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Thermal Control Challenges of High Power DUTs during Test

Jerry Tustaniwskyj

Director of Technology

Pick and Place Test Handler Group

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Overview – Factors to be Addressed

- Coolant Sources
- Geometric Constraints
- Thermal Interface to DUT
- DUT Power/ Temperature Gradient
- Temperature Control Strategies
- Misc.

Coolant Sources

Air

- Inexpensive and benign
- Practical at hot setpoints only
- Practical for limited power capacity
- High performance applications noisy

Liquid

- Higher thermal capacitance → better performance
- Best fluids are either flammable or limited in temperature range
- Water
  - Great performance
  - Limited from 0°C to 100°C (can extend somewhat by mixing glycols)
  - Requires leak tolerant design
- HFE
  - Lower performance
  - No fluid version is optimal over entire needed temperature range
- Thermal losses from cooling source to DUT control location

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Phase Change

LN2

- Can be used to extremely low temperatures
- Low thermal capacity, consumption costly, and safety concerns
- Resistance from customers due to various reasons

Refrigeration

- High thermal capacity
- Most effective with evaporator at test site (not through secondary medium)
- Routing supply and return lines complex
- Complexity and cost increase significantly below -40°C
  - Multi-stage
  - Oil return

Water

- At high temperature setpoints
  - Great performance, benign material

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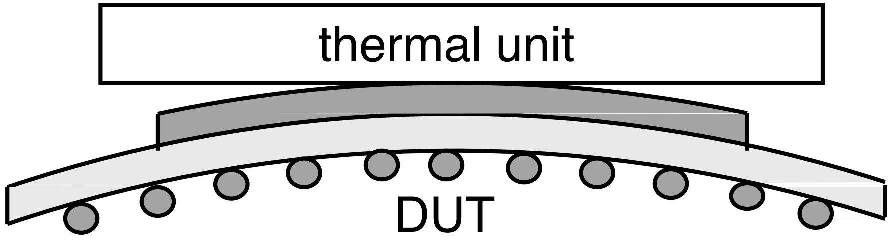
Geometric Constraints - Flatness

Large Device Area

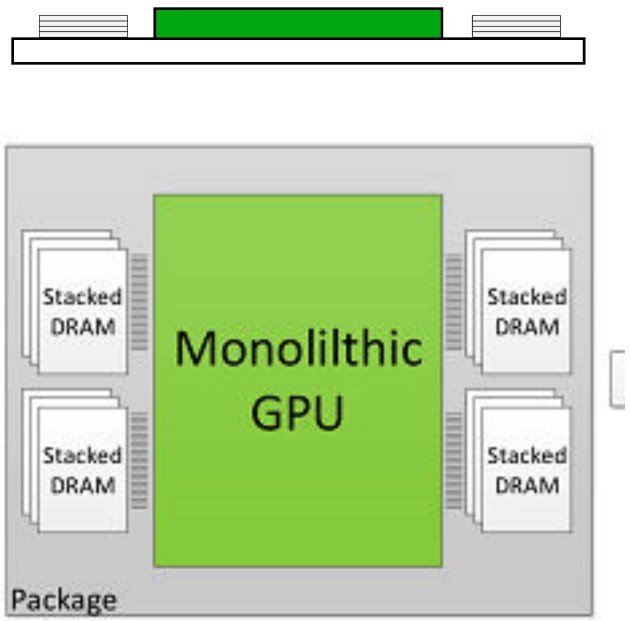
- Usually implies lower power density → easier to control
- DUT not flat
  - Larger thermal gaps
    - Poorer control
  - Convex curvature is typical
    - Larger thermal gap
    - less risk to damage bare die edges
  - Sometimes can take advantage of DUT flexibility to "flatten"
    - Significant performance improvement
    - Small risk of permanent "damage" to DUT
- Many device and package styles
  - Requires custom thermal unit designs



Geometric Constraints

Multichip Applications

- Single high-power device, multiple low power
- Contact surface on devices may not be coplanar
- High power device
  - Needs tight temperature control
- All other devices
  - Temperature control not as critical
  - Prevent exceeding maximum temperature
- Optimize TU to control high power device
- Control low power devices with compliant TIM



Source: NVIDIA MCM-GPU: Multi-Chip-Module GPUs for Continued Performance Scalability. June 26, 2017

https://research.nvidia.com/publication/2017-06_MCM-GPU%3A-Multi-Chip-Module-GPUs

