Advanced in Pulsed Thermography for NDT

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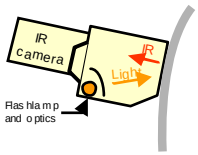
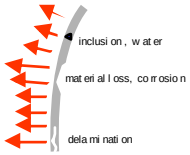
Basic Technology: Flash Thermography





EchoTherm® heats the sample surface with a light pulse, and then measures the surface temperature response to the flash with an IR camera.

Subsurface variations in the sample cause subtle changes in the way that IR energy radiates from the surface of the part.

Heat surface → Capture cooling sequence → Identify anomalous cooling

Pulsed Thermography

- Non-contact
- Fast
- Wide area
- Quantitative
- Curvature tolerant
- Real time

For many components and materials, 1 ft² can be inspected in less than 5 seconds without any surface preparation.

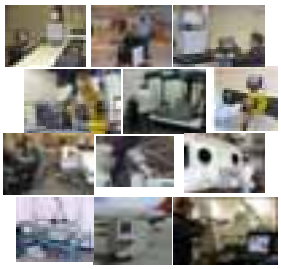
747 tear strap disbond inspection

Corrosion in steel hull of Coast Guard patrol boat.

Pulsed Thermography In Action

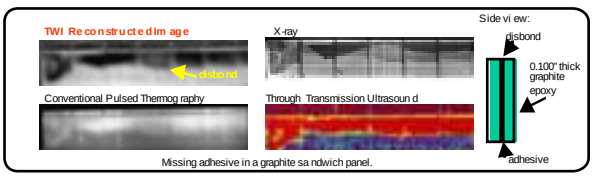
For manufacturing, maintenance or R&D…

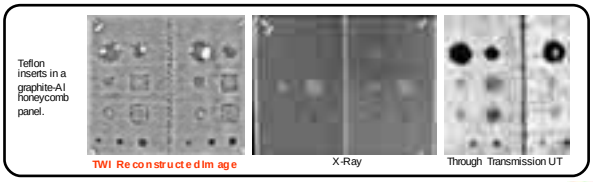
- Delamination
- Adhesive disbond
- Impact damage
- Corrosion
- Water entrapment
- FOD
- Thickness measurement
- Porosity
- TBC coating measurement



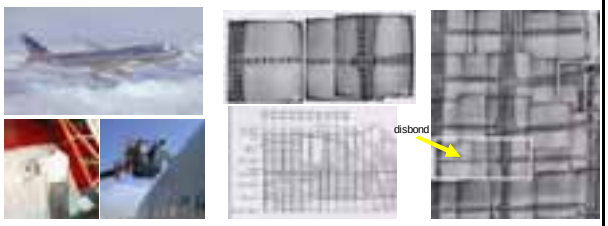
Customers (partial list)

A Viable NDT Alternative



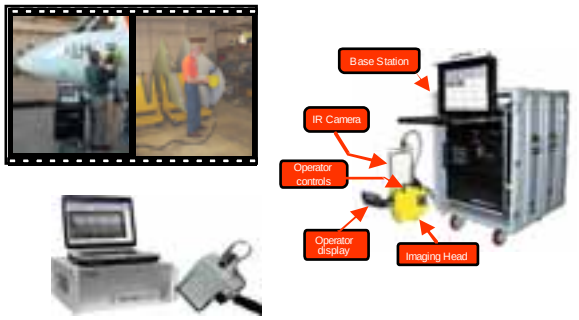


Boeing Service Bulletin 747-53A2409



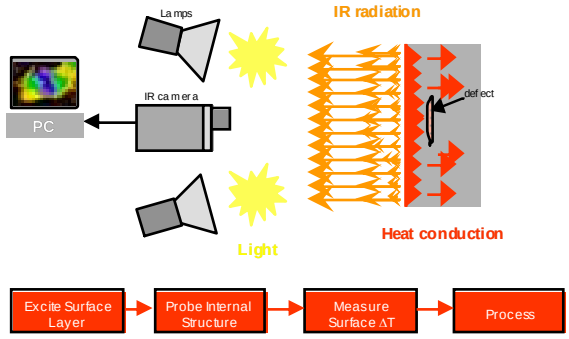
- Approved August 2001
- First commercial aircraft approval of Pulsed Thermography inspection
- For detection of 1" x 1" disbonds under 0.10" of skin or less
- For Al – Al doubler disbonds on all 7x7 aircraft
- Uses TWI EchoTherm® and MOSAIQ™

