Improving Battery Thermal Management Design using Six Sigma Process

by

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Outline

- Project Objectives & Approach
- Background Robust Design Techniques
- Prismatic NiMH Battery Thermal Analysis
  - Steady State Variation
  - Transient
- Summary and Future Plans

Objective and Approach

- The overall objective is apply variation analysis and Six Sigma design process to HEV battery thermal analysis
  - Better thermal performance
  - Longer battery life

- Approach:
  - Evaluate thermal management effectiveness of cylindrical and prismatic batteries with air or liquid cooling for HEV or Fuel Cell vehicles using FreedomCAR 40 kW power profile
  - Perform variation analysis and six sigma

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Geometry and Load Cases

Two Battery Geometries:

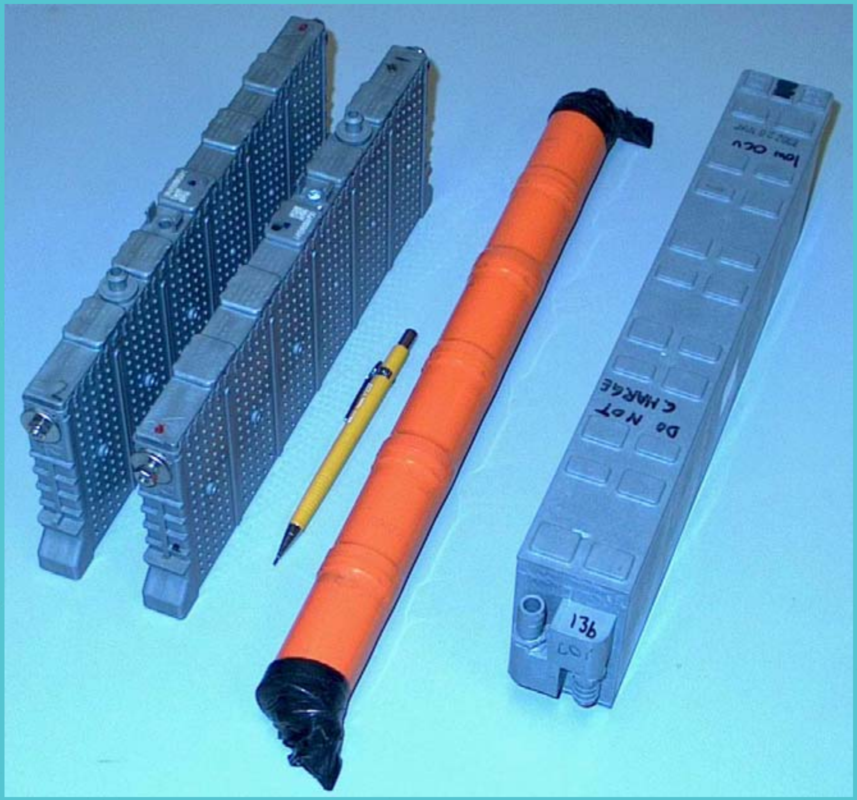
1. Prismatic
2. Cylindrical

Two Coolants

1. Air Cooled
2. Liquid Cooled

Two Ambient Load Cases:

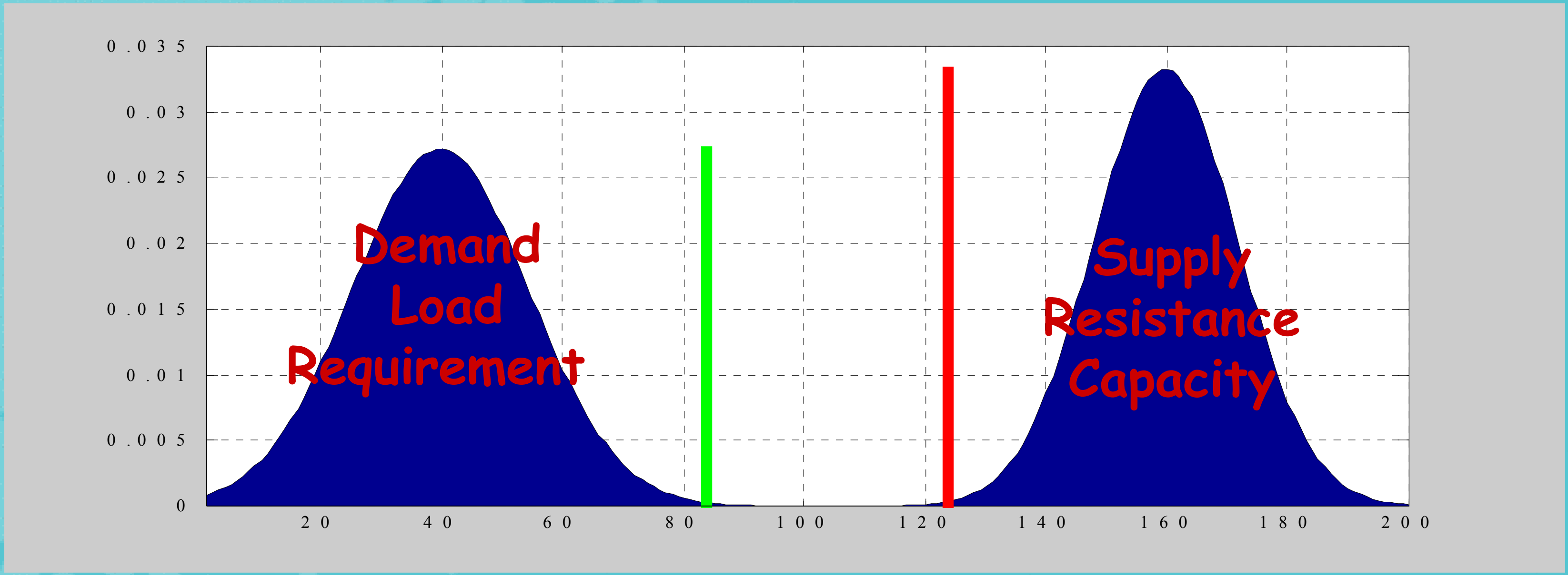
1. Buffalo, NY (-20°C amb)
2. Palm Springs (60°C amb)



Traditional Deterministic Design Approach

Accounts for uncertainties through the use of empirical Safety factors:

- Are derived based on past experience
- Do not guarantee safety or satisfactory performance
- Do not provide sufficient information to achieve optimal use of available resources

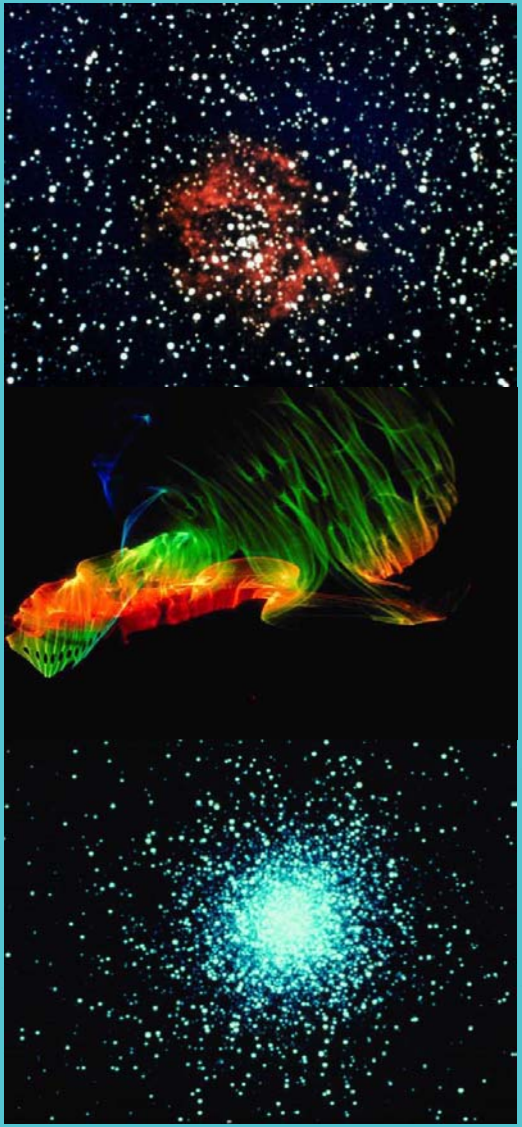


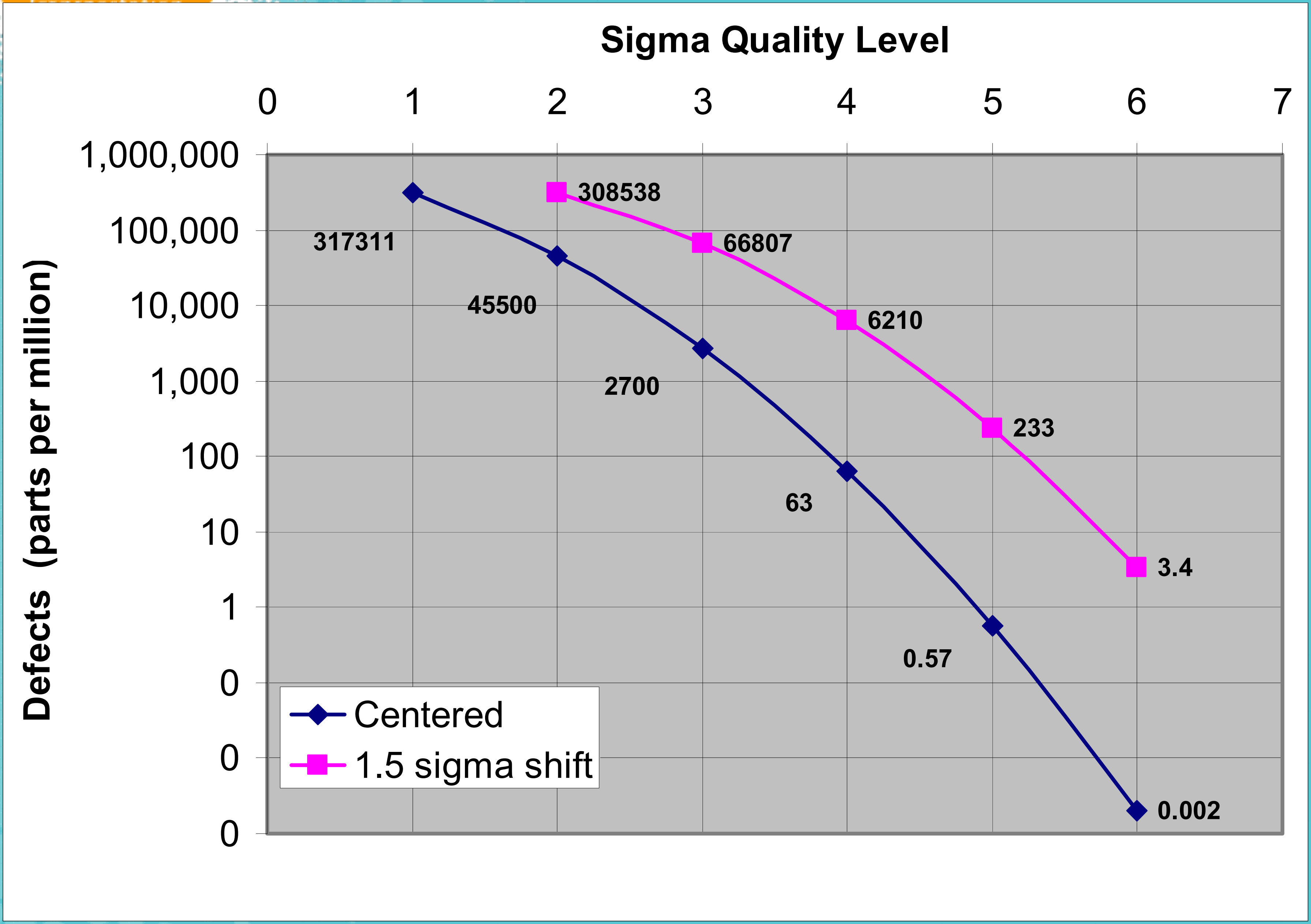
Six-sigma Design

– **Identifying & qualifying causes of variation**

– **Centering performance on specification target**

– **Achieving Sigma level robustness on the key product performance characteristics with respect to the quantified variation**




Sigma Quality Level
0
1
2
3
4
5
6
7
Defects (parts per million)
1,000,000
100,000
10,000
1,000
100
10
1
0
0
0
317311
45500
2700
63
0.57
0.002
308538
66807
6210
233
3.4
Centered
1.5 sigma shift

