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ORANGE COUNTY CONVENTION CENTER | ORLANDO, FL

Thermomechanical Reliability Aspects of Automotive Power Electronics: Current Status and Future Trends

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NREL

Thermomechanical Challenges

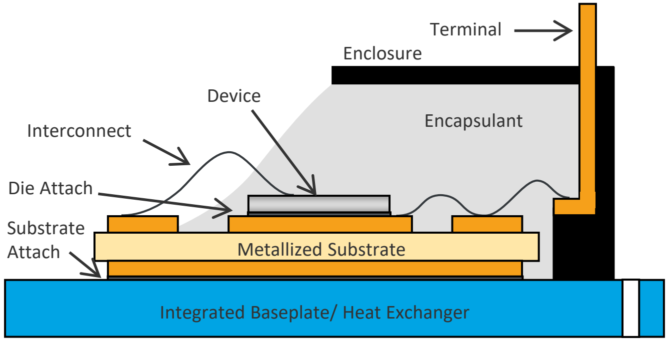
- Thermal challenges:
    - Higher operating temperatures
    - Higher heat fluxes/power densities
    - Hot spots.
- Reliability challenges
    - Attach layer fatigue
    - Interconnect fatigue.
- New package designs must address thermal and reliability concerns and be evaluated under accelerated conditions that approximate real-world conditions.

NREL APEEM RESEARCH

FMMEA of a Power Electronics Module

Potential Failure Modes (Sites)	Potential Failure Causes	Potential Failure Mechanisms (Parameters Affected)
Short circuit, loss of gate control, increased leakage current (oxide)	High temperature, high electric field, overvoltage	Time dependent dielectric breakdown (V_{th}, g_m)
Loss of gate control, device burn-out (die)	High electric field, overvoltage, ionizing radiation	Latch-up ($V_{CE(ON)}$, $V_{DS(ON)}$)
High leakage currents (oxide, oxide/substrate interface)	Overvoltage, high current densities	Hot electrons (V_{th}, g_m)
Open circuit (bond wire)	High temperature, high current densities	Bond wire cracking, lift-off ($V_{CE(ON)}$, $V_{DS(ON)}$)
Open circuit (die attach)	High temperature, high current densities	Voiding, delamination of die attach ($V_{CE(ON)}$, $V_{DS(ON)}$)

FMMEA: failure modes, mechanisms, and effects analysis



Reliability Research Approach

- Evaluate and improve reliability of new technologies
- Develop predictive and remaining lifetime models
- Multiphysics parametric modeling.

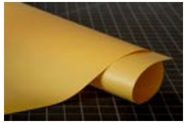
Areas of Research (Technologies)

- Attach materials (solders, Ag sinter, TLP, thermoplastics)
- Substrates (Temprion, 3D AlN)
- Interconnects (wire/ribbon bonding, metal posts).

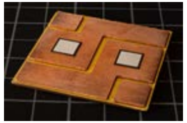
Patil, N., D. Das, C. Yin, H. Lu, C. Bailey, and M. Pecht. 2009. “A Fusion Approach to IGBT Power Module Prognostics.” In *Proc. of Thermal, Mechanical and Multi-Physics Simulation and Experiments in Microelectronics and Microsystems*. https://doi.org/10.1109/ESIME.2009.4938491

NREL APEEM Research

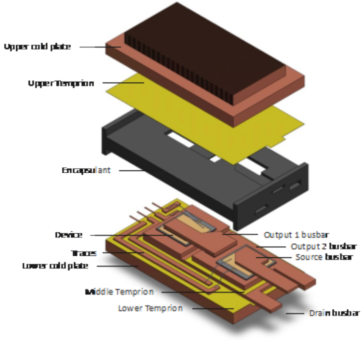
Metalized Ceramic Substrate Alternatives



