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13. ABSTRACT *(Maximum 200 words)*

Accomplishments are reported of a program of research to develop several thermal wave techniques and to explore applications of those techniques to the imaging of sub-surface features and the characterization of a variety of materials. Both experimental and theorectical studies were carried out, and the experimetns included both cw and pulsed thermal wave excitation. The mirage effect (optical probe beam) technique was used to determine thermal diffusivities in a variety of materials including diamond and polymers. The results of our measurements on single crystal diamond showed a nearly 50% increase in thermal diffusivity at room temperature on (IR) thermal wave imaging for nondestructive evaluation (NDE) included synchronous imaging in the time domain, a technique for thermal wave tomorgaphy was developed, and the inverse scattering problem was solved and an algorithm developed to implement the solution on digitally acquired images. A U.S. Patent was issued to Wayne State Univeristy on the lock-in video technique. Instrumetnal development was carried out culminating in a Beta-site development at an aerospace company and negotiations with several companies towards commercialization of the instrumentation for technolgy transfer.

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THERMAL WAVE IMAGING AND CHARACTERIZATION OF SOLIDS

FINAL REPORT

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

MARCH 4, 1992

U.S. ARMY RESÉARCH OFFICE

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TABLE OF CONTENTS

LIST OF APPENDICES, ILLUSTRATIONS AND TABLES

Illustrations:

Tables:

ACCOMPLISHMENTS UNDER THE CONTRACT

A. STATEMENT OF THE PROBLEM STUDIED

A three year program of research was proposed to develop several thermal wave techniques and to explore applications of those techniques to the imaging of subsurface features and the characterization of a variety of materials, including layered structures, semiconductor materials and surfaces, semiconductor device interconnect structures, diffusion bonds and welds, and polymer composite materials. Both experimental and theoretical studies were to be carried out, and the experiments were to include both cw and pulsed thermal wave excitation. Experimental detection techniques originally proposed included mirage-effect optical probe, photothermal deflection and reflectivity, photothermal (IR) radiometry, along with both heterodyne and Fabry-Perot interferometry. In our revised scope of work, necessary because of ARO's requirement for a 20% reduction in our originally proposed budget, as set forth in our letter correspondence dated February 8, 1988, the experiments and theory were reduced to the following selected project areas:

* **Mirage effect materials characterization**

Theoretical studies were to be based on the existing analytical framework developed by the PI's, together with detailed numerical evaluations and least-squares comparison with experimental data.

* **IR thermal wave nondestructive evaluation (NDE).**

Research on synchronous video IR thermal wave imaging was proposed for both the frequency domain (lock-in imaging) and the time domain (box-car imaging), and research was also proposed for thermal wave imaging in the velocity domain (flying-spot imaging).

Another objective, related to both of the projects cited above, was

* **The further instrumental development** of thermal wave imaging and characterization techniques. Finally,

* In collaboration with our scientific colleagues from DoD and industrial laboratories, we sought **to exploit these new techniques for application to current NDE problems.**

During the course of the present contract, excellent progress has been made in each of these four areas. Some of the most important results are summarized below.

B. SUMMARY OF THE MOST IMPORTANT RESULTS

1. Thermal wave material characterization: measurements of thermal diffusivity

The mirage effect detection scheme can also be used as a means of characterizing materials through the determination of thermal diffusivity, a combination of the thermal conductivity and heat capacity. We have developed an analytic solution for the mirage effect signal in the case of three dimensional thermal diffusion from a localized periodic heat source in a layered structure.[1] This theory takes into account the finite sizes of the heating and probe beam focal spots, the finite height of the probe beam above the sample of the surface, the thicknesses and material parameters (thermal conductivity, density, heat capacity) of each layer, and is expressed in such a form that it makes comparison with experiment straightforward and numerically convenient. We have developed such a numerical comparison procedure which is much more complete than that which we developed earlier in a previous ARO contract. In our earlier work, we made use only of the mirage effect experimental data corresponding to the two 90-degree phase change regions for the transverse deflection component of the probe beam, thereby estimating the thermal wavelength and subsequently the thermal diffusivity. During the present contract, we make use of the entire data set, including both the transverse and normal deflection components for all phase increments. Furthermore, the data set is comprised of a sequence of scans taken for several (typically 8) frequencies and/or probe beam heights. Comparison with theory is accomplished with a nonlinear, multiparameter, least-squares fitting program developed under this contract. In addition to the desired thermal parameters (e.g. the thermal diffusivities of the film and/or substrate material), the fits give values for the gaussian beam radii, the diffusivity of the air, and the probe beam height(s) which are in excellent agreement with independent experimental measurements.

We have applied our mirage effect thermal wave characterization method to study the thermal diffusivities of several bulk and thin film materials. A material of considerable interest in this regard is diamond, both in single crystal form and as polycrystalline films deposited on a variety of substrates. We will first describe our preliminary (near room temperature) studies on single crystal diamond specimens.

---

1 "Photothermal Deflection (mirage) Detection of Diffusivities and Surface and Subsurface Defects in Solids", by P.K. Kuo, L.D. Favro, and R.L.Thomas, in *Photothermal Deflection Spectroscopy and Applications*", ed. J.A. Sell, Academic Press, New York (1988), Chapter 6, pp. 191-212.

Single Crystal Diamond Results

In this project, we have been collaborating closely with our colleague Prof. Roger W. Pryor, director of IMR's diamond materials research laboratory, and with research staff at the General Electric Research and Development Center in Schenectady, N.Y. The preliminary results from this work are contained in a joint publication in Physical Review B.[2] Additional details are to be published in the proceedings of the 1991 International Topical Meeting on Photoacoustic and Photothermal Pheneomena.[3] A schematic diagram of our experimental setup is shown in Fig. 1. An argon-ion laser beam is chopped by an acousto-optic modulator at several kilohertz and focused on the surface of the sample to provide a periodic localized surface heat source that generates approximately hemispherical thermal waves in the diamond crystal. Thermal waves are also produced in the air which is in contact with the surface of the sample. The near-surface behavior of the waves in the air is dominated by the behavior of the waves in the sample. As a result, the properties of the sample can be studied by detecting the waves in the air. The presence of the thermal waves in the air is detected by a means of a 60 μm diameter He-Ne laser probe beam that bounces at near grazing angle ($\cong 2\,^\circ$) from the diamond surface in the vicinity of the focal area of the heating beam. As this beam passes through the heated region of the air, it is refracted by the time-varying gradient in index of refraction of the air (the mirage effect) which accompanies the thermal waves. The magnitude and phase of the vector deflection of this probe beam is then measured by means of a position-sensitive, quad-cell detector, the outputs of which are amplified and fed to two separate vector lock-in amplifiers (one to monitor the vector component of the deflection which is normal to the surface, the other to monitor the transverse deflection). A microcomputer-controlled stepping motor stage is used to move the position of the heating beam across the surface of the sample at right angles to the direction of the probe beam. The two components of the time-varying vector deflection are measured synchronously (magnitude and phase) for each position of the stepping motor scan, and are recorded in separate memory locations of the microcomputer for later numerical comparison to theory. The scans are repeated for several different frequencies (typically 8), with the computer controlling the entire set of scans, including programmed changes in parameters of the two lock-in amplifiers, and data storage. The resulting data set (typically 12,800 points) are fit to the

