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A program of basic research was carried out, whose objective was to make the promising qualitative thermal wave imaging NDI technique a truly quantitative tool, which can have a major impact on the rapid, wide-area inspection of Air Force aircraft for hidden corrosion. Such thermal wave images of a square foot (or so) of aircraft skin are acquired on short time scales (a few seconds). Techniques were developed and studied to measure skin thickness and to identify corrosion products. The resulting corrosion analysis has been shown to have a quantitative capability of measuring material losses as small as 1% on aluminum aircraft skins, and can be implemented rapidly to evaluate regions of corrosion which have been identified in the thermal wave images. The technique has also been shown to be capable of measuring intergranular corrosion in the vicinity of fasteners in KC-135 and B-52 wing skins.

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THERMAL WAVE IMAGING OF HIDDEN CORROSION

FINAL TECHNICAL REPORT

R.L. THOMAS, L.D. FAVRO AND P.K. KUO

MARCH 31, 1998

AIR FORCE OFFICE OF SCIENTIFIC RESEARCH

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WAYNE STATE UNIVERSITY

Thermal Wave Imaging of Hidden Corrosion **FINAL REPORT**
R.L. Thomas, L.D. Favro and P.K. Kuo *WAYNE STATE UNIVERSITY*
AFOSR Grant No. F49620-96-1-0166

EXECUTIVE SUMMARY

A program of basic research was carried out, whose objective was to make the promising qualitative thermal wave imaging NDI technique a truly quantitative tool, which can have a major impact on the rapid, wide-area inspection of Air Force aircraft for hidden corrosion. Such thermal wave images of a square foot (or so) of aircraft skin are acquired on short time scales (a few seconds). Techniques were developed and studied to measure skin thickness and to identify corrosion products. The resulting corrosion analysis has been shown to have a quantitative capability of measuring material losses as small as 1% on aluminum aircraft skins, and can be implemented rapidly to evaluate regions of corrosion which have been identified in the thermal wave images. The technique has also been shown to be capable of measuring intergranular corrosion in the vicinity of fasteners in KC-135 and B-52 wing skins.

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Zhong Ouyang (M.S. 1997)

Other: Research Associate/Scientist
Dr. Tasdiq Ahmed
Huijia Jin

Publications

1. "From Photoacoustic Microscopy to Thermal Wave Imaging," R.L. Thomas and L.D. Favro, Invited Paper for the October, 1996 Issue of the Materials Research Society Bulletin on "Acoustic Imaging and Characterization Technique," pp. 47-51 (1996).

2. "Measuring corrosion thinning by thermal-wave imaging," L.D. Favro, Xiaoyan Han, T. Ahmed, P.K. Kuo, and R.L. Thomas, Proc.*SPIE, Scottsdale, AZ, December 3-5, 1996,* Vol. 2945, pp. 374-379 (1996).

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4. " Defect Depth Determination by Thermal-Wave Imaging," L.D. Favro, Xiaoyan Han, P.K. Kuo, and R.L. Thomas, Prog. in Natural Science, Suppl. to Vol. 6, pp. S139-S141 (1996).

5. "Quantitative Thermal Wave Imaging of Corrosion on Aircraft," Xiaoyan Han, L.D. Favro, T. Ahmed, Zhong Ouyang, Li Wang, Xun Wang, Feng Zhang, P.K. Kuo and R.L. Thomas, *Review of Progress in Quantitative NDE*, **Vol. 16**, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 353-356 (1997).

6. "Thermal Wave Imaging for Detection and Quantification of Corrosion and Disbonds in Aging Aircraft," Prof. Xiaoyan Han, Prof. Lawrence D. Favro and Prof. Robert L. Thomas, Proc. First Joint DoD/FAA/NASA Conference on Aging Aircraft, The David Eccles Conference Center - Ogden, Utah, 8-10 July, 1997 (to be published).

7. "NDE of Corrosion and Disbonding Using Thermal Waves," Xiaoyan Han, L.D. Favro, Tasdiq Ahmed, Zhong Ouyang, Li Wang, Xun Wang, P.K. Kuo and R.L. Thomas, *Review of Progress in Quantitative NDE*, **Vol. 17**, edited by D.O. Thompson and D. Chimenti, Plenum New York, to be published (1998).