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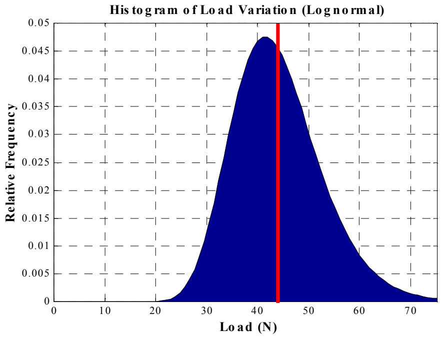
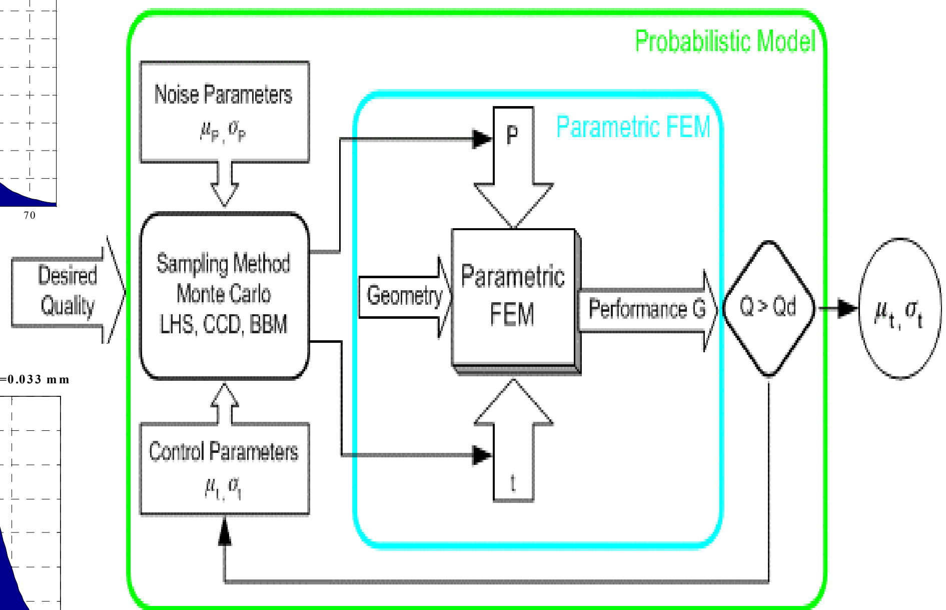
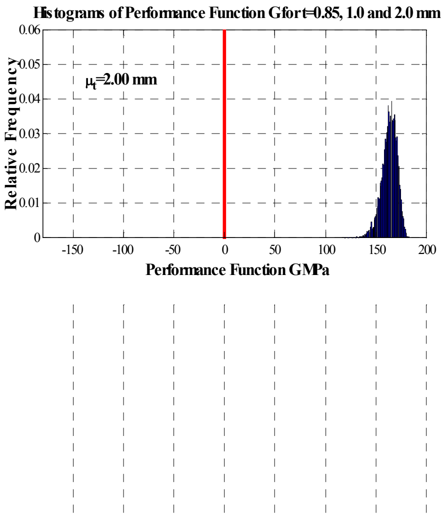
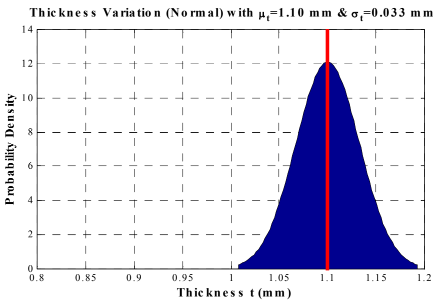
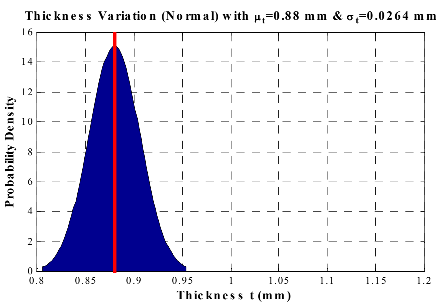
Robust Optimization

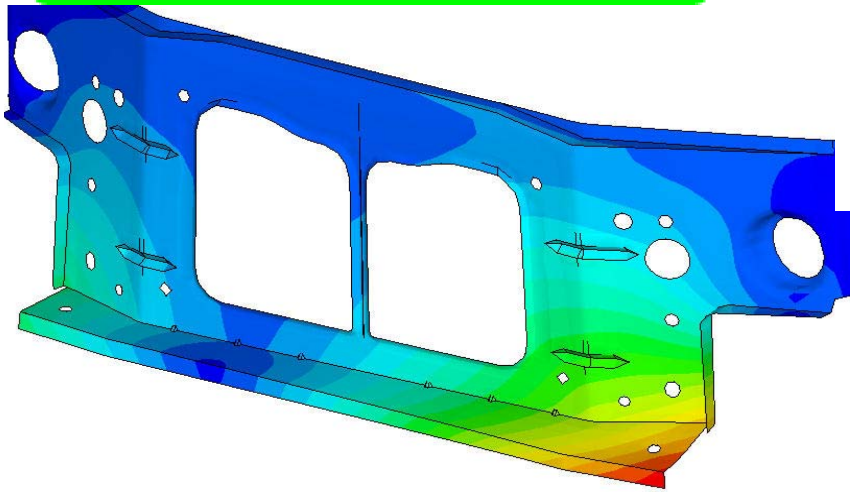


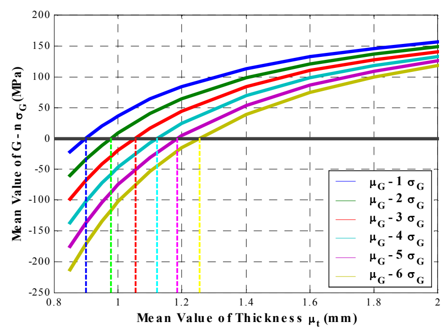




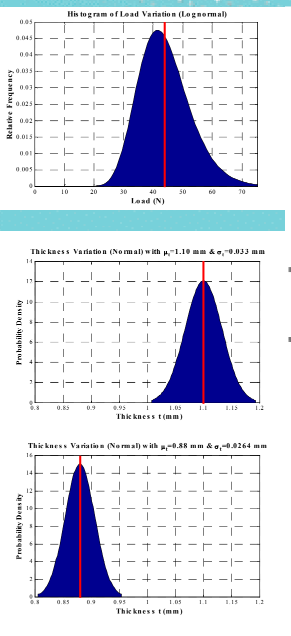


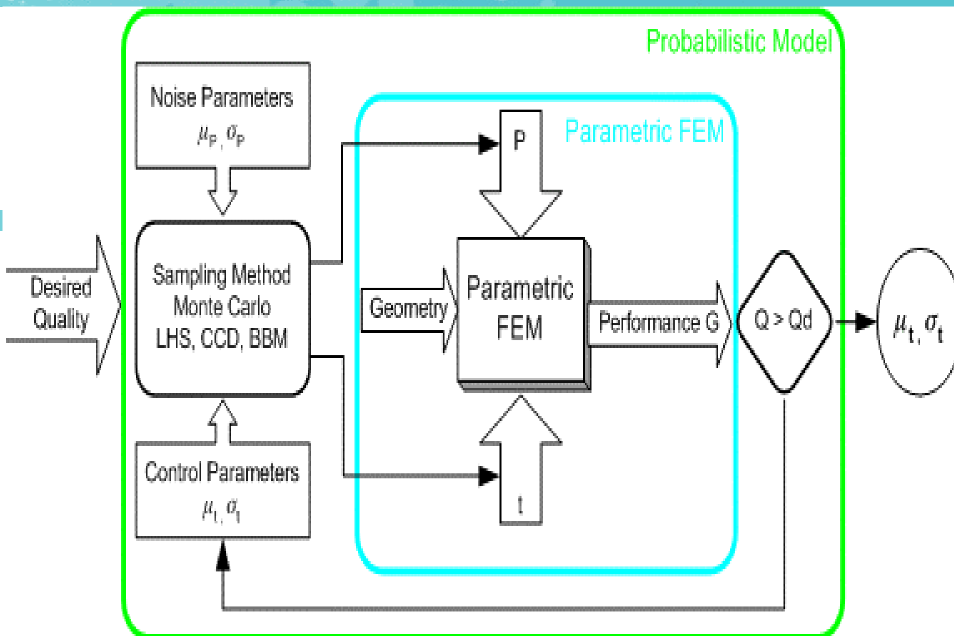


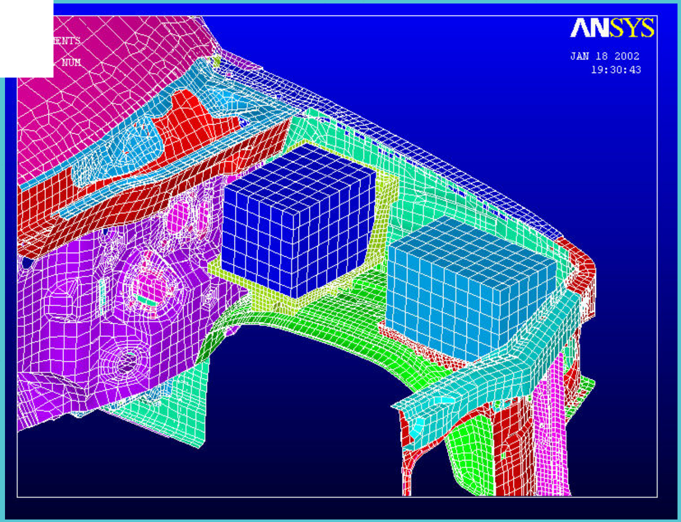




Robust Optimization
reusable workflow template







Ford Motor Company

SAE – IEBEC 2001

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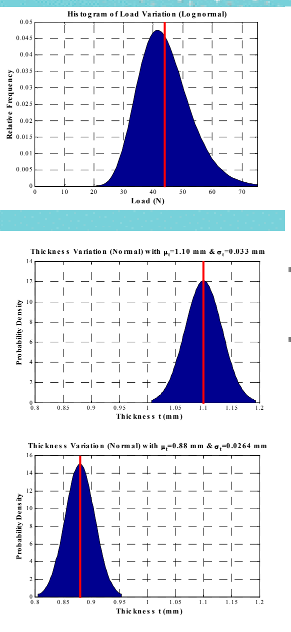
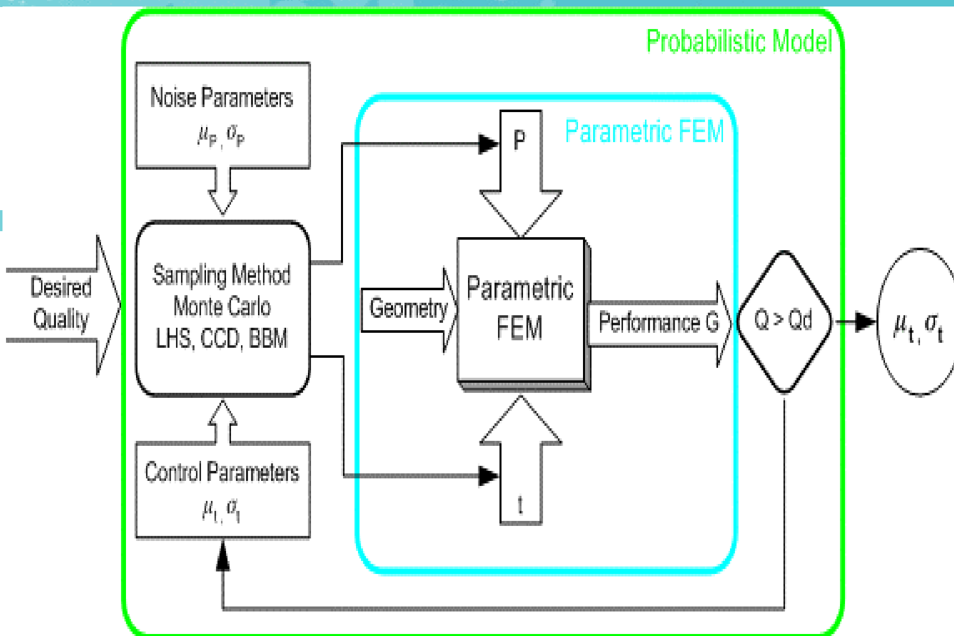
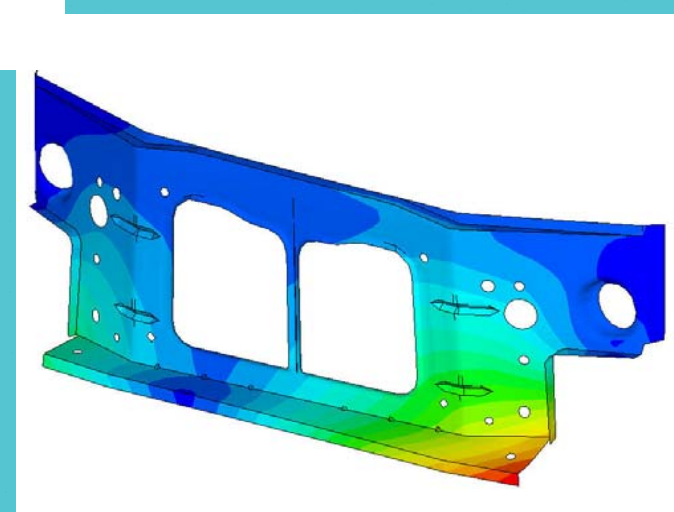
Robust Optimization reusable workflow template