2 "Thermal Diffusivity of Isotopically Enriched ^{12}C Diamond", T.R. Anthony, W.F. Banholzer, J.F. Fleischer, Lanhua Wei, P.K. Kuo, R.L. Thomas, and R.W. Pryor, Phys. Rev. B42, pp.1104-1111 (1990).

3 "Thermal Diffusivity Measurements of Diamond Materials, "P.K. Kuo, Lanhua Wei, and R.L.Thomas, accepted for Proc. 7th Int. Topical Meeting on Photoacoustic and Photothermal Phenomena, Doowerth, The Netherlands, August 26-30, 1991.

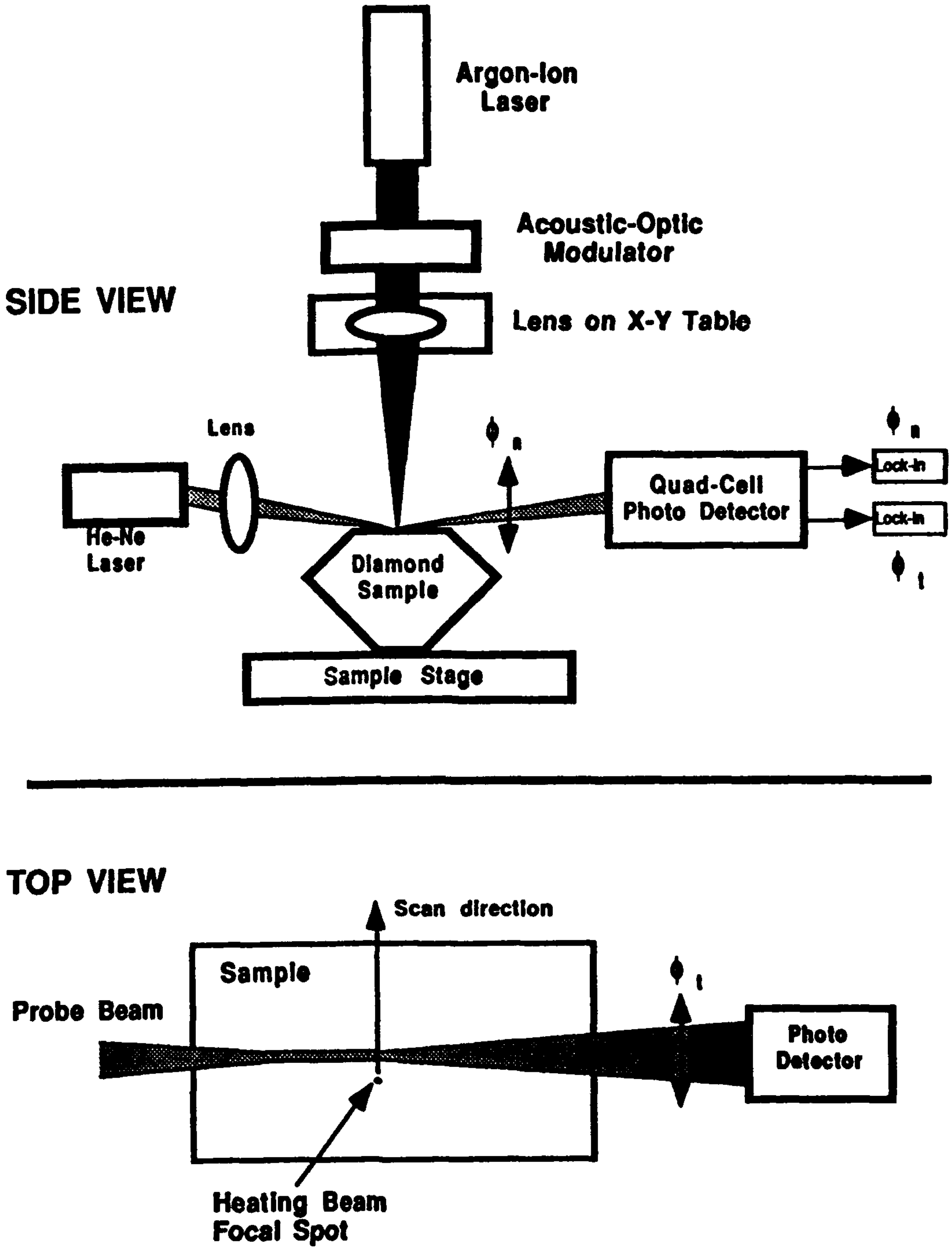

Fig. 1 Schematic diagram of the mirage-effect thermal wave technique for determining thermal diffusivities of the diamond materials studied.

theoretical predictions described below, utilizing a multi-parameter, least-squares fitting routine. It should be pointed out that the measurement is a fundamental one, in the sense that, it consists simply of a measurement of length (offset between the two beams) and time (the frequency). No determination of absolute temperature is necessary, only the spatial and temporal distributions of the temperature are required. A typical comparison between experiment and theory is displayed in Fig. 2, and