8. "Quantitative detection and characterization of corrosion in aircraft," Xiaoyan Han, L.D. Favro, and R.L. Thomas, Proc. Workshop on Intelligent NDE Sciences for Aging and Futuristic Aircraft, University of Texas at El Paso, September 30 - October 2, 1997, to be published.

9. "Thermal Wave Imaging of Aircraft for Evaluation of Disbonding and Corrosion", R.L. Thomas, Xiaoyan Han, and L.D. Favro, Proc. 7th European Conference on Non-Destructive Testing in Copenhagen May 26-29, 1998. (to be published)

Interactions/Transitions

- L.D. Favro and R.L. Thomas attended the Air Transport Association Meeting in Seattle, WA, Sept. 28, 1996, and demonstrated the thermal wave imaging instrumentation.

- L.D. Favro, R.L. Thomas, Tasdiq Ahmed and Xun Wang imaged the entire belly skin of a DC-9 aircraft at Mobile Aerospace in Mobile, Alabama, November 9, 1997.

- L.D. Favro, R.L. Thomas, Tasdiq Ahmed and Xun Wang imaged sections of KC-135 and B707 aircraft at Foster-Miller, Inc., Waltham, Massachusetts, November 18, 1997.

- L.D. Favro and R.L. Thomas attended the SPIE Conference on Nondestructive Evaluation of Aging Aircraft, Airports, and Aerospace Hardware, Scottsdale, AZ, December 3-5, 1996, Vol. 2945, pp. 374-379 (1996).

- L.D. Favro, R.L. Thomas, Tasdiq Ahmed, and Xun Wang imaged Section 41 of a B747 aircraft, as well as regions of corrosion on B757 and DC-10 aircraft at the Northwest Airlines Maintenance Facility in Minneapolis, MN, Feb. 3-5, 1997.

- L.D. Favro and R.L. Thomas imaged Section 41 of a B747 at the Boeing facility, Wichita, Kansas, Feb. 26-28, 1997.

- L.D. Favro, R.L. Thomas, Xiaoyan Han, and Zhong Ouyang did a demonstration of the thermal wave imaging capability at the FAA's AANC facility in Albuquerque, NM, attended by Air Force personnel.

- L.D. Favro gave a presentation at SPIE Thermosense XIX, An International Conference on Thermal Sensing and Imaging Diagnostic Applications, held 22-25 April 1997 in Orlando, Florida.

- L.D. Favro and R.L. Thomas gave a demo of the thermal wave imaging capability at the ADPA Meeting in Indianapolis, IN, April 27-30, 1997.

- Zhong Ouyang, L.D. Favro and R.L. Thomas attended the Eighth International Symposium on Nondestructive Characterization of Materials, and presented a paper in the Session on NDE Applied to Process Control, June 15-20, 1997 Boulder, Colorado

- L.D. Favro and Xiaoyan Han presented a paper at THERMAL SOLUTIONS '97, "NDE in the Aerospace Industry", held June 24-26, 1997 Cleveland, Ohio

- Xiaoyan Han, L.D. Favro, and R.L. Thomas attended the First Joint DoD/FAA/NASA Conference on Aging Aircraft, The David Eccles Conference Center - Ogden, Utah, 8-10 July, 1997. They presented a paper and did a tabletop demonstration of the thermal wave imaging equipment.

- Students and faculty participated in, and presented papers at the Review of Progress in QNDE, held at the University of San Diego, San Diego, CA, July 27-August 1, 1997.

- L.D. Favro presented a paper at the Workshop on Intelligent NDE Sciences for Aging and Futuristic Aircraft, at The University of Texas at El Paso, El Paso, September 30 - October 2, 1997.

- L.D. Favro presented a paper at the MRS 1997 Fall Meeting, Symposium on Nondestructive Characterization in Aging Systems, Boston, MA, November 30 – December 5, 1997.