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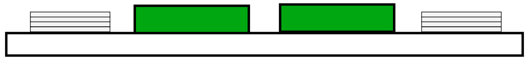
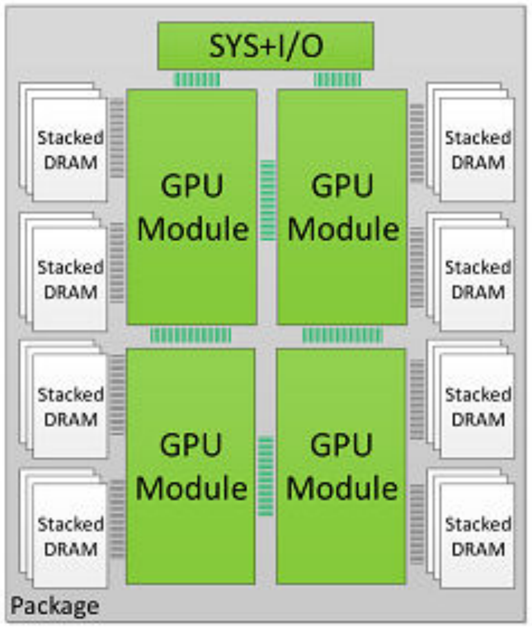
Geometric Constraints

Multichip Applications

- Multiple high-power devices, multiple low power
- Requires that contact surfaces for high power chips be coplanar
- If not:
  - Multiple thermal units or control zones
    - Technically feasible but costly
  - High performance TIM
- Increasing requests to test multichip bare die
  - No lid → lower thermal resistance path (a plus)
  - Non coplanar → higher thermal resistance path (a minus)





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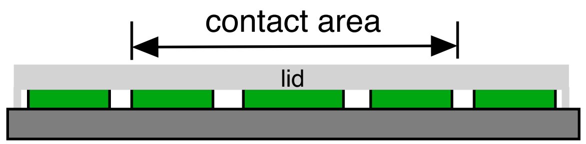
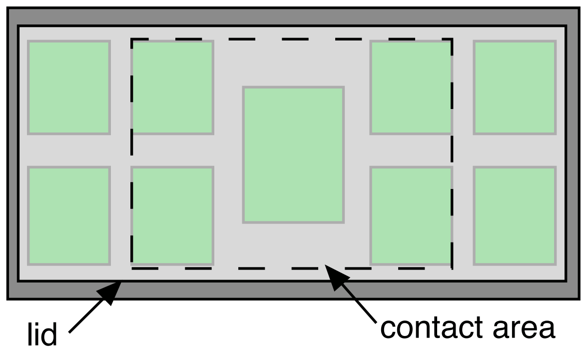
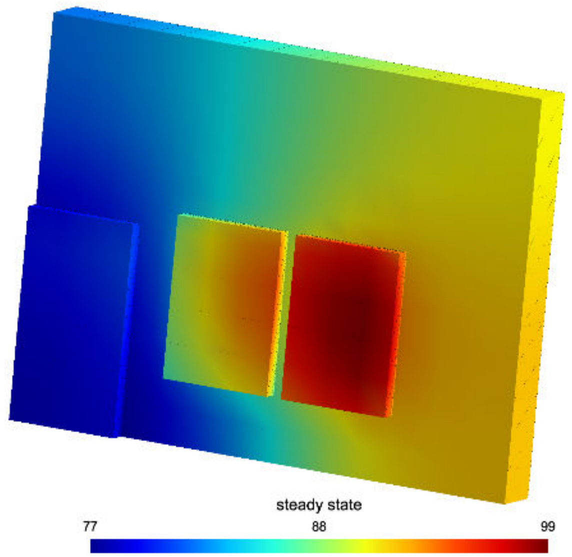
Geometric Constraints

Large Lidded Multichip Devices

- Contact surface is planar (Yay!)
- Still a testing challenge
- Assume
  - Power density is equal on all devices pictured
  - Thermal unit does not contact entire device
- Quarter symmetry analysis → large temperature gradient
- Large device requires large thermal unit
- Many different sizes on the market (no standard)







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Thermal Interface Materials (TIM)

❑ Requirements

- Low thermal resistance
- Highly compliant
- Reusable to many cycles
- Repeatable performance
- No residue or easily cleaned
- Easily refurbished

Thermal Interface to DUT

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TIM Examples

Helium

- Inert
- Substantially better than a dry interface
- High consumption cost
- Global shortage

Malleable Metal

- Usually indium
- Good conductivity
- Subject to oxidation (unless Au)
- Creep over time
- Limited life
- Indium melts at ~150℃

Liquid Metal Alloy

- Excellent conductivity and compliance
- Oxidation
- Needs containment mechanism
- Limited temperature range
- May attack other metals (gallium)

TIM Examples

Volatile Liquid

- Good conductivity and compliance
- Limited temperature range
- Possible application, removal, and cleaning issues

Elastomeric

- Bulk conductivity may be good
- Good compliance
- Compression pressure may be limited
- Subject to creep
- Typically needs additional treatment or material to easily release from DUT
  - → Additional thermal resistance

Graphite/Carbon-based

- Excellent bulk conductivity but may be directional
- Usually not very compliant
- Fairly robust
- Only as good as thermal contact resistance to DUT and thermal unit

Practical Good Performing TIM is a Critical Need!

