# Ultrasonic Thermometry for Recession Measurements in Ablative Materials

5th Ablation Workshop: University of Kentucky : February 28, to March 1 2012

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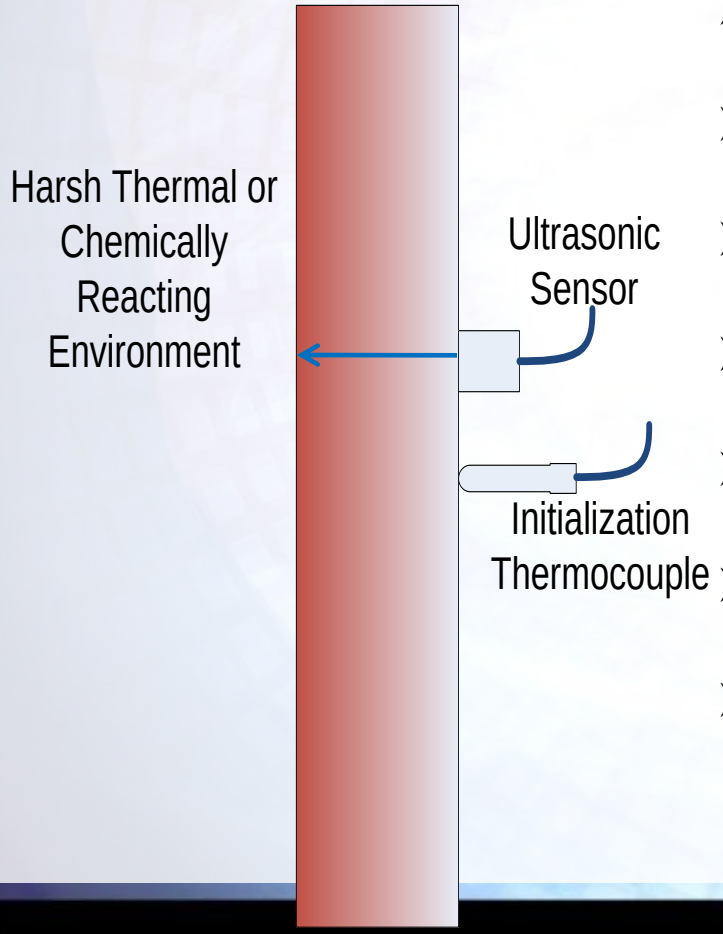
# Outline

- Background of Ultrasonic Thermometry
- Applications
  - Regenerative Combustors
  - Extreme Temperature
  - Thermal gradients
- Re-Entry Applications:
  - Challenges
  - Recession Measurement Concept
  - Scoping studies

# Background

- Auto ignition or “cook-off” is one of the most serious safety concerns when firing large caliber guns.
- NETS - Non-intrusive Erosion & Temperature Sensor

# Background




## Key Components

- **Ultrasonic Sensors**
- **High Speed Data Acquisition**
- **High Bandwidth Ultrasonic Instrumentation**
- **High Speed Data transfer/Storage**
- **Independent Temperature Sensor /Normalization**
- **Cooperative/Characterized Materials**
- **Relevant Property Data over Operating Range**

# Background

Overarching integral relationship:

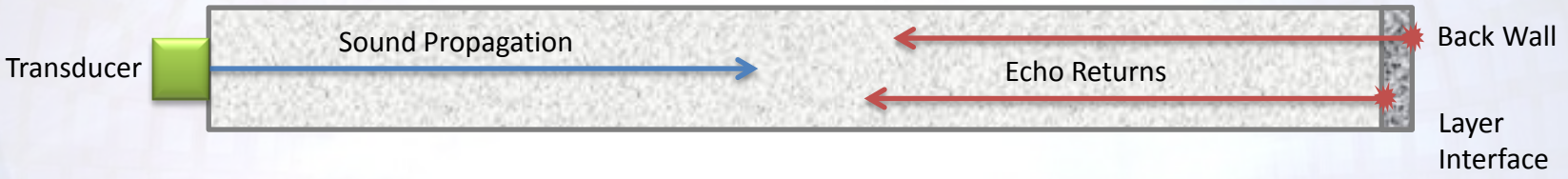
$$G = 2\int_0^L \frac{1}{V(T(x))}\,dx \approx \frac{2}{V_0}\int_0^L [1 + \xi\theta(x)]\,dx$$

$G$ = Ultrasonic ToF
$L$ = Length of Propagation
$\xi$ = Velocity-Expansion coefficient
$V_0$ = Velocity of Sound at reference temperature $T_0$
$\theta(x) = T(x) - T_0$

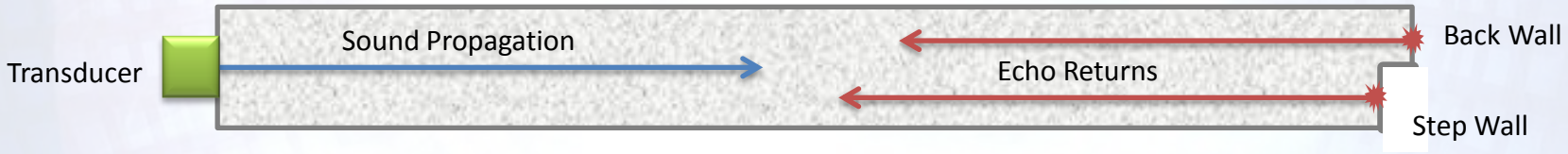
Under isothermal thermal conditions, $\frac{\Delta G}{G} = \xi(T - T_0)$