Modern Thermography Equipment



Issues and Problems

Pulsed Thermography Basics



Three Distinct Physical Processes

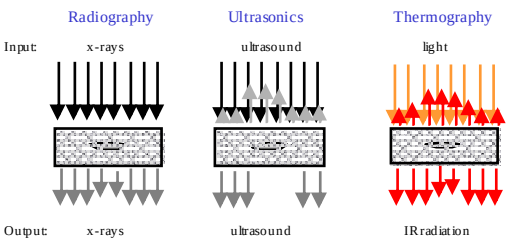
Light
Hot air
Hot water
Cold water
EM induction
Acoustic

Heat conduction

IR radiation

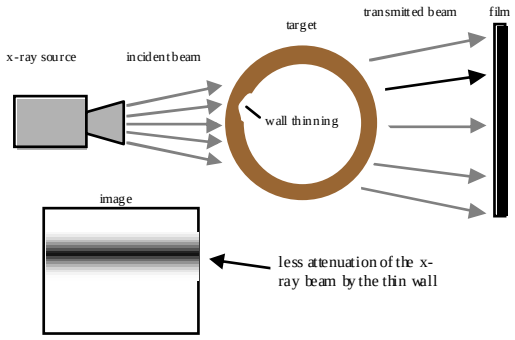
Each process must be optimized and understood or misleading and incorrect results may occur.

Thermography is an Indirect Process



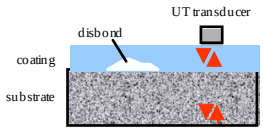
In thermography, we only infer what is beneath the surface, based on the surface temperature response.

Industrial Radiography



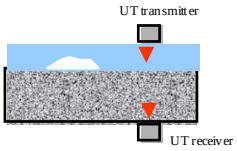
Industrial Ultrasonics

Pulse-echo mode



UT is reflected at interfaces

Through transmission mode

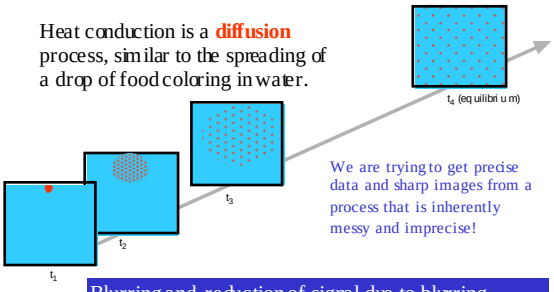


UT is attenuated by poor conductors

- Contact and UT conductive couplant required.
- Image is built by scanning single point.
- Resolution depends on transducer size.

A Fundamental Problem!

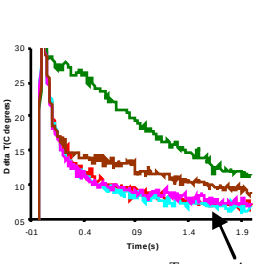
Heat conduction is a **diffusion** process, similar to the spreading of a drop of food coloring in water.

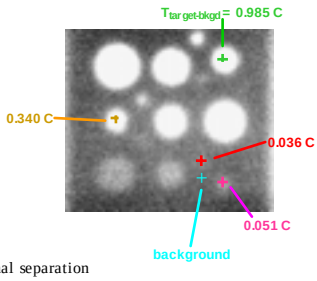


We are trying to get precise data and sharp images from a process that is inherently messy and imprecise!

Blurring and reduction of signal due to blurring becomes more severe as time progresses.

Target – Bkgd Contrast May be Extremely Small





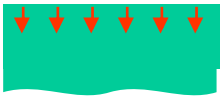
Target – signal separation is difficult as signal amplitude is on the order of camera noise.

Thermographic Signal Reconstruction

Semi-Infinite Model

1-d diffusion equation:

$$\frac{\partial^2 T}{\partial z^2} - \frac{1}{\alpha}\frac{\partial T}{\partial t} = 0$$



Thick, defect free sample

Solution for surface temperature due to a uniform, instantaneous heat pulse:

$$\Delta T = \frac{Q}{e\sqrt{\pi t}}$$

Taking the log of both sides:

$$\ln(\Delta T) = \ln\left(\frac{Q}{e}\right) - \tfrac{1}{2}\ln(\pi t)$$

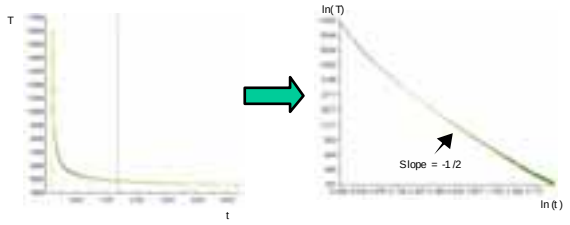
Q = input energy

e = thermal effusivity ($K\rho c$)

In the logarithmic domain the time dependence and material properties are separated.