DuPont Temprion polyimide film

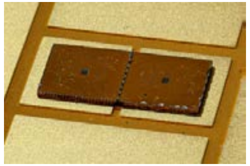


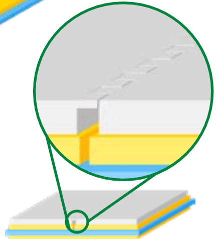
NREL prototype substrate



Direct Device Interconnection

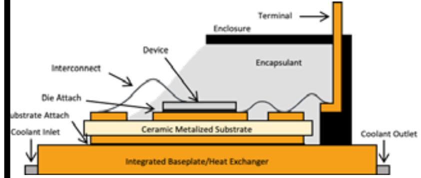
Traditional Bond Wires



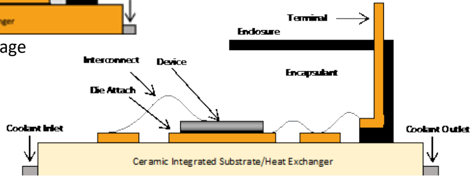


Quilt packaging interconnect by IIC

Integrated Ceramic Cooling

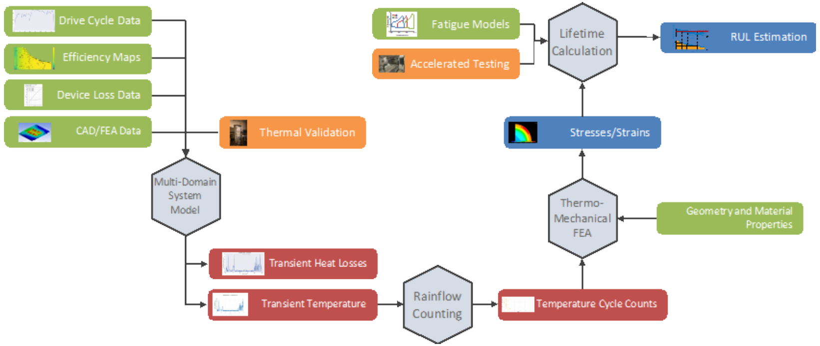


Traditional package



AlN substrate/heat exchanger printed by Synteris

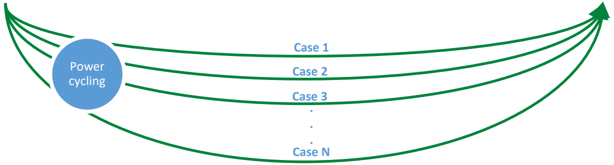
Drive Cycle RUL Estimation Tool



Automated Design for Reliability (Machine Learning for Power Electronics)

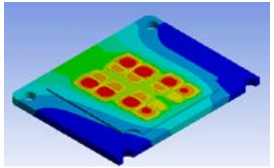
Design Parameters
Switching frequency
DC-link voltage
Baseplate material
Ceramic material
Solder material
Baseplate thickness
Ceramic thickness
Solder thickness

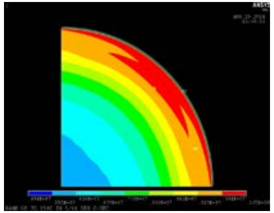
Output Parameters
Junction-case thermal resistance
Junction temperature
Maximum stress
Maximum strain
Strain energy density/cycle

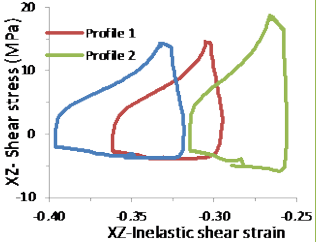


NREL APEEM Research

Accelerated Modeling, Testing, and Evaluation



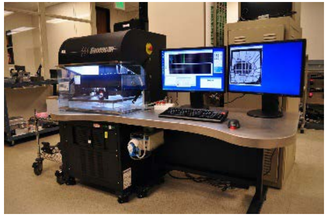


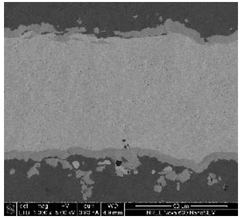


Thermal and thermomechanical modeling

Thermal (cycling/shock)

Combined vibration (sinusoidal/shock), thermal (cycling), and humidity





Optical, acoustic, and scanning electron microscope (SEM) analysis

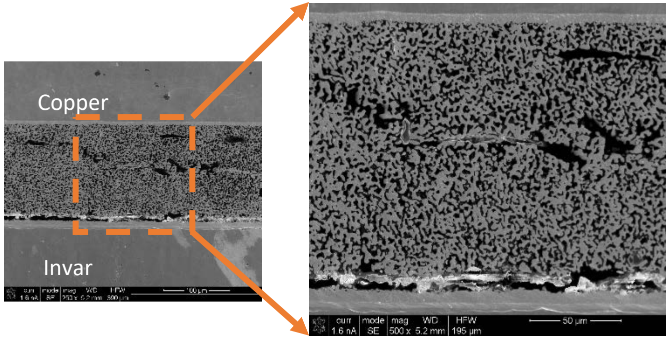
Power cycling and transient thermal analysis