# Background: Localization

## Layered Structural Echoes

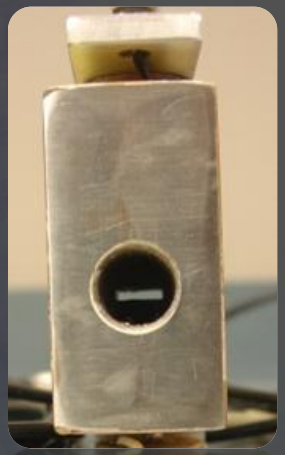


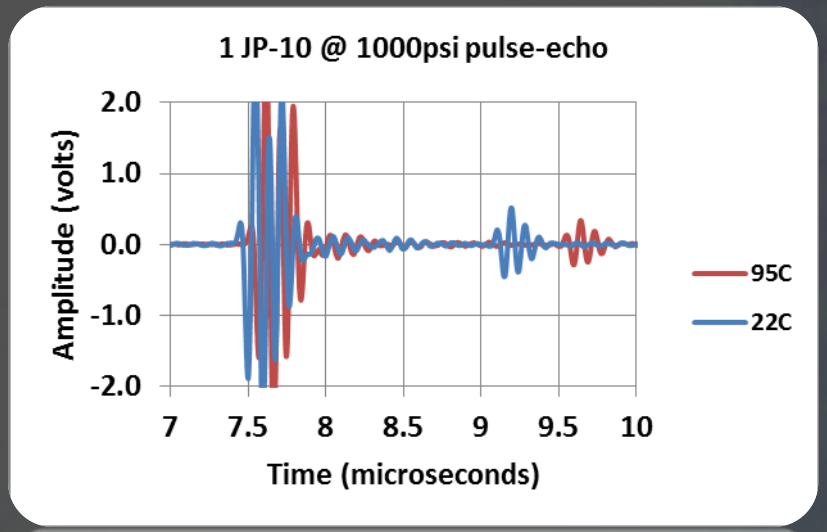

## Step Structural Echoes

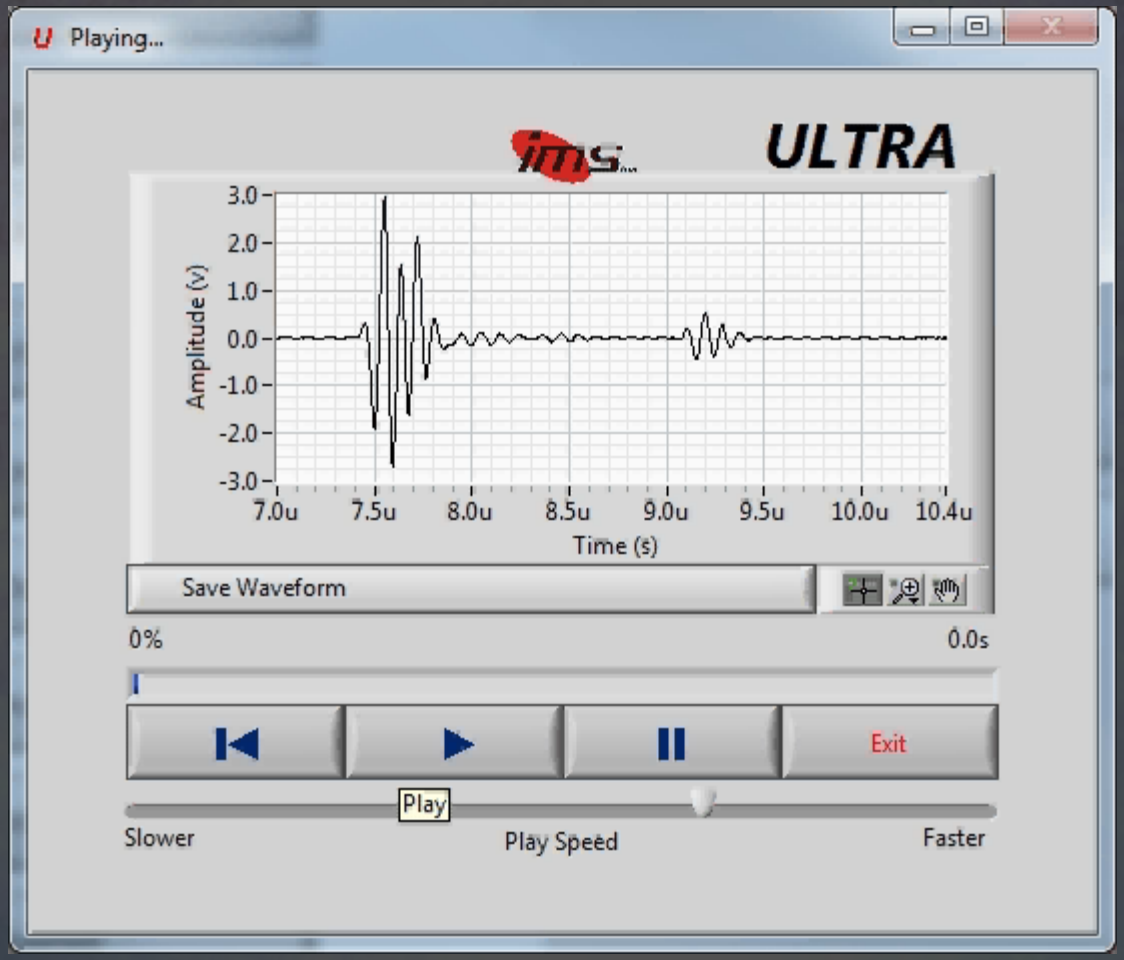



## Backscatter Structural Echoes

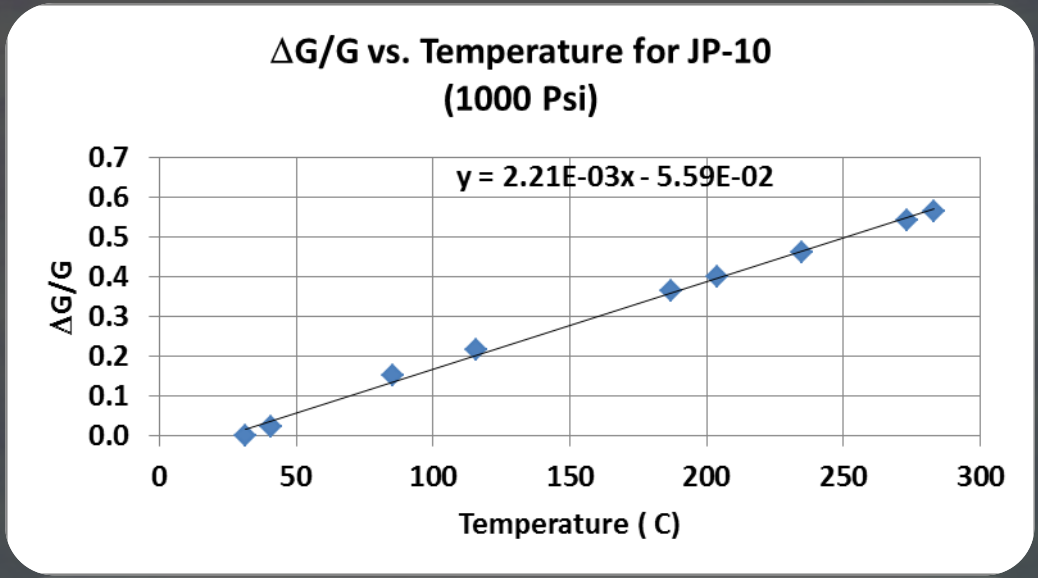