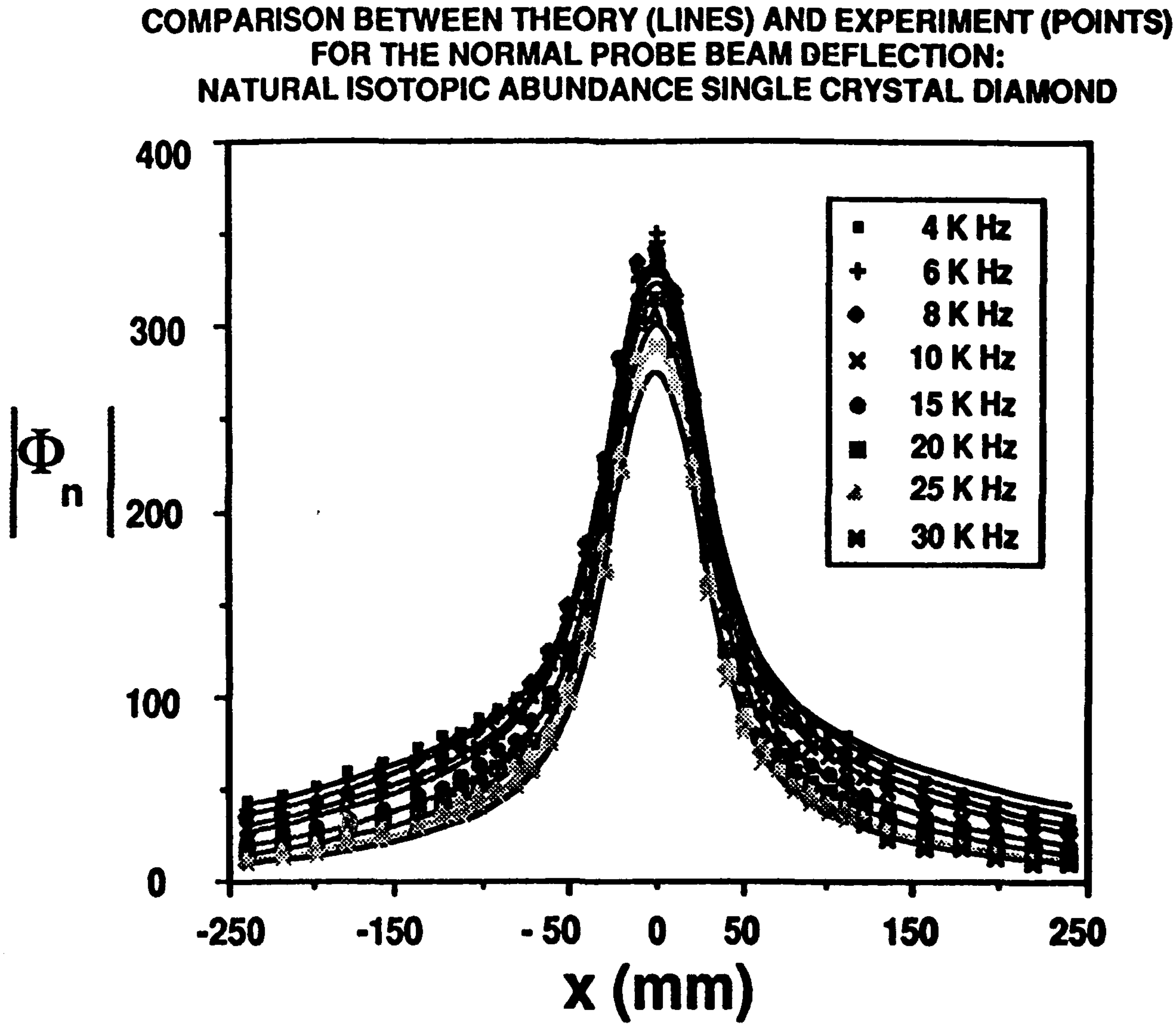

Fig. 2 Comparison between experiment and theory for a mirage effect measurement on single crystal diamond.

a summary of all the results of our diamond thermal diffusivity measurements is given in Table I. The column labelled "variance" in Table 1 is a measure of the quality of the multiparameter fit, and is simply the statistical variance between the theory and the typically 12,800 values of experimental data. Our thermal diffusivity result (12.4 ± 1 cm^2/s) for synthetic samples having the natural isotopic abundance is in good agreement with values calculated from handbook values of thermal conductivity and heat capacity. Our result for the natural crystal (12.2 ± 1 cm^2/s) is in similarly good agreement. Our measured values (18.5 ± 1 cm^2/s) for the 99.9% isotopically enriched samples are indicative of a 50% enhancement in thermal diffusivity. Our measured value (14.5 ± 1 cm^2/s) for the intermediate (99.5%) isotopic purity sample is consistent with the other results. A summary (log-log) plot of all the diamond diffusivity values from Table 1 is given in Fig. 3. A naive extrapolation of this plot to ^{13}C concentrations of the order of 0.01% could result in a 100% enhancement in room temperature diffusivity from that of high-quality natural diamond. In summary, our 99.9% ^{12}C-enriched crystals have the highest room-temperature thermal diffusivity (18.5 ± 1 cm2/s)) of any solid naturally occurring or previously synthesized.

Table 1 Summary of thermal diffusivity results on single crystal diamond.

Sample #	Nominal C13%	Coating	Orientation	No. of freqs	No. of hgts.	Diffusivity (cm2/s)	Variance
1	0.07	Ti (1000 A)	Large (100)	8	1	18.5	0.0026
1	0.07	Ti (1000 A)	Large (100)	8	1	18.6	0.0014
1	0.07	Ti (1000 A)	Large (100)	1	5	18.6	0.0032
1	0.07	Ti (1000 A)	Large (100)	8	1	18.6	0.0018
1	0.07	Ti (1000 A)	Large (100)	8	1	18.4	0.001
1	0.07	Ti (1000 A)	Large (100)	8	1	18.3	0.001
1	0.07	Ti (1000 A)	#1 (111)	8	1	18.5	0.0011
1	0.07	Ti (1000 A)	#2 (111)	8	1	17.2	0.0011
1	0.07	Ti (1000 A)	#2 (111)	5	1	18.3	0.0008
1	0.07	Ti (1000 A)	#2 (111)	8	1	18.6	0.0009
1	0.07	Ti (1000 A)	#1 (111)	8	1	21.2	0.0014
1	0.07	Ti (1000 A)	#1 (111)	8	1	17.2	0.0012
1	0.07	Ti (1000 A)	#1 (111)	8	1	17.6	0.0014
2	0.1	Ti (1000 A)	#1 (111)	8	1	18.8	0.0009
3	1.04	Graphite (600 A)	Large (100)	5	1	11.2	0.0034
3	1.04	Graphite (600 A)	Large (100)	5	2	11.4	0.0048
3	1.04	Graphite (600 A)	Large (100)	5	1	12.1	0.0041
3	1.04	Ti (1000 A)	Large (100)	8	1	12.9	0.0023
3	1.04	Ti (1000 A)	Large (100)	8	1	12.8	0.0011
3	1.04	Ti (1000 A)	Large (100)	8	1	13.5	0.0008
3	1.04	Ti (1000 A)	Large (100)	8	1	12.9	0.001
4	1	Ti (1000 A)	Large (100)	8	1	12.7	0.003
5	0.5	Ti (1000 A)	#1 (111)	8	1	14.6	0.0012
5	0.5	Ti (1000 A)	#1 (111)	8	1	14.7	0.0012
5	0.5	Ti (1000 A)	#3 (111)	8	1	14.2	0.001
6	Natural IIA	Ti (1000 A)	Large (100)	8	1	12.2	0.0008
copper		no coating		3	1	1.3	0.001
copper		no coating		3	1	1.3	0.0021
copper		no coating		3	1	1.2	0.0015
copper		Ti (1000 A)		5	1	1.25	0.001