Device electrical analysis

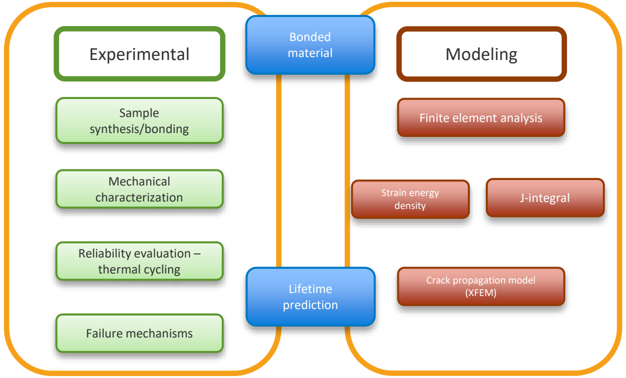
DESIGN FOR RELIABILITY

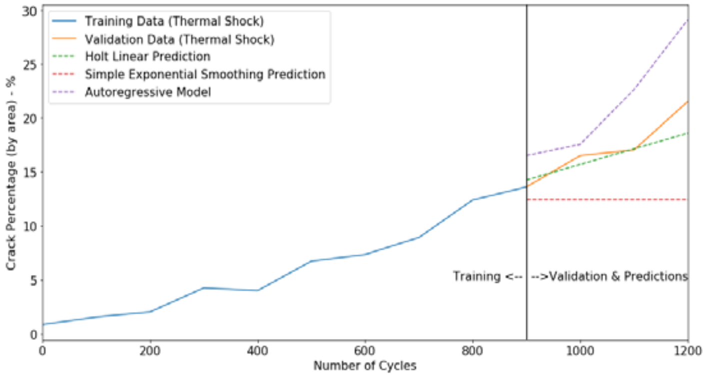
Attach Materials

- Traditional bonded interfaces (solders) are replaced with materials that are reliable under under extreme thermal stress conditions.
- Materials are bonded in sample configurations and evaluated for their reliability under thermal cycling, thermal shock, and extended elevated temperature conditions.
    - Sintered Ag – Virginia Tech
    - Sintered Cu – Institute of Innovative Mobility (Germany)
    - Cu-Al transient liquid-phase (TLP) alloy – Georgia Tech
    - HM-4 polymeric material – ADA Technologies



SEM image of sintered Ag

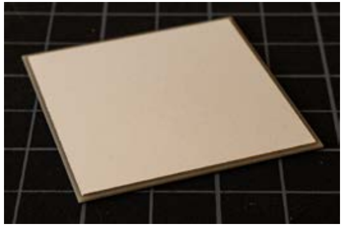




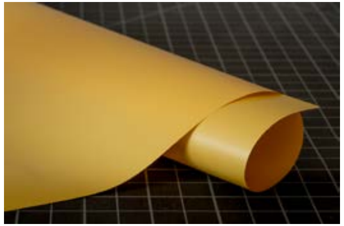
Crack growth forecasting of different statistical models

Electrically Insulating Substrates

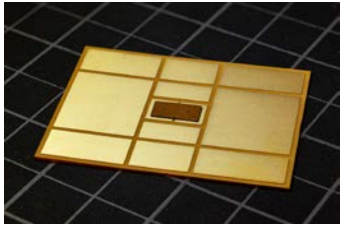
- Alternative electrically insulated substrate designs are required to enable reliable packages that operate with higher power densities and higher temperatures.
- Traditional metallized ceramic substrate technologies:
  - Direct-bond copper (DBC)
    - Oxidation of copper (Cu) foils during bonding lowers melt temperature from 1,083°C to 1,065°C
    - Maximum metallization thickness of 1 mm
    - Must have metallization layers on both sides of the ceramic
    - Examples include aluminum oxide (Al_2O_3), aluminum nitride (AlN), and zirconia (ZrO_2)-doped high-performance substrates (HPS).
  - Active metal bonding (AMB)
    - Brazing process with silver-copper (Ag-Cu) alloy between Cu and ceramic at 850°C in vacuum
    - Requires more processing steps and is more expensive than DBC
    - Silicon nitride (Si_3N_4) substrate is an example.
- ODBC
  - A polyimide dielectric is bonded with metal through elevated temperature and pressure
  - No limitations in metal material or metallization thickness
  - Maintains electrical and thermal performance after 5,000 thermal shock cycles (−40°C to 200°C, 5-minute dwells).



Traditional substrate



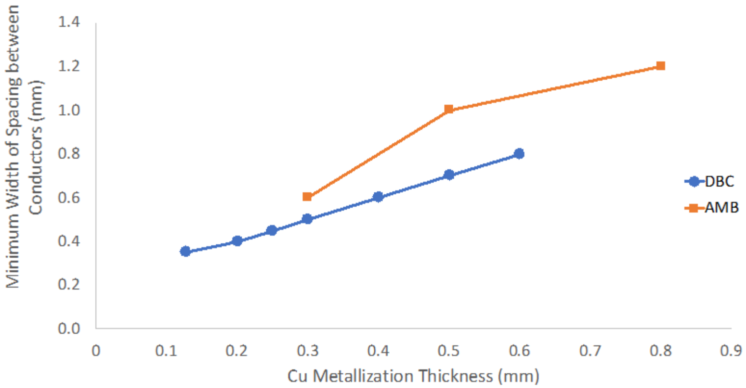
DuPont Temprion polyimide film



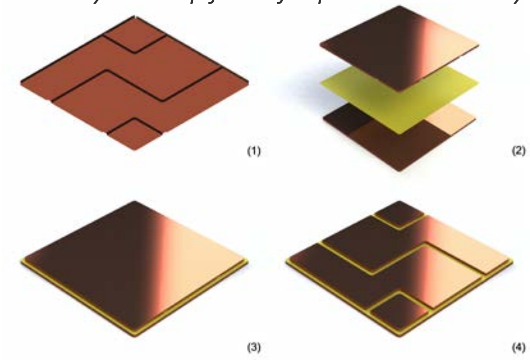
DuPont ODBC substrate

Electrically Insulating Substrates

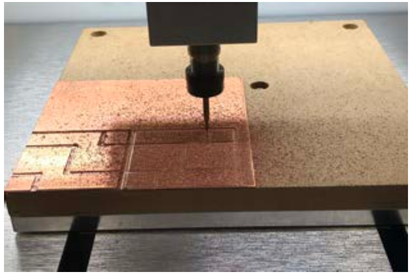
- The ability to bond thick copper metallization layers (1–1.5 mm) improves heat spreading directly below devices and lowers their junction temperatures.
- Mechanical etching allows for fine width spacing (<1 mm) between conductor traces through thick metallization layers.
  1. *Mechanically etch bottom face of top metallization layer.*
  2. *Assemble Temprion and metallization layers.*
  3. *Apply temperature and pressure to substrate stack.*
  4. *Mechanically etch top face of top metallization layer.*