- In high power applications, major thermal resistance is between DUT and thermal unit
- Currently TIM when used is limited to a particular type of application
- Market for TIM used in test is small → limited supplier competition

Thermal Interface to DUT

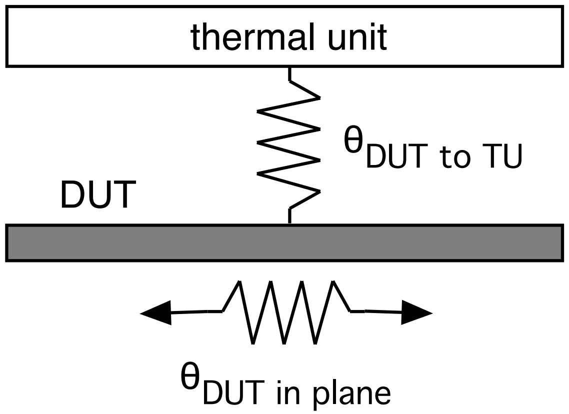
Manufacturing Test Environment

- Need procedure to test TIM performance in manufacturing test environment
- Typical method is steady state
  - Well proven direct method
  - Not an option if DUT thermal sensor is not available
  - Applying known amount of power not trivial
  - For lidded devices, lid to DUT thermal resistance variation may be greater than resolution needed for measuring the resistance of the TIM between the lid and heater

Thermal Interface to DUT

Temperature Gradient

- For high power devices one must minimize thermal resistance from the thermal unit to the DUT, $\theta_{DUT\ to\ TU}$
- When $\theta_{DUT\ to\ TU}$ approaches the DUT in plane resistance θ_{DUT} in plane or becomes less → DUT can develop significant temperature gradients
- Temperature gradients proportional to power dissipated
- Important to understand gradient
  - Location of temperature sensor important
  - One application controlled DUT at sensor location well
    - Gradient caused solder balls to melt
- See example on next slide
  - Center sensor poor choice for control