Ford Motor Company

SAE – IEBEC 2002

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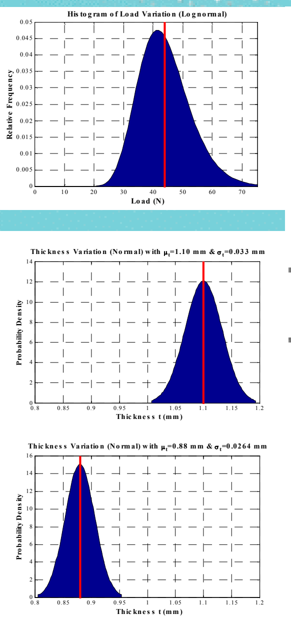
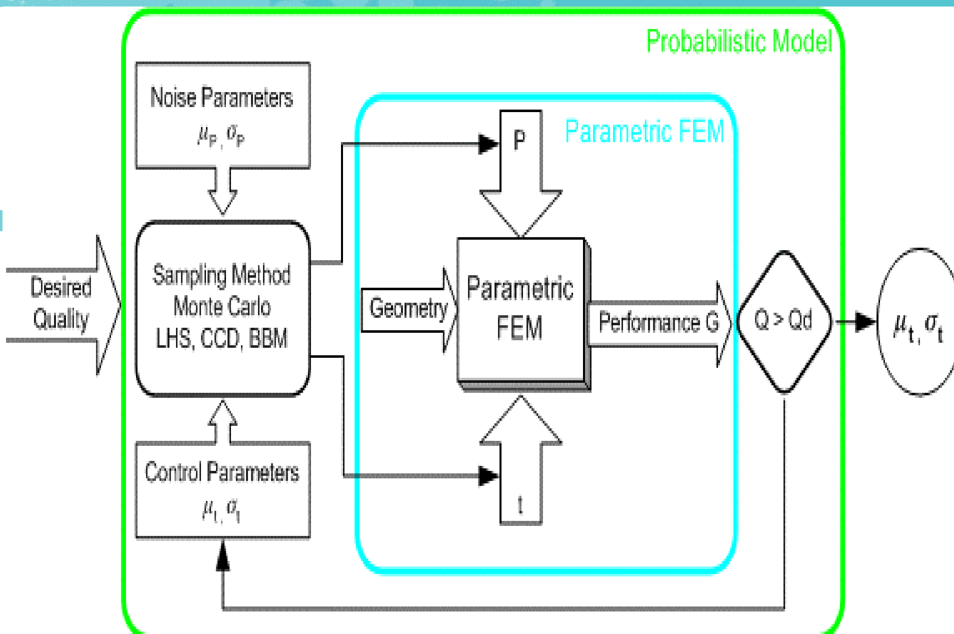
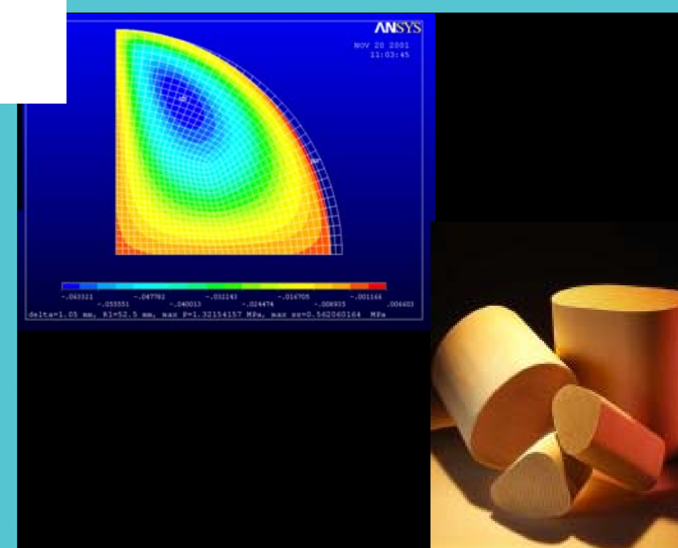