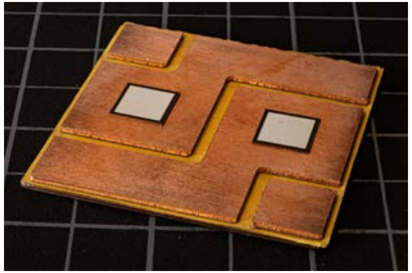
Minimum width of spacing between conductors based on metallization thickness using chemical etching [1]



Substrate assembly process



Machining process

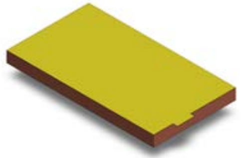


NREL prototype substrate

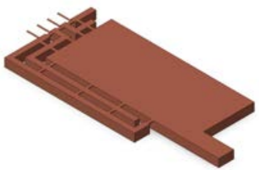
[1] Rogers Corporation. 2022. “curamik® Ceramic Substrates Technical Data Sheet.” 2022. https://rogerscorp.com/-/media/project/rogerscorp/documents/advanced-electronics-solutions/english/data-sheets/technical-data-sheet-curamik-ceramic-substrates.pdf.

Electrically Insulating Substrates

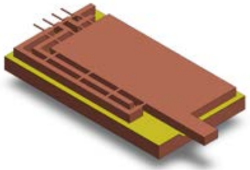
- Simplified packaging process has been envisioned with ODBC substrates in a double-side-cooled module.



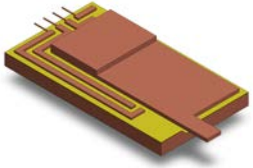
1. Bond lower Temprion layer to lower cold plate.



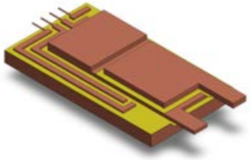
2. Etch bottom face of drain busbar and traces.



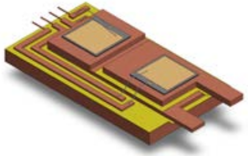
3. Bond drain busbar and traces to lower Temprion layer.



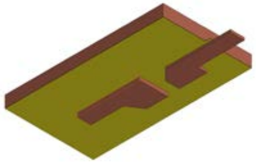
4. Etch top face of drain busbar and traces.



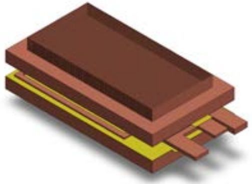
5. Bond middle Temprion layer and output 2 busbar.



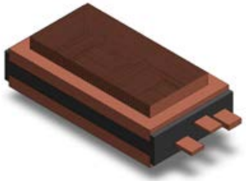
6. Sinter and wire bond devices.



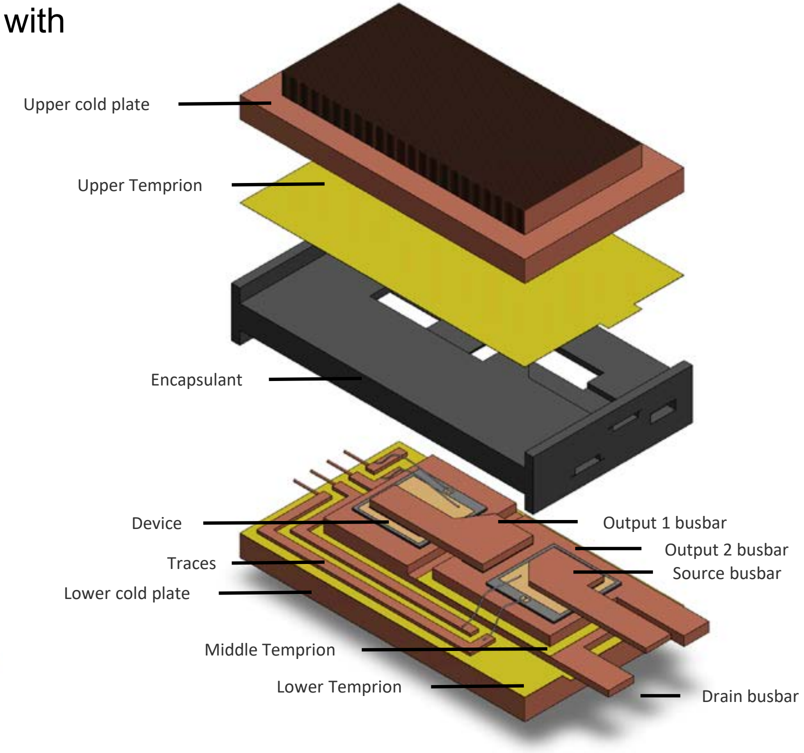
7. Bond output 1 and source busbars to upper Temprion and upper cold plate.



