Terahertz NDT on Insulation Materials

Introduction:

Insulation materials are critical for safeguarding the structural integrity of aerospace vehicles against extreme heat, erosion, and mechanical pressure. **TeraLumen's Terahertz (THz) technology** provides a non-contact, non-ionizing insights for verifying bonding integrity, layer thickness, and subsurface defects.

We have successfully evaluated two primary classes of insulation with our terahertz technology: **Silica Tiles** and **Inhibition Materials**.

1. Silica Tiles

Silica tiles are lightweight, highly porous ceramic insulators engineered for extreme thermal protection. Silica tiles (e.g., LI-900) are mad of composite materials that includes silica, alumina-borosilicate and aluminum oxide.

- **Thermal Properties:** Withstands up to 1,200°C by radiating heat and maintaining low thermal conductivity.
- **THz Transparency:** With a composition of approximately 90% air, the material exhibits a low **dielectric constant (approx. 1.13)** and a low **loss tangent (tan δ ~4 x 10^{-4})**, making it highly transparent to THz frequencies.

Typical Composite Structure:

1. **Borosilicate Coating (Top):** Black glass layer shedding ~95% of heat.
2. **Silica Core (Middle):** 90% air / 10% SiO_2 fibers; provides bulk insulation.
3. **Felt/Wool (Interface):** Fiber-based buffer to absorb mechanical stress.
4. **Silicone Adhesive (Glue):** Flexible bond between tile and airframe.
5. **Substrate (Aluminium/CFRP):** The primary structure; acts as a total THz reflector (back-wall).

2. Inhibition Material:

Inhibition materials (often referred to as **ITP** or **Inhibition Thermoplastic/Polymer**) are critical components in high-heat shielding systems. This material is specialized, high-density compound designed to prevent chemical migration and provide an additional layer of thermal buffering. Unlike the highly porous silica core, these materials are typically dense, often composed of a fluoroelastomer or a refined thermoplastic matrix. They serve as a critical "inhibition" layer, protecting the underlying structural components from the volatile off-gassing or oxidative products generated during extreme thermal cycles. Due to the material's higher dielectric constant (typically 2.0), THz Time-Domain Spectroscopy (THz-TDS) can precisely measure the thickness of the inhibition layer to within tens of microns.

Traditional Inspection & Challenges for Silica and Inhibitor:

- **Visual Inspection:** It can be used to inspect visual defects only. Users can detect visible cracks, chips, or coating damage. However, this technique cannot be used to detect internal problems such as subsurface cracks or adhesive bond failure after the applied to substrate.
- **Tap testing:** This is a contact-based testing technique. It is done by gently tapping the tile and listening to the sound. A change in sound reflections may indicate issues in the coating structure or bonding. This method depends heavily on the inspector's experience. Results may vary from person to person, and internal defects are often missed.
- **Ultrasonic Testing:** This is a well-known NDT technique for sub-surface defect detection. To inspect low density materials, very low frequency probes are used. Due to SNR and less penetrable capability, this testing method was found to be ineffective.

Terahertz Inspection Workflow:

Step 1: Define the Inspection Requirement

- Material type: Silica / Inhibitor / Polymer
- Target outputs: Thickness map / Bond quality map / Defect map

- Acceptance limits: tolerance, minimum detectable defect size, scan area, cycle time

Step 2: Material Feasibility & Setup Selection

- Measured refractive index (n) and absorption (α) across the usable THz bandwidth
- Decide configuration: Reflection mode (preferred for bonded stacks)
- Choose best geometry: near-normal incidence to maximize return signal and reduce artefacts
- Fix standoff distance and spot size (example: ~1.5 mm focal spot, controlled standoff)

Step 3: Calibration & Scan plan

- Daily reference scan
- Calibrate with known thickness standards/ known defect inserts
- Convert time-delay → thickness using measured n (note uncertainty)
- Set gates for coating/interface echoes + back-wall reflection