DUT Power/ Temperature Gradient

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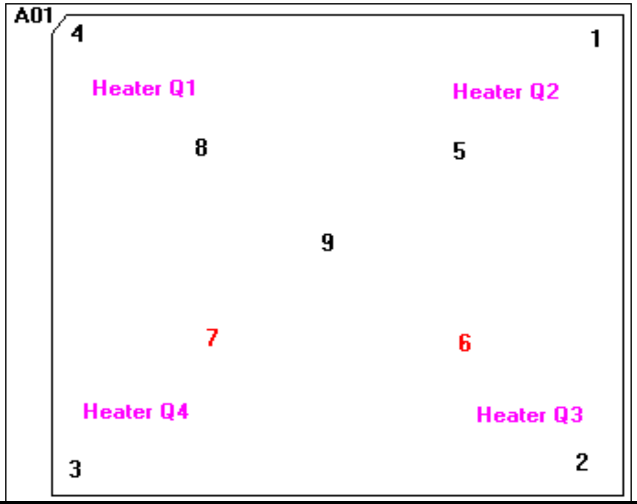
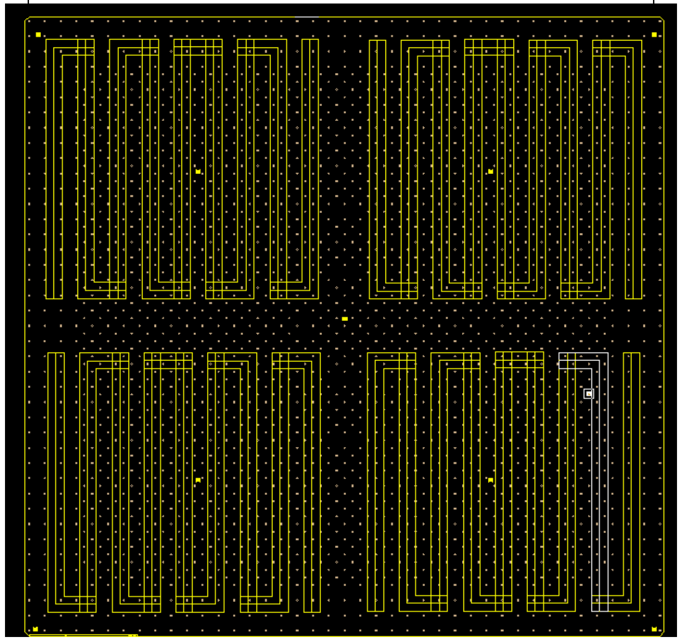
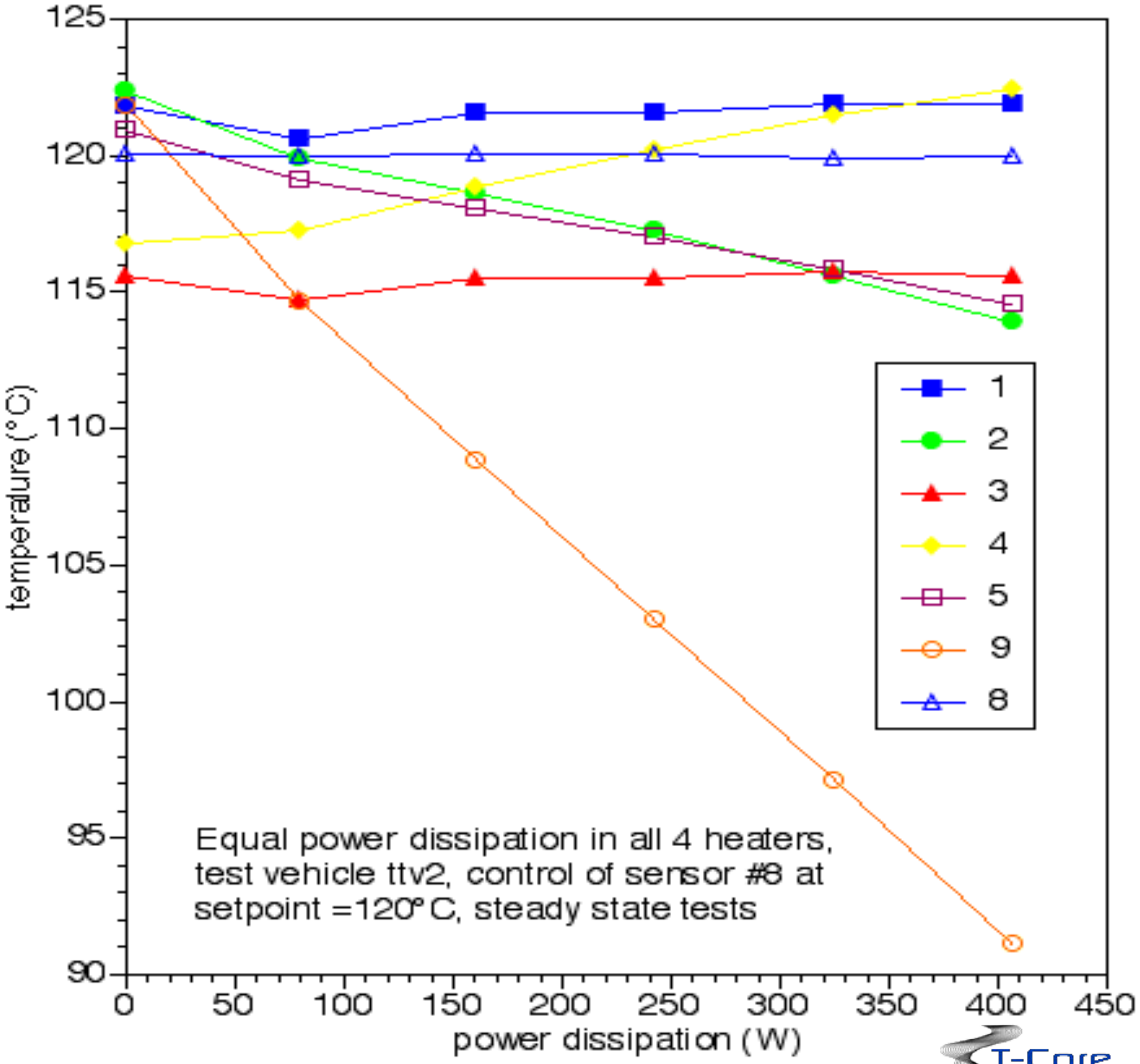
Center Sensor Poor Choice for Control







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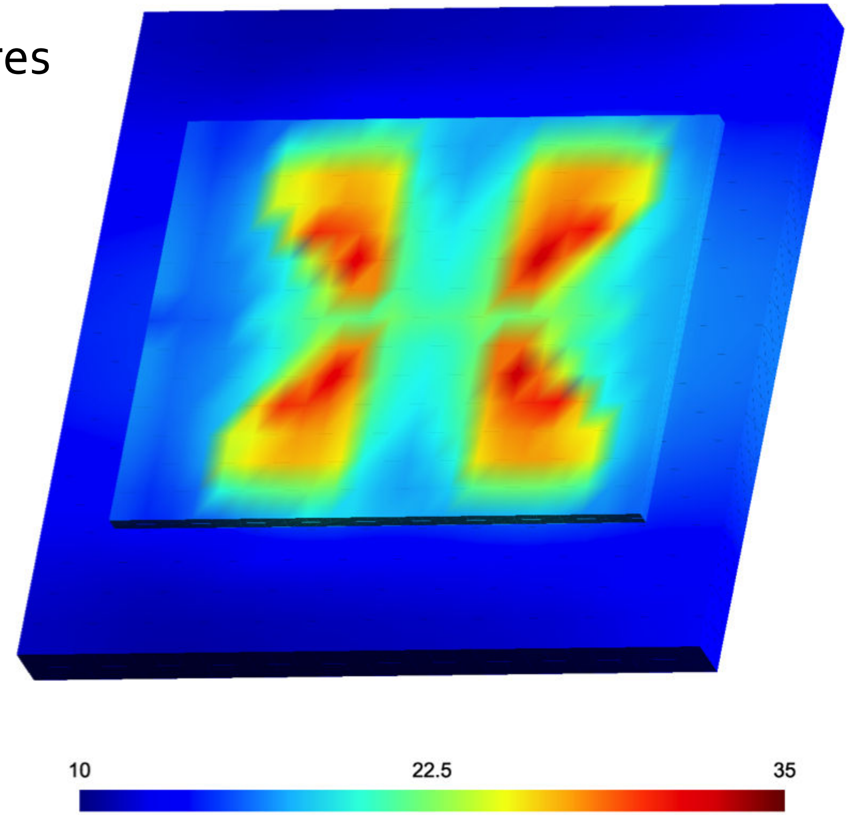
Power Dissipation on most Devices not Uniformly Distributed