New discoveries, inventions, or patent disclosures

None

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Thermal Wave Imaging of Hidden Corrosion **FINAL REPORT**
R.L. Thomas, L.D. Favro and P.K. Kuo *WAYNE STATE UNIVERSITY*
AFOSR Grant No. F49620-96-1-0166

Introduction

At the AFOSR Logistics Workshop: *Basic Research for Logistics*, held in Dayton, Ohio, October 31 - November 1, 1995, Brig. General Michael Moffitt pointed out the increased reliance of the Air Force on sustainment of aircraft, as the result of a decrease in the purchases of new aircraft. He noted that corrosion, fatigue, and cracking pose the greatest danger to the sustainment, pointing out that 22% of the C/KC-135 fleet currently is in depot status, as compared to a normal expectation of 10-15%. One of the organizers of the Workshop, Dr. Neal Glassman of AFOSR, next reported that the AFOSR Spring Initiative Review had identified the resulting Logistics issues as major research thrusts for new basic research grants. The research conducted under AFOSR Grant No. F49620-96-1-0166 was carried out in response to some research issues which were discussed extensively throughout the ensuing Workshop.

At the outset of the Grant, thermal wave imaging had been demonstrated to have good capability for detection of hidden corrosion, as well as of disbonded tear straps and doublers. However, the quantitative assessment of the degree of corrosion - a very important goal for the successful application of the technique to the airworthiness program - required further basic research. A three-year program of research had been proposed, but, because of budgetary limitations, the research was funded for eighteen months under AFOSR Grant No. F49620-96-1-0166. This Final Report presents the results of that eighteen month program of research.

Description of the Experimental Technique

The pulse-echo thermal wave imaging system, which was developed by Wayne State University[1], consists of a pulsed heat source (typically high-power photographic flash lamps), an IR video camera, and image processing hardware and software, all of which is controlled by a personal computer.

The energy from the pulsed flashlamps is absorbed at the surface of the aircraft, and launches a thermal wave pulse into its skin. When this pulse is reflected, either from the rear surface of the skin or from a locally corroded interface, the reflected portion propagates back to the surface, where it modifies the time dependence of the temperature. The modification is greater over a corroded region than over an uncorroded one. Time delays of the reflected pulses are determined by the thermal wave transit times to the defect and back. These transit times to the rear of the skin and back are shorter for corroded (thinner) skin than for the uncorroded skin. The returning thermal wave reflections are detected by means of the IR video camera, which monitors the time-dependent surface distribution of the IR emission from the surface. The signal from the camera is processed in real time by fast imaging hardware and software in the computer, and the thermal wave image of subsurface corrosion is displayed on a video monitor. A photograph of the camera, flashlamps and shroud typical of the system is shown in Fig. 1

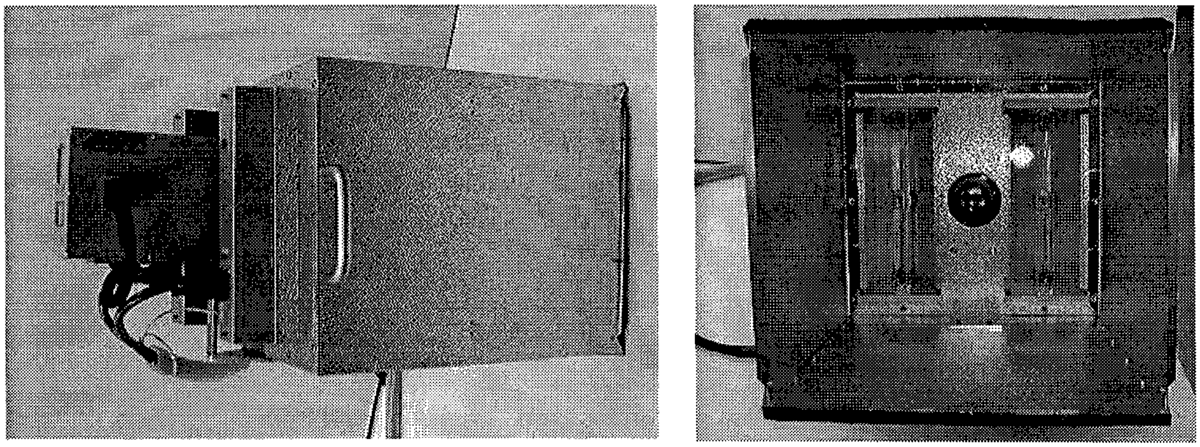


Fig. 1 Photographs of the exterior (left) and interior (right) of the thermal wave imaging head, showing the IR focal plane array camera, aluminum box, and two linear flash lamps. The opening of the shroud is approximately 30 cm on a side.