Step 4: Scanning & Data Acquisition

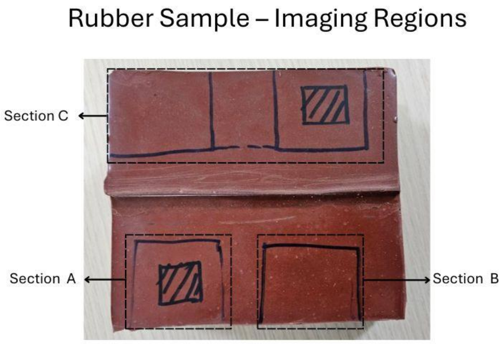
- Scan (point/line/area) with step size matched to spot; set averaging for porous/scattering regions
- Monitor drift (timing) and amplitude stability (standoff/coupling)

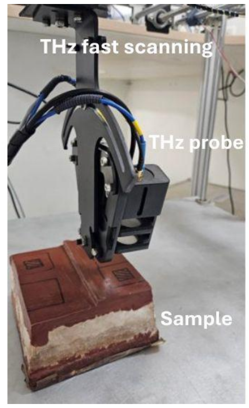
Step 5: Feature Extraction & Decision Outputs (Choose one)

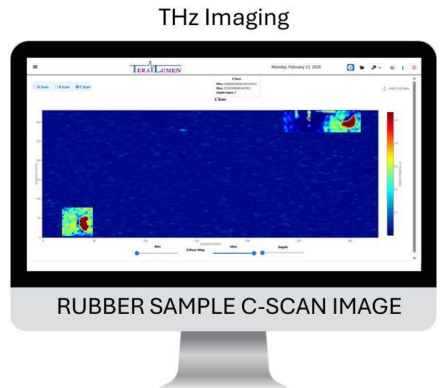
1. Thickness Map (best for inhibitor layer; micron-level potential depending on setup)
2. Bond Integrity Map (interface reflectivity + phase change indicators)
3. Defect/Anomaly Map (voids, cracks, delamination, moisture-like signatures)

Step 6: Reporting

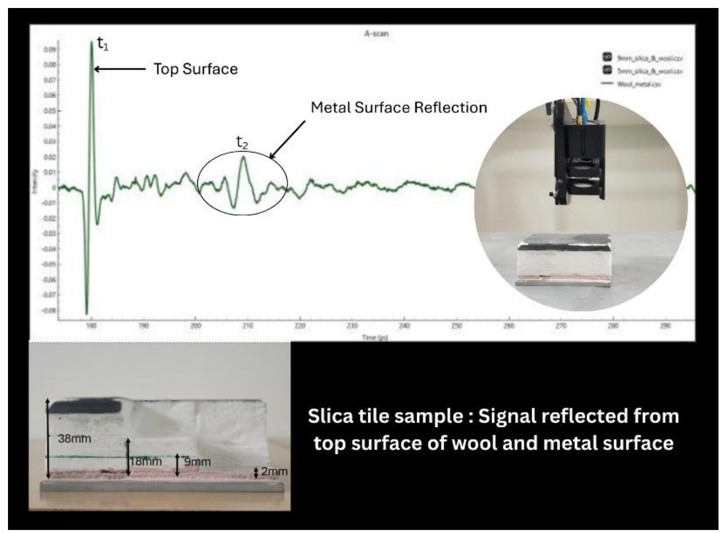
- Report: recipe/settings + gates, C-scan images, pass/fail with defect locations and confidence notes







THz Inspection Results & Key Advantages:



- THz Probe setup was in reflection mode with 1.5mm THz Focal spot
- Measured Refractive Index (n) for silica at 1.07 and for the inhibition material at 2.0 between selected bandwidth within 0.1 to 3.5 THz.
- Penetration Depth: Successfully penetrated layers up to 18 mm in silica and 25mm in Inhibitor. Terahertz waves are capable to penetrate up to >40mm with a high power configurations.
- Defect Imaging: Identified hidden porosities and debonding as shown in the imaging.
- **Chemical Monitoring: Potential to monitor the curing state or thermal degradation of the polymer matrix in the inhibition layer,** identifying regions where the material may have lost its inhibitory properties.

Conclusion:

We found the THz-TDS system is capable to inspect silica and inhibitor materials. By allowing analysis on the material's refractive index and internal structure, gives the ability to user to verify the material integrity. Using a high signal-to-noise data acquisition system, better THz

Probe bandwidth and an optimized optical setup at normal incidence can improve penetration depth. With these improvements, the system is expected to penetrate >40 mm in materials having refractive index between 1.0 to 2.0.