8. Sinter previous assembly to devices.



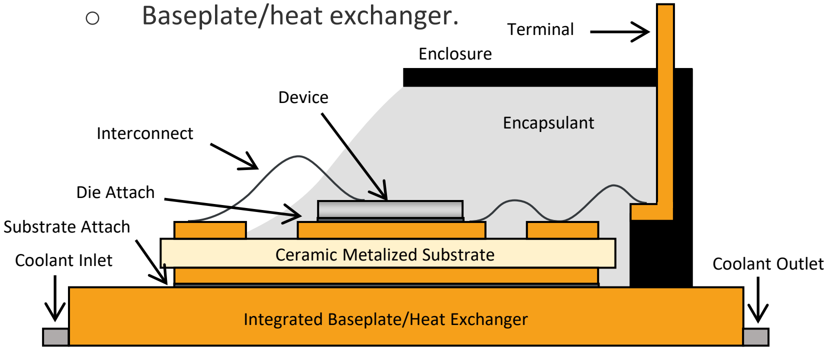
9. Fill cavity with encapsulant.

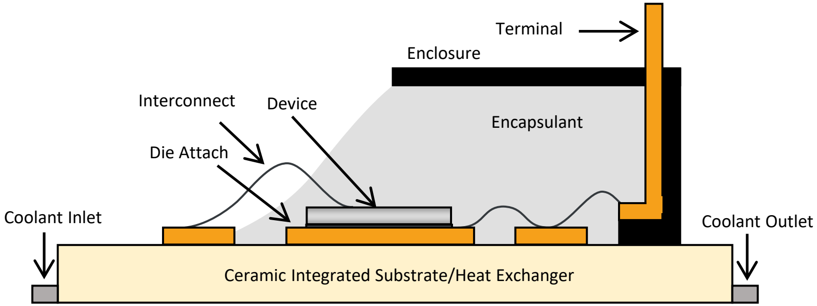


3D-Printable Ceramic Packaging

Breaking the Board: Bringing Three-Dimensional Packaging and Thermal Management to Power Electronics (ARPA-E OPEN 2021)

- Synteris has developed a proprietary and patent-pending additive manufacturing technology known as selective laser reaction sintering (SLRS).
  - Fabricate isovolumetric, complex, non-oxide ceramics (e.g., AlN, SiC, Si_3N_4).
- Funded work will further develop the additive manufacturing process to create AlN packaging that acts as both an electrical insulator and heat exchanger.
- This one AlN component will replace several traditional components:
  - Insulating metallized substrate
  - Substrate attach
  - Baseplate/heat exchanger.

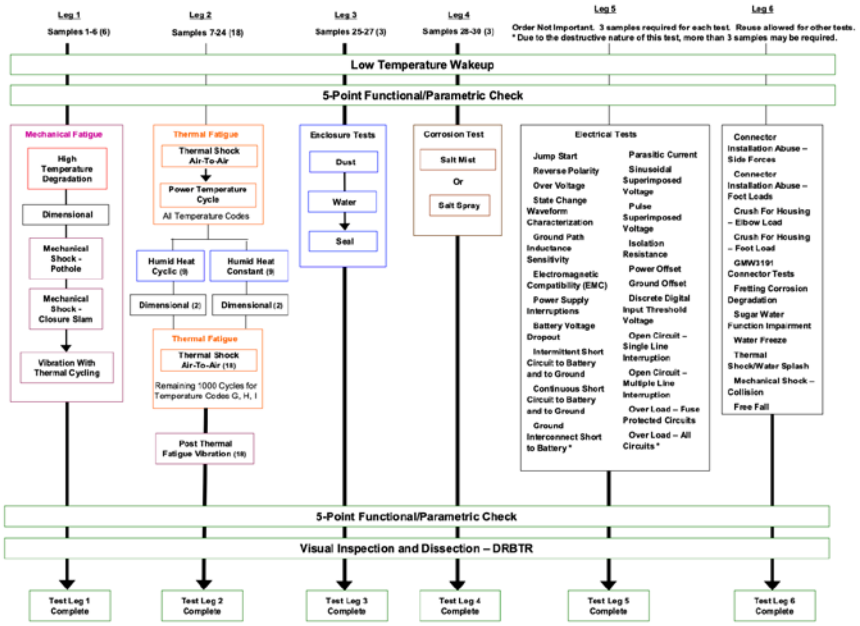




RELIABILITY METHODS AND TOOLS

Automotive Test Standards

GM Test Standard GMW3172



European Center for Power Electronics
Automotive Power Module Qualification (AQG 324)