# Propulsion Applications



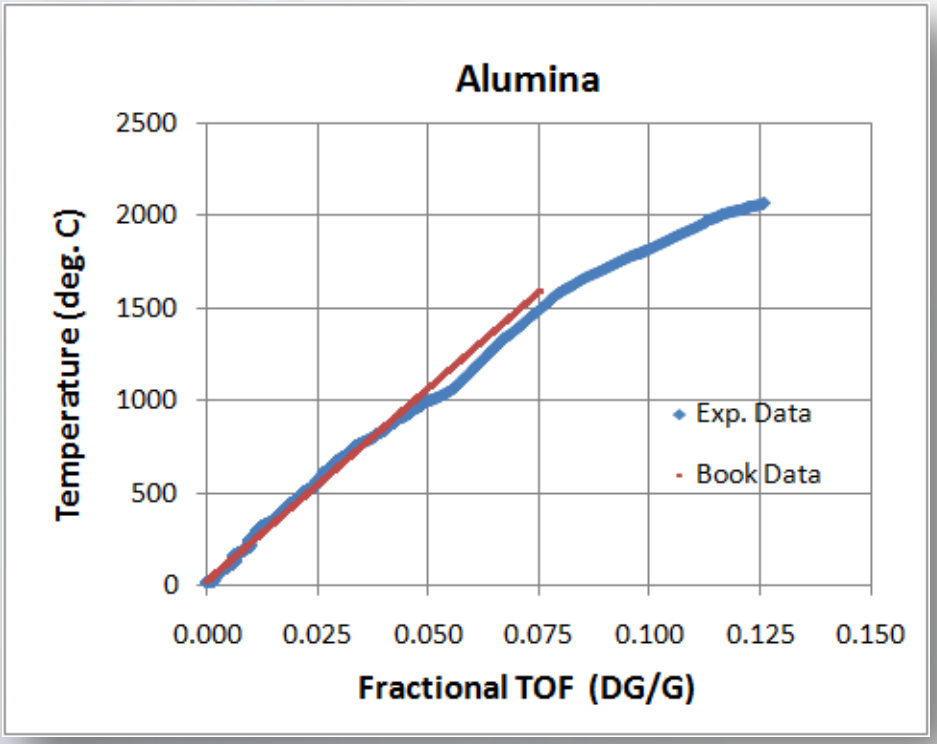


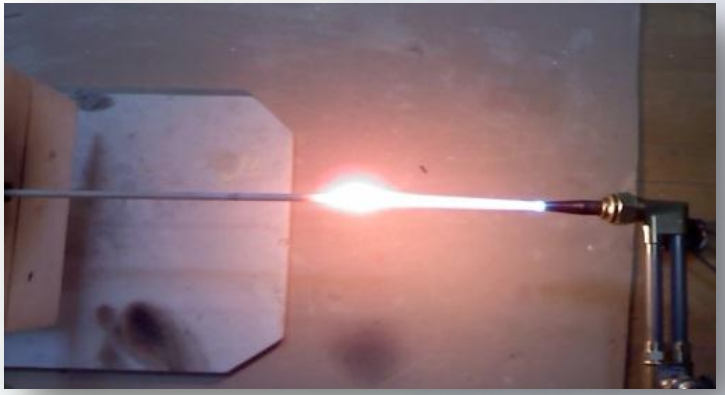

Playing...
ULTRA
Amplitude (v)
3.0
2.0
1.0
0.0
-1.0
-2.0
-3.0
7.0u
7.5u
8.0u
8.5u
9.0u
9.5u
10.0u
10.4u
Time (s)
Save Waveform
0%
0.0s
Exit
Play
Slower
Play Speed
Faster

