Solid State Power Generation for High Speed Vehicles

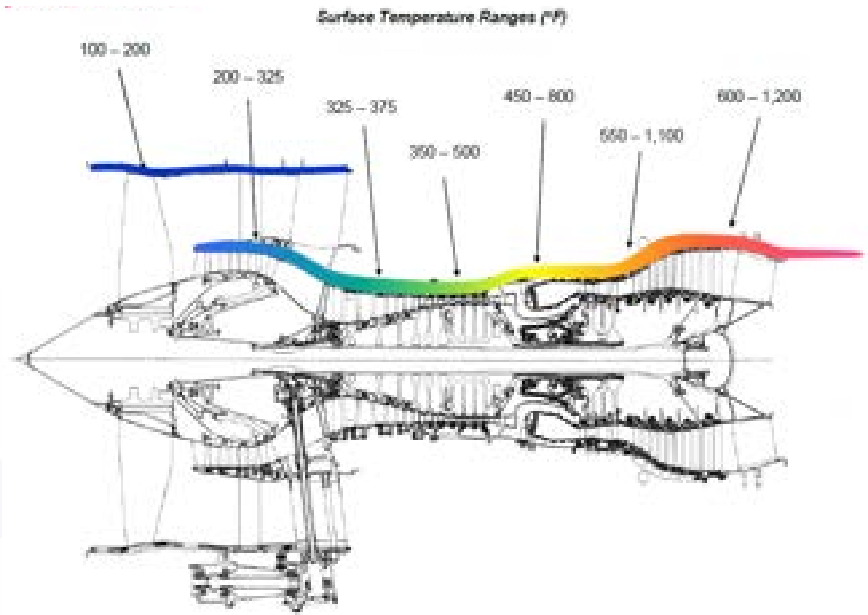
Student:	Spencer Schaiper
Student Email:	schaipers1@udayton.edu
Faculty:	Dr. Rydge Mulford
Faculty Email:	rmulford1@udayton.edu
AFRL Sponsor:	Mr. Zachary Adamson
AFRL Directorate:	AFRL RQQ

PA #: AFRL-2024-6105

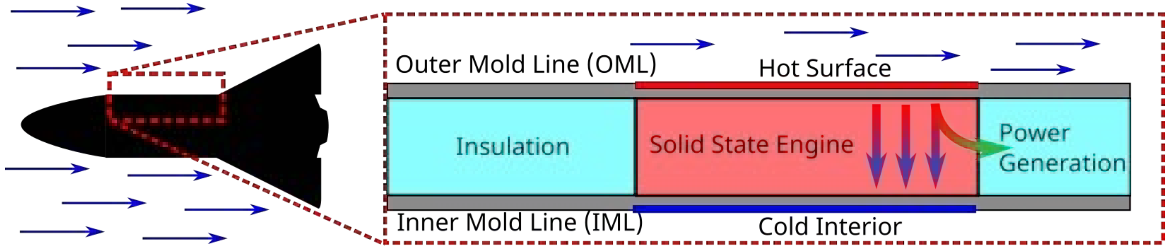
Overview

- Introduction
- ThermoElectric Generator (TEG) Operation
- 1D Aerothermal Modeling
- Low Temperature Testing
- High Temperature Testing
- Future Work

Aircraft Power Generation

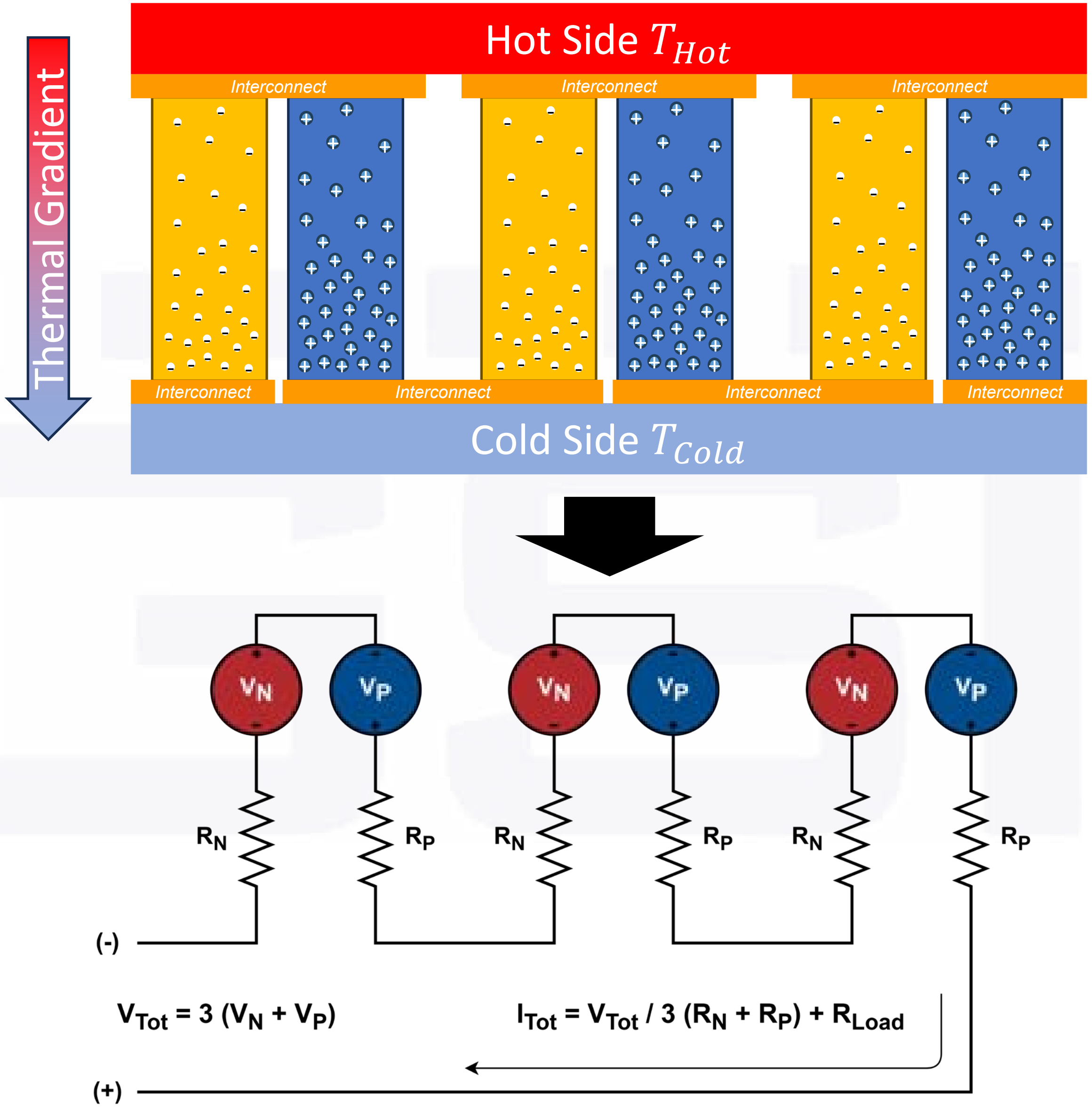


- Traditional Aircraft
  - Could extract energy from waste heat streams
    2009 Boeing analysis showed 0.5% improvement in fuel consumption
  - Can’t compete with rotating, mechanical generators
    Generator: 1–2 kW/kg
    TEG: 0.1–0.5 kW/kg
- Hypersonic Aircraft
  - RAMJET/SCRAMJET lack rotating core
    No rotating shaft for traditional generator
  - Aerothermal heating must be managed
    Large Delta T to preserve internal systems
    All this heat was carried as chemical energy in the fuel!