Description of the Scientific and Technological Barriers for Quantitative Corrosion Thinning Determinations, Using Thermal Wave Techniques

Pulsed thermal waves result from the sudden application of a short pulse of heat to the surface of a solid object. This launches what is, in effect, a temperature wave into the solid. When observed at a distance, x, beneath a planar surface of the object, the pulse has a Gaussian shape given by

$$T(x,t) = \frac{A}{(4\pi\alpha t)^{1/2}} e^{-\frac{x^2}{4\alpha t}} \quad , \tag{1}$$

where T is the temperature, t is the time, α is the thermal diffusivity of the object, and A is a proportionality constant which depends on the heat input. At a defect interface, a second (reflected) pulse is generated with the same Gaussian shape, but with an amplitude which depends on the reflection coefficient at the interface. The reflection coefficient is a function of the ratios of the thermal properties on the two sides of the interface, and can be either positive or negative. The reflected pulse appears to have originated at the image of the object surface, as seen in the "mirror" of the defect interface. Thus, it looks like a thermal wave "echo" from that interface. When it reaches the surface (x=0), it modifies the time-dependence of the surface temperature by contributing an additional term to the inverse square root of time behavior of Eq. (1) at x=0:

$$T(0,t) = \frac{A}{(4\pi\alpha t)^{1/2}} \left(1 + R e^{-\frac{(2d)^2}{4\alpha t}} \right). \tag{2}$$

Here, d is the depth of the defect, and R is the reflection coefficient. The time at which the additional term in Eq. (2) becomes significant depends on d^2/α. Thus, one can, in principle, measure the depth (e.g., thickness of a corroded skin) by observing the time at which the deviation from Eq. (1) occurs. However, this measurement is complicated by variations in the (unknown) value of R, and by the effects of three-dimensional diffusion, which have been ignored in this simplified one-dimensional picture. Also, if one waits a bit longer, one gets additional terms in Eq. (2), due to multiple reflections of the pulse. It should also be kept in mind that thermal waves are extremely dispersive, so that the pulses broaden dramatically as time progresses, and the multiple "echoes" all overlap. Nevertheless, if the surface temperature is observed at short enough times after the flash, one can essentially eliminate the effects of both multiple reflections and three-dimensional diffusion, and make a determination of the "time-of-flight". A mathematical model[2] based on three-dimensional wave scattering theory, accurately predicts the temperature-time profiles at a given point, and also predicts the variations of the temperature on the surface above an arbitrarily-shaped defect. This theory has been used to calculate theoretical images of defects with several simple geometries in steel and composite materials, and has been confirmed by comparison with experimental thermal wave images of corresponding test specimens.

The challenge for this research project, both scientifically and experimentally, was to seek ways to exploit the early-time behavior so as to determine the nature of the corrosion and to measure the residual skin thickness. Since the characteristic transit times for aluminum skins are very short (comparable with the frame times of the IR imaging systems which the were state-of-the-art at the outset of the project), we considered alternative strategies for processing the data from such cameras. We also considered the potential benefits of utilizing more advanced IR focal plane arrays which became available during the period of performance of the Grant. Both approaches proved to be beneficial.