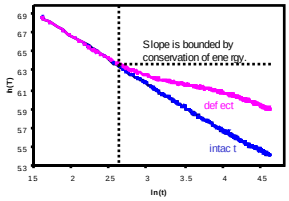
Transform to Natural Log Domain

$$\ln(\Delta T) = \ln\left(\frac{Q}{e}\right) - \tfrac{1}{2}\ln(\pi t)$$



Log T-t plot of a defect free sample is a monotonically decreasing straight line with slope –0.5.

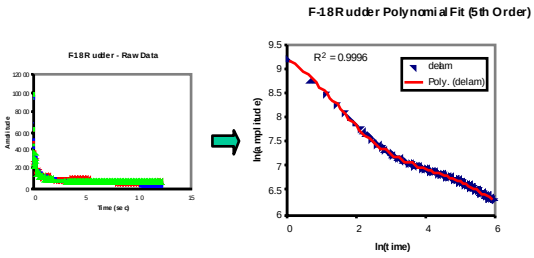
Log Curves are "Well-Behaved"



- Monotonically decreasing
- No transient thermal events
- Function and derivatives are continuous

Although the plot of a defect point is not linear, its behavior is constrained and relatively smooth. It can easily be approximated by a series expansion.

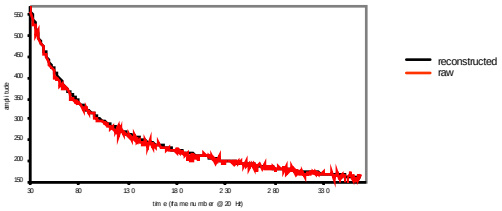
Polynomial Fit of ln(T-t) Data?



- 368 data points reduced to an equation with 5 coefficients
- Temporal noise reduced (low pass filter) with low order polynomial

Thermographic Signal Reconstruction

A New Approach to Thermographic Signal Processing!



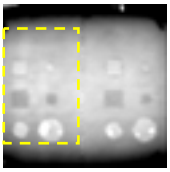
- Based on deviation of pixel cooling from ideal 1-d behavior.
- Accurately replicates thermal characteristics of signal
- Eliminates temporal noise
- Fast conversion (< 10 sec)
- Compact representation

U.S. Patent 6,516,084

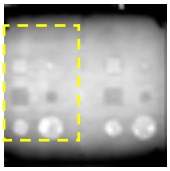
TSR Temporal Noise Reduction

TSR signal / noise improvement is the result of the removal of temporal noise from the pixel time series.

The smaller honeycomb cells are partially obscured by temporal noise in the raw image.



Raw image @ 2.5 sec



TSR image @ 2.5 sec

Temporal noise has been removed in the TSR image derived from the same data sequence.

Derivatives of the Reconstructed Signal

Reconstructed signal:

$$T = A\exp\left(-\sum_{n=0}^{N} a_n \ln(t)^n\right)$$

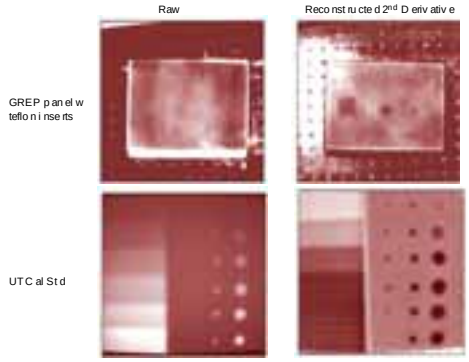
1st derivative:

$$\frac{dT}{d\ln(t)} = \left[\sum_{n=0}^{N} n a_n \ln(t)^{n-1}\right]\exp\left(-\sum_{n=0}^{N} a_n \ln(t)^n\right)$$

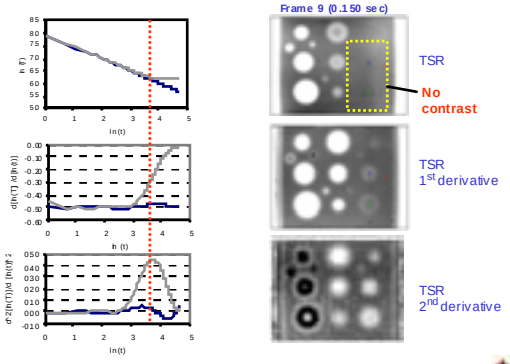
Time derivatives of the reconstructed signal can be calculated quickly and without adding noise to the image.