TEG Theory

- Heat Conduction Drives Power Generation
  - $Q_{Cond} = K(T_{Hot} - T_{cold})$
    Power scales with $|Q_{Cond}|$
  - $V_{Tot} = N\alpha(T_{Hot} - T_{Cold})$
    Voltage scales with Seebeck coef. & # of couples
- Power Generation Creates Resistive Losses
  - $I_{Tot} = N\alpha(T_{Hot} - T_{Cold})/(R_{TEG} + R_{Load})$
    Current constrained by load and internal resistance
  - $Q_{TEG} = I_{Tot}^2 R_{TEG}$
    Internal couple resistance is ohmic loss
- Delta T is Proportional to Heat Flow
  - Ability to manage heat flow determines delta T
  - This is a coupled problem!
    - Temperature-varying properties:
      - $K(T),\ \alpha(T),\ R(T)$
    - Time-varying heat fluxes:
      - $Q_{In}(T), Q_{Out}(T), Q_{Cond}(T), Q_{TEG}(T)$
    - Need to impedance match the TEG and the load



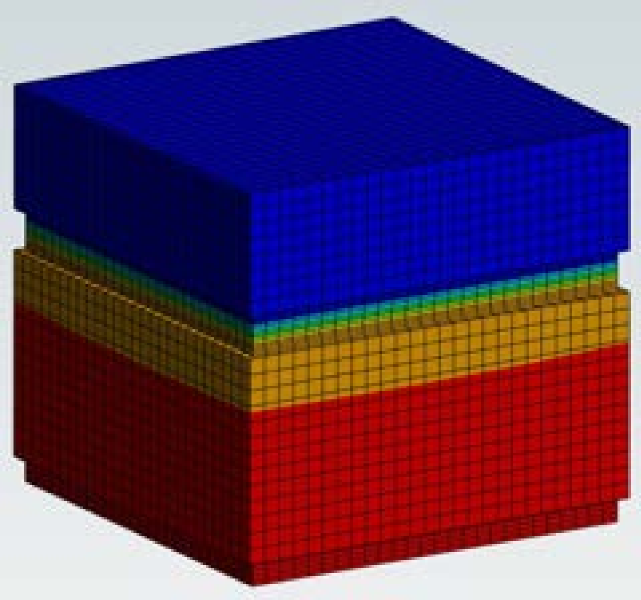
$V_{Tot} = 3\ (V_N + V_P)$

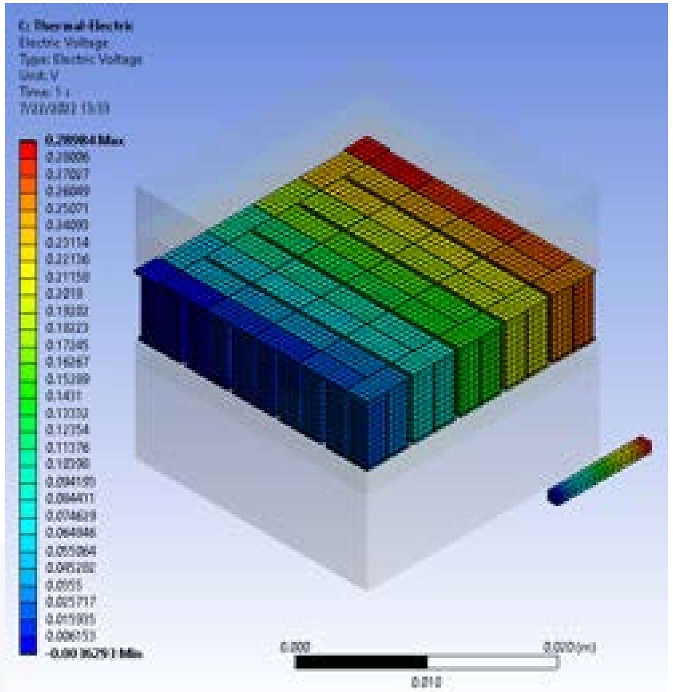
$I_{Tot} = V_{Tot}\ /\ 3\ (R_N + R_P) + R_{Load}$

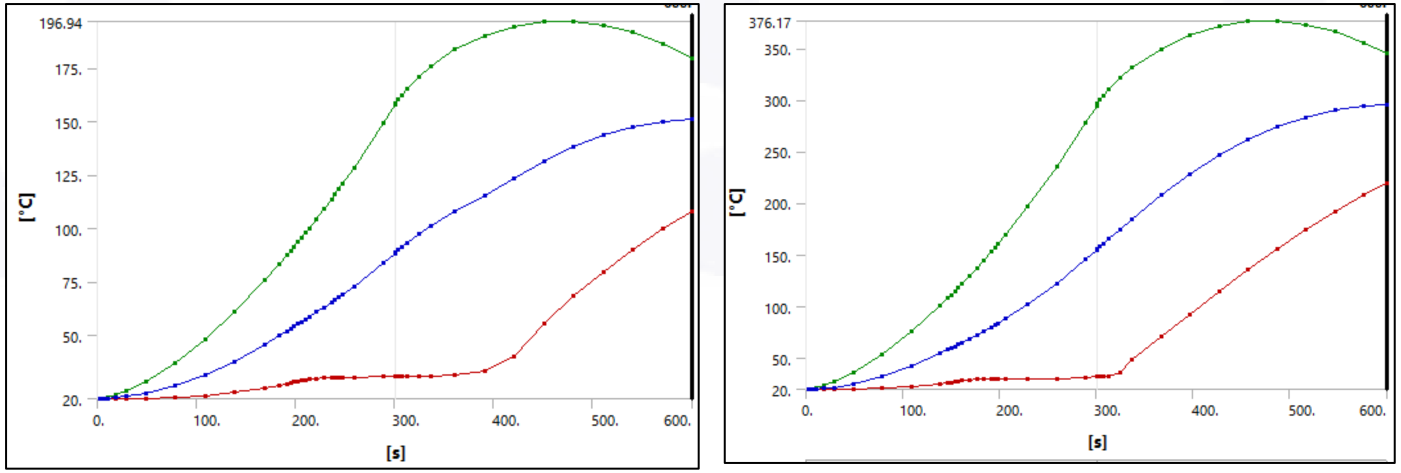
TEG Modeling

- Integrated TEG Model
  - Full detail TEG modeled with stack layers
  - Used to visualize steady state heat flow and power generation in early stages
- Pseudo TEG Model
  - TEG treated as generic box
  - Identified sufficient thermal isolation
  - Evaluated the requirement for cooling between tests

    Will backfill chamber between tests
- TEG-only Model
  - Deeper look into TEG performance
  - Steady state model with resistance load
  - Highlighted importance of impedance matching







Response of proposed test system to generic thermal step input

Distribution Statement A. Approved for public release: distribution is unlimited. PA AFRL-2024-6105.

Impedance Matching

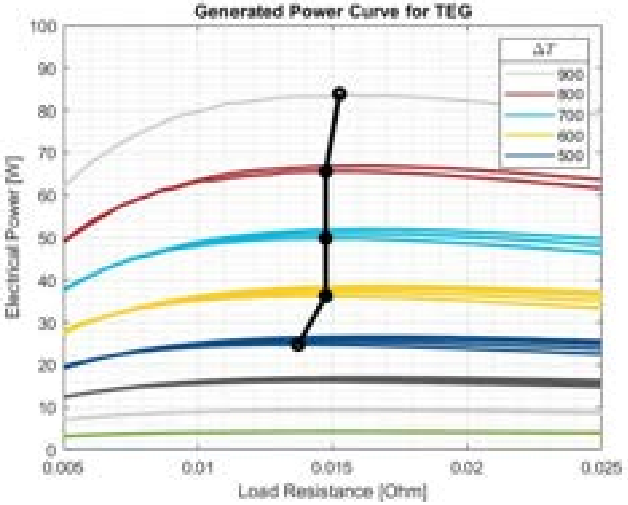
- Impedance is not naturally stable
    - Requirement of the load controller
    - Impedance is matched when:

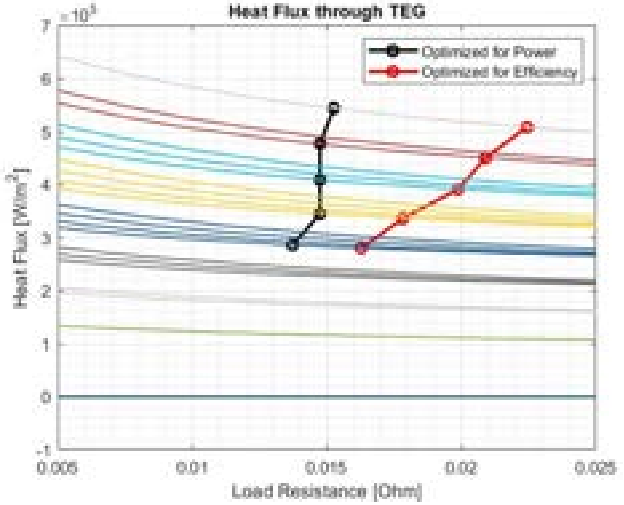
$$\Omega_{TEG} = \Omega_{Load}$$

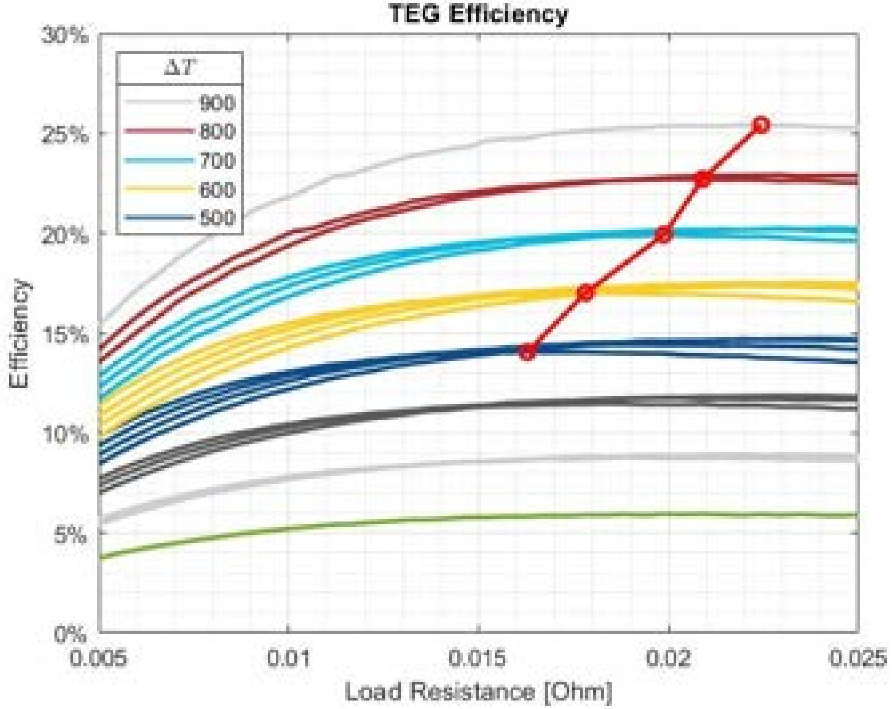
- Determining TEG efficiency:

$$I = J * A_{e,min}$$
$$P_e = V * I$$
$$P_Q = Q'' * A_{TEG}$$
$$\eta_{TEG} = \frac{P_e}{P_Q} = \frac{V * J * A_{e,min}}{Q'' * A_{TEG}}$$

- Where:
    - J = *Current density*
    - P_Q = *Heating power*
    - P_e = *Electrical power*

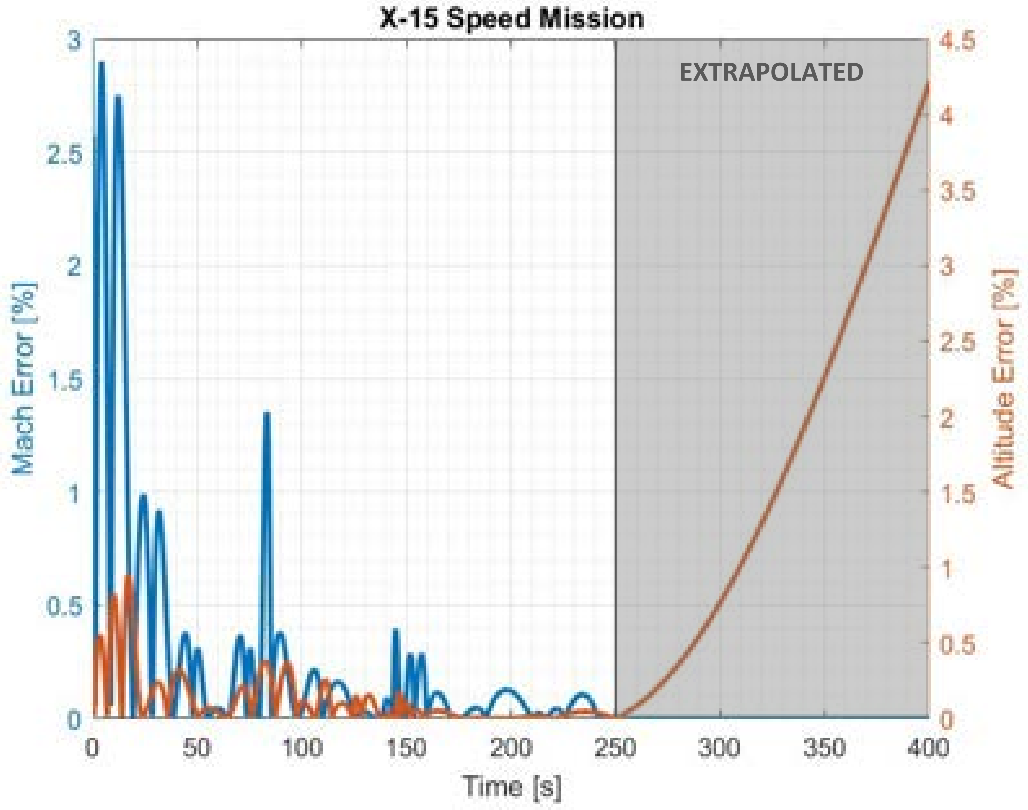


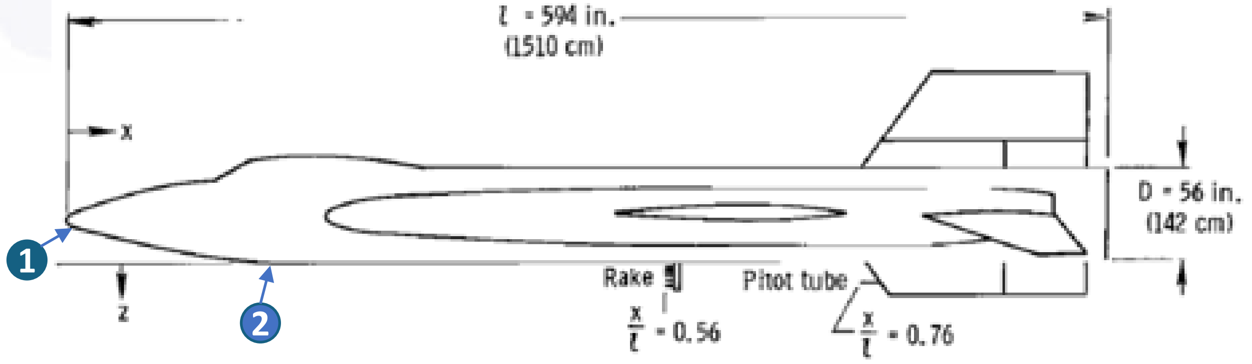




1D Modeling Overview

- X-15 ‘Speed Mission’ Profile Selected
  - 7.33 G Pullout
  - Speed brakes closed
  - M > 4 at 240 sec
  - Extrapolated to 400 sec
- Two locations selected on X-15
  - Location 1: Higher Temperature
    - 25 cm from nose, $\theta = 15°$
  - Location 2: Lower Temperature
    - 300 cm from nose, $\theta = 1°$





Aerothermal Heating

1. Choose Mach number and altitude

2. Get air density, viscosity, and Prandtl number at farfield conditions

   Using tables, $Pr \approx const.$

1. Using $r = Pr^{1/3}$, calculate T_{aw} (or T_r)

$$T_{aw} = T_e \left(1 + r\frac{\gamma - 1}{2} M^2\right)$$

1. Calculate the reference temperature T^*

   T_w is wall

   T_{aw} is adiabatic wall

   T_e is far field

$$T^* = 0.5T_w + 0.16T_{aw} + 0.34T_e$$

1. Using reference, get μ^*

$$\frac{\mu}{\mu_0} = \left(\frac{T}{T_0}\right)^{3/2} \frac{T_0 + S}{T + S_\mu}$$