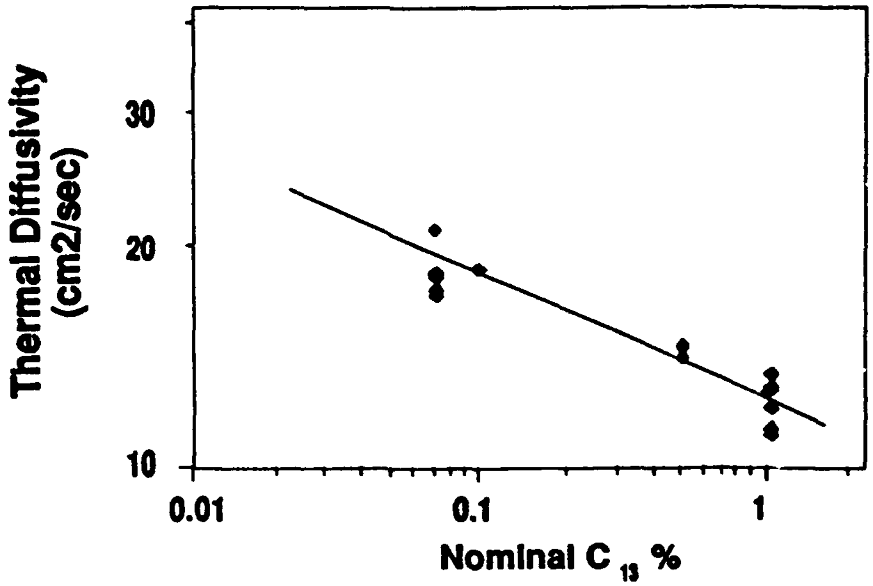

Fig. 3 Log-log plot of thermal diffusivity vs. nominal % of carbon 13

Temperature Dependence of the Thermal Conductivity of Single Crystal Diamond

We have also measured the thermal diffusivities of Type IIA diamond crystals of two isotopic compositions as a function of temperature between 255 K and 390K.[4] Our results, summarized in Fig. 4, show that the isotopically enriched (0.1 % ^{13}C) sample is consistently higher (approximately 50%) than the natural abundance sample. The temperature dependence of the thermal conductivities of both samples follow an empirical power law ($T^{-1.55}$) which has previously been reported in the literature for adamant materials.

4 "Temperature Dependence of the Thermal Conductivity of Type IIA Diamond Crystals," Lanhua Wei, P.K. Kuo, R.L. Thomas, T.R. Anthony and W.F. Banholzer, Proc. Second Int. Conf. on the New Diamond Science and Technology, Washington, D.C., Sept. 24-27, 1990, "New Diamond Science and Technology," Proceedings of ICNDST-2, Publications Dept., Materials Research Society, Pittsburgh (1991), pp. 875-880.

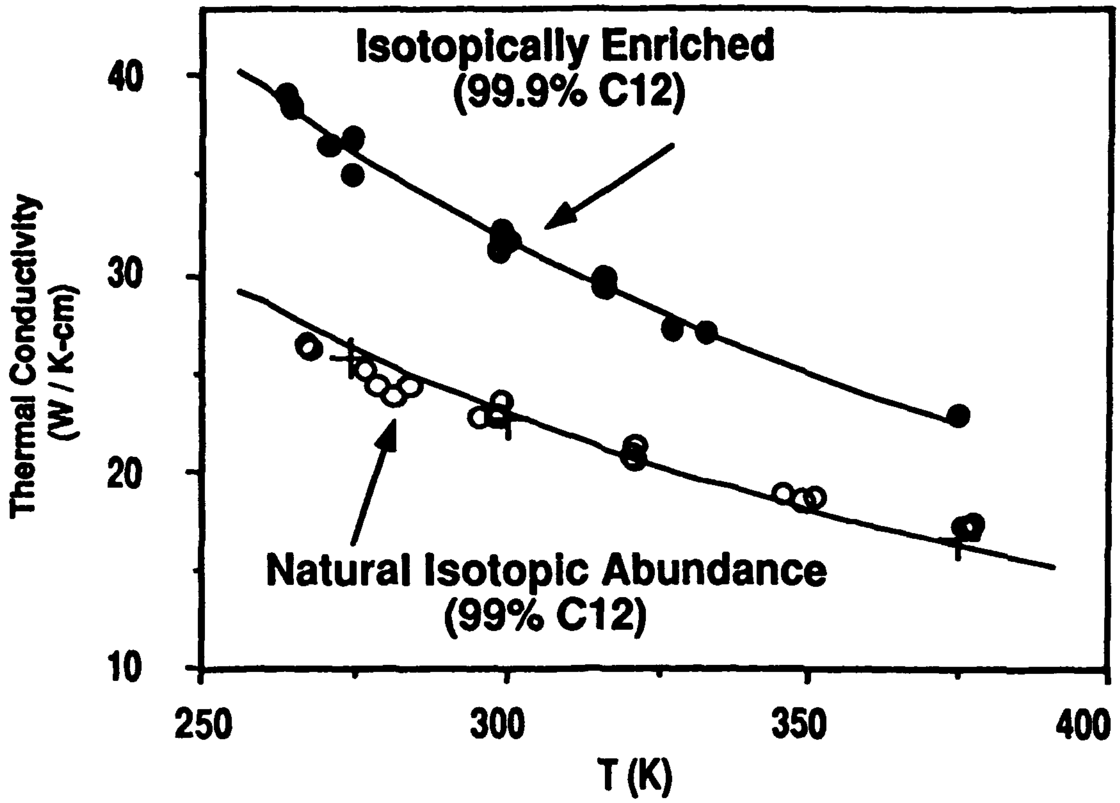

Fig. 4. Thermal conductivity of natural gem (open circles) and synthetic, isotopically enriched (solid circles) Type IIA diamond single crystals. The solid lines represent the empirical $T^{-1.55}$ power law. The crosses are literature values for the natural Type IIA crystals.