U.S. Patent 6,516,084

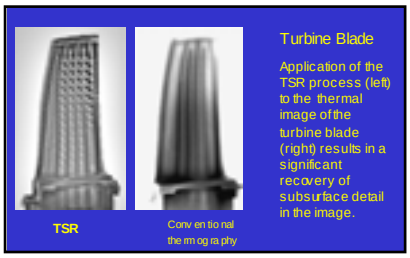
Low Thermal Contrast Features



Earlier Defect Detection With Derivatives



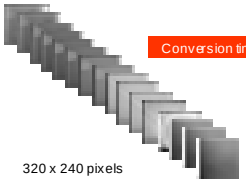
Thermographic Signal Reconstruction (TSR)



The **Thermographic Signal Reconstruction* (TSR)** method gives thermography an unprecedented degree of clarity, penetration depth and resolution.

Reconstructed Image Sequence

5 Second Raw Image Sequence:



Conversion time ~ 10 sec

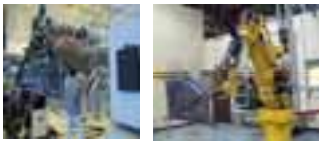
5 Second Reconstructed Sequence:

320 x 240 pixels
x 2 bytes / pixel
x 300 frames

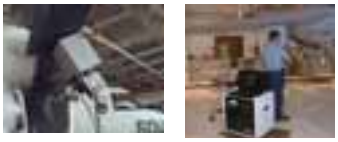
46 MB

We can reconstruct an image for any time in the sequence from a 2-d matrix of the coefficients $a_{i,j,n}$

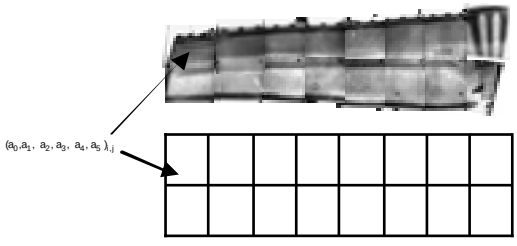
4.5 MB



Large Area Inspection



Reconstruction of Large Area Data

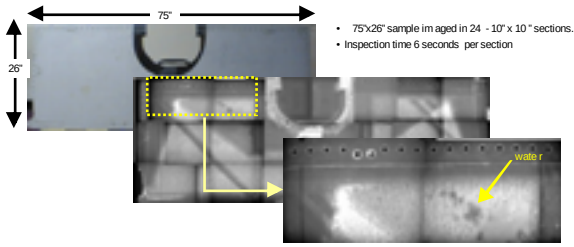


Each sub-image in the mosaic contains the N coefficients for each pixel so that the time sequence can be recreated for the entire mosaic.

Thermographic Signal Reconstruction (TSR)

Inspect the part using EchoTherm or ThermoScope. → A MOSAIQ image of the part is built dynamically as the data is acquired. → Use advanced TSR processing to see hidden subsurface detail.

Example: 757 Spoiler



- 75"x26" sample imaged in 24 - 10" x 10" sections.
- Inspection time 6 seconds per section

Zoom in to look at problem areas in detail.

MOSAIQ allows you to inspect large structures quickly, with a subsurface image of the entire structure

Case Studies: Manufacturing QA

Nordam Mfg. – Engine Cowl Door

Previous NDI: Ultrasound C-scan
Total Inspection time : 4 hours

TWI inspection time: 45 minutes

Boeing St. Louis: Defense aircraft part

Previous NDI: Ultrasound C-scan
Total Inspection time : 12 hours

TWI inspection time: 45 minutes

Case Study: E2-C Inspection

E2-C Hawkeye

Subsurface crack in E2-C propeller

Acceptance inspection

On-aircraft inspection

- Propeller cracks not detectable using conventional NDI
  - Coin tap used previously
  - 16 prop failures
  - X-ray and UT ineffective
- TWI NDI implemented 1998
  - NADEP Cherry Point
  - 100% inspection
  - 1 hour inspection
  - 17 inspectors trained
  - No failures since thermography implemented

Case Study: Large Area Inspection

110ft.

TWI inspection of U.S. Coast Guard Patrol Boat "SAPELO" found corrosion missed by ultrasound.

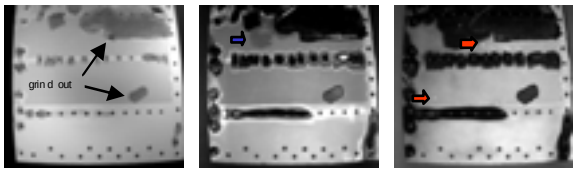
Previous inspection: A-scan UT
- Point inspection only

Thermography
- NADEP Cherry Point
- 100% inspection
- 40% more corrosion identified

110 Foot Cutter: Hull Inspection

LARGE AREA OF BACK SIDE CORROSION.