2. Calculate Reynolds number

$$Re_x = \frac{\rho_e u_e x_e}{\mu_e}$$

1. Use scale factor to get the incompressible Re

$$F_{Re_x} = \frac{\mu_e T_e}{\mu^* T^*}, Re_{x,i} = F_{Re_x} Re_x$$

8. Use an incompressible correlation for friction coefficient

   $c_{f,i} = 0.592 Re_{x,i}^{-0.2}$ for a turbulent boundary layer

8. Use different scale factor to recover the compressible friction coefficient

$$F_c = \frac{T^*}{T_e}, c_{f,i} = F_c c_f$$

8. Use shape factor to scale flat plate results to a cone

   $c_f = \sqrt{3}$ for laminar

   $c_f = 1.176$ for turbulent

8. Calculate compressible Stanton number

$$\frac{2C_H}{c_f} = R_f, R_f = Pr^{-2/3}$$

8. Get heat transfer coefficient from Stanton number (C_H and St)

$$St = \frac{h}{c_p \rho V} = \frac{Nu}{RePr}$$

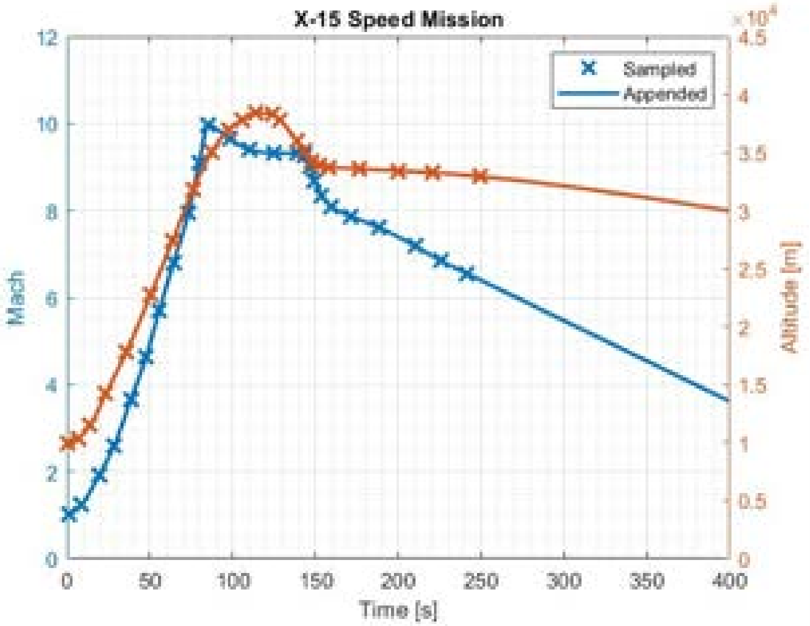
8. Finally, heat flux to surface is given by

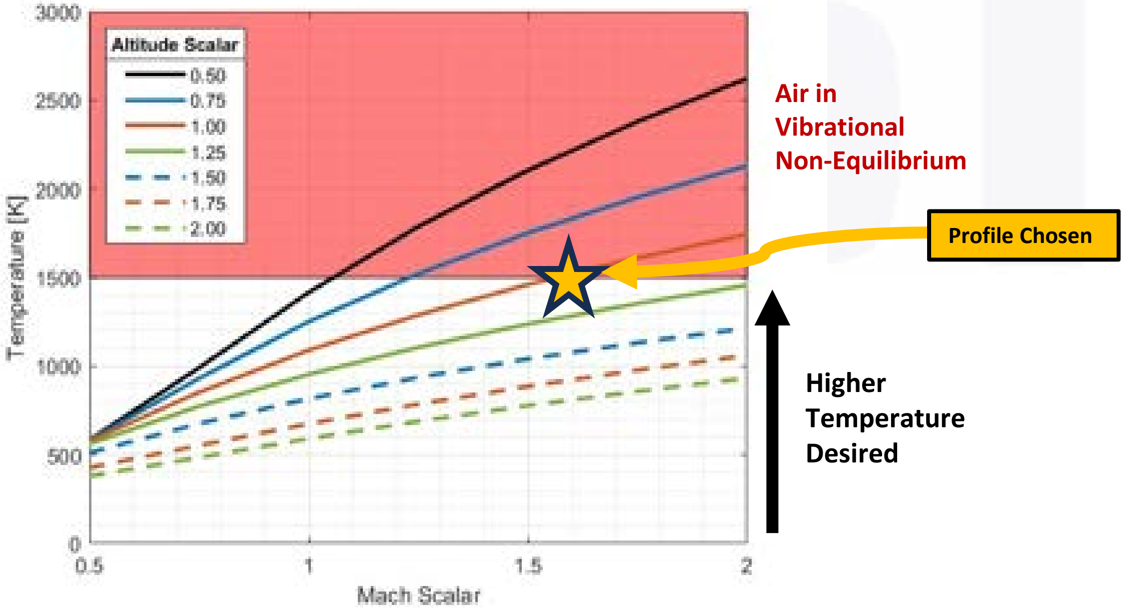
$$q'' = h(T_{aw} - T_w)$$

Flight Profile Modification

- Flight profile was scaled for higher T_{aw}
    - Mach number
    - Altitude
- ISA model used as starting point for each appended point
- Gas relations used beyond
- Agreement between atmospheric data

Scalars	
Mach Number	1.55
Altitude	1.00
Maximums Throughout Flight Profile	
Altitude	38,453 m (454,243 ft)
Mach Number	9.9564
Stagnation Temperature	4921 K
Adiabatic Wall Temperature	1491 K