- Device shown is 4 core processor
  - DUT power concentrated near cores
  - Hottest near cores



DUT Power/ Temperature Gradient

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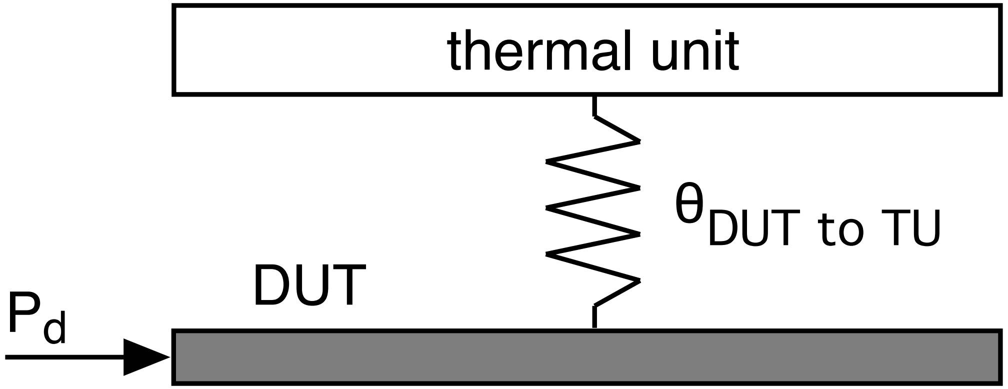
DUT Power vs. Time

❑ Referencing the simplified figure shown

- For constant DUT power Pd thermal unit required temperature is also constant
- Slow or small changes of Pd require simple changes of thermal unit temperature
- Large or fast changes of Pd require more difficult changes of thermal unit temperature
    - ➢ Lagging changes of required thermal unit temperature can result in significant DUT temperature rise → increased DUT power (higher leakage current) → thermal runaway