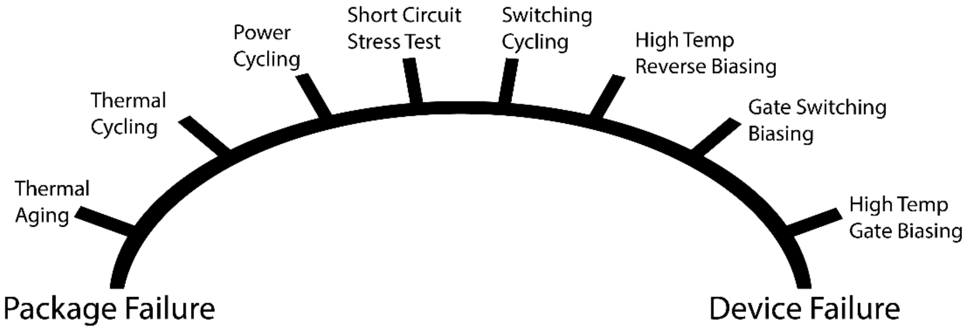
AQG 324

ECPE Guideline AQG 324

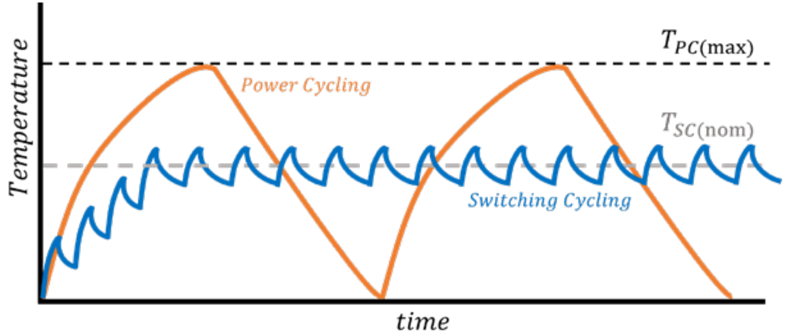
Qualification of Power Modules for Use in Power Electronics Converter Units (PCUs) in Motor Vehicles

Accelerated Testing Spectrum

- Selection of an appropriate accelerated test, from passive thermal tests to power cycling tests, is based on the desired failure modes and mechanisms we wish to explore.

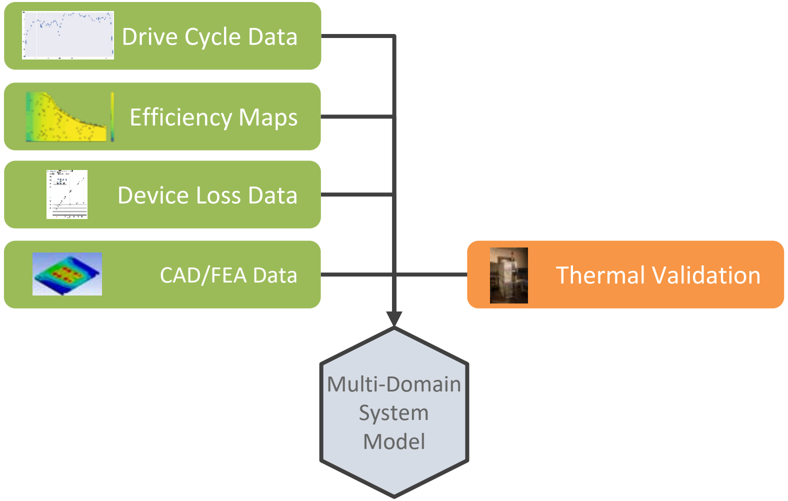


Accelerated life testing spectrum



Effect of device temperature during switching cycling and power cycling

Drive Cycle RUL Estimation Tool



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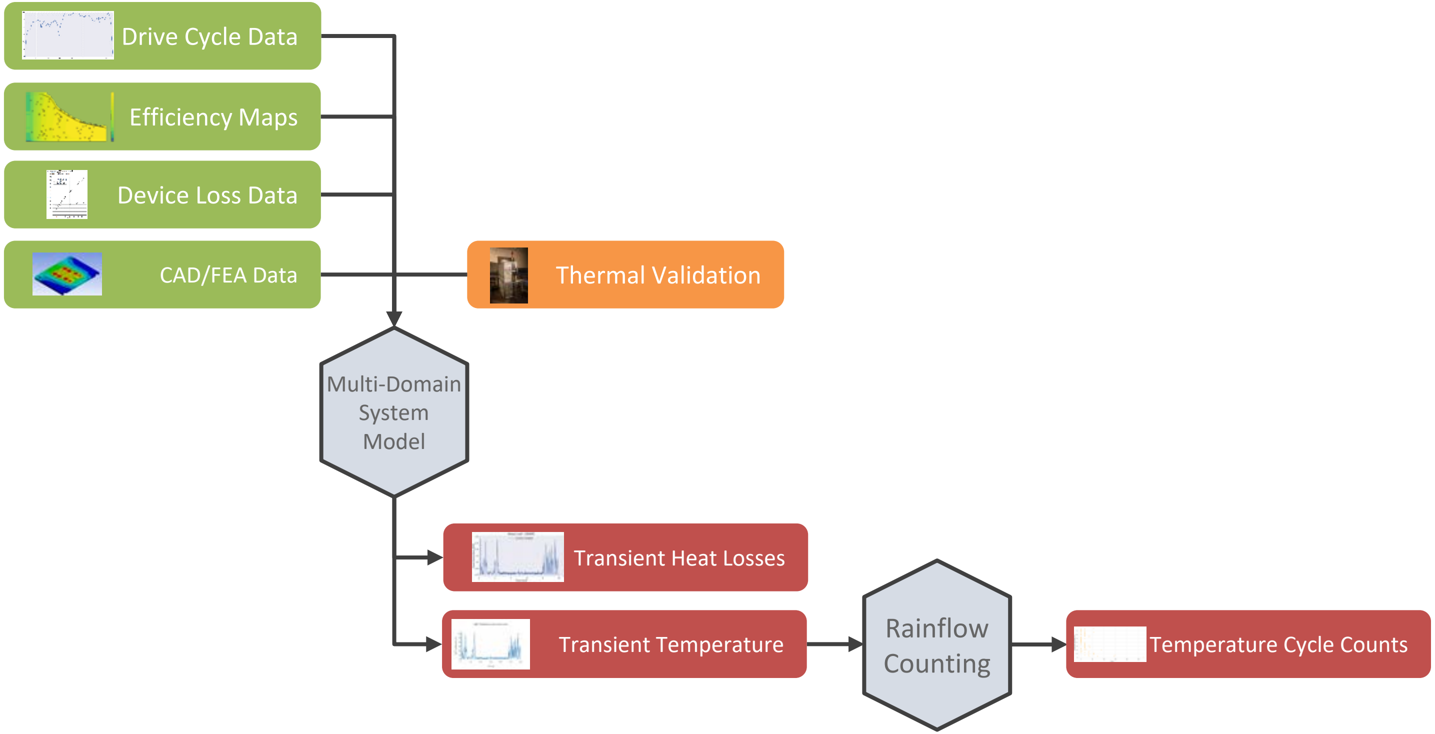