Data Processing: Implementation of a Corrosion Analysis Program in the Thermal Wave Imaging Software

Another practical consideration which was noted in our Research Proposal on this Grant is that an aircraft skin provides no thick background area for determining image contrast. Test specimens which had been used in our preliminary research had been fabricated from thick metal, which made a convenient background reference for pulse-echo analysis. However, in an aircraft skin, the reference will have to be the undamaged skin areas, which are of the order of 1mm in thickness. This reference, must then be compared with the corroded areas, which may be only a few percent thinner. Nevertheless, despite the lack of a thick reference, we noted in our Proposal that we had achieved sensitivity to corrosion thinning of a few percent material loss. The problem was to determine a strategy for making quantitative measurements of this percentage loss. We developed such a strategy, based upon the following analysis, described in greater detail in the Ph.D. Dissertation of Dr. Xiaoyan

Han of Wayne State University.[3]

Consider a sample which has two insulated surfaces S_1, S_2 at $z = 0$ and $z = d$ shown in Fig. 2. For one-dimensional heat propagation along the z-direction with the initial condition,

$$T(z,0^+) = \delta(z) \quad , \tag{3}$$

Applying Eq. (2) to the case of a thermally thin material, and setting R=1 (insulating boundaries), we have

$$T(z,t) = \frac{1}{(4\pi\alpha t)^{1/2}} \sum_{n=-\infty}^{\infty} e^{-\frac{(z-2nd)^2}{4\alpha t}} \quad . \tag{4}$$

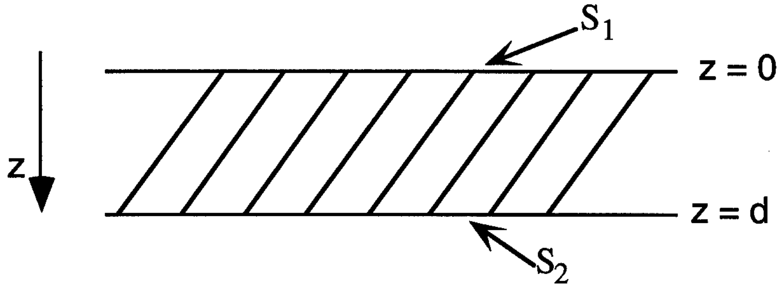


Fig. 2 Schematic diagram of a perfect sample with two insulated surfaces S_1, S_2 at $z = 0$ and $z = d$ respectively.

This solution is good for theoretical calculations when we deal with short time scales since it converges quickly for small t. However, when we need to look at longer time scales, we need another form of the solution to the heat equation,

$$\frac{\partial^2 T(z,t)}{\partial^2 z} = \frac{1}{\alpha}\frac{\partial T(z,t)}{\partial t} \quad . \tag{5}$$

Choosing the solution in the form,

$$T(z,t) \sim \cos(kz)e^{-\gamma t} \quad , \tag{6}$$

after some manipulation[3], we obtain an expression of the form

$$T(z,t) = \sum_{n=0}^{\infty} A_n \cos(\frac{n\pi}{d} z) e^{-\frac{\alpha n^2\pi^2}{d^2} t} \quad . \tag{7}$$

According to the boundary condition expressed by Eq. 3, we have,

$$\sum_{n=0}^{\infty} A_n \cos(\frac{n\pi}{d} z) = \delta(z) \quad . \tag{8}$$

$$\sum_{n=0}^{\infty} A_n \int_0^d dz \cos(\frac{n\pi}{d} z) \cos(\frac{m\pi}{d} z) = \int_0^d dz \delta(z) \cos(\frac{m\pi}{d} z) \quad , \tag{9}$$

$$\sum_{n=0}^{\infty} A_n \int_0^d dz \cos(\frac{n\pi}{d} z) = \int_0^d dz \delta(z) \quad \text{, and} \tag{10}$$

Eqs. 8-10 lead to

$$A_m = \frac{2}{d} \quad , \text{ for } m \neq 0 \quad , \tag{11}$$

and,

$$A_0 = \frac{1}{d} \quad . \tag{12}$$

So, the general solution to Eq. 5 can be written as,

$$T(z,t) = \frac{1}{d}[1 + 2\sum_{n=1}^{\infty} \cos(\frac{n\pi}{d} z) e^{-\frac{\alpha n^2\pi^2}{d^2} t}] \quad . \tag{13}$$