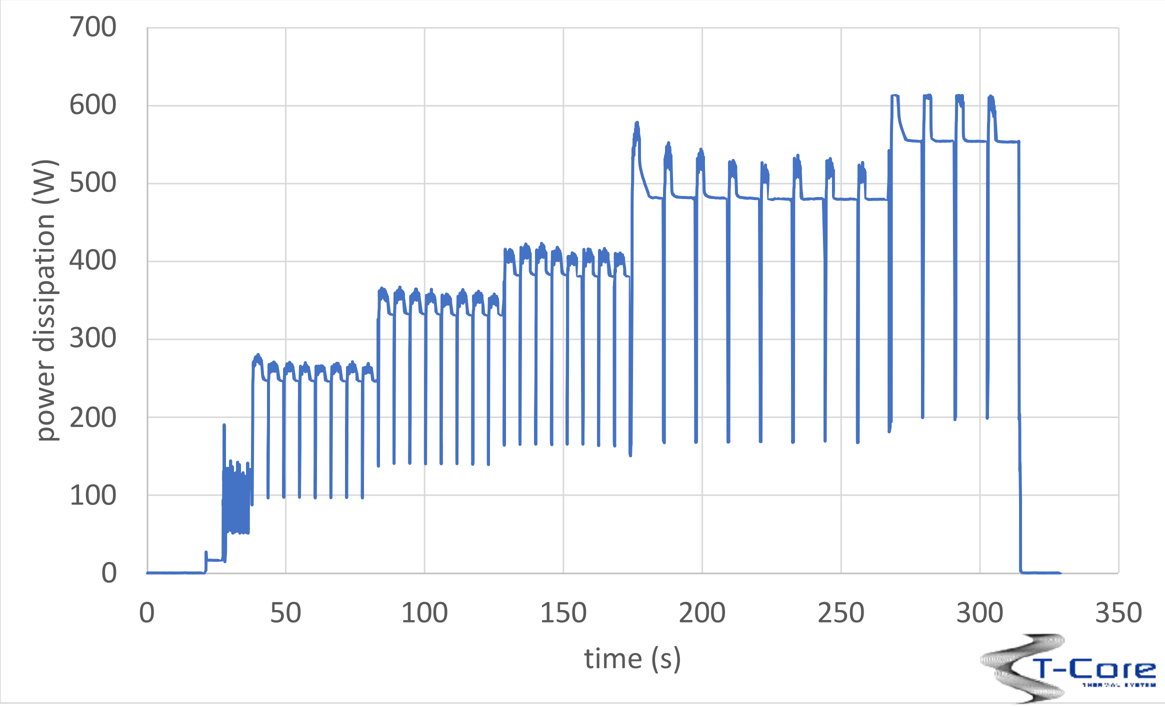


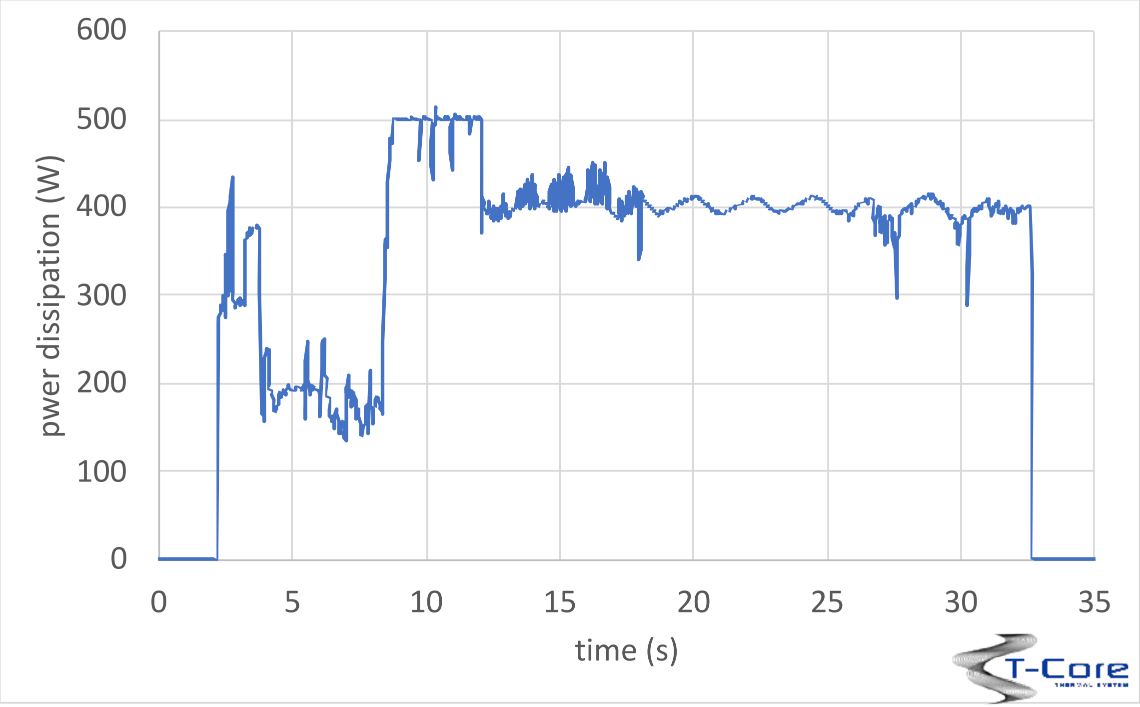
DUT Power/ Temperature Gradient

Importance of DUT Power Change Magnitude

❑ DUT power change magnitude more important than absolute power magnitude

- Burn-in power dissipation fairly constant → easy to control
- Functional test & SLT power varies → harder to control
- Figures below show two DUT power dissipation profiles





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Temperature Control Modes

- ❑ **HTF – control temperature of thermal unit**
  - Constant temperature of thermal unit
    - ➢ DUT temperature = (Pd * $\theta_{DUT\ to\ TU}$) + temperature of thermal unit
    - ➢ May be acceptable if $\theta_{DUT\ to\ TU}$ is small : very good TIM!
  - Change temperature of thermal unit based on anticipated power profile (open loop)
    - ➢ Can't use for non-constant power profiles (example: test with branching)
- ❑ **HTF-PF - control temperature of thermal unit as a function of measured DUT power**
  - Called power following mode
  - Fast dynamic control to get DUT temperature to desired set point temperature
  - Sensitive to varying $\theta_{DUT\ to\ TU}$
- ❑ **Dynamic-PF - control temperature of thermal unit as a function of measured DUT power changes**
  - Dynamic power following
  - Used with in conjunction with other control modes