Diamond Film Results

In this application of our materials characterization technology, we have once again collaborated with Prof. R.W. Pryor of IMR, who has grown high-quality polycrystalline films on Si and a variety of other substrate materials, using IMR's plasma-assisted chemical vapor deposition (PACVD) facility at Wayne State University. Prof. Pryor has also carried out microfocus Raman spectroscopic characterization of these films, and we find that there is a good correlation between the diamond/graphitic structure ratios, estimated by Raman spectra and the thermal diffusivity measurements, as obtained by our thermal wave technology. Preliminary reports of our results have been presented at several national and international conferences.[5,6,7] A typical

5 "Thermal Wave Measurement of Diamond Films," P.K. Kuo, Lanhua Wei, R.L. Thomas, and R.W. Pryor, in Springer Series in Optical Sciences, Vol. 62, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 124-126.

6 "Thermal Diffusivity Measurements of Diamond Materials", Lanhua Wei, P.K. Kuo, And R.L.Thomas, Proc. 18th Annual Review of Progress in Quantitative NDE, Brunswick, ME,

comparison between theory and experiment for a diamond film on a silicon substrate is given in Fig. 5. A correlation plot between the resulting thermal diffusivities of a number of such films, grown under different conditions, and the graphitic percentage, estimated from Raman spectroscopy, is shown in Fig. 6.

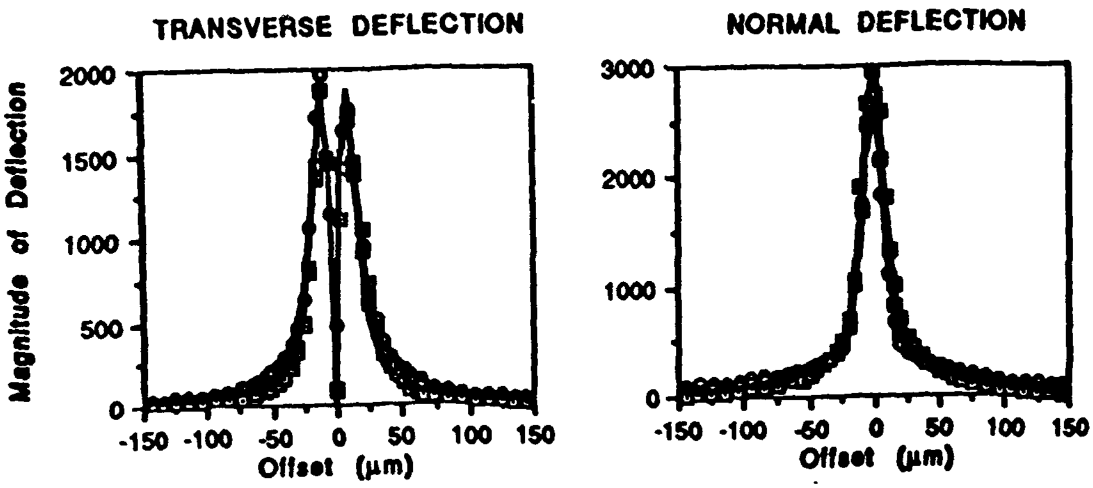

Fig. 5 Comparison between theory (lines) and experiment (points) for the thermal wave mirage signal for a free-standing polycrystalline diamond film.

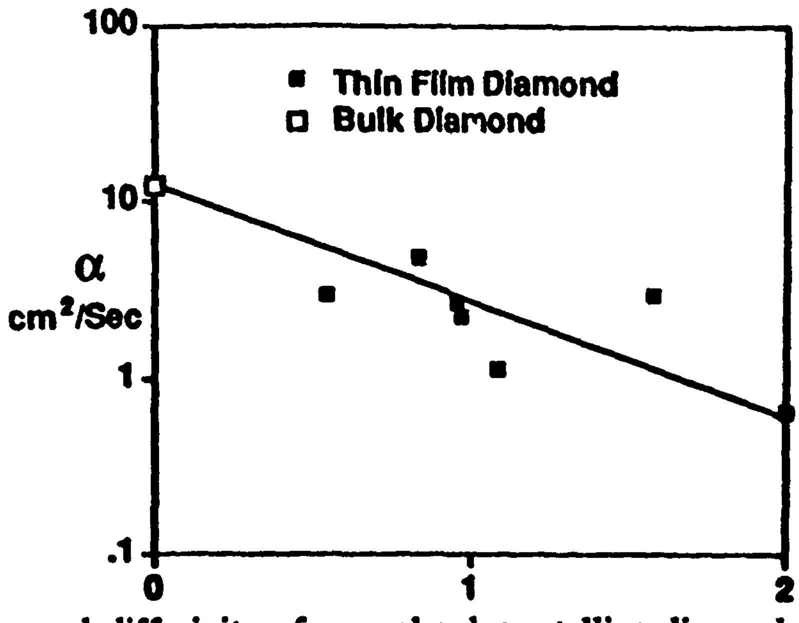

Fig. 6 Thermal diffusivity of several polycrystalline diamond films as a function of the estimated percentage of graphitic material, determined by Raman spectroscopy.

July 28-Aug. 2, 1991, to be published in *Review of Progress in Quantitative NDE*, Vol. 11, edited by D.O. Thompson and D. Chimenti, Plenum New York, (to be published).

7 "Thermal Diffusivity Measurements of Diamond Materials, "P.K. Kuo, Lanhua Wei, and R.L.Thomas, accepted for Proc. 7th Int. Topical Meeting on Photoacoustic and Photothermal Phenomena, Doowerth, The Netherlands, August 26-30, 1991.