Air in Vibrational Non-Equilibrium

Profile Chosen

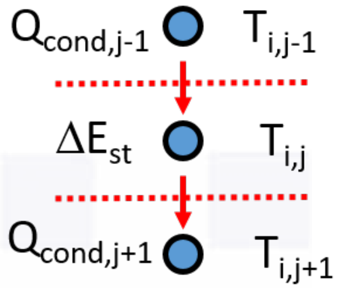
Higher Temperature Desired

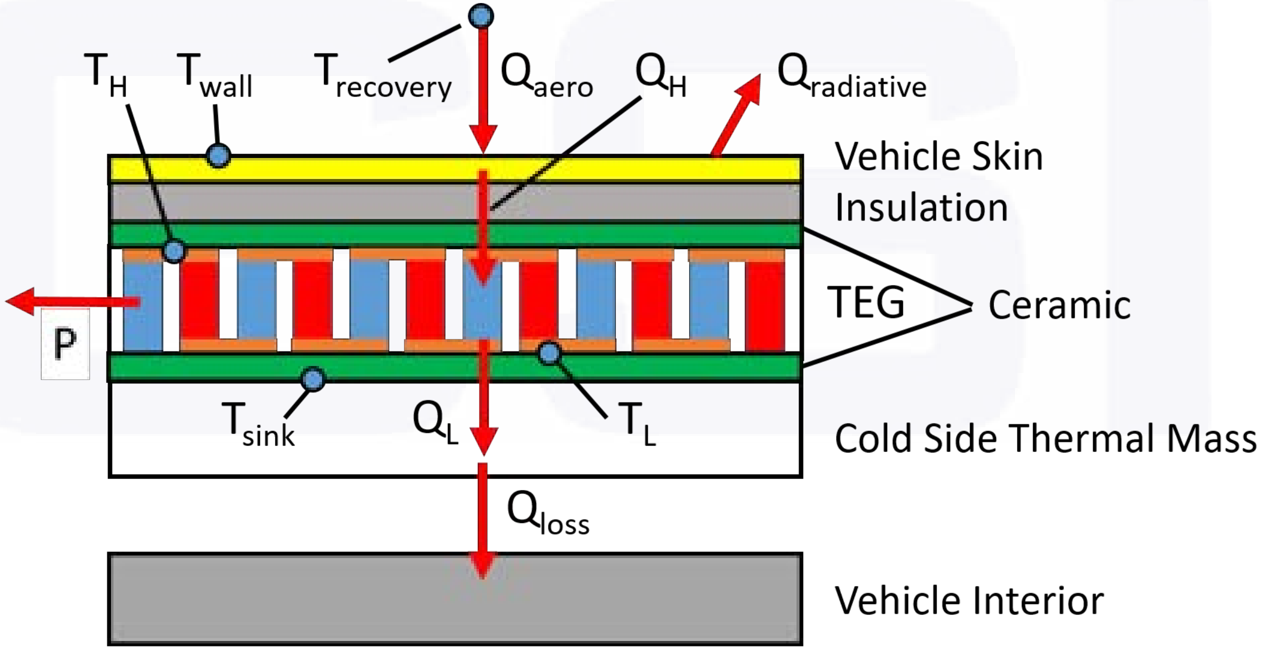
Transient Conduction Model

- Properties calculated
  - $R = N_{junction}\left(\frac{\phi_p t_p}{A_p} + \frac{\phi_n t_n}{A_n}\right)$
  - $K = N_{junction}\left(\frac{k_p A_p}{t_p} + \frac{k_n A_n}{t_n}\right)$
- Power predicted with voltage and current calculations
  - $V_{TEG} = N_{junction}\alpha(T_H - T_L)$
  - $I_{TEG} = \frac{V_{TEG}}{R_{TEG}+R_{load}} = \frac{V_{TEG}}{2R_{TEG}}$
  - $I_{TEG} = \frac{V_{TEG}}{R_{TEG}+R_{load}} = \frac{V_{TEG}}{2R_{TEG}}$
- Hot and cold side heat transfer is given by the ideal equations
  - $Q_H = -\frac{1}{2}R_{teg}I_{teg}^2 + nIT_H\alpha + K_{teg}(T_H - T_L)$
  - $Q_L = \frac{1}{2}R_{teg}I_{teg}^2 + nIT_L\alpha + K_{teg}(T_H - T_L)$

Energy Balance:

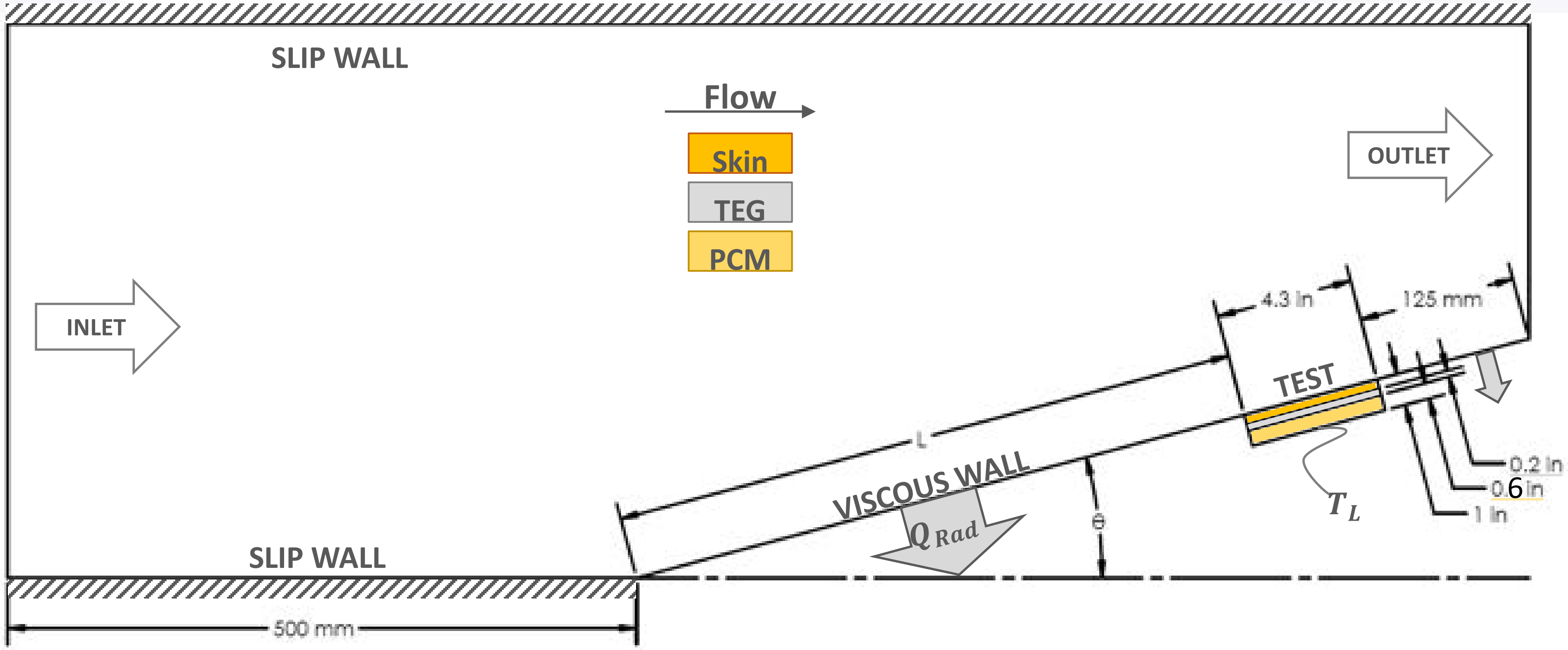
$$A_{i,i}T_{i,j}^{p+1} + A_{i,j-1}T_{i,j-1}^{p+1} + A_{i,j+1}T_{i,j+1}^{p+1} = b$$





CFD Flow Visualization and Validation

- Aerothermal heating data used in conduction model assumes a certain vehicle skin thickness/material properties, but these change in the conduction model
- A fully parallel CFD model will solve the aerothermal heating and conduction problem simultaneously, removing the mismatch between aerothermal and conduction models



Distribution Statement A. Approved for public release: distribution is unlimited. PA AFRL-2024-6105.

Overview

- 4 BiTe TEG array
- Vacuum testing environment
- Heat flux via 4 AlN heaters
- Temperatures up to 600 C
- Active and passive cooling