Temperature Control Strategies

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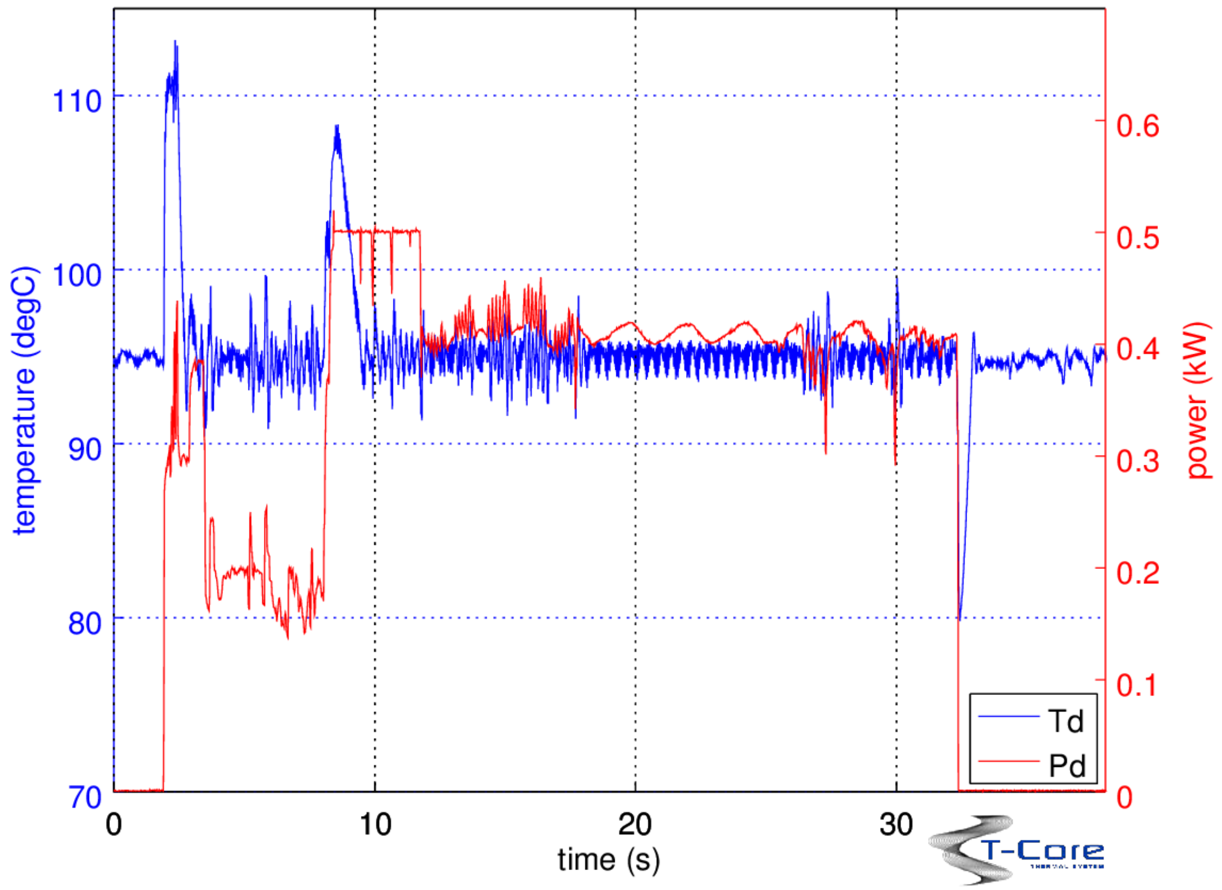
Direct Temperature Feedback (DTF)

- **Control with DUT temperature sensor(s) present**
  - Typically diode or RTD on chip
  - Theoretically more accurate and more stable
  - Sensor output varies with manufacturing tolerances
    - In-situ calibration with heater eliminates error
    - Use saturation current cancellation technique
  - Sensor location may not be optimal
    - Non uniform power dissipation
    - Large temperature gradients across chip
  - Digital sensors beginning to appear (must be provided at fast rate)
  - Common feedback from tester (not useable)
    - Access available between subtests only
    - No feedback without DUT power
  - Strategies exist to use multiple sensor combinations
    - Multichip modules may change sensors when powering different chips

Temperature Control Strategies

Direct Temperature Feedback (DTF)