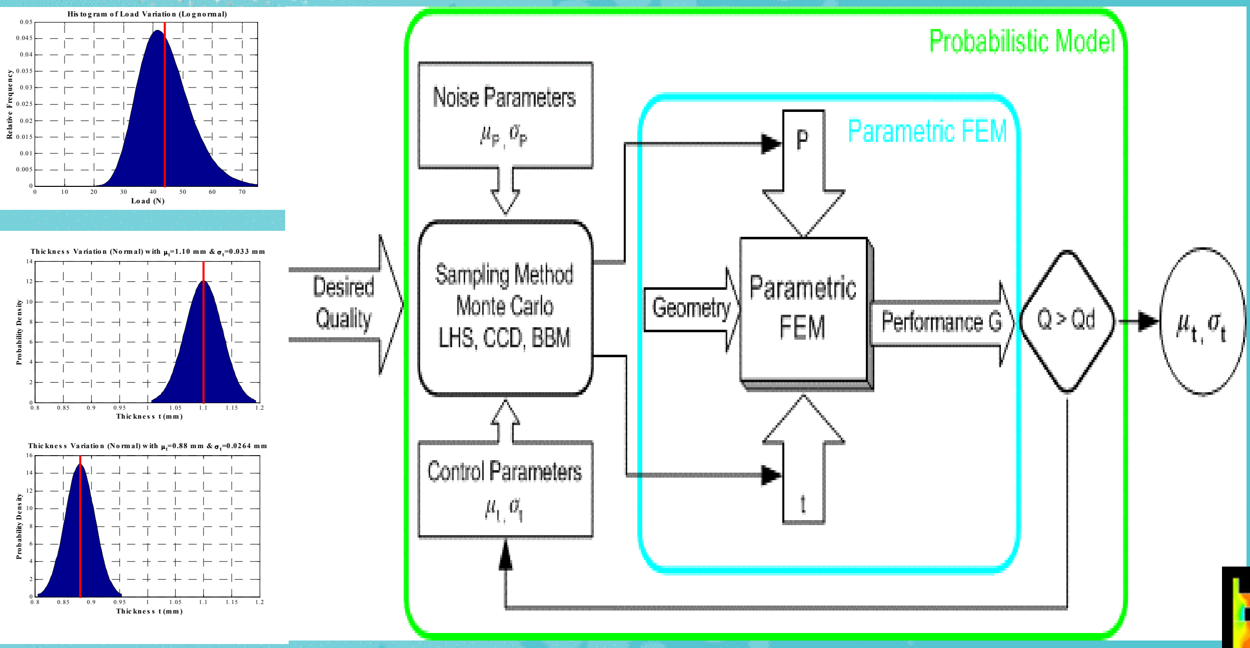


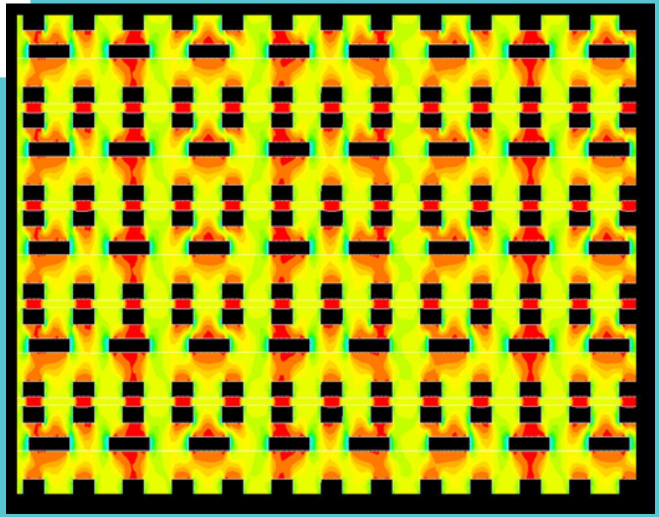


Daimler Chrysler

SAE Powertrain Conference

Robust Optimization reusable workflow template

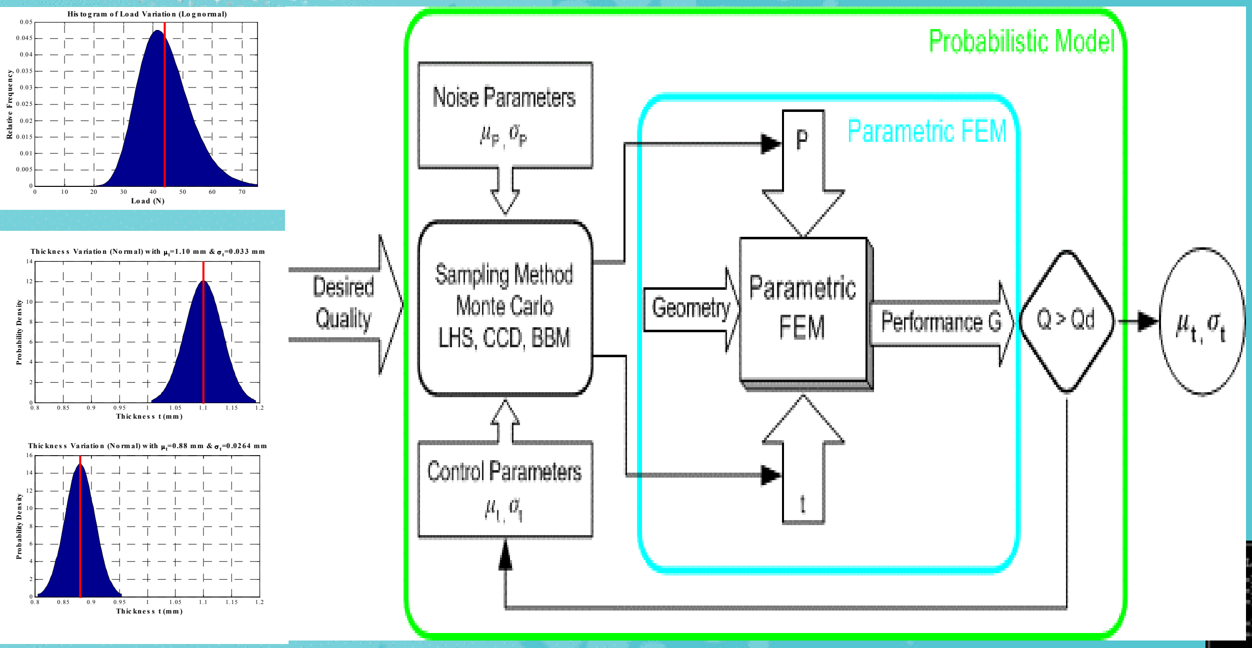


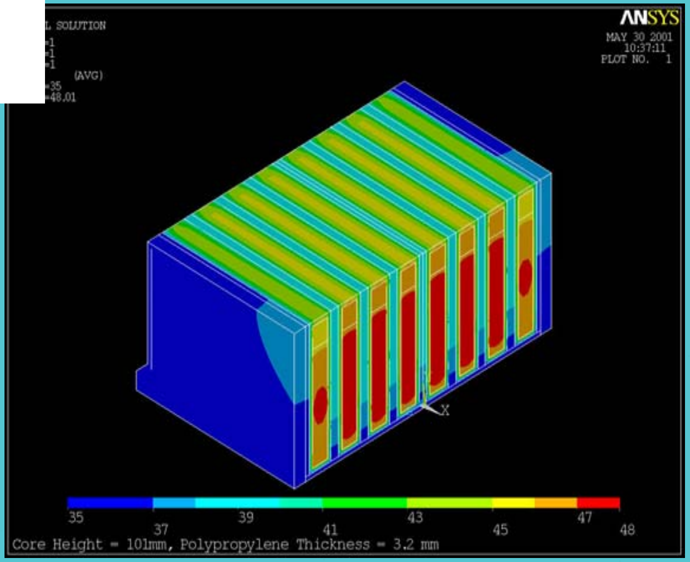


Plug Power

ASME / RIT Fuel Cell Conference

Robust Optimization
reusable workflow template

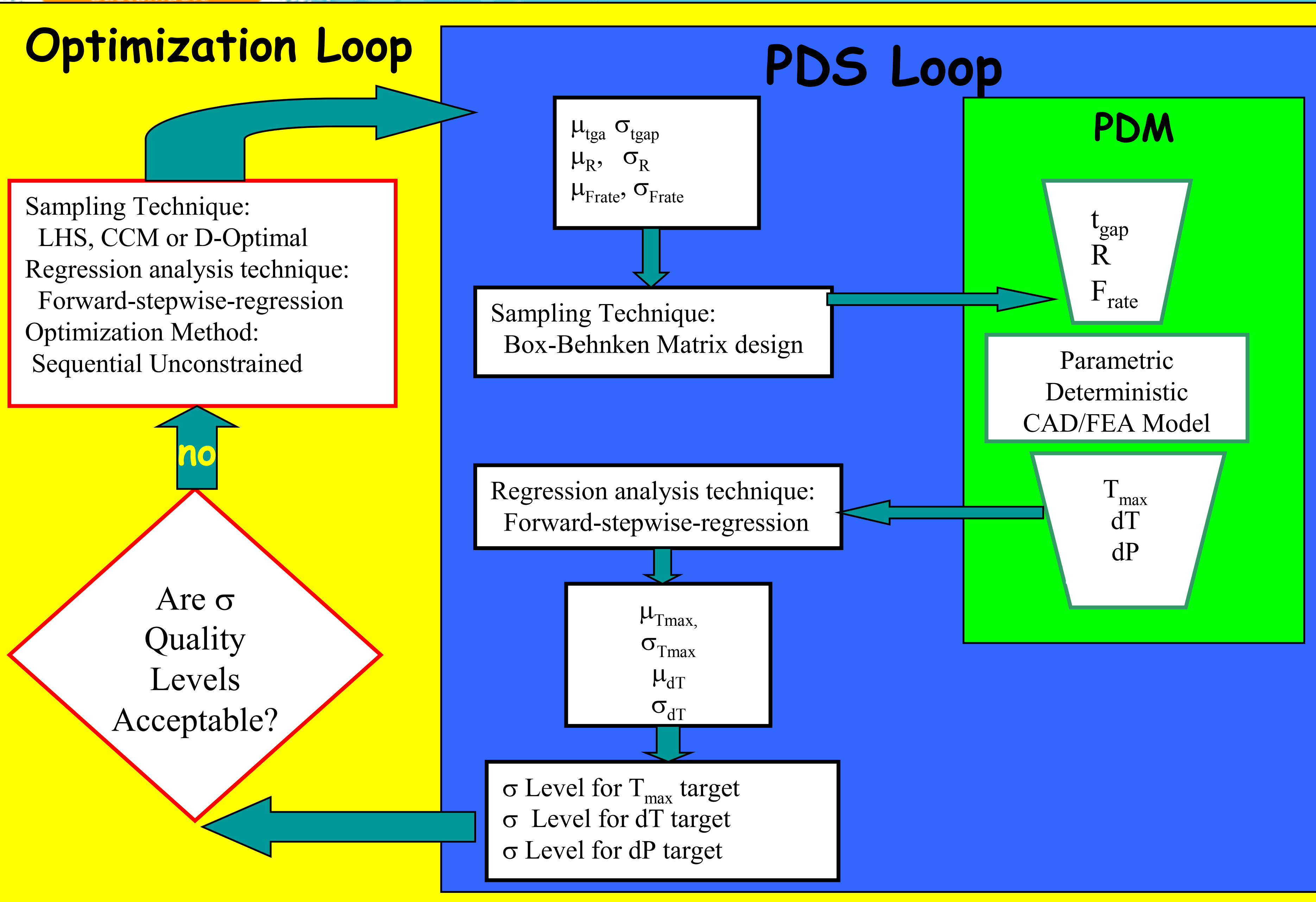




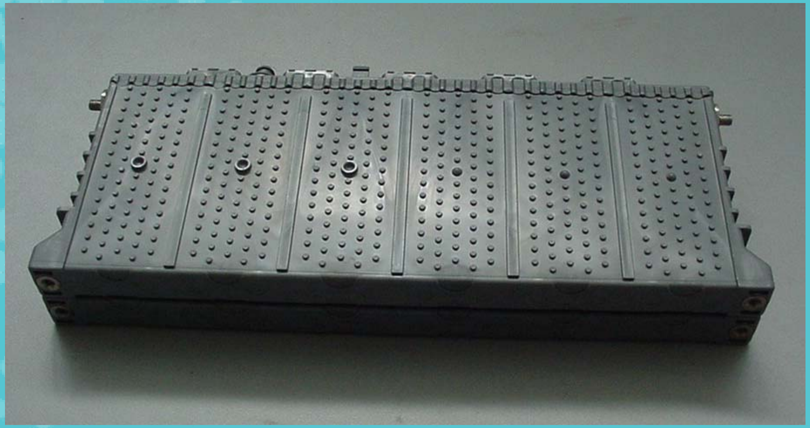
USABC / Ford

American Society of Quality

Reusable Process Template

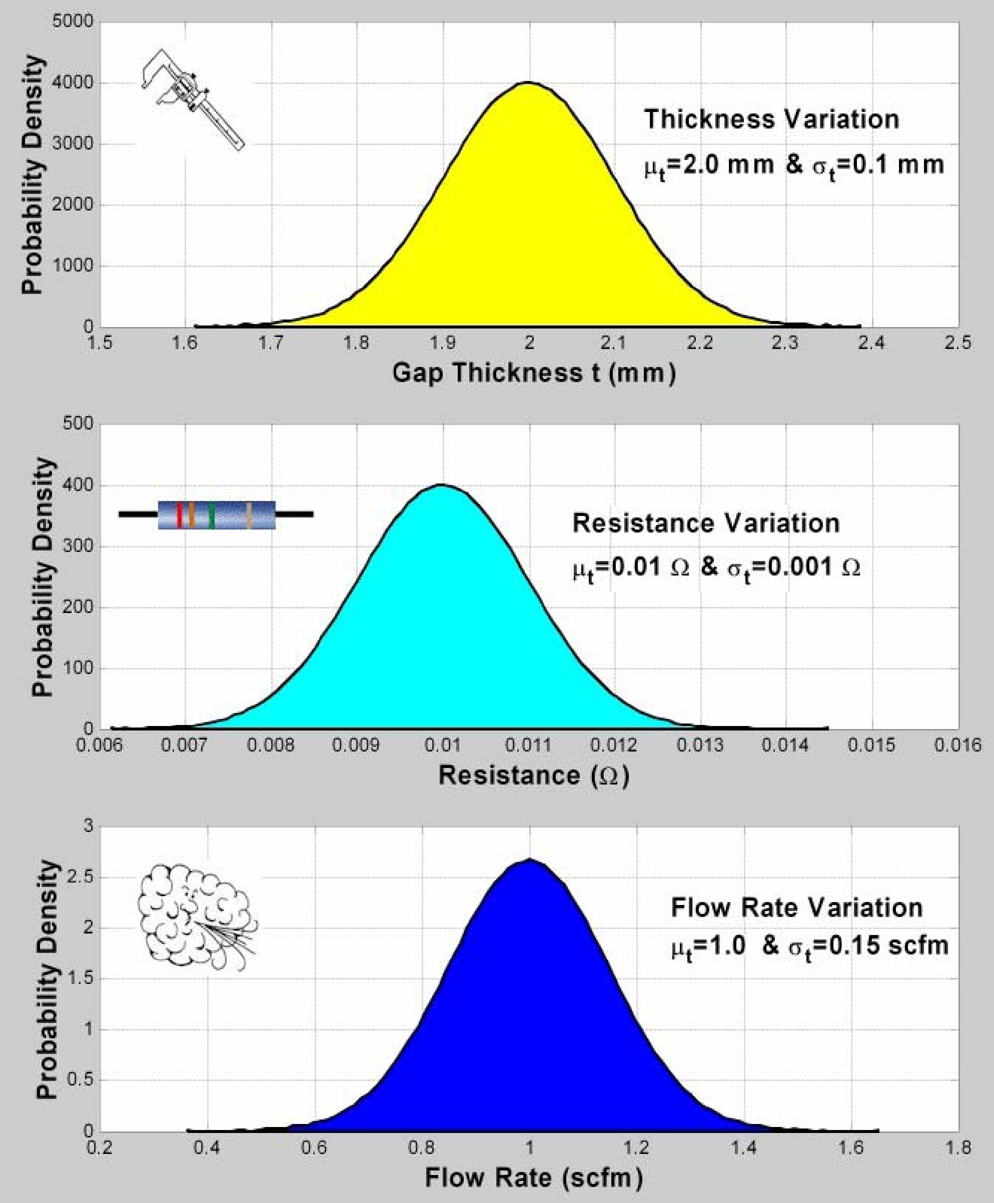


Steady State Thermal Analysis with Input Parameter Variations



Inputs with Variation

- Gap Thickness
- Cell Resistance
- Flow Rate
- Six input parameters:
  1. μ_{tgap}
  2. σ_{tgap}
  3. μ_R
  4. σ_R
  5. μ_{Frate}
  6. σ_{Frate}



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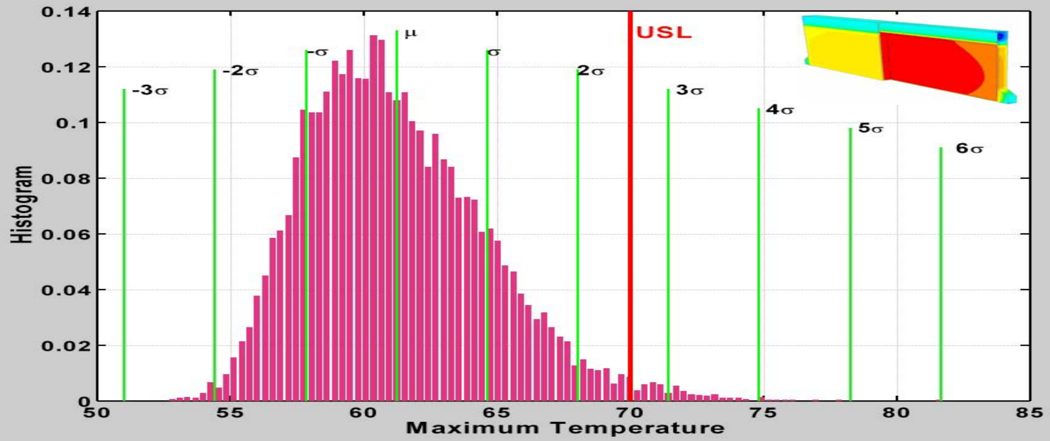
Model Outputs

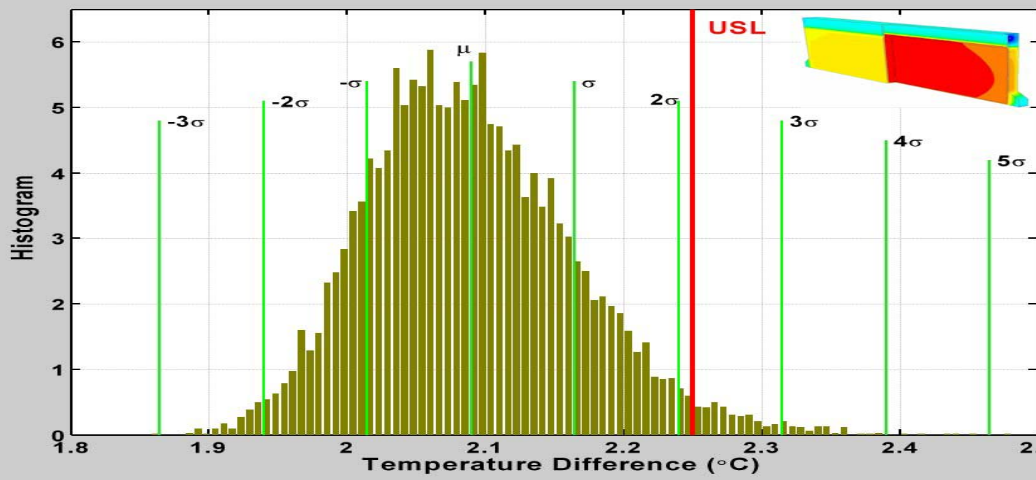
- max temperature
- differential temperature
- pressure drop

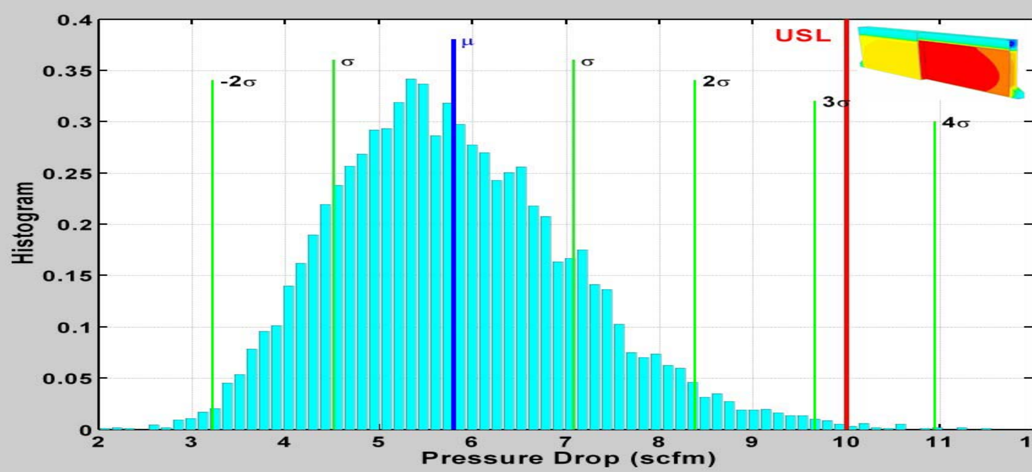
Six output parameters:

1. μ_{Tmax}
2. μ_{dT}
3. μ_{dP}
4. σ_{Tmax}
5. σ_{dT}
6. σ_{dP}

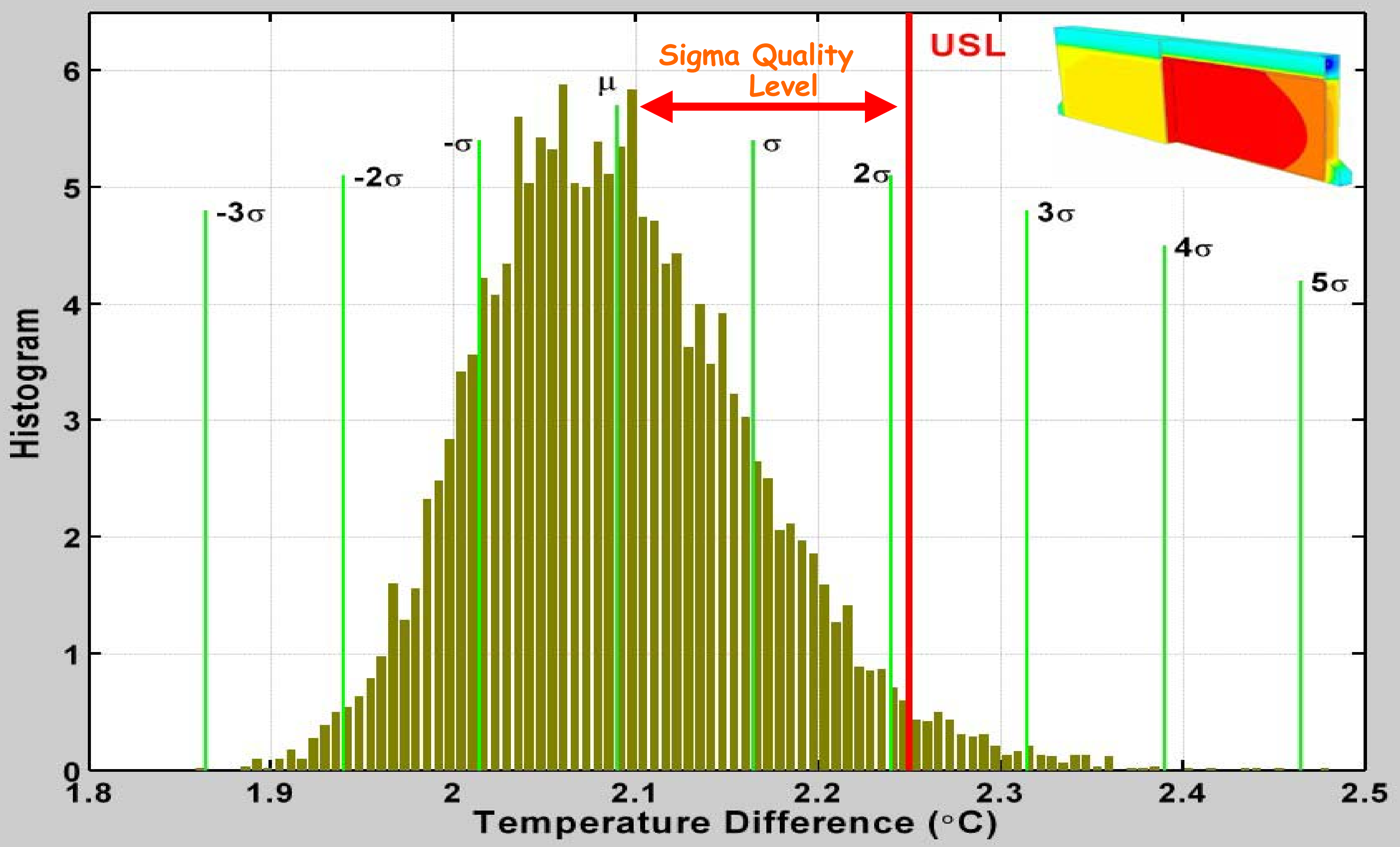
Three Upper Specification Limits (USL)