Polymer Foils Results

In this application of our materials characterization technology, we have collaborated with J. Rantala of the Dept. of Physics, University of Helsinki and J. Jaarinen of Neste Corporate Technology, Porvoo, Finland. Here, we are extending our materials characterization technique to a situation in which the thermal diffusivity is 3 or 4 orders of magnitude lower than that of diamond. Furthermore, since the foils of most practical interest have comparatively much lower melting points and are free-standing, we are faced with a number of additional technological problems, such as heating beam intensity restrictions and mechanical vibrations. Nevertheless, the preliminary results[8] are encouraging, and indicate that the technology is on a sound basis theoretically, experimentally and computationally. A typical result from this work for a polyethylene foil is shown in Fig. 7, below.

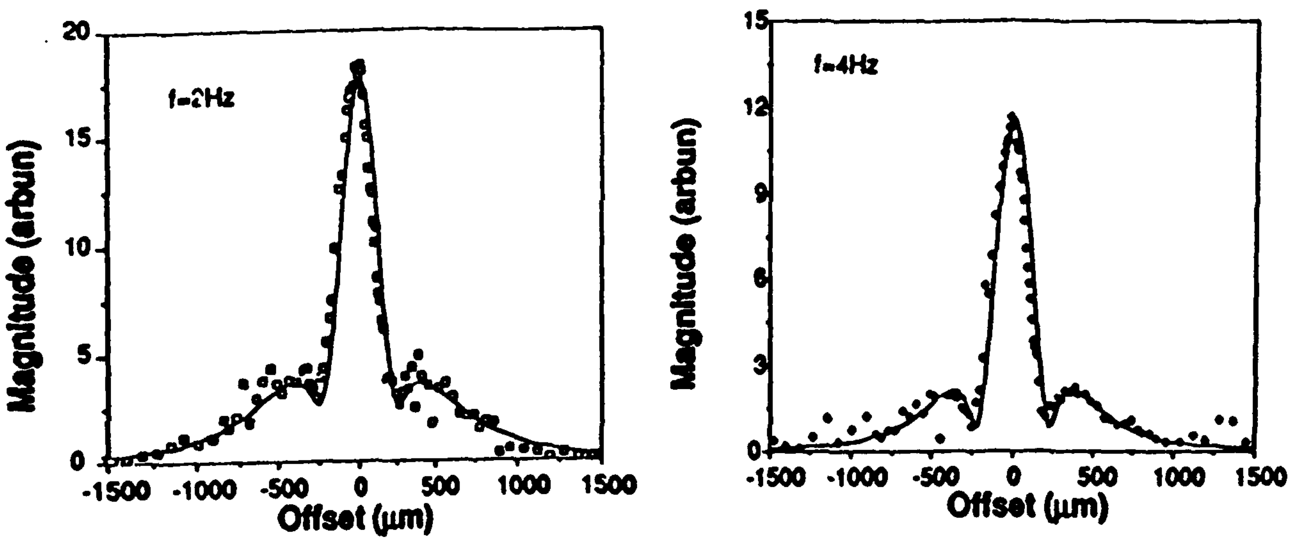

Fig. 7 Comparison between theory (lines) and experiment (points) for the thermal wave mirage signal for a polyethylene foil.

8 "A Thermal Wave Technique to Determine Thermal Diffusivities of Polymer Foils," J. Rantala, J. Jaarinen, Lanhua Wei , P.K. Kuo, and R.L. Thomas, *Review of Progress in Quantitative NDE*, Vol. 10B, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 2165-2172 (1991).

Diamond-Like Carbon and Co-Pt-Cr films Results

In this application of our materials characterization technology, we have collaborated with Dr. Bharat Bhushan of the IBM Almaden Research Center, San Jose, CA. A joint publication of our results is being prepared for submission for publication. We are encouraged by the fact that our results for a diamond-like-carbon (DLC) film also gives consistent results for the thermal diffusivity, a typical plot from which is shown below in Fig. 8.

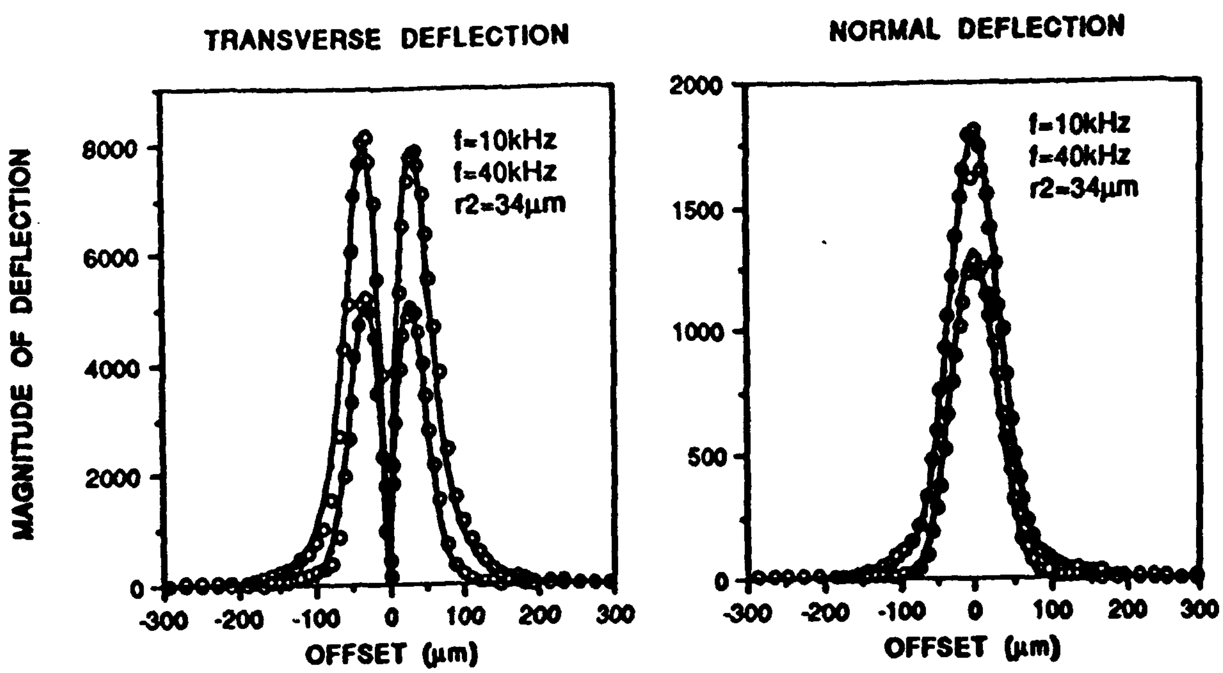

Fig. 8 Comparison between theory (lines) and experiment (points) for the thermal wave mirage signal for a 3000 A DLC coating on a Si substrate.