- Liquid cooled application, DUT temperature Td vs. DUT power Pd



Temperature Control Strategies

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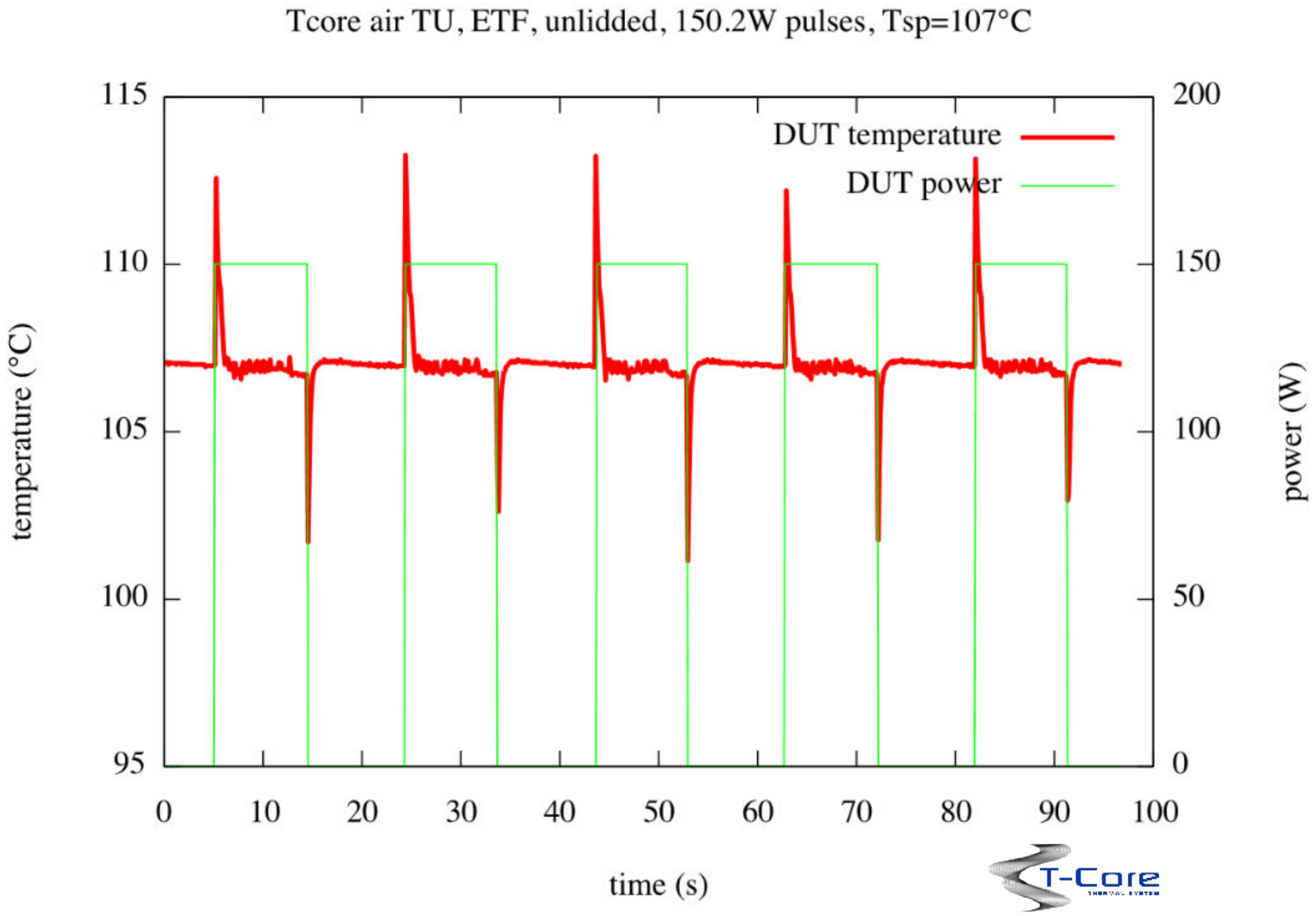
Extrapolated Temperature Feedback (ETF)

- Some devices do not allow device or power feedback
  - Power feedback may only be partial
- Calculate DUT Temperature based on thermal head dynamics only
  - Multiple sensors in thermal unit
- Not as robust as PF
- Requires low $\theta_{DUT\ to\ TU}$ → (excellent TIM!)
  - Cannot extrapolate too far
- Contains dynamic term

Temperature Control Strategies

Extrapolated Temperature Feedback (ETF)

- Air cooled with thermal test vehicle
- Controlled with ETF
- Monitored with thermal sensor



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Much Easier Temperature Control at Hot Setpoints vs Cold

- Fortunately, power dissipation is typically much lower at cold than hot
- Larger difference between setpoint and cold source temperatures allows high heat transfer rates
- -40℃ often considered a practical limit
- As cold source temperatures decrease, complexity and costs go up exponentially
  - Multi-stage compressor
  - LN_2
  - Condensation control
- Secondary paths to ambient
  - Helps control at hot
  - Adds additional burden at cold

Other comments

- Absolute power not the best measure of temperature control difficulty
  - Dominant factors:
    - DUT power dissipation density
    - Magnitude of DUT power dissipation changes during test
    - Test temperature setpoint
    - DUT package resistance
    - Device geometry
- Application requirement vary greatly
- Initial requirements for application often erroneous
  - Sometimes too stringent and sometimes too lax
- New temperature control candidates (such mobile or automotive applications)
  - Newest devices dissipate significant amount of power
  - New territory for these test engineers

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SHUKRIYA
Go raibh maith agaibh
Cảm ơn
DANKE
Hsieh hsieh
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