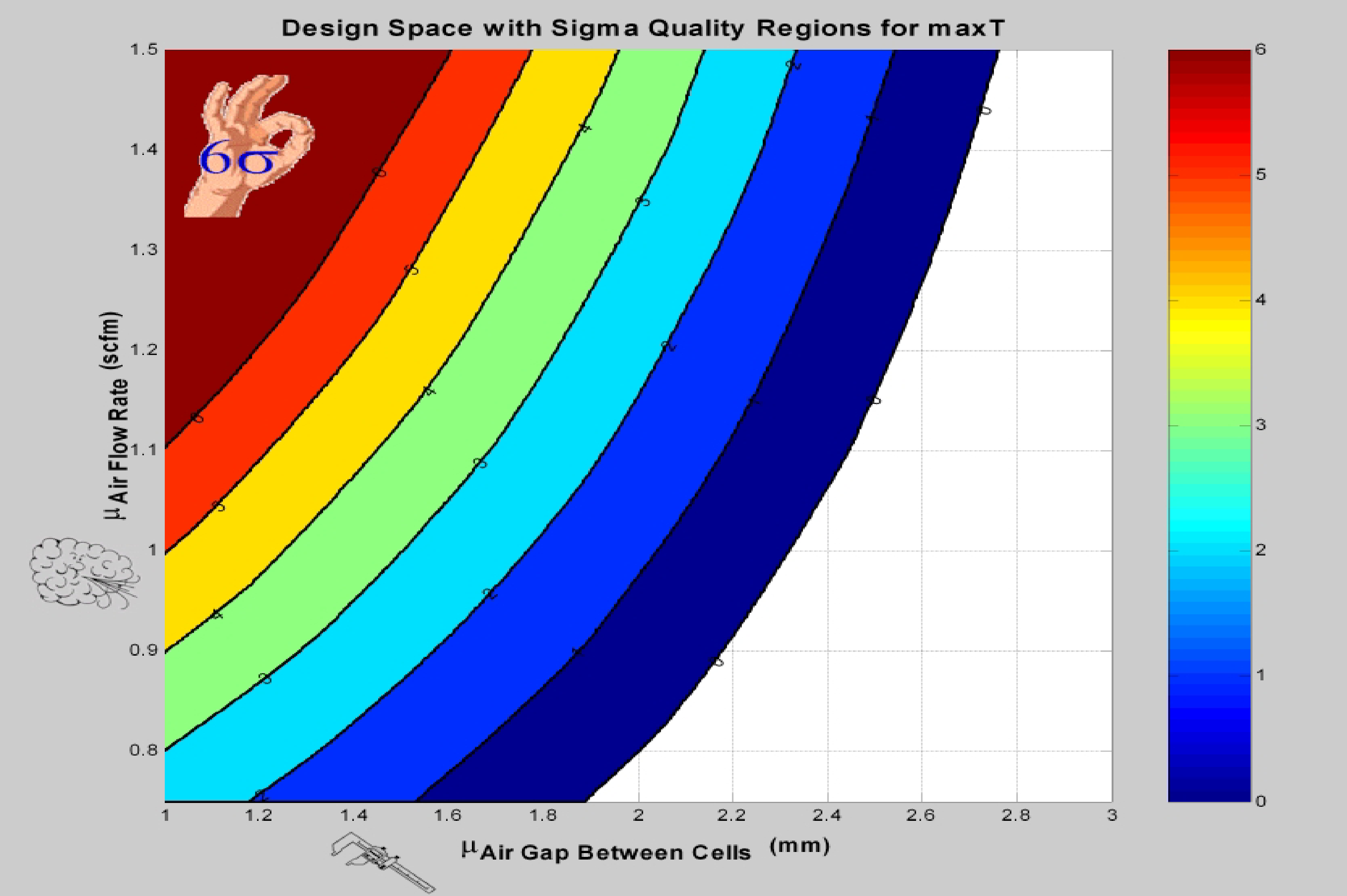




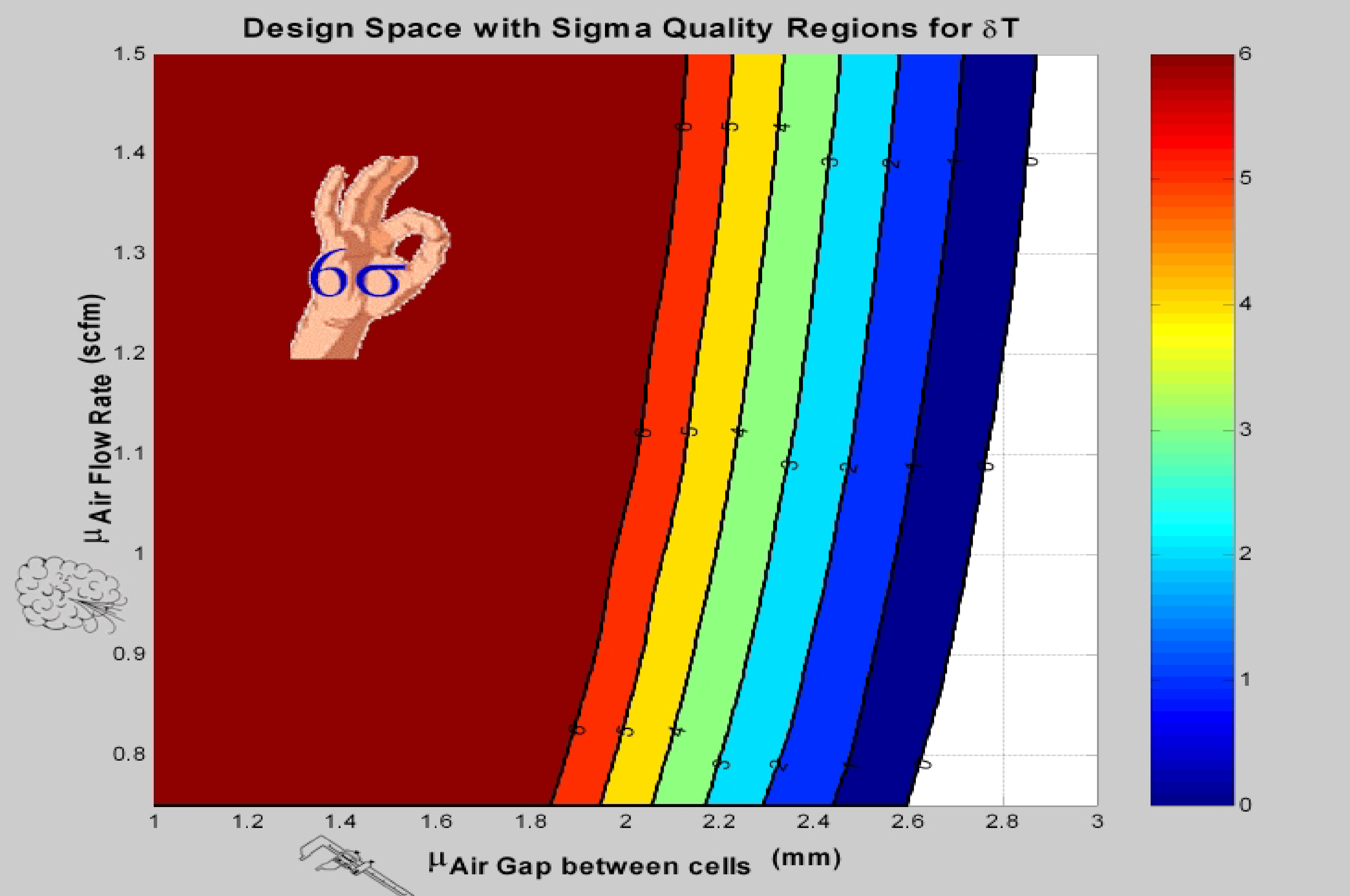
Temperature Differential and Sigma Quality Levels



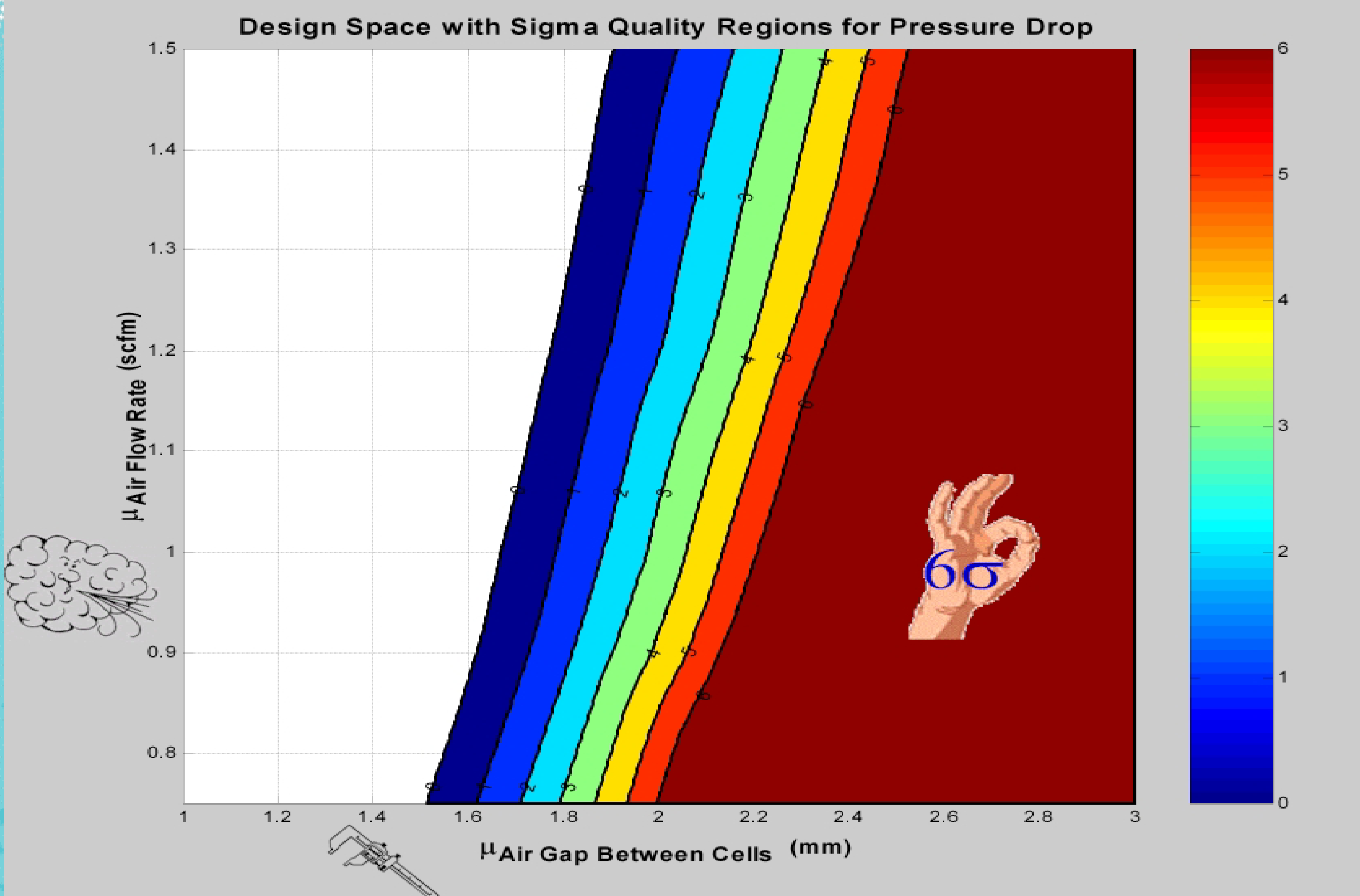
Design Space with σ Quality Regions T_{max}