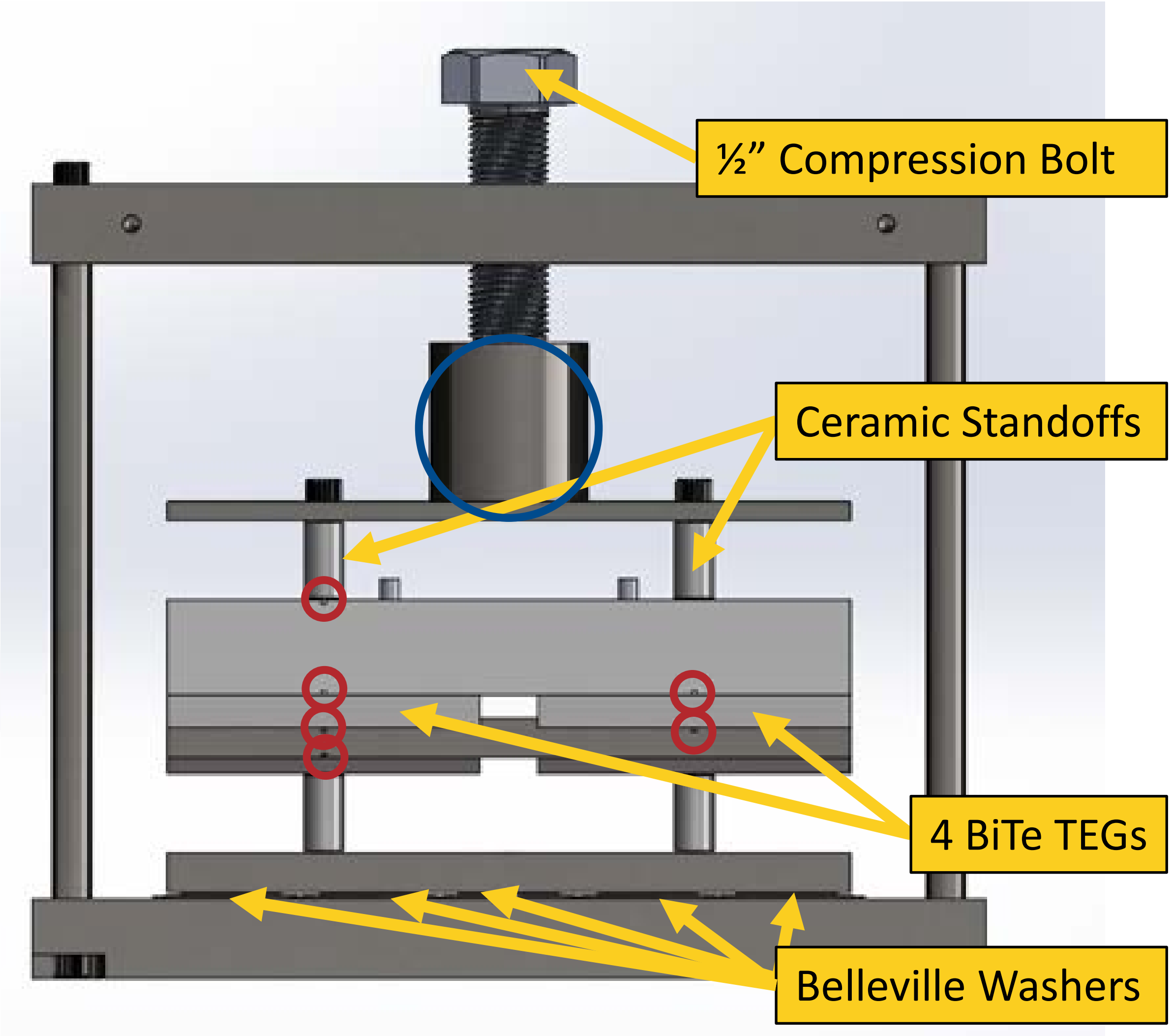
	BiTe TEG (Cold)
Number of Legs	12
Leg Width	2.5 mm x 5 mm
Cross Sectional Area	60 mm x 20 mm = 1200 mm^2
TEG Thickness	6 mm
PCM Thickness	10 cm
Distance from Leading Edge*	25 cm
Max Temperature	600 C

With Multi-Layer Insulation (MLI)

“Hidden” MLI

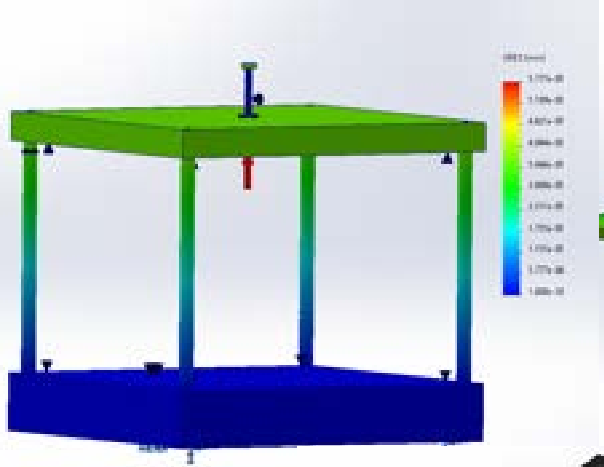
Instrumentation & Key Features

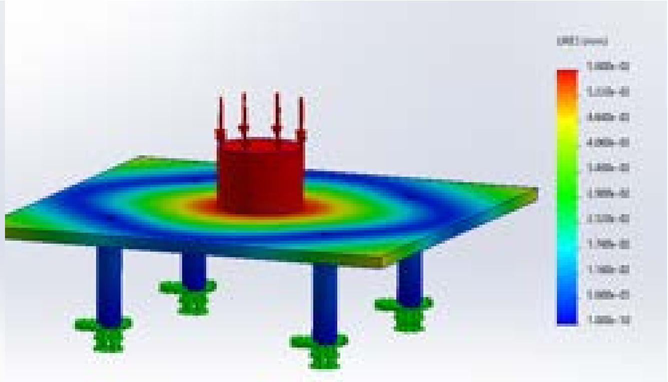
- Data recorded with multi-channel data logger
  - ⊙ 11 K-Type Thermocouples
    For various temperature/heat flux measurements
  - 1 Pressure Transducer
    To monitor chamber pressure
  - 1 Voltage, 1 Current
    To measure electrical power
  - ⊙ 1 Force Transducer
    To set and monitor mechanical load
- 4 AlN Heaters
  - High power-density heaters interface with faux skin
    Large, controllable heat flux input to system
  - Minimal parasitic thermal capacitance
    AlN – Low specific heat and density
  - Significant control authority



Structural Analysis

- Load Frame Structure
  - Test stack loaded in compression
    Compressive forces decrease thermal contact resistance
  - Outer frame loaded in tension
    Designed to be mores stiff than internal structure
  - Self-locking bolt to set initial pressure
    Force transducer for constant mechanical load measurement
- Load frame FEA
  - Determined reaction & deflection to loading
    Outer structure much stiffer than inner structure
  - Verified peak stresses with FOS
    Ceramic standoffs and steel plate survive
- Self-Locking Bolt
  - Thread will apply and hold mechanical force
    Governed by lead angle and coefficient of friction





For a zinc plate steel bolt ½”-20:

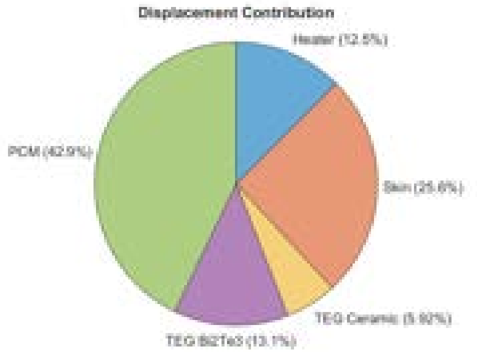
$$\tan(\lambda) = \frac{L}{\pi D} = \frac{0.05}{\pi(0.5)} = 0.0318$$

D – Diameter (in)
L – Lead (in/rev)

$\mu_f = 0.10 - 0.18$ [3,a-b]

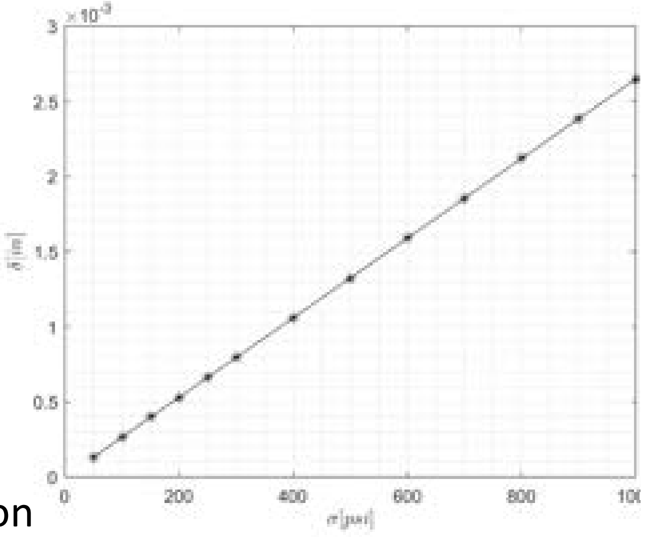
$\therefore \mu_f > \tan(\lambda)$ for the entire range