2. IR thermal wave nondestructive evaluation (NDE).

Frequency domain (lock-in imaging)

In work which we reported at the 6th International Topical Meeting on Photoacoustic and Photothermal Phenomena[9], held in Baltimore, July 31-Aug. 3, 1989 the development of an "asynchronous/synchronous" lock-in video processing system, in which the heating/image-processing period is asynchronous with the camera's scan frequency. This considerably simplifies both the hardware and the software necessary to control the system, and enables it to operate at arbitrary heating frequencies. We have presented a more detailed account of the lock-in technique, as well as the box-car technique in a review paper published in J. Nondes. Eval.[10]

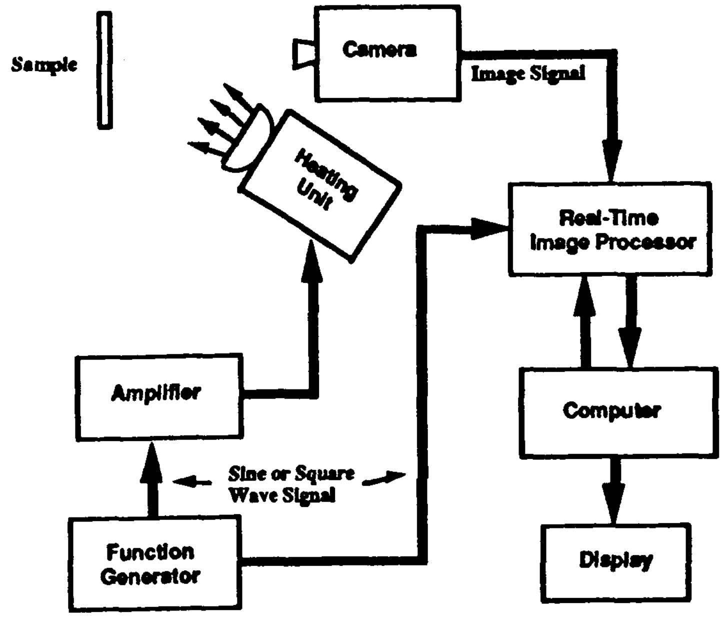

Fig. 9 Block diagram of the Lock-In Imaging System.

A block diagram of the apparatus is shown in Fig.9. The sample is heated with a periodic signal which is synchronized with an *external* reference signal. An IR camera, which is focussed on the sample, sends a continuous video image to an image processor in which the signal is digitized and

9 "Real-Time Asynchronous/Synchronous Lock-In Thermal-Wave Imaging With an IR Video Camera," L.D. Favro, T. Ahmed, H.J. Jin, P. Chen, P.K. Kuo, and R.L. Thomas, in Springer Series in Optical Sciences, Vol. 62, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 490-492.

10 "Synchronous Thermal Wave IR Video Imaging for NDE", P.K. Kuo, T. Ahmed, L.D. Favro, H-J Jin, and R.L. Thomas, *J. Nondestr. Eval.*8, 97-106 (1989); "IR Thermal Wave Imaging of Ceramics," R.L. Thomas, T. Ahmed, L.D. Favro, H.J. Jin, P.K. Kuo, and X. Wang, Proc. 37th Sagamore Army Materials Research Conf., Plymouth, MA, October 1-4, 1990, 489-495 (1990).

processed in synchronism with a reference signal, which also originates in the function generator and which provides the synchronism with the same external reference signal. The heating/reference period is uncorrelated with either the camera's horizontal (line) scan period or its vertical (frame) period, and is limited only by the digitizing rate of the image processor. The image processing consists of multiplying the image signal by the cosine and sine of the reference signal, and averaging and storing the results as an in-phase image and a quadrature image, respectively. The averaging is done in real time, and then the images are post-processed in an attached computer, where they can be stored on a hard disc or displayed in gray scale or pseudo-color.

Both the previously reported synchronous/synchronous (S/S) lock-in and the present asynchronous/synchronous (A/S) version are capable of real-time thermal wave imaging, and both offer improved signal-to-noise ratios as a result of their ability to average out background images and noise. As we described above, the A/S version is normally much easier to implement, because it is free of the need to synchronize the heating and image processing with the somewhat bizarre signal timing sequences of video cameras. However, there is another important distinction between the two methods. In the S/S method, the averaging can be *exact* in the sense that, after an integral number of frames have been averaged, a fixed, noise-free, background image will be exactly cancelled, because the number of positive half cycles of the heating period in the average will be exactly equal to the number of negative half cycles. The A/S method, on the other hand, relies on a *statistical* cancellation of the background. That is after many frames of asynchronous operation, there will *on the average* be as many positive as negative half cycles of heating.

An example of the use of the A/S lock-in technique is shown in Fig. 10, where we show two images of a pair of printed circuit traces which were being heated with an ac current. The first of the images was made with a modulation frequency of a 15 Hz. At this frequency the two traces are unresolved and show as one in the image. The second image was made with a modulation frequency of 102 Hz, and clearly shows the two separate traces.

During this period the following United States Patent was issued on this technique:

> United States Patent Number 4,878,116, "Vector Lock-in Imaging System", L.D. Favro, P.K. Kuo, and R.L. Thomas, October 31, 1989.

Figure 10. Asynchronous/Synchronous Lock-in images of two printed circuit traces being heated, left, at 15.5 Hz, and, right, at 101.6 Hz. Note the difference in resolution.

More recently, we have developed several <u>in-camera</u> methods for carrying out video lock-in imaging. This work has not yet been published, but a patent application has been filed. One of the methods described in that application is used to carry out lock-in video imaging in the <u>visible</u> part of the electromagnetic spectrum, and as we shall point out in the following section describing our proposed research program, we have recently (unpublished) extended the frequency range to <u>1 MHz</u>. This version has good potential for use in the <u>photoreflectance</u> version of thermal wave imaging which currently finds extensive commercial applications in the microelectronics industry, and we will address this potential as one portion of our proposed program.