At the surface z = 0, the temperature can be expressed as,

$$T(0,t) = \frac{1}{d}[1 + 2\sum_{n=1}^{\infty} e^{-\frac{\alpha n^2\pi^2}{d^2} t}] \quad . \tag{14}$$

Finally, at a time t, when

$$2\sum_{n=1}^{\infty} e^{-\frac{\alpha n^2\pi^2}{d^2} t} << 1 \quad , \tag{15}$$

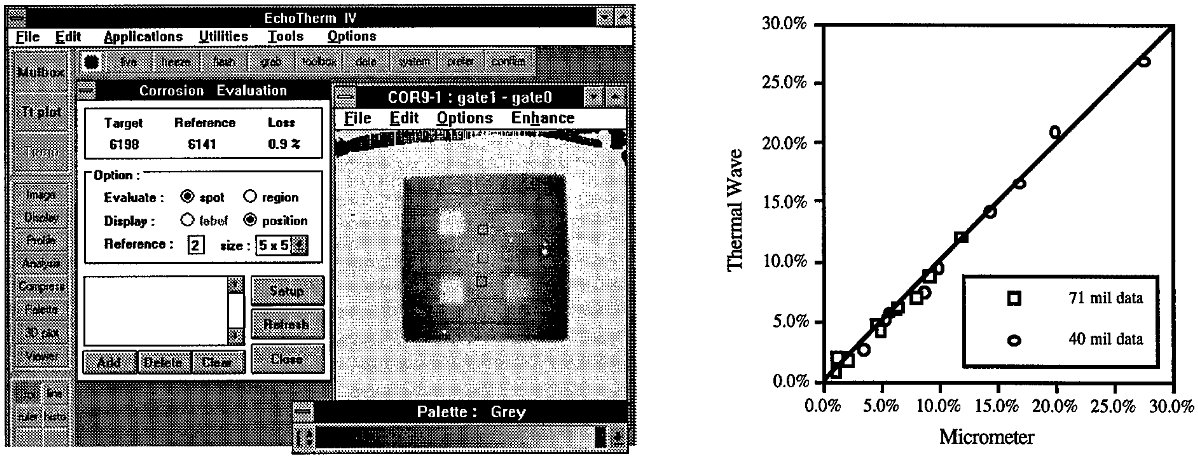
we have,

$$T(0,t) \propto \frac{1}{d} \quad . \tag{16}$$

At sufficiently long time, t, Eq. 16 can be used to measure the skin thickness d. However, if t is too long, the assumed boundary conditions will be poorer approximations, and will lead to systematic errors. Thus, it is important to wait long enough after the flash so that the sample achieves local thermal equilibrium, but not so long that heat losses to the environment or to thicker regions of the sample become important. As a practical matter, for typical aluminum aircraft skins, the term represented by Eq. 15 is negligibly small after about 20ms following the flash. In our experiments, we typically acquire a first image at about 80ms following the flash, so we expect the simple approximation of Eq. 16 to hold, and utilize this approximation in an algorithm to determine the fractional loss in thickness by the expression

$$\frac{\Delta T_2 - \Delta T_1}{\Delta T_2} = \frac{d_1 - d_2}{d_1} \quad . \tag{17}$$

We have implemented such an algorithm, based on Eq. (17), in our thermal wave imaging corrosion analysis window software, and have tested it on a number of intentionally corroded regions of different thicknesses of aluminum skins.[4] The window, shown in Fig. 3 (left), contains "draggable" regions of interest for corrosion analysis, including some which are placed over uncorroded reference regions of the specimen. The percentage corrosion of the other regions of interest read out immediately as they are dragged above the region of the image containing suspected rear-surface corrosion. The results of the read-out of percentage corrosion are plotted on the right in Fig. 3, and indicate excellent agreement with direct micrometer measurements of percentage material loss for greater than 1% corrosion material loss.