# Propulsion Applications

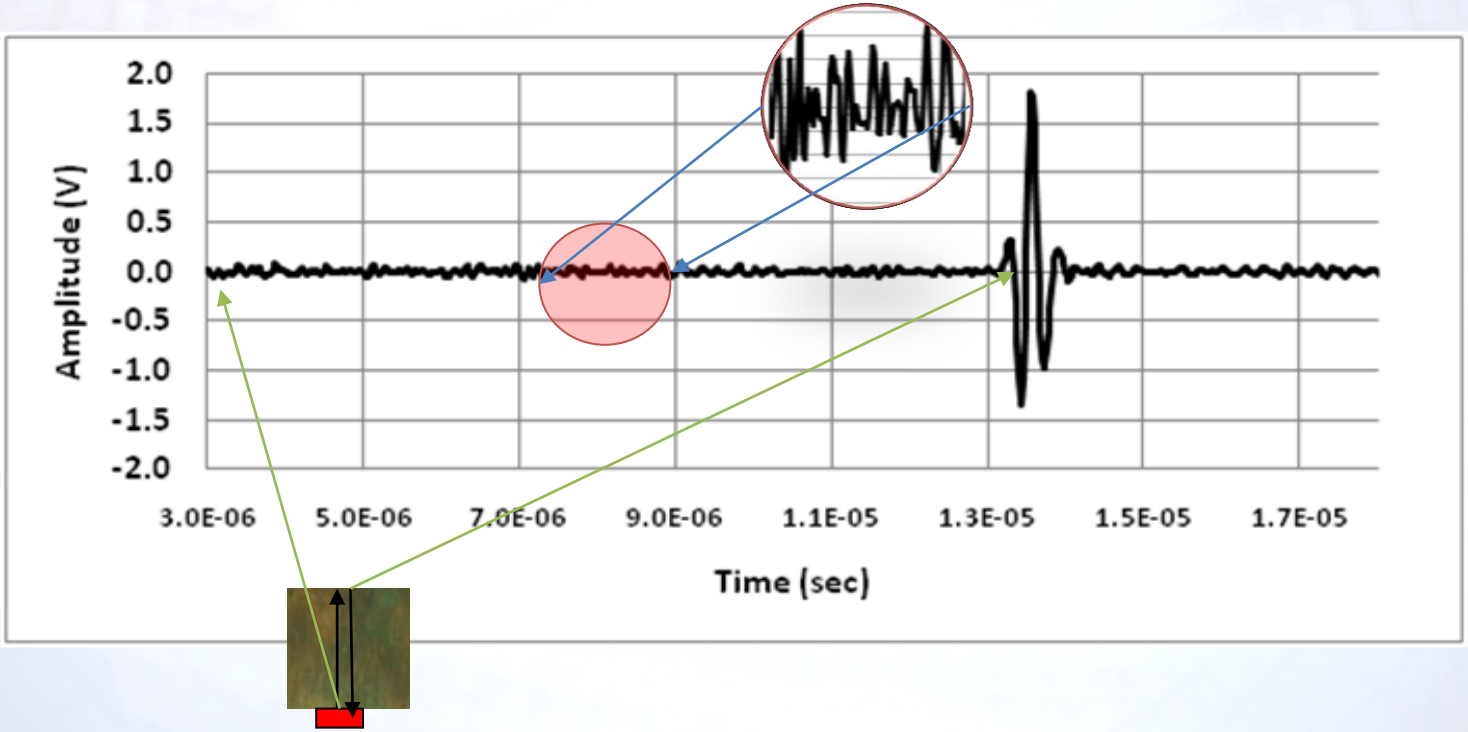


# Extreme Temperatures



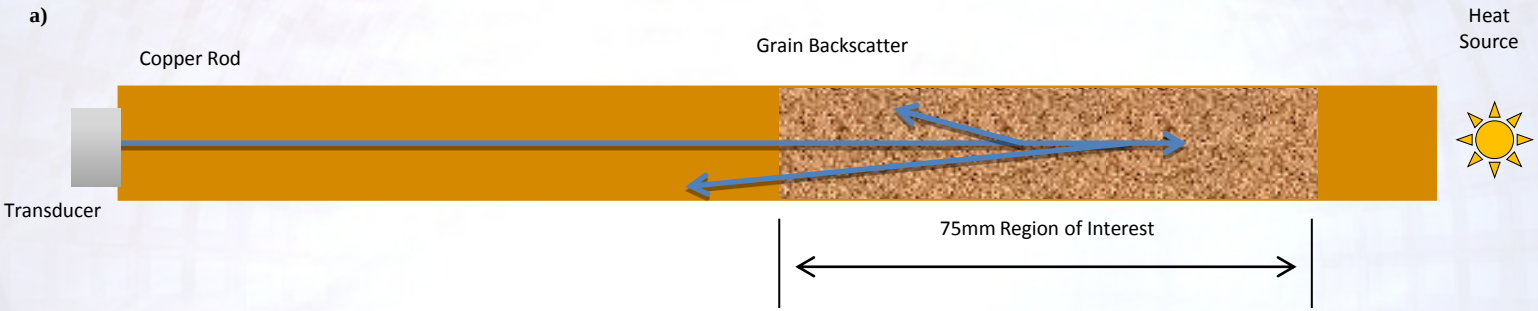



# Backscatter: Copper

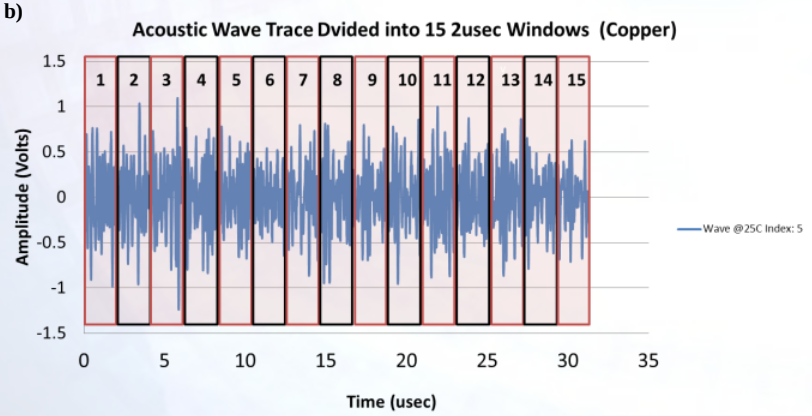


# Backscatter: Copper

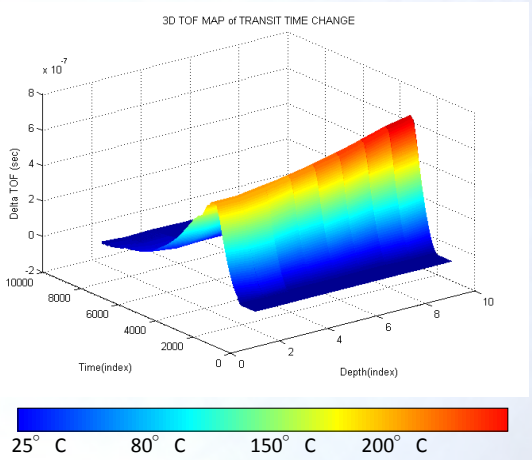
a)



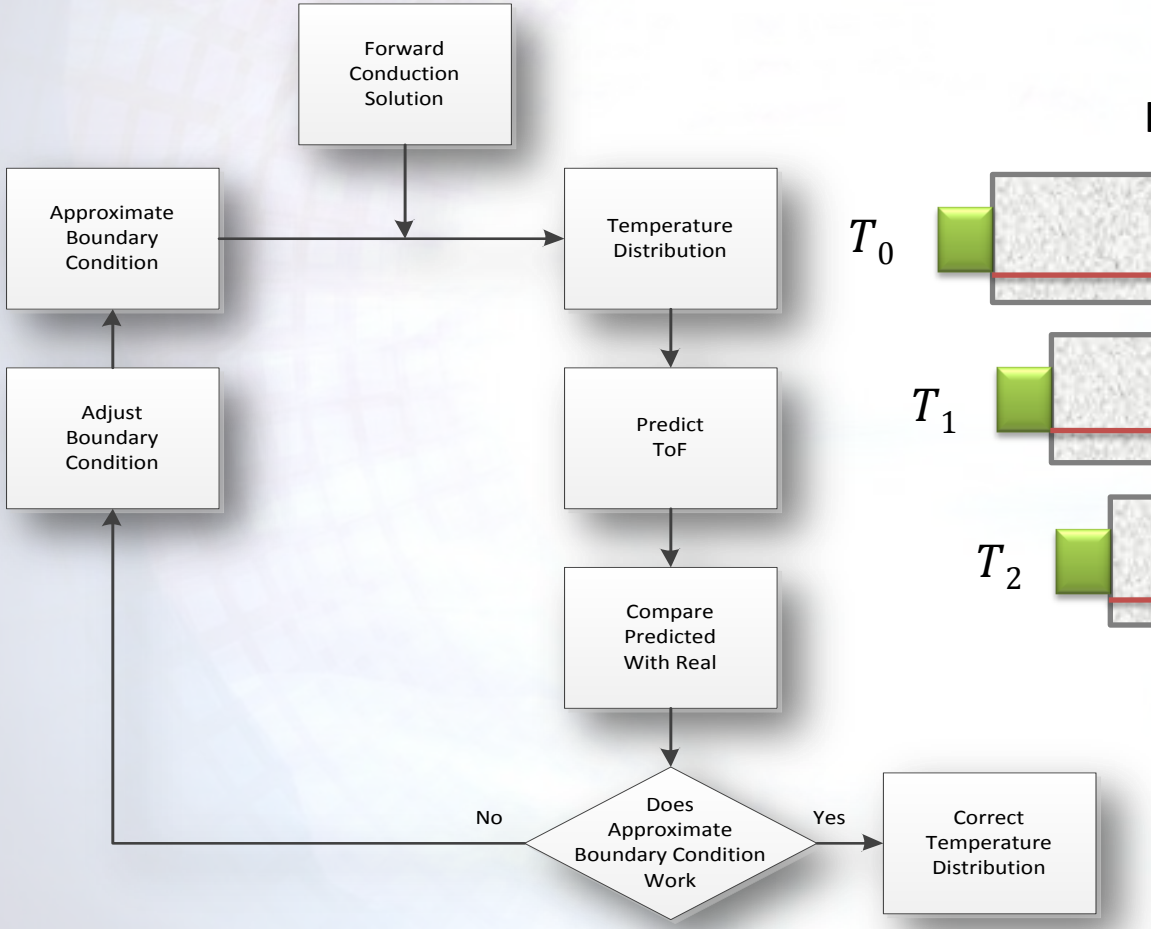

b)