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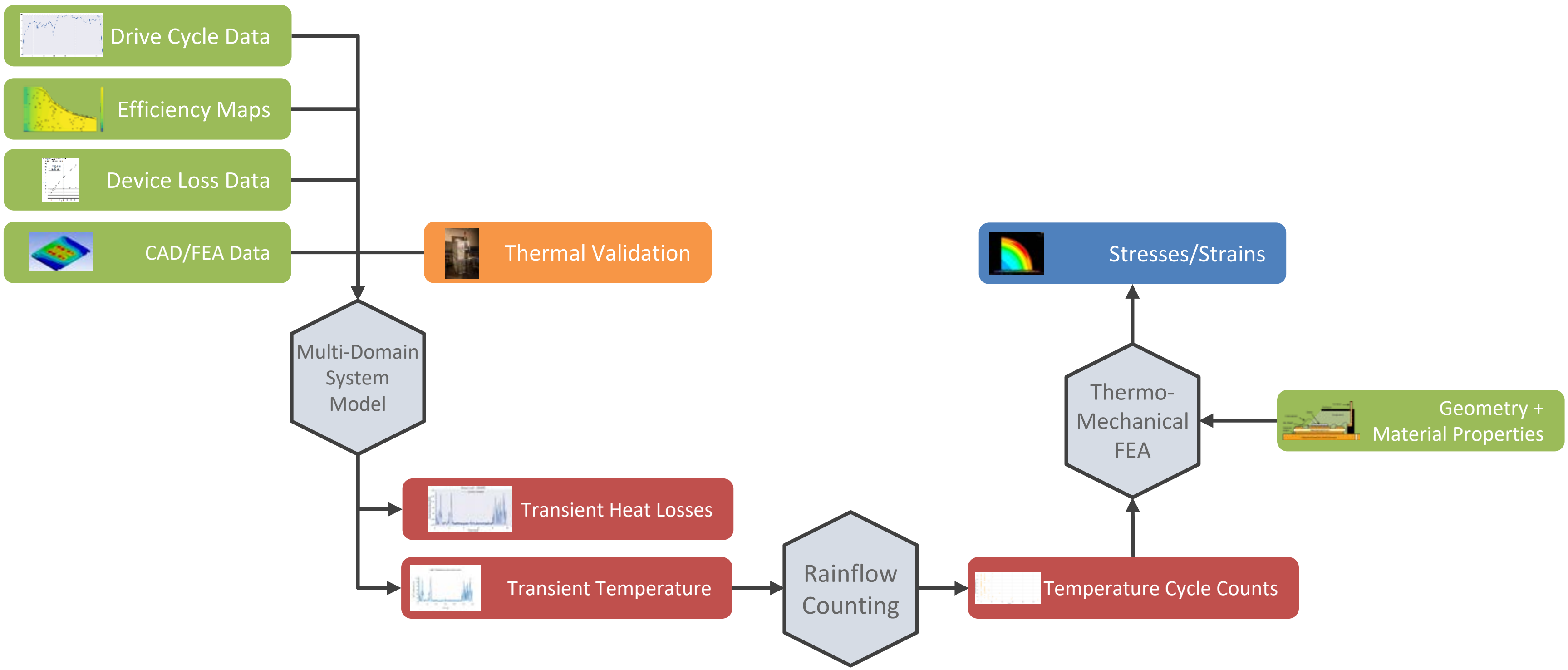