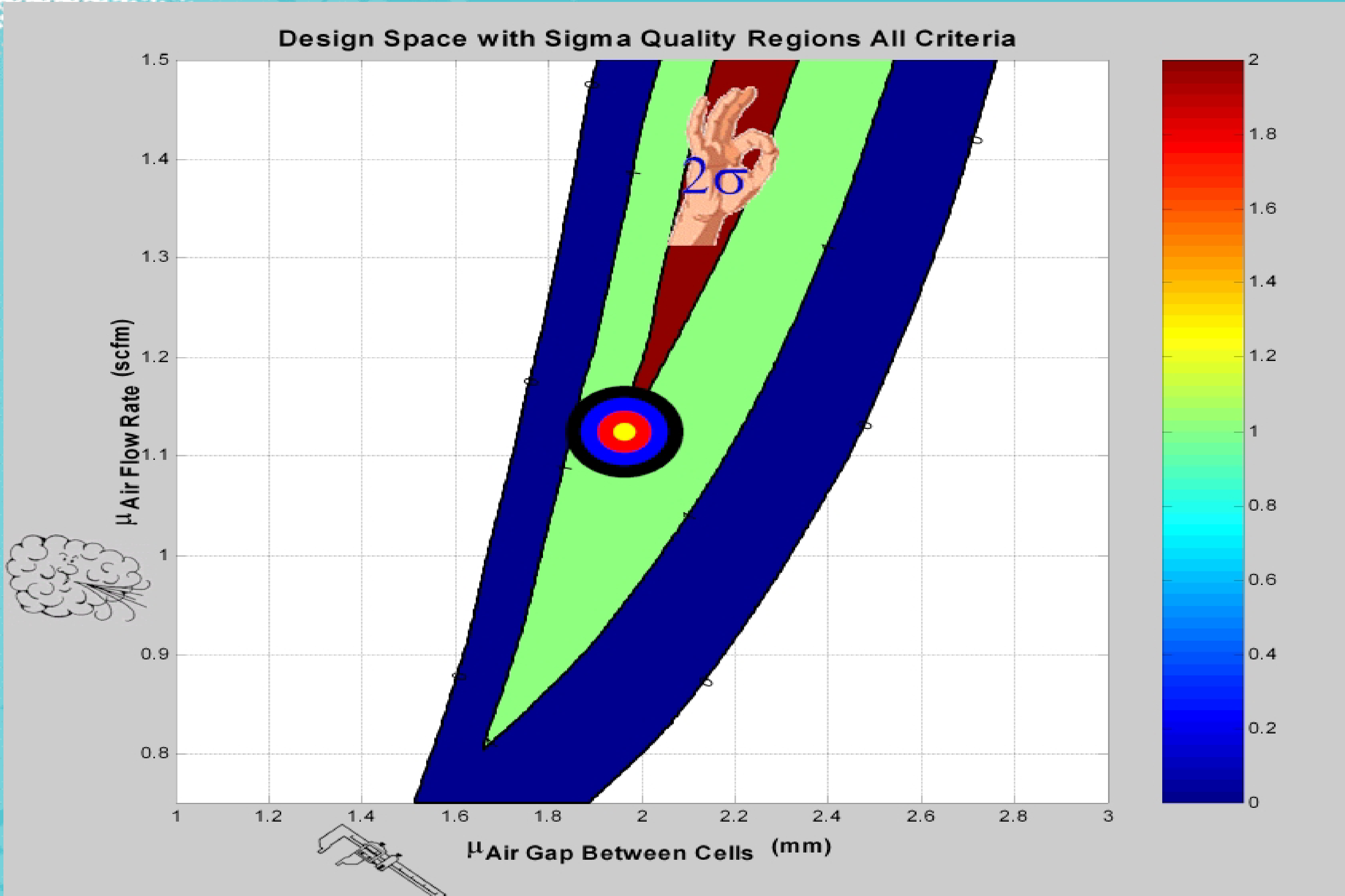
Design Space with σ-Quality Regions dT



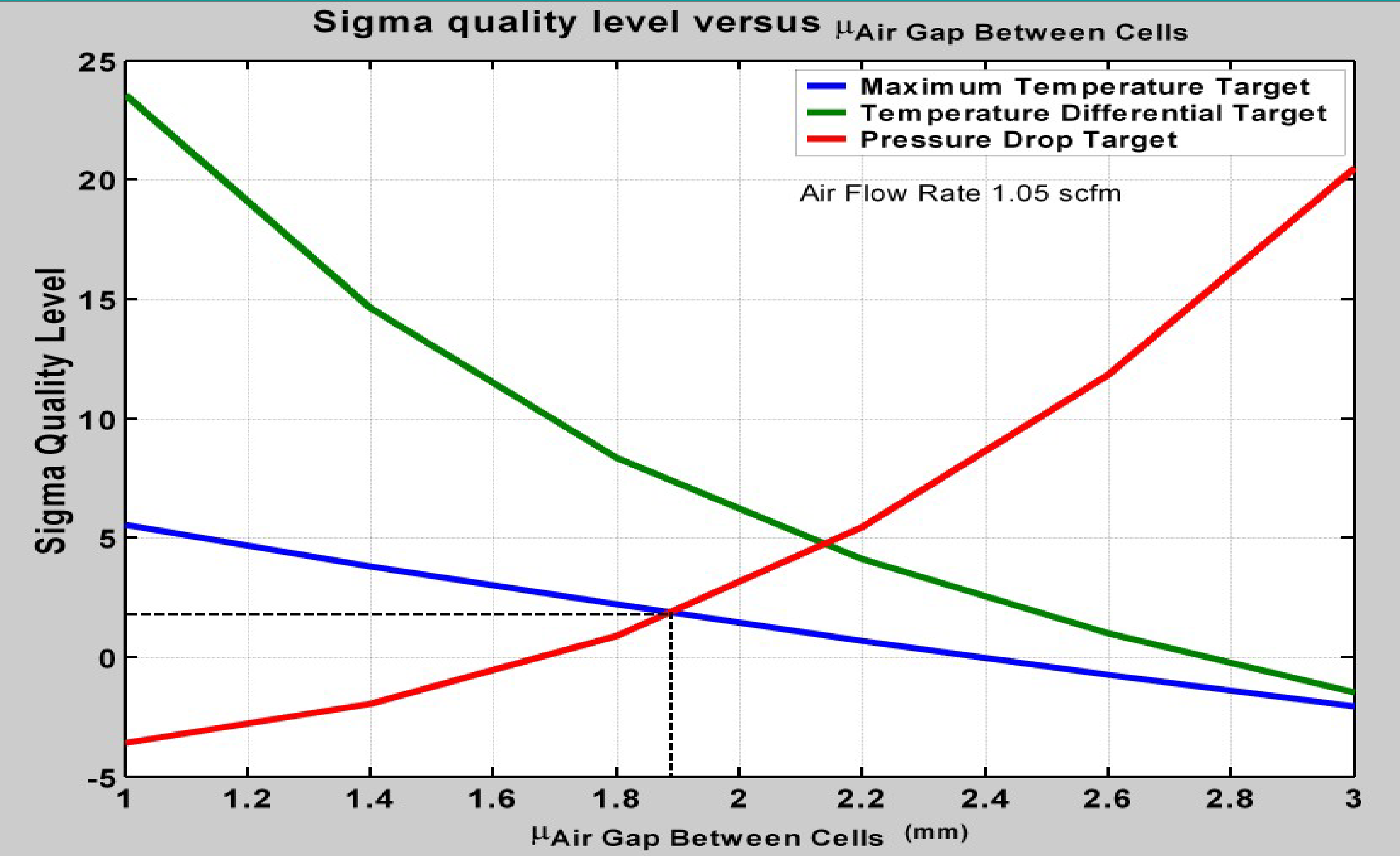
Design Space with σ-Quality Regions dP



Design Space with σ Quality Regions All Parameters

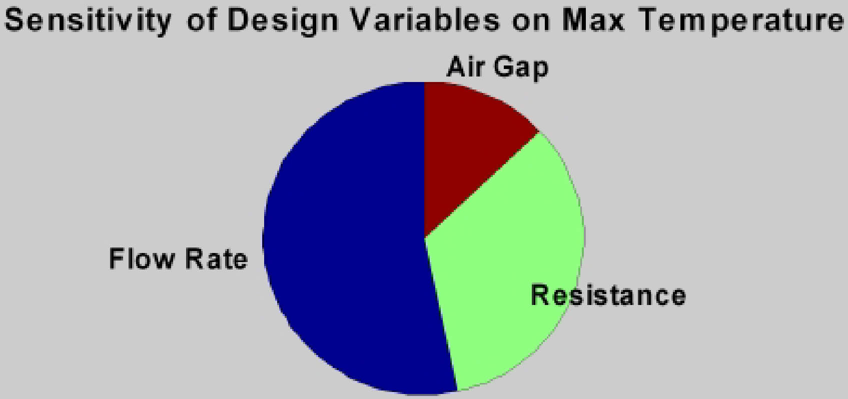


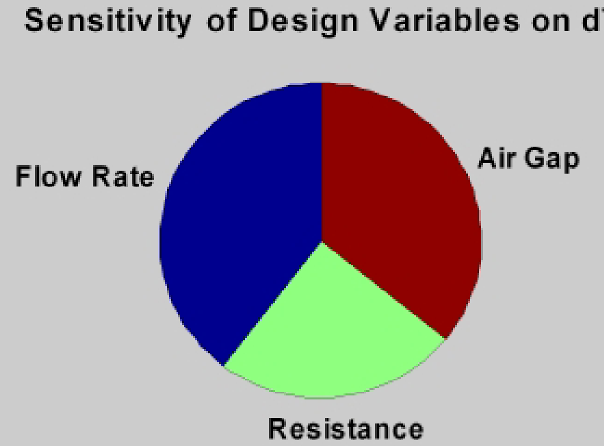
Sigma Quality Levels Versus Mean Value

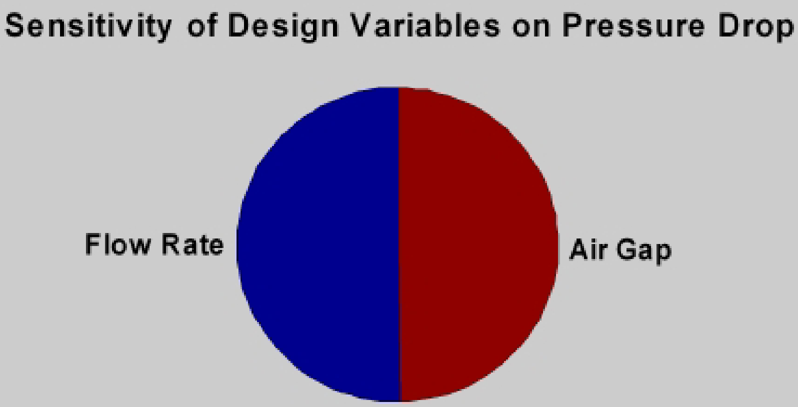


Sensitivity Analysis

- The flow rate has the most impact on the maximum temperature
- All three input design variables have about equal effect on the temperature differential
- The internal battery resistance has no effect on the pressure drop.

