estimation (MLE) method to estimate best fit of the modelling parameter λ for Poisson distribution

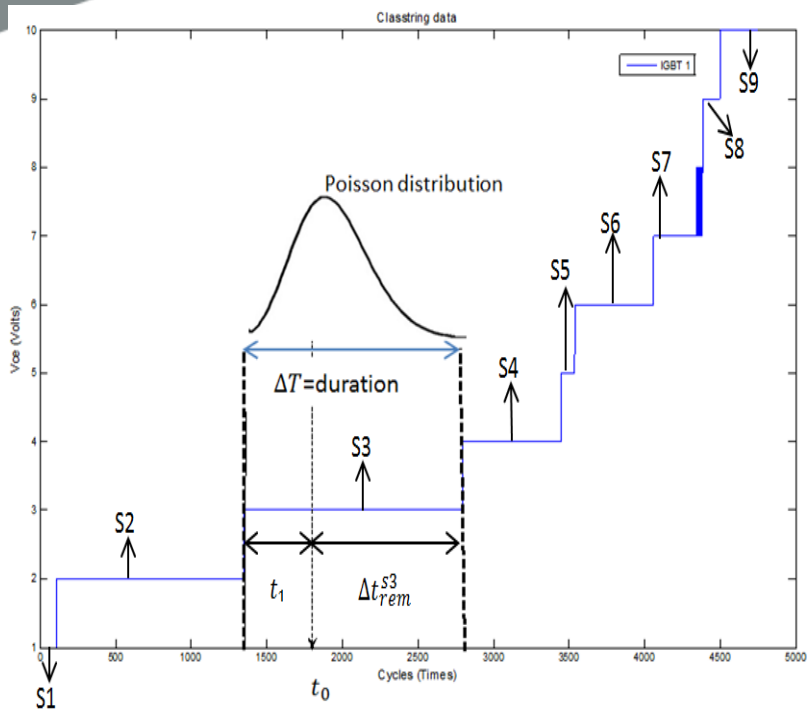
$$P(x_i|\lambda) = \left[\frac{\lambda^{x_i}.e^{-\lambda}}{x_i!}\right], x_i \geq 0$$

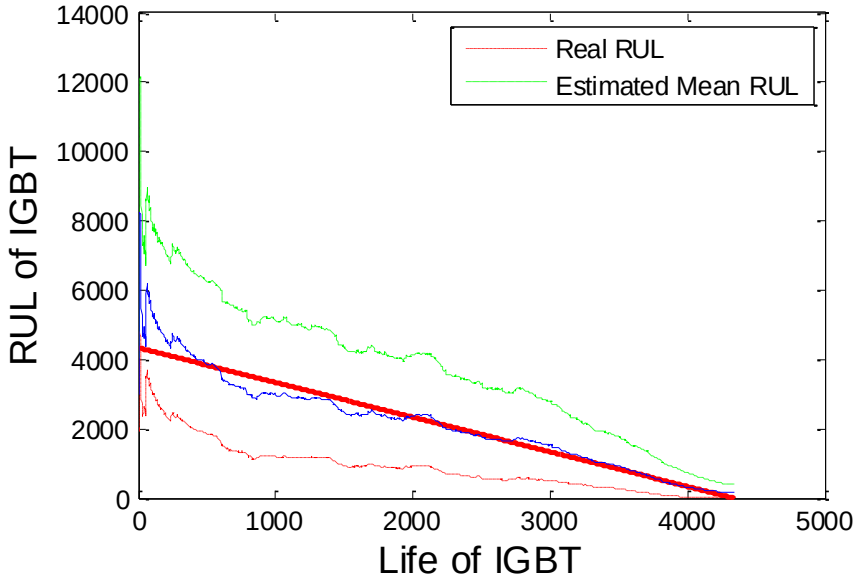
$$\hat{\lambda}MLE = \frac{1}{n}\sum_{n=1}^{N} x_n$$

MLE for Poisson Probability Distribution

Parameter	λ
Model 1	2
Model 1	98
Model 1	1210
Model 1	1531
Model 1	520
Model 1	330
Model 1	520
Model 1	211
Model 1	126
Model 1	70

Results from RUL Estimation Using Weibull Model





Constructed Markov model & Monte Carlo simulation for RUL prediction

Conclusions

- Reliability and maintenance-free power solutions are important for wide adaption of Wide Bandgap technology.
- Cranfield could assist industry to develop reliability models for Wide Bandgap applications.
- Cranfield could develop prognostics capabilities for Wide Bandgap applications.
- This will enable safety-conscious industry, such as electric aircraft, to adapt Wide Bandgap.