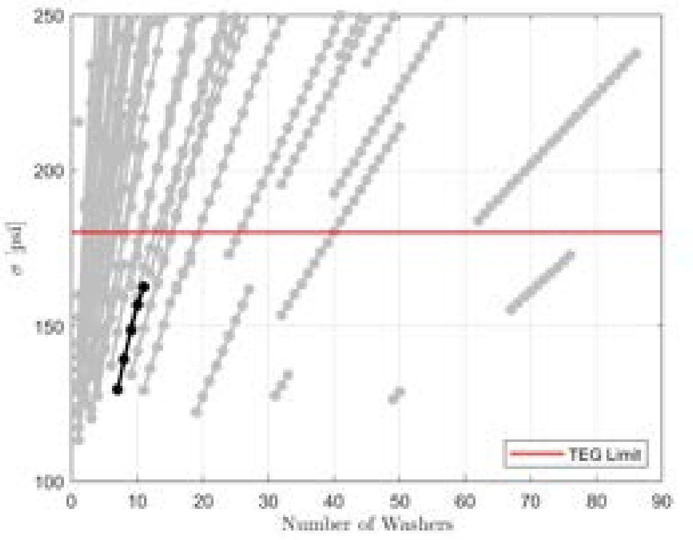
Where
μ_f–Coefficient of thread friction
λ – Lead angle, degrees

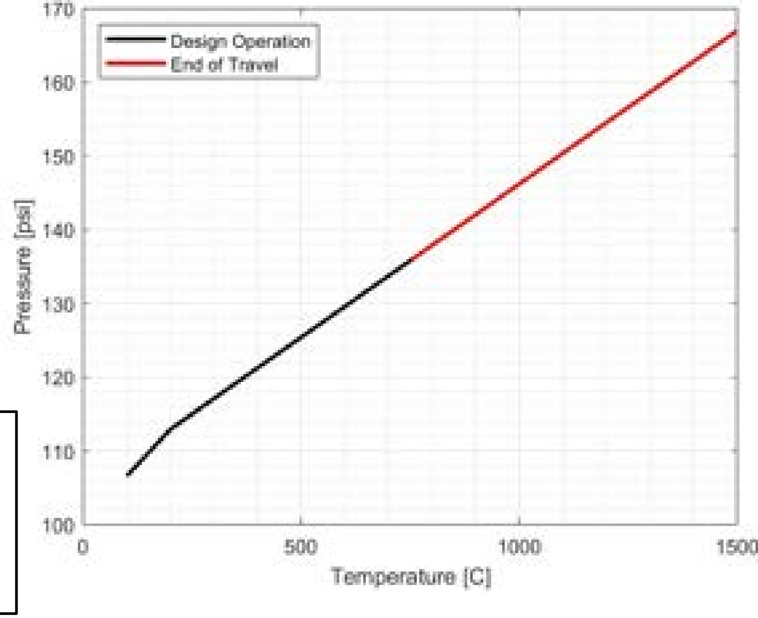


Structural Analysis

- Thermal Isolation and Insulation
  - Ceramic standoffs to transfer pressure
    Minimal thermal conductivity and contact area
  - MLI reduces radiation losses
    Radiation is significant due to low conductive losses
- Thermal Expansion
  - Need compliance to allow for thermal expansion
    Constrained thermal expansion will destroy the TEGs
  - Incorporated Belleville springs for compliance
    Accounts for pre-load and thermal expansion
  - Can vary spring arrangement to change force
    Series-Parallel combination
- Accounts for Expansion
  - Belleville springs absorb thermal expansion
    Prevents structure from 'bottoming out' with FOS
  - Design allows for wide range of pressures and temperatures
    Variable spring combinations







For a +600 C heat soak & 100 psi preload:

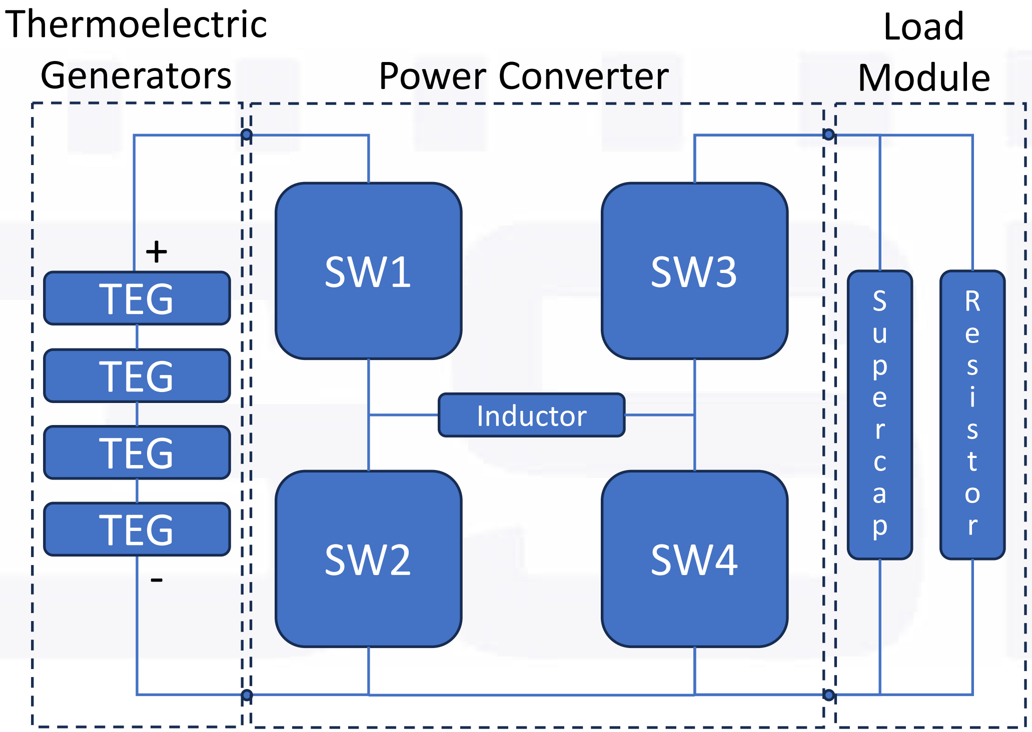
$\sigma_{MAX} \cong 130$ psi when heat soaked