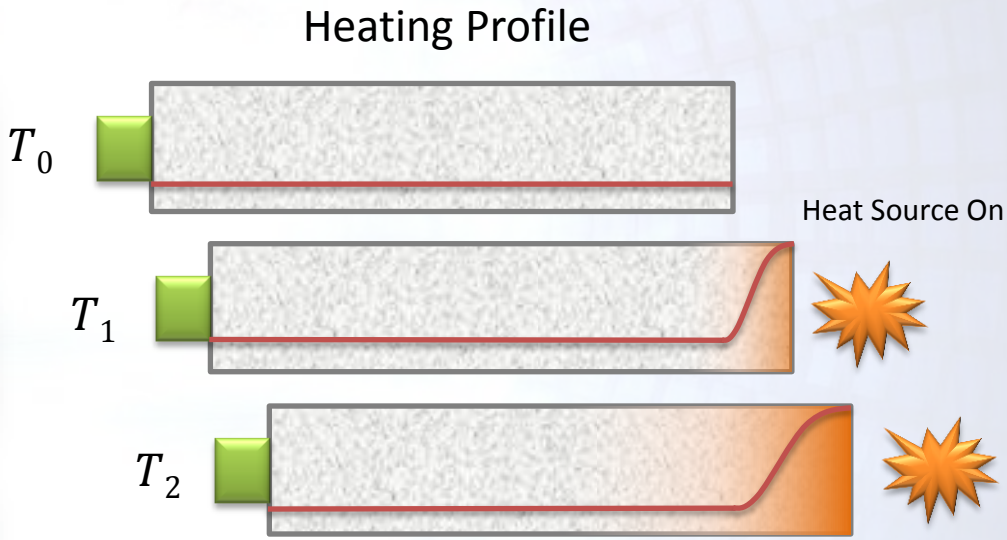



C)

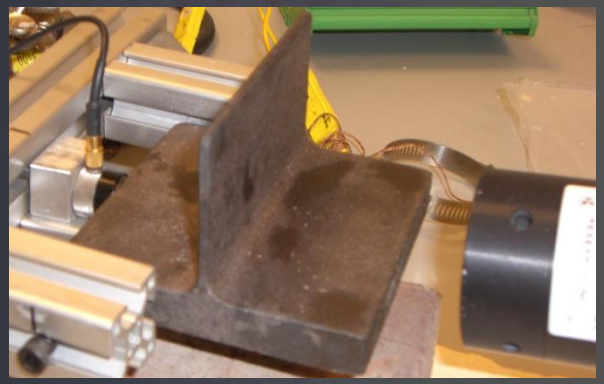


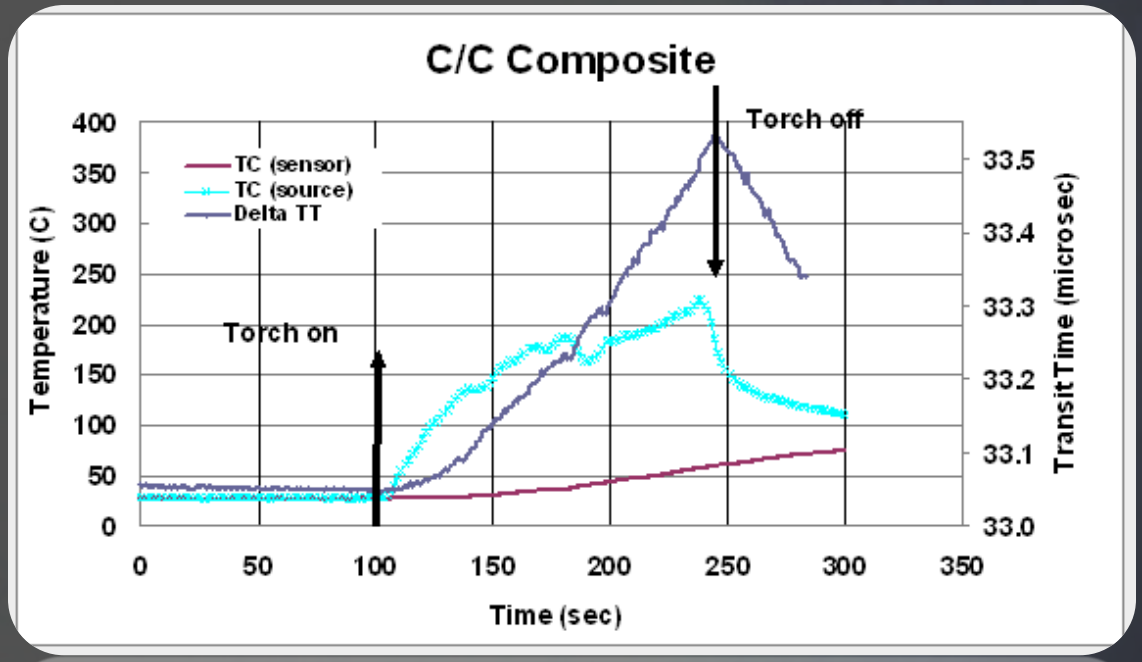
# Inversion and Heat Flux



# Re-Entry Applications





# Re-Entry Applications

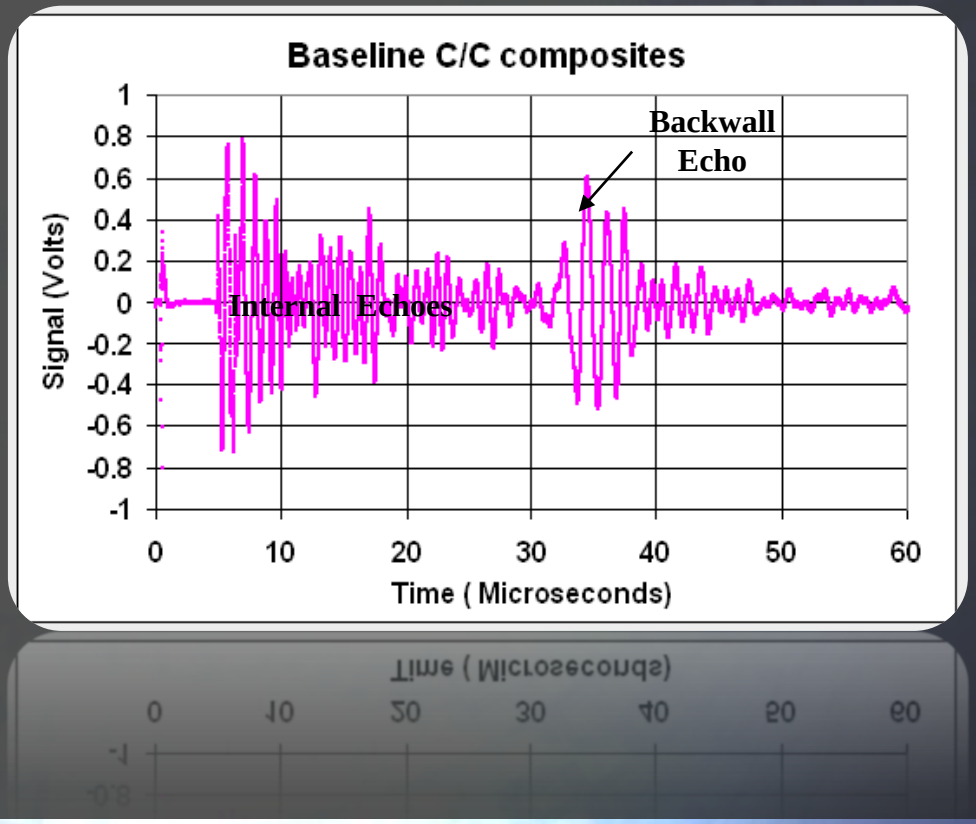
## Challenges:

**High Attenuation**

**Significant Backscatter**

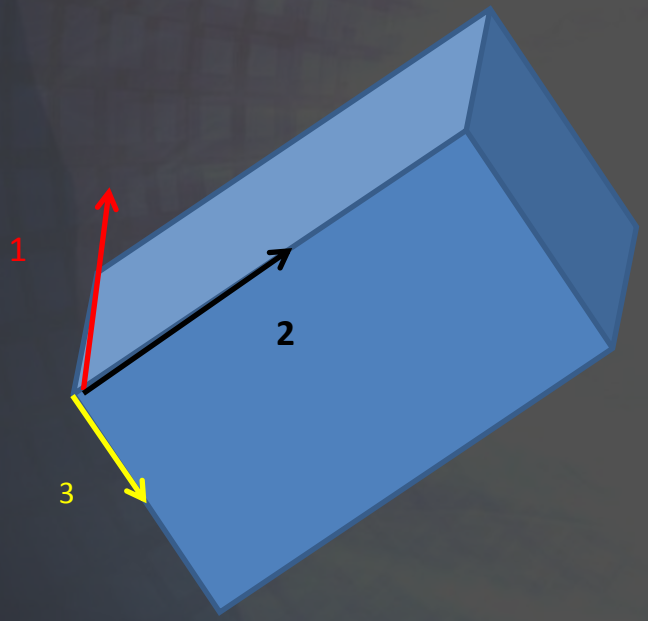
**Anisotropy**

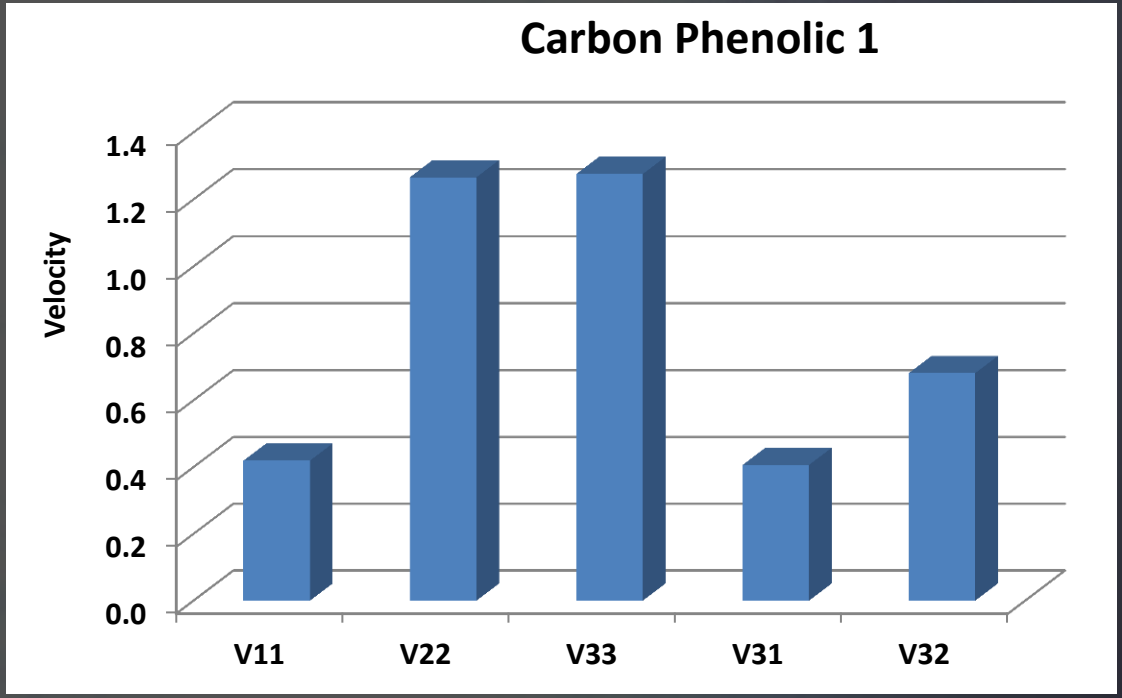
**Recession/Temperature**



# Anisotropy

## Re-Entry Applications:



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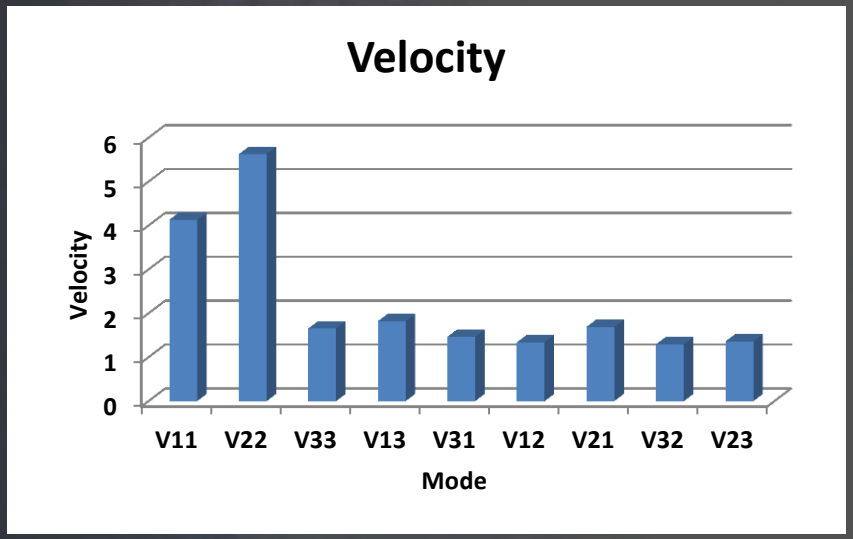
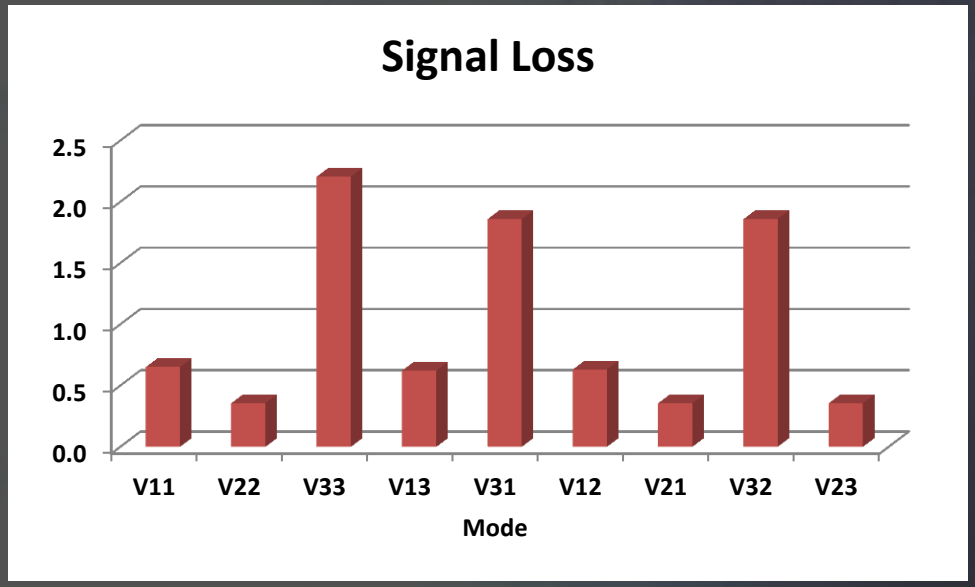