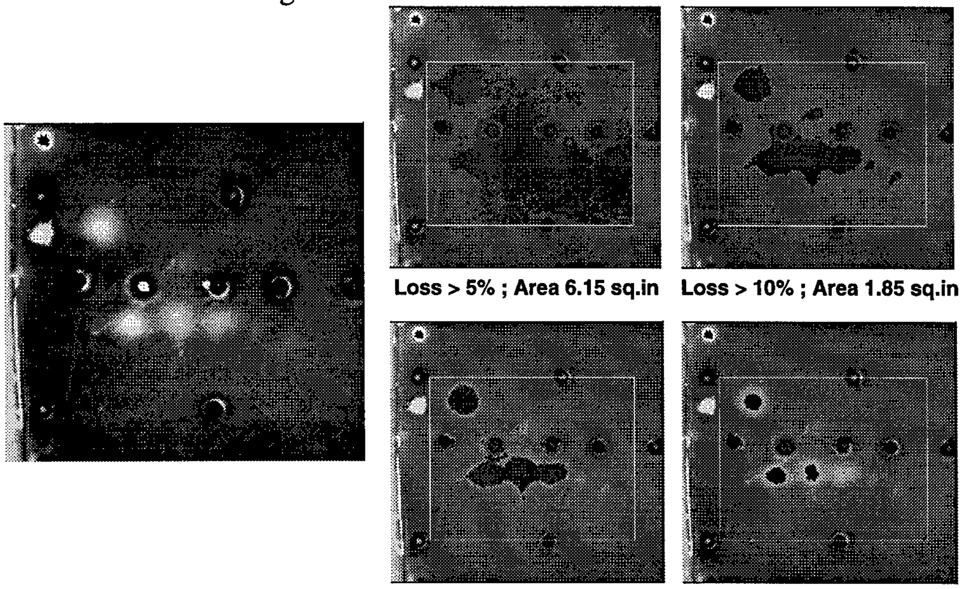


Target	Reference	Loss
6198	6141	0.9 %

Option :
Evaluate : ● spot ○ region
Display : ○ label ● position
Reference : 2 size : 5 x 5

Fig. 3 Corrosion analysis window (left), containing a thermal wave image of an aluminum test panel, the rear surface of which has five intentionally corroded regions. Also shown in the image are smaller squares which indicate the region being analyzed and two reference regions. The resulting comparison with micrometer measurements shown on the right for this and similar panels, indicates excellent agreement from less than one percent to nearly thirty percent material loss.

Using the same algorithm, we can also "paint" regions of corrosion identified on a thermal wave image, "painting" regions whose material loss exceeds a threshold value which can be chosen by the inspector. This is illustrated in Fig. 4.



Loss > 5% ; Area 6.15 sq.in **Loss > 10% ; Area 1.85 sq.in**

Loss > 15% ; Area 1.17 sq.in **Loss > 25% ; Area 0.28 sq.in**

Fig. 4 (Left) a raw thermal wave image of a corroded riveted two-layer sample which contains rear surface corrosion of the front layer with the corrosion products in place, supplied by Boeing. (Right) four analysis images, prepared using our real-time algorithms. In red are shown the areas with: >5% (top left), >10% (top right), >15% (lower left), and >20% (lower right) corrosion material loss. Also printed out as part of the analysis are the actual areas (in square inches) of corrosion exceeding these bounds.

Advanced IR Focal Plane Array Imaging System

A camera, whose technology was based on our one-of-a-kind, 512x512 Imager, which was described in detail in the Proposal, since became available as a commercial product and with a price that is competitive with other FPA cameras. This camera (Amber/Raytheon Galileo) is a 256x256 array, with a base frame rate of 125 Hz, and, like our 512x512 camera, operates in the snapshot mode. This camera also has a modified version of the windowing capability which we had designed into our research camera, and reaches a maximum frame rate of 2kHz. In addition, whereas the 512x512 research camera has liquid nitrogen cooling, this commercial camera has its own Stirling Engine cooler, making it quite suitable for use in a hangar environment. In conjunction with our technology transfer effort, and with funds from other (non-AFOSR) sources, we have purchased one of these commercial cameras, and utilized it in support of this research. Because of the fact that the Research Program terminated at eighteen months, rather than thirty six months effort, the Galileo camera was utilized less extensively than originally planned. However, we initiated its use to obtain temperature/time curves at the higher frame rates, and anticipate that this approach could prove to be a useful complement to the corrosion analysis algorithm described above.