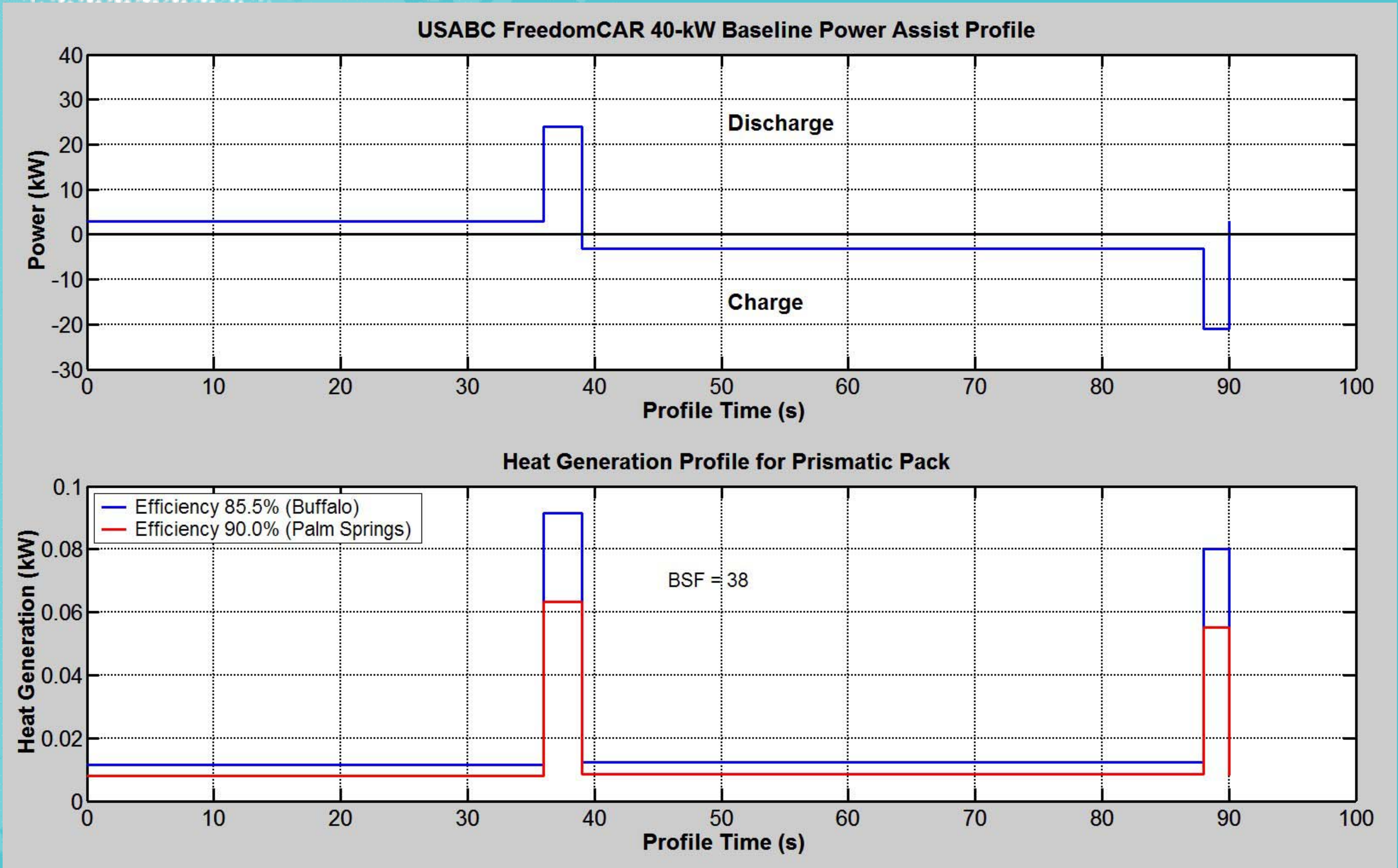




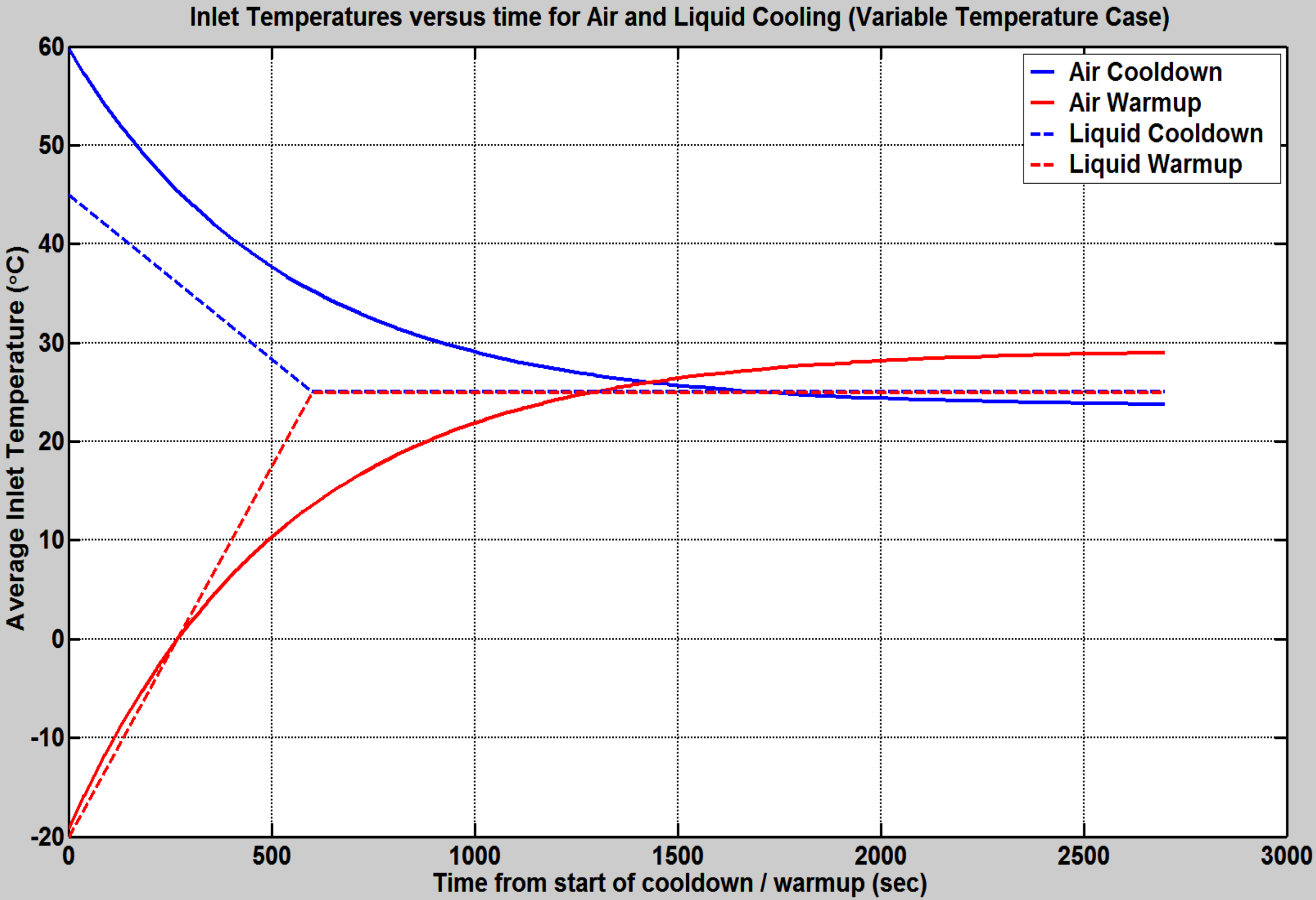


Transient Thermal Response of Prismatic Batteries

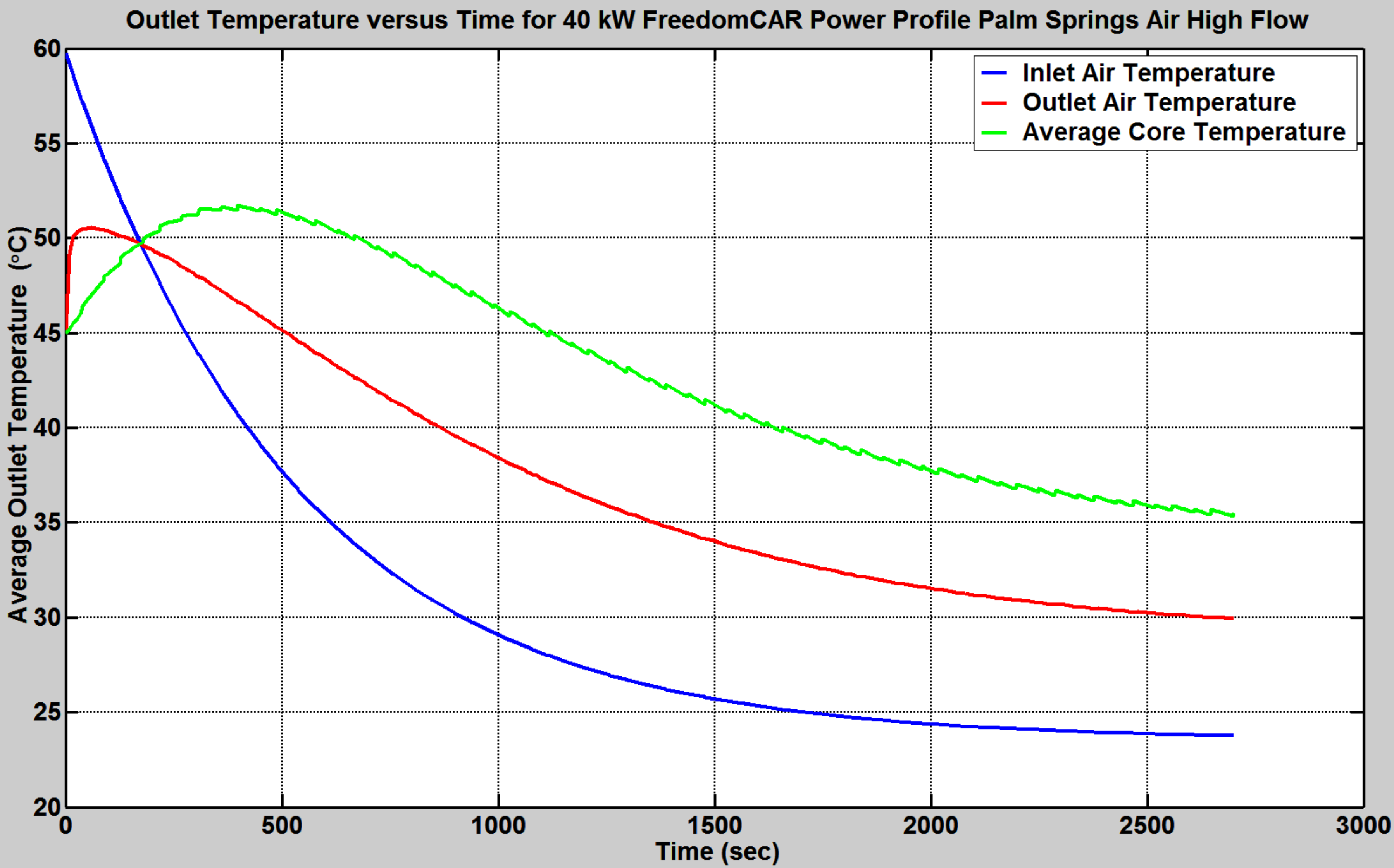
FreedomCAR 40-kW Baseline Power Assist & Heat Generation Profiles



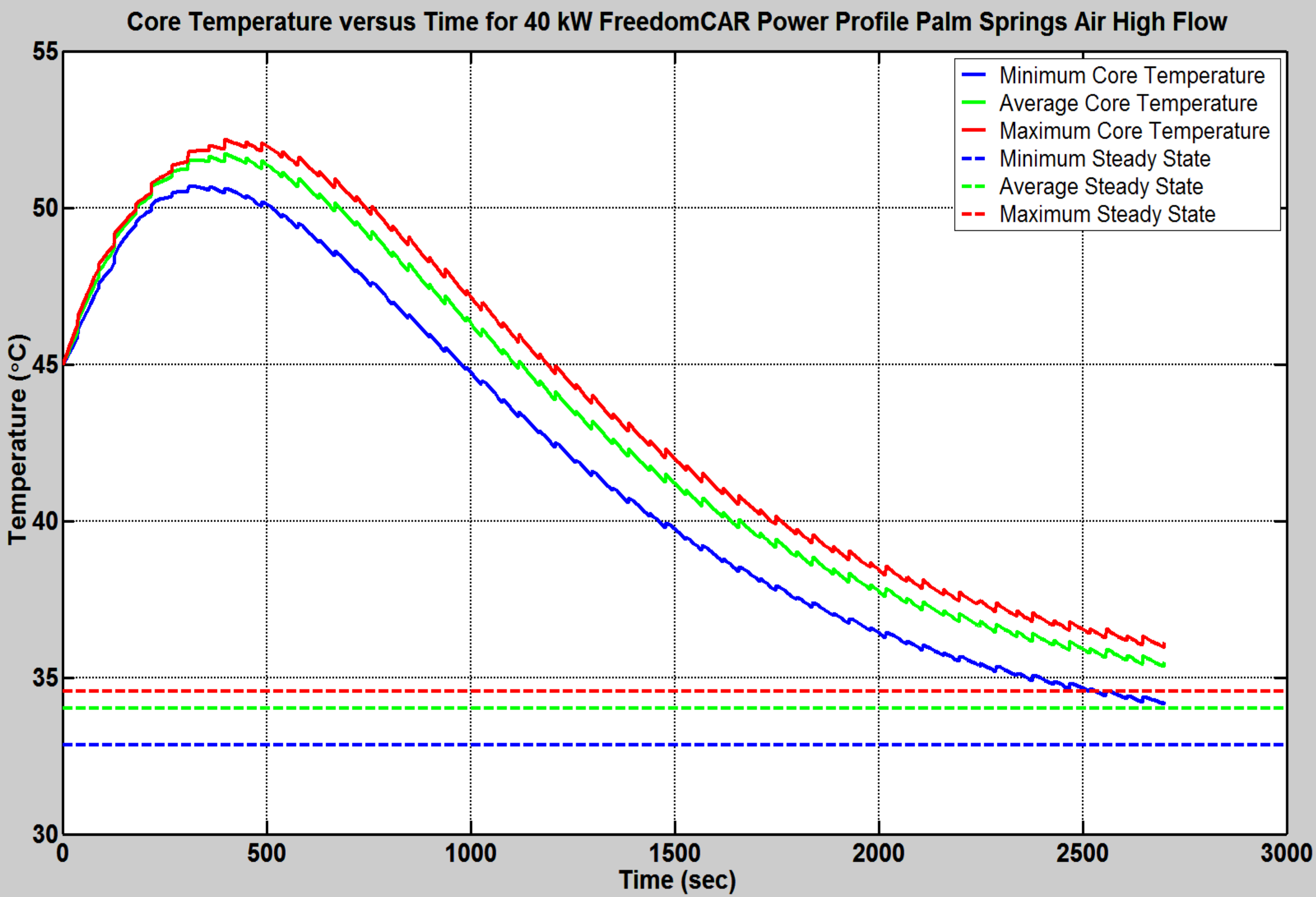
Inlet Temperatures for Air and Liquid Cooling



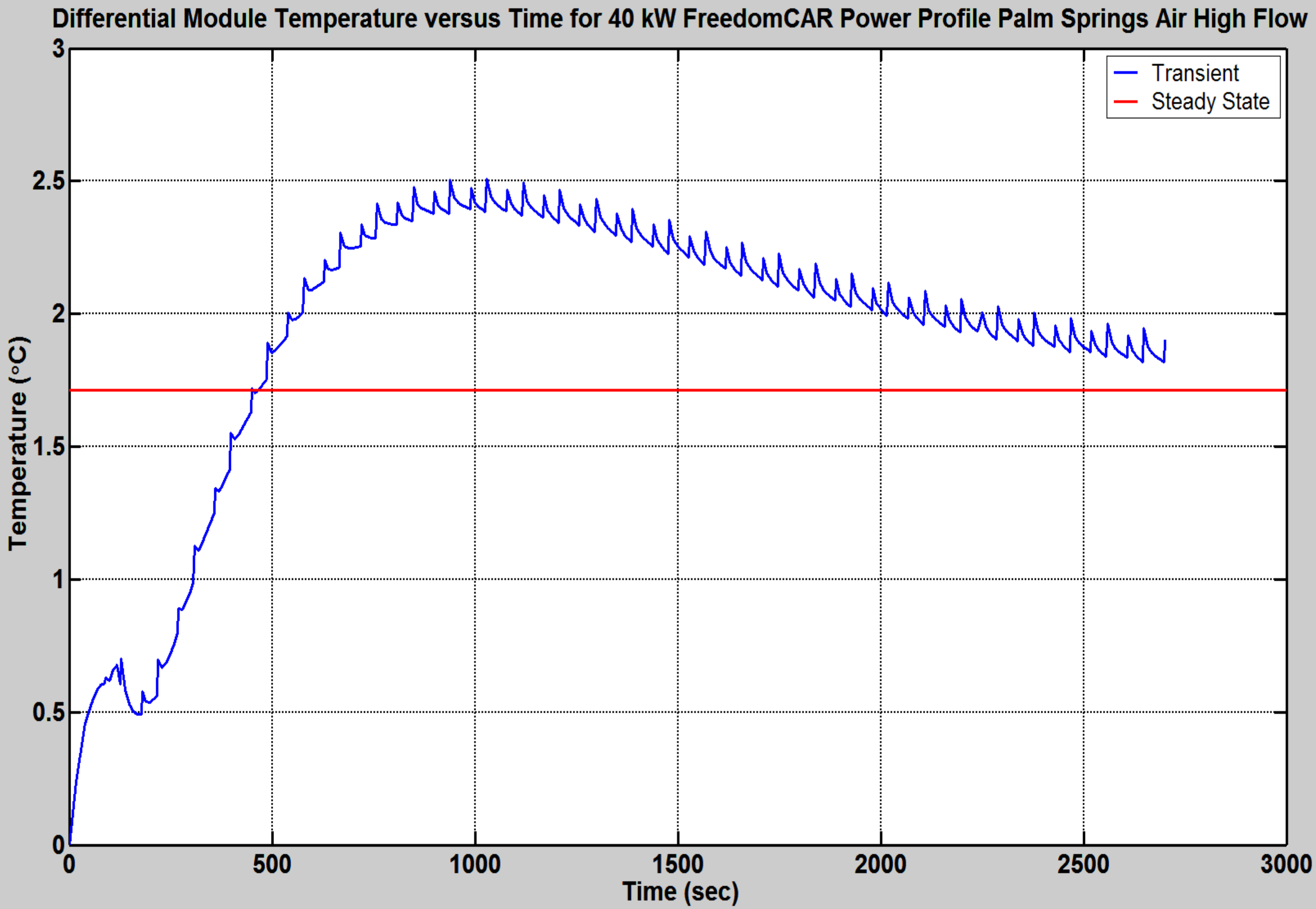
Inlet, Outlet and Core Temperature for Palm Springs with High Air Flow Rate