93% of washer displacement used

Final 7% yields an extra 150 C

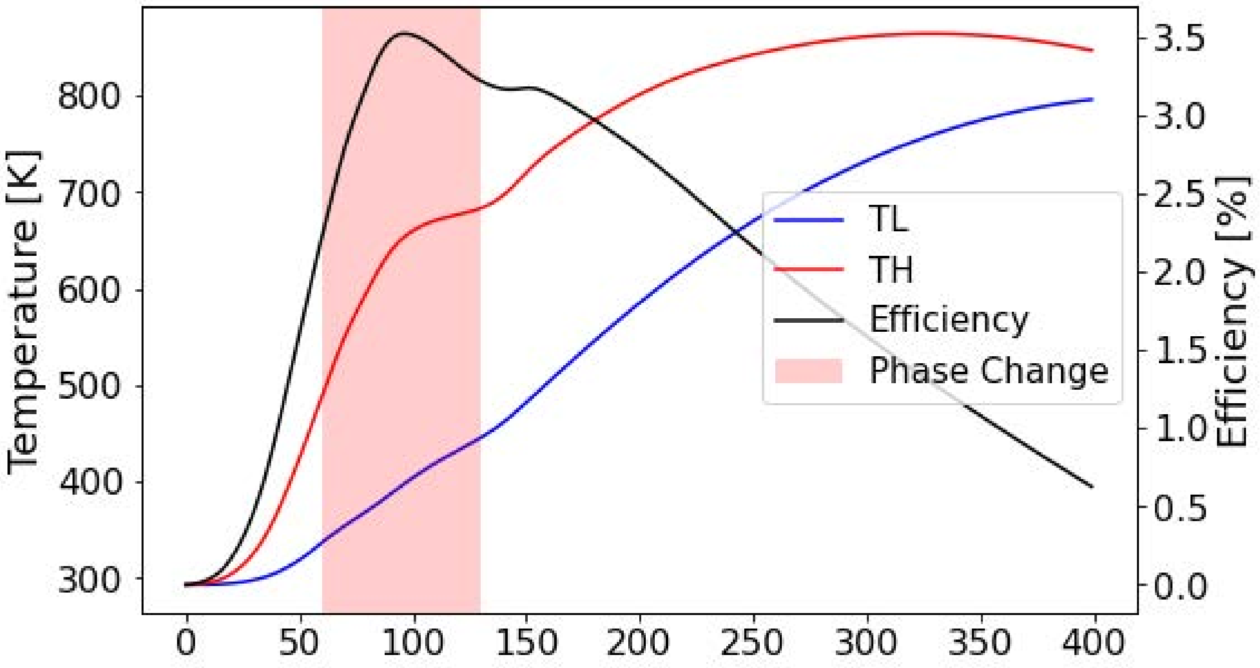
Maximum Power Point Tracking

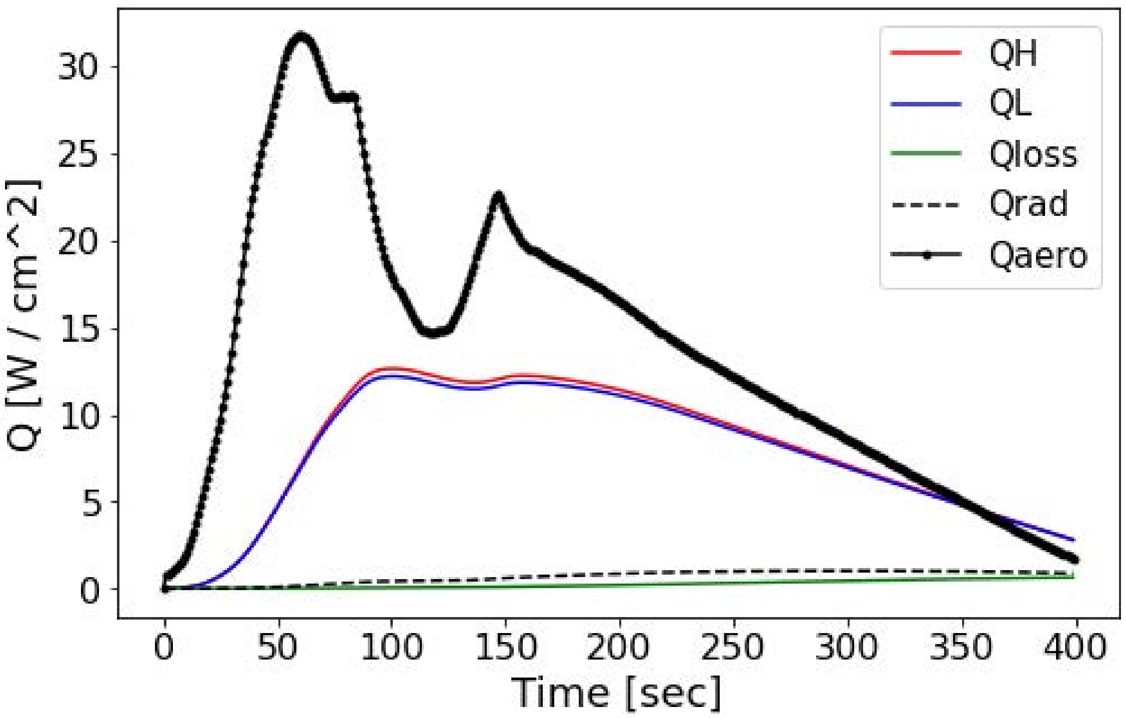
- Buck-Boost DC-DC converter provides Maximum Power Point Tracking (MPPT)
  - Live, self-adjusting impedance matching
    Allows for maximum electrical power extraction
  - Designed for up to 40V, 30A
    More than covers this test and future testing
- Designed for maximum power conversion in minimal space & weight
  - GaN switches enable 500kHz – 1MHz switching
    Decreases size/weight of passive components
  - TEG Von = 0.3V
    Low Von captures as much energy as possible
- Designed with future efforts in mind
  - Onboard power storage
  - Built-in measurements
  - Built-in monitoring and protection



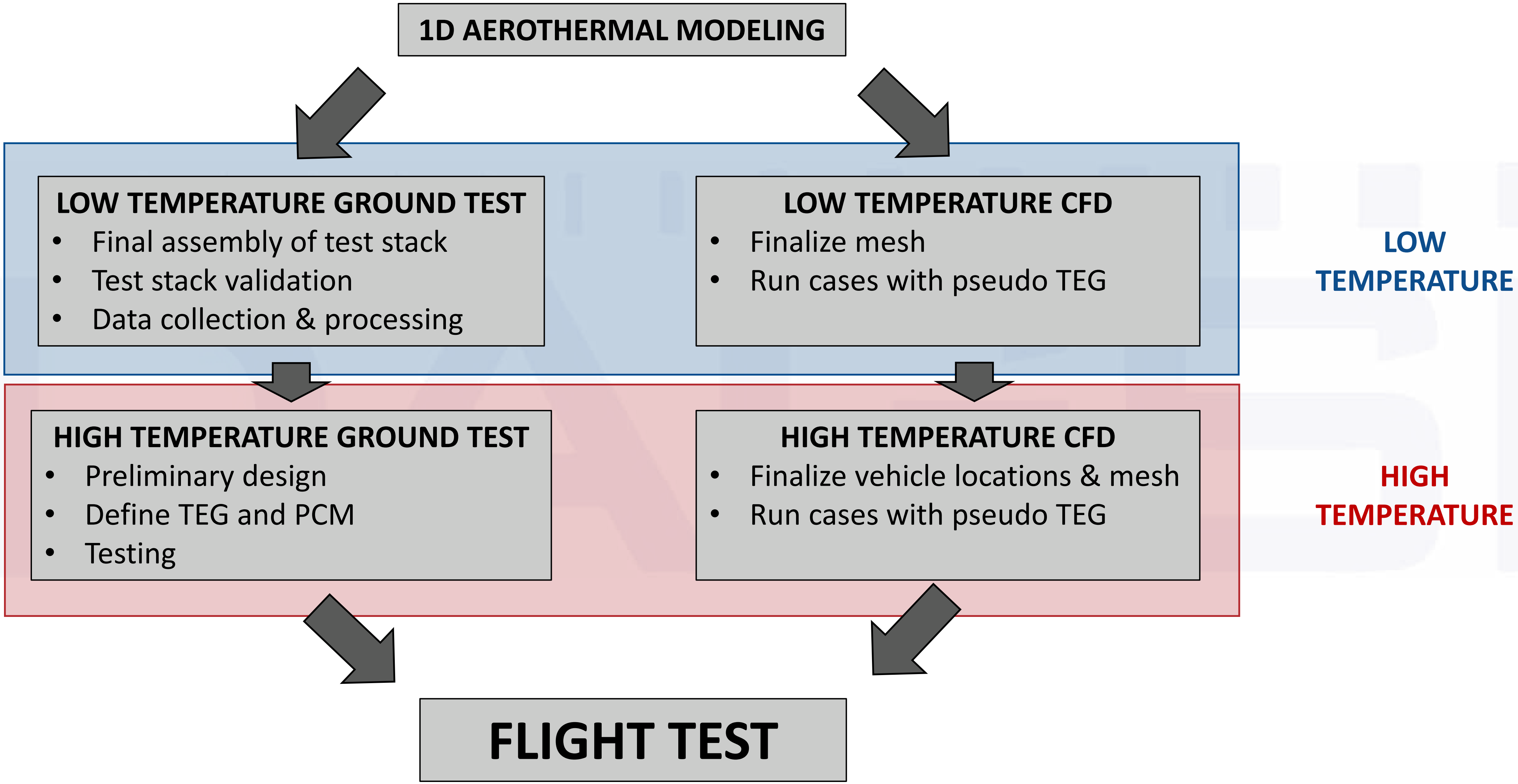
Heating Profile

Simulated response based on X-15 mission profile and TEG properties.





$$T_{max,equilibrium} = 522.9619\ C$$
$$T_{max,adiabatic} = 1218.1672\ C$$



1D AEROTHERMAL MODELING

LOW TEMPERATURE GROUND TEST
- Final assembly of test stack
- Test stack validation
- Data collection & processing

LOW TEMPERATURE CFD
- Finalize mesh
- Run cases with pseudo TEG

LOW TEMPERATURE

HIGH TEMPERATURE GROUND TEST
- Preliminary design
- Define TEG and PCM
- Testing

HIGH TEMPERATURE CFD
- Finalize vehicle locations & mesh
- Run cases with pseudo TEG

HIGH TEMPERATURE

FLIGHT TEST