Technology Transfer Project: KC-135 and B-52 Wingfastener Corrosion

At the request of Oklahoma City ALC, ARINC conducted a round-robin study of the capability of various NDE techniques to detect intergranular corrosion in the vicinity of steel fasteners in KC-135 and B-52 wingskins. We participated in the study January 27, 1997, which included a blind test of 80 such fasteners. Example images of four of these fasteners are shown in Fig. 5. We had zero "false calls" in our blind test, and correctly identified 87.5% of the corroded fasteners at a rate of 0.5 fasteners inspected per minute. Thermal wave imaging is a very promising inspection technique for this important ALC inspection requirement.

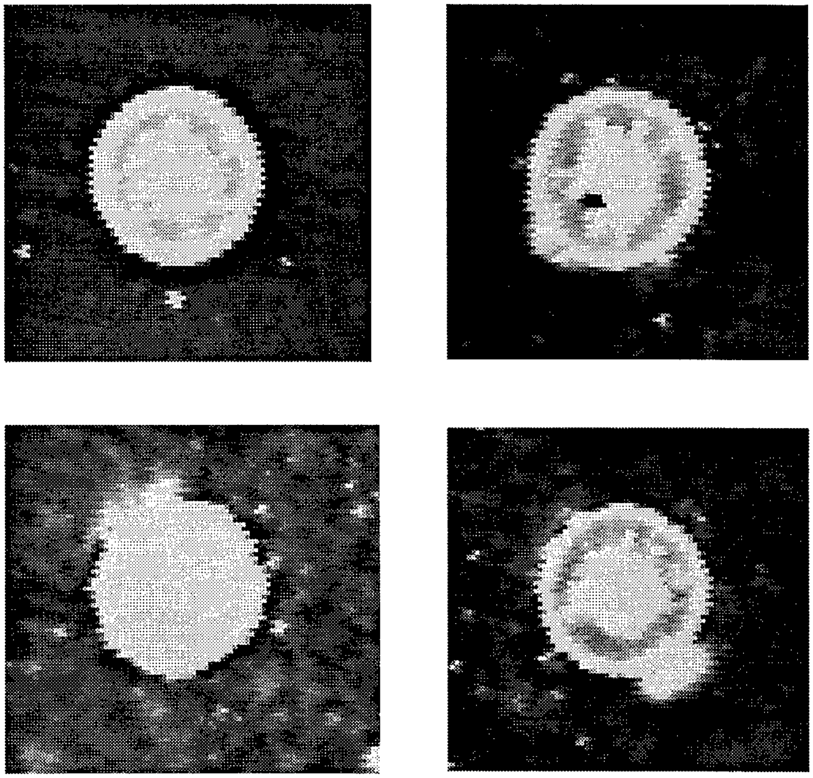


Fig. 5 Images of an uncorroded (top left) and three corroded wing fastener regions, taken from an ARINC test of corroded C/KC-135 wing skins. The intergranular corrosion shows up as an irregular boundary around the image of the fastener.

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[1] "Thermal Wave Hardware Evolution Using the NDI Validation Center," L.D. Favro and R.L. Thomas, Materials Evaluation, **53**, 840-843 (1995).

[2] "An Inverse Scattering Algorithm Applied to Infrared Thermal Wave Images," D.J. Crowther, L.D.Favro, P.K.Kuo and R.L.Thomas, J. Appl. Phys.Vol. **74**, pp. 5828- 5834 (1993).

[3] "Measuring Subsurface Defect Depth and Metal Loss by Thermal Wave Imaging & Inverse Scattering of Photon Density Waves", Xiaoyan Han, Ph.D. Dissertation, Wayne State University, 1997.

[4] "Quantitative Thermal Wave Imaging of Corrosion on Aircraft," Xiaoyan Han, L.D. Favro, T. Ahmed, Zhong Ouyang, Li Wang, Xun Wang, Feng Zhang, P.K. Kuo and R.L. Thomas, Review of Progress in Quantitative NDE, Vol. **16**, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 353-356 (1997).