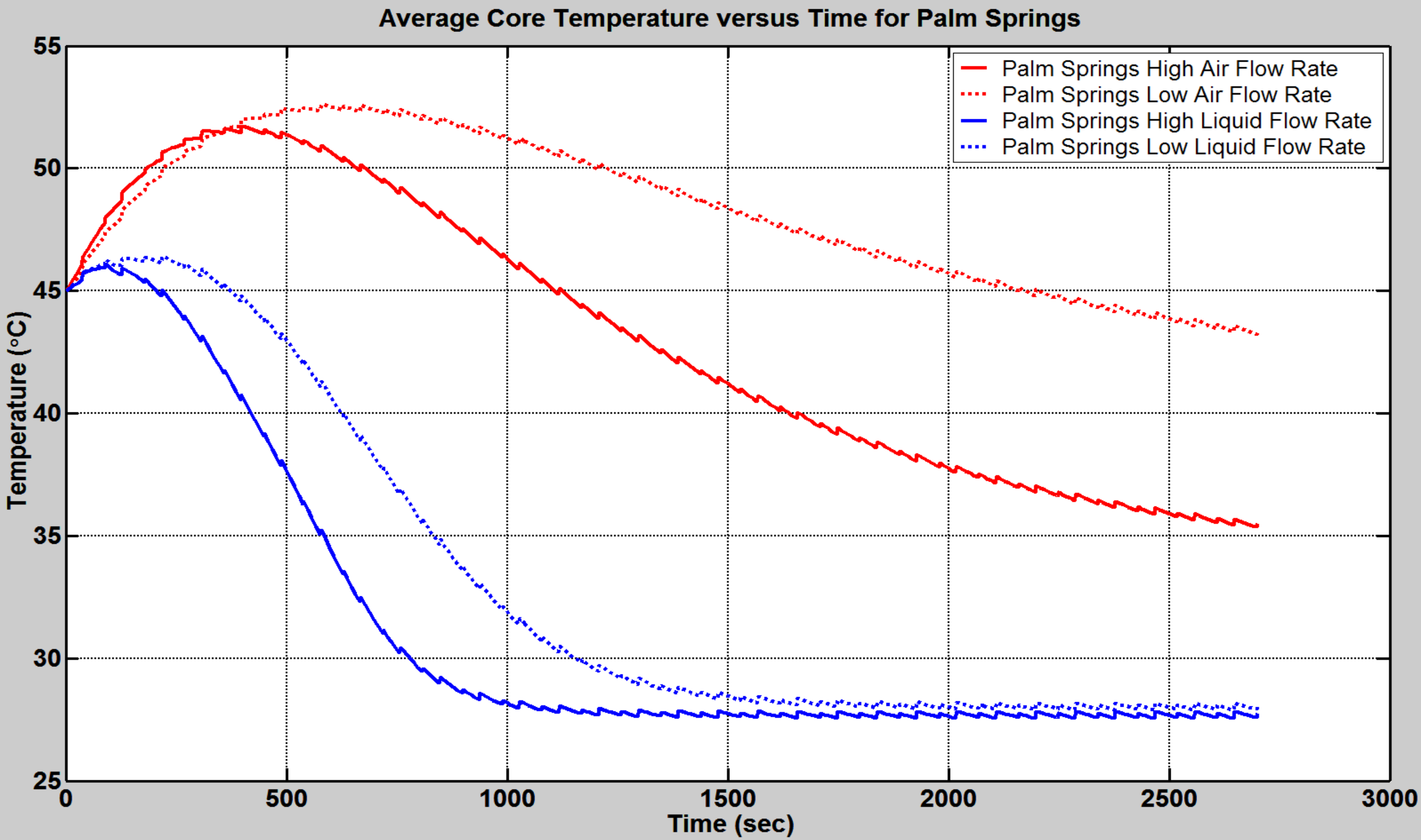
Core Temperature for Palm Springs with High Air Flow Rate



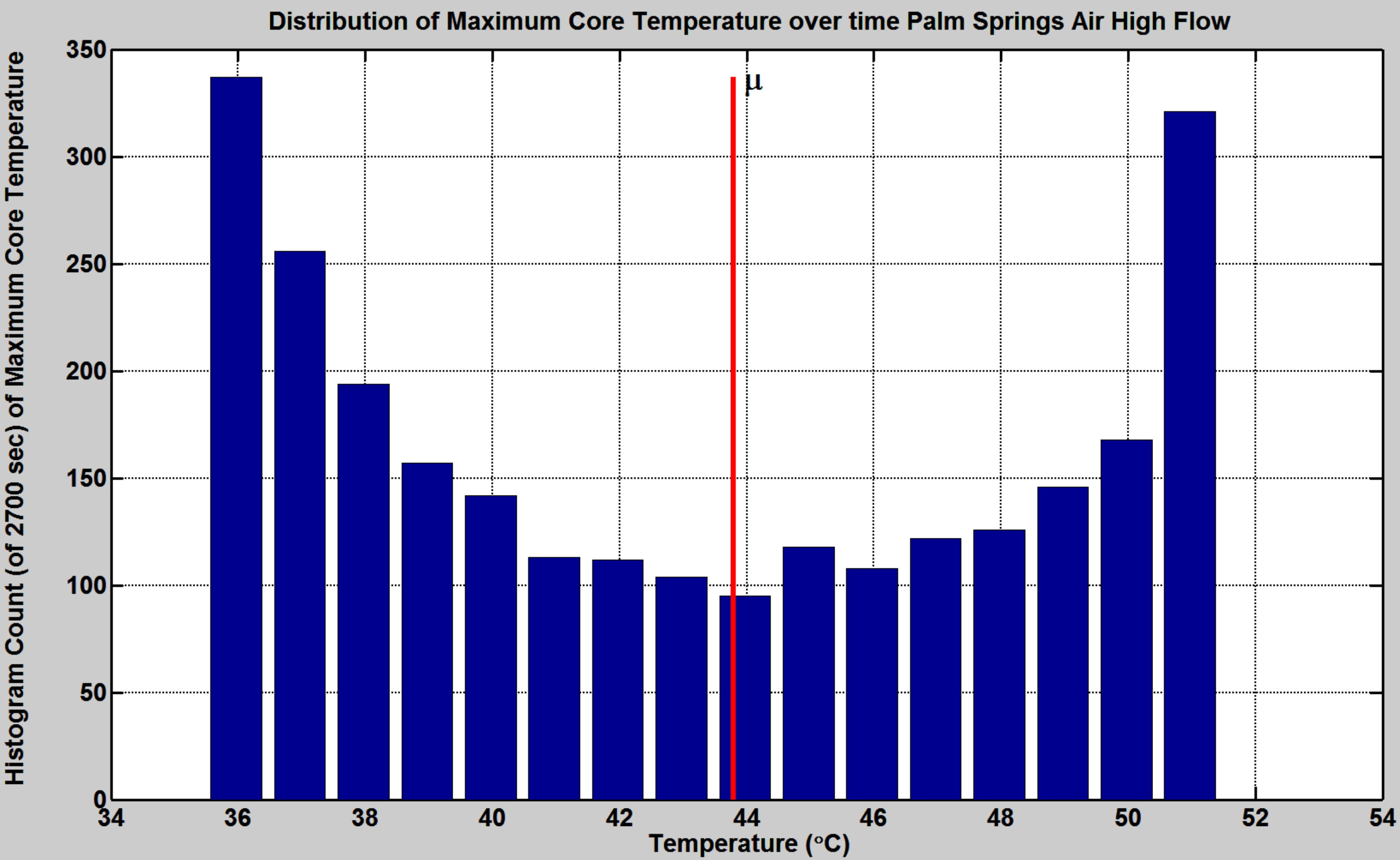
Core Differential Temperature for Palm Springs with High Air Flow Rate



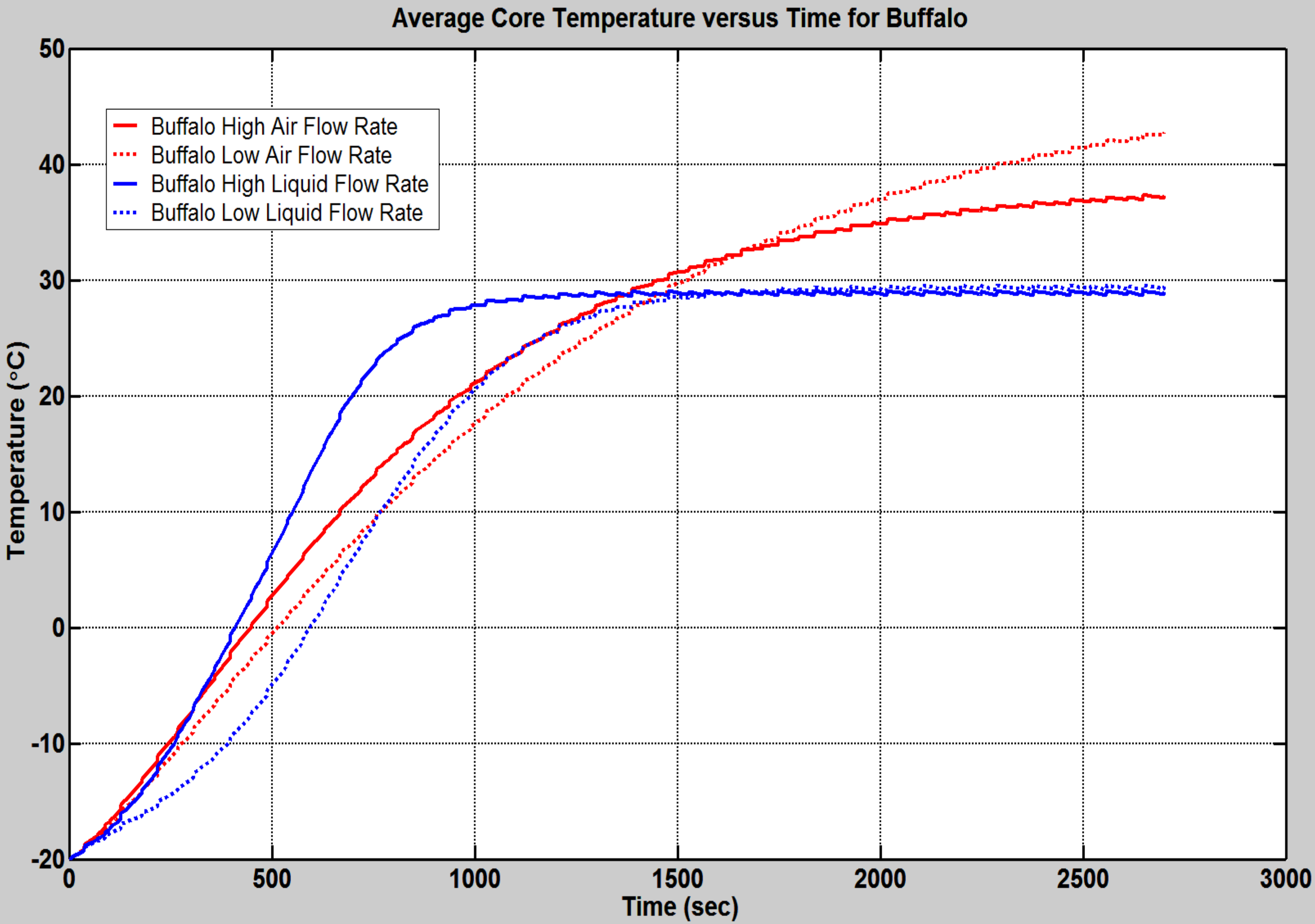
Average Core Temperature
(Palm Springs)



Distribution of Max Core Temperature



Average Core Temperature
(Buffalo)



Summary

- Demonstrated a re-usable process for including statistical variation of input parameters for battery thermal analysis
- Initial analysis with variation shows:
  - T_{max} is most difficult criterion to achieve with the given design constraints and assumptions
  - Effect of conflicting design constraints on sigma quality level
- Completed first round of transient thermal analyses on prismatic design
- Initial transient results show
  - the importance of including transient analysis
  - liquid cooling is more effective, but pressure drop higher
  - transient cooling and warm up time of the heat transfer fluid needs to be considered.

Future plans

1. Introduce feedback control on the fan
    1. Fan on–off, speed levels, etc
    2. Evaluate the effectives of various control systems on thermal performance.
2. Find the effect of power pulses in the load cycle on thermal transient .
3. Obtain a non-uniform heat generation profile from published information or other test data (thermal imaging).
4. Modify duty-cycle to include appropriate diurnal ambient and load conditions
5. Perform transient thermal analysis on cylindrical battery pack

Acknowledgments

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- Ted J. Miller of Ford Motor Company and FreedomCAR Battery Tech Team Chairman
- Bruce Bryant, of Ford Motor Company