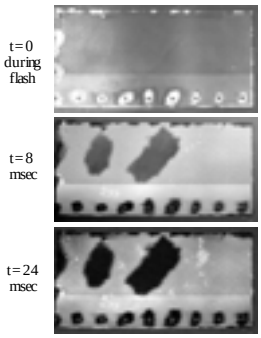
Corrosion Under Paint: F-18 Splitter Plate



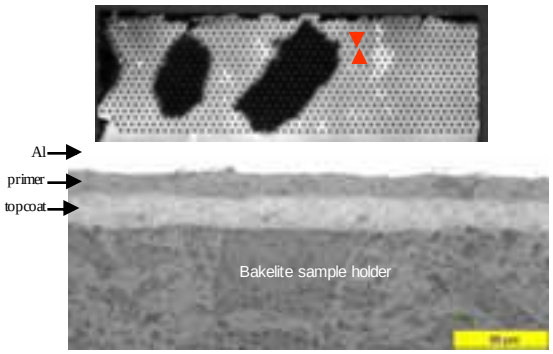
passive IR | t = 0 (during flash) | 8 msec

- Gray paint/chromate primer
- Paint is not IR transparent
- Difficult to inspect with most methods due to acoustic holes
  - 0.150" center to center
  - 0.082" diameter

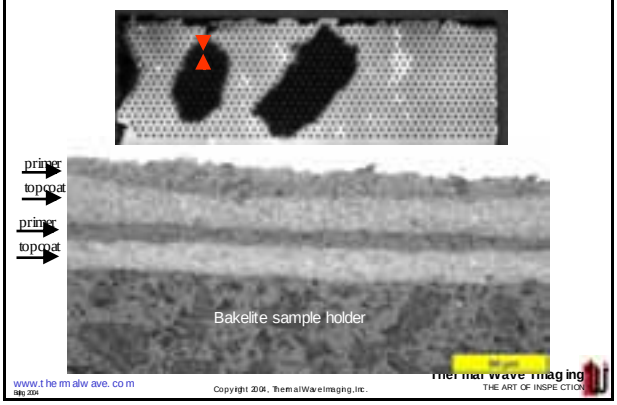
Splitter Plate Section



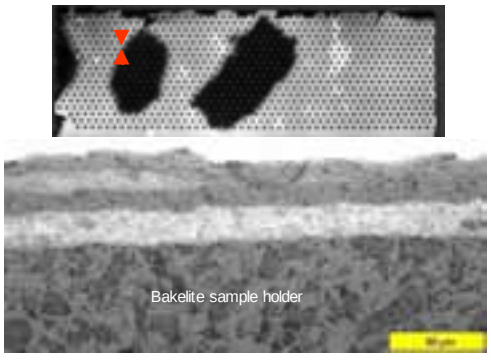
Benign Area @ 200x



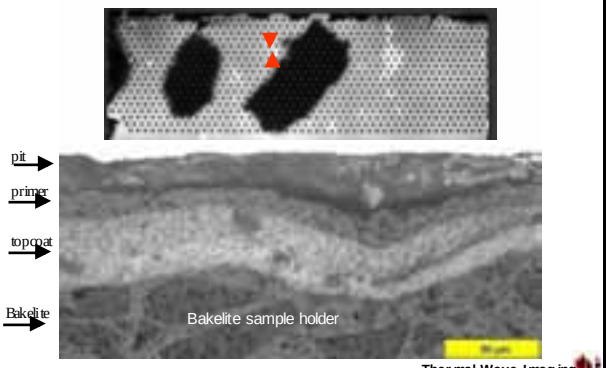
Double Paint / Primer @ 200x



Double Paint Transition @ 200x



Corrosion Under Paint / Primer @ 200x



Thermographic Inspection of Space Shuttle Leading Edge Components

NASA: Space Shuttle Return to Flight

Thermal Wave Imaging has been awarded a contract to assist NASA in developing procedures and best practices for thermographic inspection of the thermal protection system (TPS) on the space shuttle orbiter. The team is using the TWI EchoTherm® system to inspect the Reinforced Carbon-Carbon (RCC) panels on leading edges of the shuttle's wings.

Summary

- There has been a significant increase in the acceptance and use of pulsed thermography for manufacturing and maintenance applications.
- Thermographic Signal Reconstruction increases sensitivity, provides significant reduction of data volume.
- The use of time derivatives allows significant improvement in detection of deep and subtle features.