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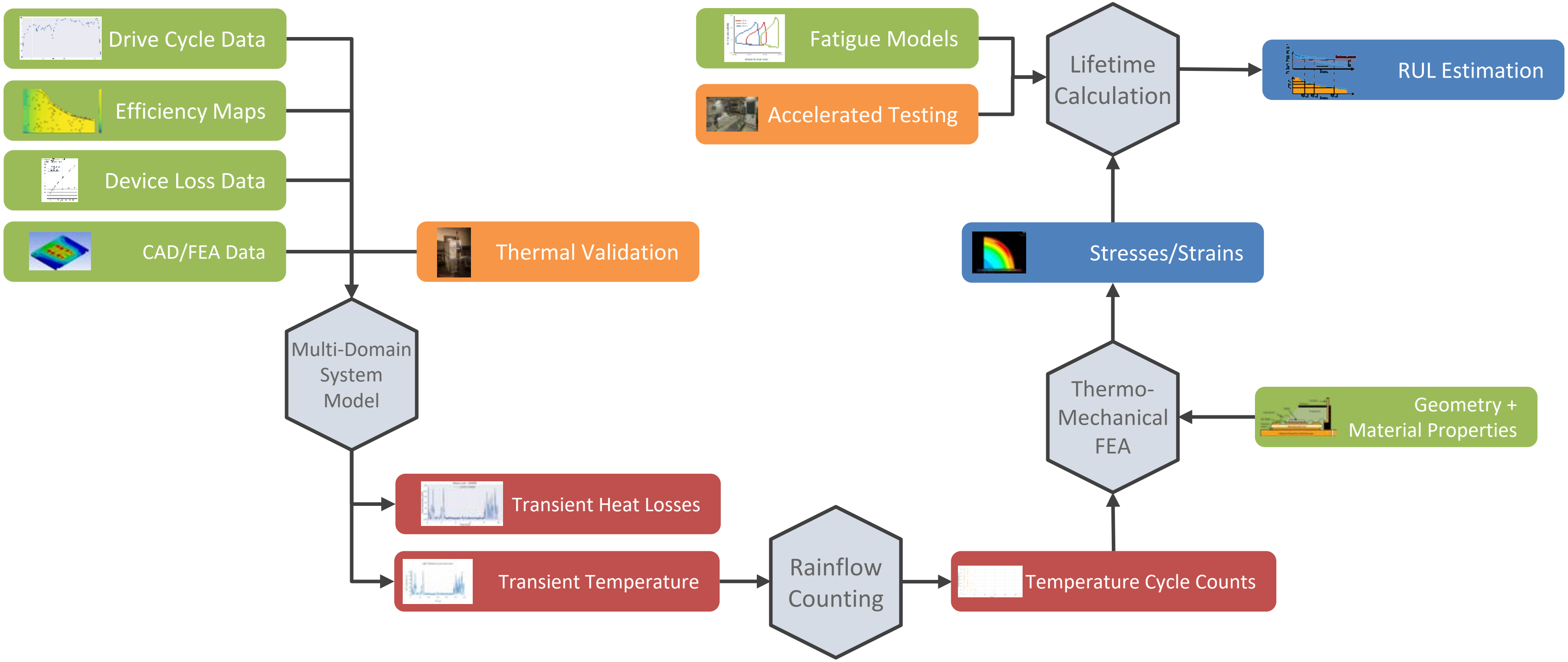
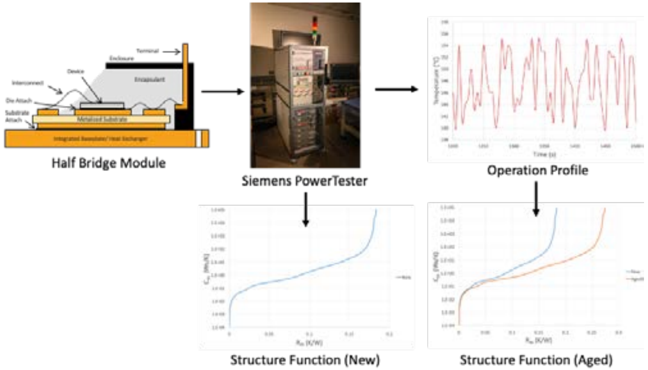
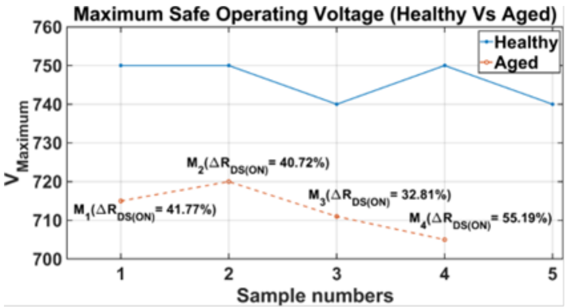


Future RUL Methods

- Goals:
  - Onboard health monitoring and prognostics
  - Digital twin/RUL estimates tied to individual vehicles.
- Solution:
  - Smart gate driver to measure aging and define dynamic safe operating area
  - This real time health monitoring feature may eliminate unforeseen system downtime/repairs, thus reducing operation and maintenance costs.



Junction-to-coolant thermal degradation



Safe operating voltage degradation

Thank You

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