## Carbon Phenolic 2



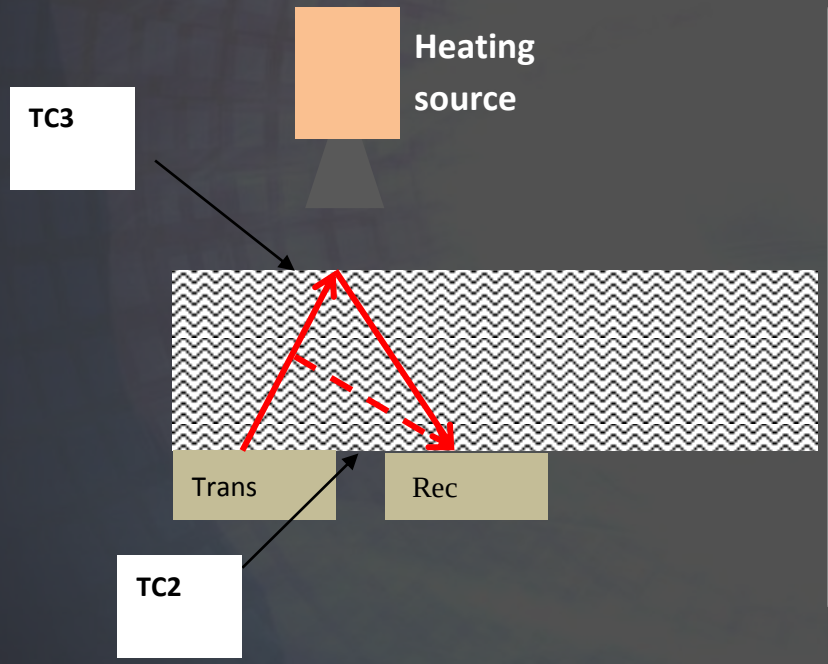
# Re-Entry Applications

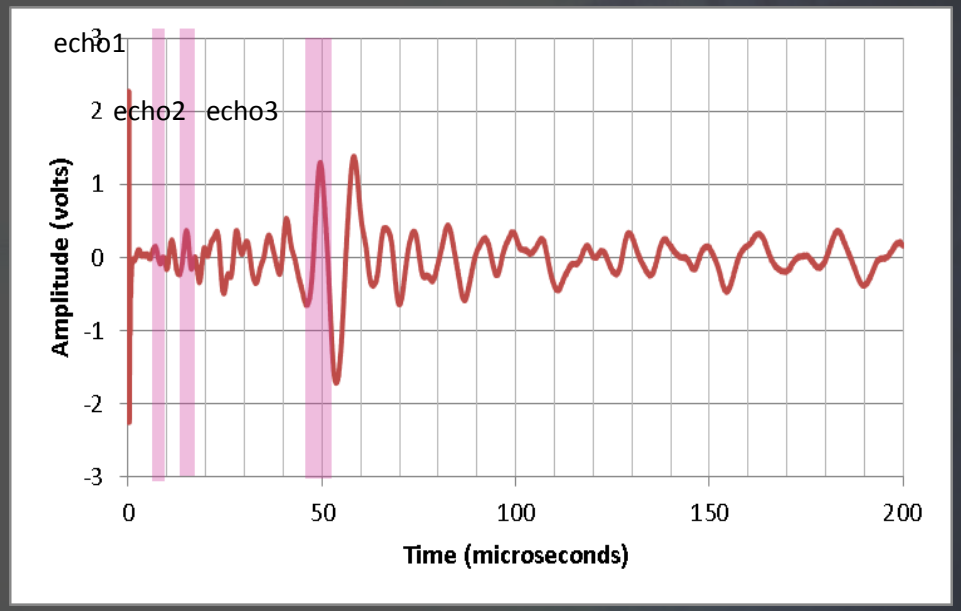
## Recession Measurement Concept

$$\Delta G(t) = [{}^{\partial G}/_{\partial L}]\Delta L(t) + [{}^{\partial G}/_{\partial \theta}]\,\langle \Delta\theta(t)\rangle$$

- **Determine frequency & configuration**
- **Understand echo origin & Measure ultrasonic properties**
- **Track & measure Δ G for eroding surface**
- **Use non-eroding, internal, backscatter echoes to estimate temperature and material property effects**

# Re-Entry Applications



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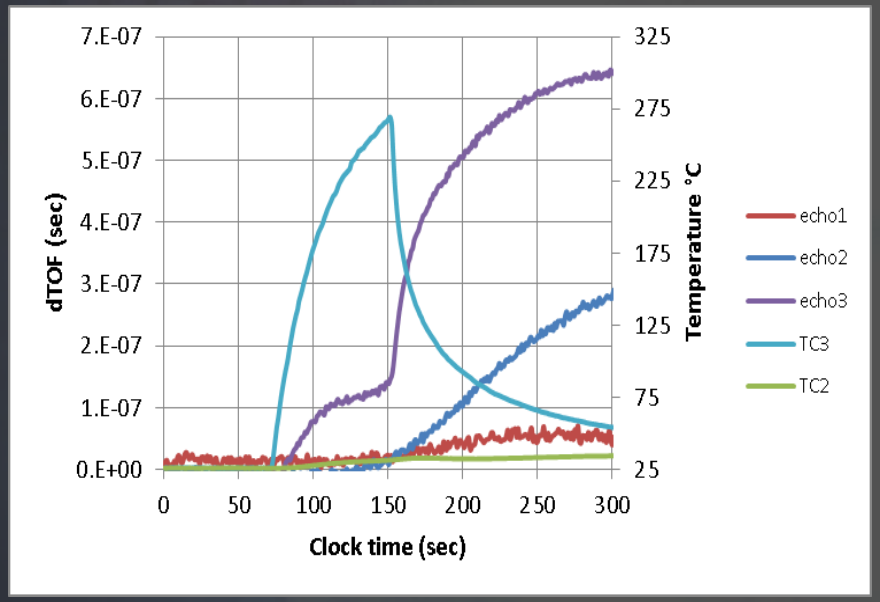


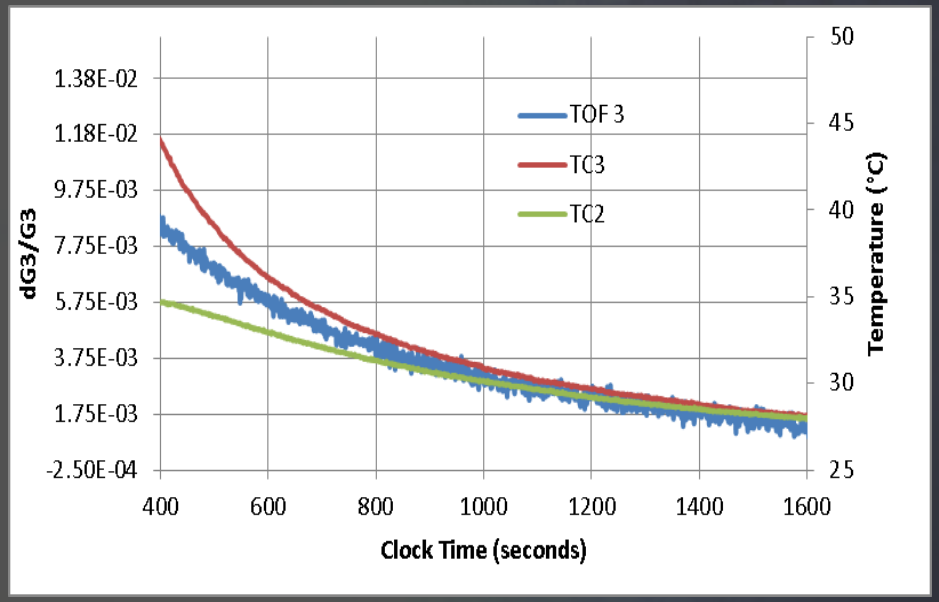

# Summary

- Ultrasonic Thermometry:
  - Model-independent local temperature measurement
  - Only material property needed for temperature measurement is the Velocity-Expansion Coefficient
  - Material structure becomes the sensor
    - Non-destructive, Non-Intrusive
    - Remote mounting away from harsh, chemically reactive environments
    - Does not disrupt thermal transport
    - Rapid Response
  - Backscatter useful for correcting recession data.

# Next Steps

- Continue Scoping Experiments
- Velocity-expansion Coefficient
- Real-time Studies
- Backscatter Temperature Analysis
- Need Teaming Partners  for Phase II programs

# ACKNOWLEDGEMENTS:

## Co-conspirators

| | |
|---|---|
| Mark Mutton, Jack Remiasz, Carol Vorres | IMS Inc. |
| Dr. Joseph Koo | University of Texas |
| Dr. Greg Walker and Michael Myers | Vanderbilt University |

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INDUSTRIAL MEASUREMENT SYSTEMS, INC.

# Back-up Slides

# Background

- Maximum probe operation: ~500°C
  - But probes can be mounted remotely
- Fast Response: 5000Hz
  - 50 kHz under development
- Heat Flux measurement not limited by thermal mass
  - 2 - 170,000 KW/$m^2$ have been demonstrated to date

# Background

- Maximum probe operation: ~500°C
  - But probes can be mounted remotely
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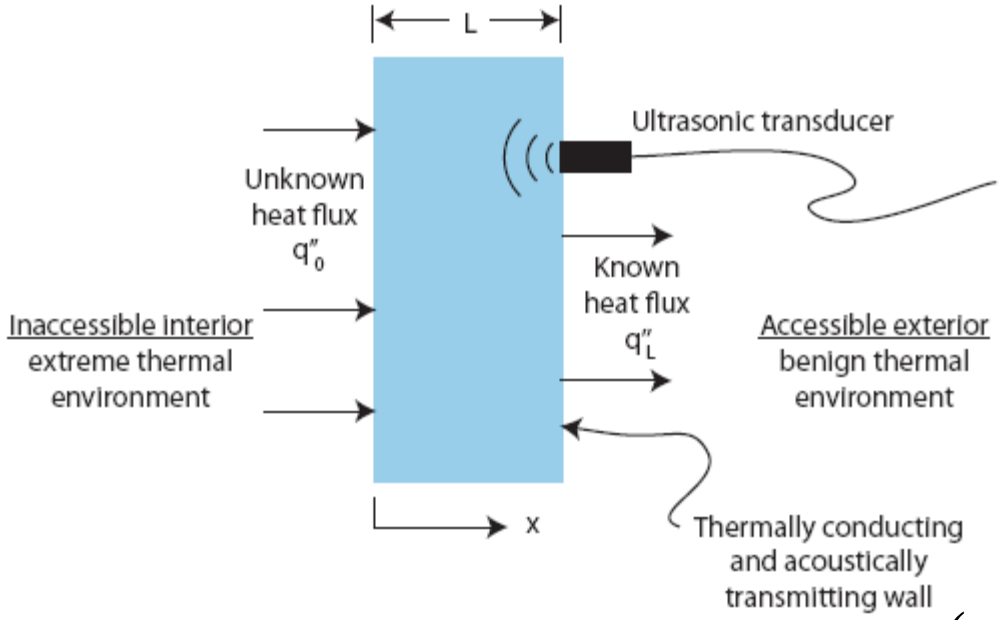
# Instrumentation

# One Dimensional Model & Heat Flux




$$G = \frac{2}{v_0}\int_0^L [1+\xi\theta(x)]dx.$$

$$G = \frac{2L}{v_0} + \frac{2\xi}{v_0}\int_0^L \theta(x)dx.$$

$$q''(x=0) = \rho c_p \int_0^L \frac{\partial\theta(x)}{\partial t}dx + q''(x=L).$$

$$q''_0 = \frac{\rho c_p}{\Delta t}\int_0^L \Delta\theta(x)dx + q''_{L,}$$

# SIGNIFICANCE OF ΔG

$$q_0'' = \frac{\rho c_p}{\Delta t}\frac{c_0 \Delta G}{2\xi} + q_L''.$$

$$q_0'' = \frac{L\rho c_p}{\xi}\left(\frac{\Delta G}{G_o}\right)\frac{1}{\Delta t} + q_L''.$$

**Change in the time-of-flight from one pulse to the next is really a measure of the stored energy in the system**

# Contact

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