We have also carried out IR thermal wave lock-in imaging with the use of an intensity-modulated laser as a heat source (unpublished work). The second portion of our proposed research program will address the problem of extending the range of frequencies for this method to the region 10 kHz - 1 MHz, in order to address a number of NDE problems which require much shorter thermal diffusion lengths in order to achieve the necessary sensitivity and level of discrimination.

Time domain (box-car imaging)

In work which we also reported at the 6th International Topical Meeting on Photoacoustic and Photothermal Phenomena,[11] the application of the box-car technique (see Ref. 9 for a detailed description of the technique) to the practical NDE problems of plasma-sprayed coatings and adhesive bonds was described. In brief, it may be noted that infrared video cameras typically produce complete frames in times of the order of a fraction (say 1/30) of a second. There are many thermal wave phenomena for which this, or longer, time scales are appropriate. For instance, the times required for pulsed thermal waves to propagate through typical plasma-sprayed protective coatings on metal surfaces may range from about a hundred milliseconds to perhaps several seconds. On these time scales, the frame time of the camera may be considered to be approximately instantaneous, and the image in the frame considered to be a "snapshot" of the sample's surface temperature distribution at that time. Operating on this time scale, we have used a fast image processing system (DataCube), in conjunction with an IR video camera (Inframetrics), to produce a box-car image processor which performs gated averages of pulsed thermal wave images. A heating pulse is triggered by a signal from the camera to start a box-car cycle and to synchronize the heating with the camera's frame period. The heat source consists of up to eight 6 kJ flash lamps which produce pulses approximately 2 ms long. A gate consists of a frame, or several frames in succession, grabbed at some specified time after a given heating pulse. Up to four independent gates may be set within *each* heating pulse cycle. The images taken in different gates can be combined arithmetically in real time to produce processed images in two separate buffers. Each of the resulting images is combined with images taken with previous heating pulses to form two averaged and processed images in the two buffers. After a suitable number of averages with a given set of gates, the averaged images are transferred to a computer workstation (Sun 3/160) for further arithmetic manipulation. The effect of the processing is the removal of background effects and thermal emissivity artifacts. The combination of processing and averaging improves the sensitivity of the camera and allows the imaging of defects which are ordinarily invisible to the camera.

To date we have used our box-car system primarily to study laminated structures. Examples are plasma-sprayed coatings, painted surfaces, adhesive joints between metal or plastic panels, and both fiber-polymer[12] and carbon-carbon composites. When imaging a new material or

11 "Real-Time Thermal-Wave Imaging of Plasma-Sprayed Coatings and Adhesive Bonds Using a Box-Car Video Technique,"T. Ahmed, H.J. Jin, P. Chen, P.K. Kuo, L.D. Favro, and R.L. Thomas, in Springer Series in Optical Sciences, Vol. 62, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 30-32.

combination of materials, one must first determine the appropriate time scale(s) for setting the box-car gates. This is accomplished by analyzing preliminary images with our (WSU-developed) system software. This software includes provisions for mouse-driven, on-screen plotting of the time dependence of the spatial average of the signals corresponding to any arbitrary rectangular area of the image, and for comparing the time dependances for different areas. This comparison is used to set gate delays and gate widths which maximize the thermal wave contrast of the image. This process takes only a few minutes and then the system is set to produce the final image of the sample. Subsequent samples of the same type require no further set-up, and are done essentially in real time.

As an illustrative example, in Fig. 11, we show a front-surface (both heat source and camera in front), box-car image of an adhesive which was applied in a pattern to the rear surface of a 0.95 mm thick painted automotive steel panel. (Note the adhesion defect in the border of the pattern on the right hand side.) For comparison, in Fig.12, we display an image of an similar pattern as seen through a panel which is only 0.2 mm thick, thus demonstrating the expected improvement in the resolution of the pattern with the thinner metal.

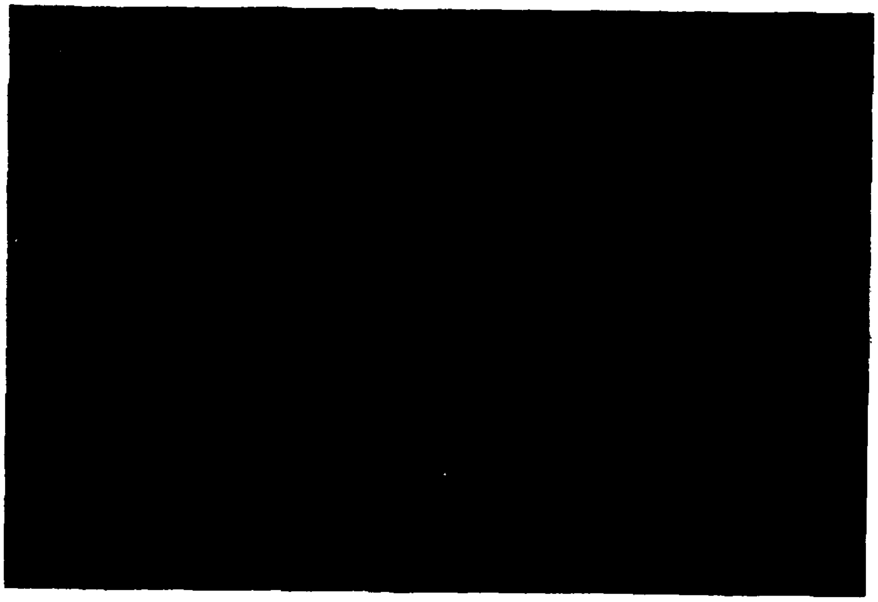

Figure 11. Box-car image of an adhesive pattern as seen through a 0.95 mm thick steel panel.

12 "Infrared thermal-wave studies of coatings and composites," L.D. Favro, T. Ahmed, D. Crowther, H.J. Jin, P.K. Kuo, R.L. Thomas, and X. Wang, Proc.*SPIE Thermosense XIII, Orlando, FL, April 3-5, 1991, Vol. 1467 Thermosense XIII (1991), pp. 290-294,* and *132 (1991).*

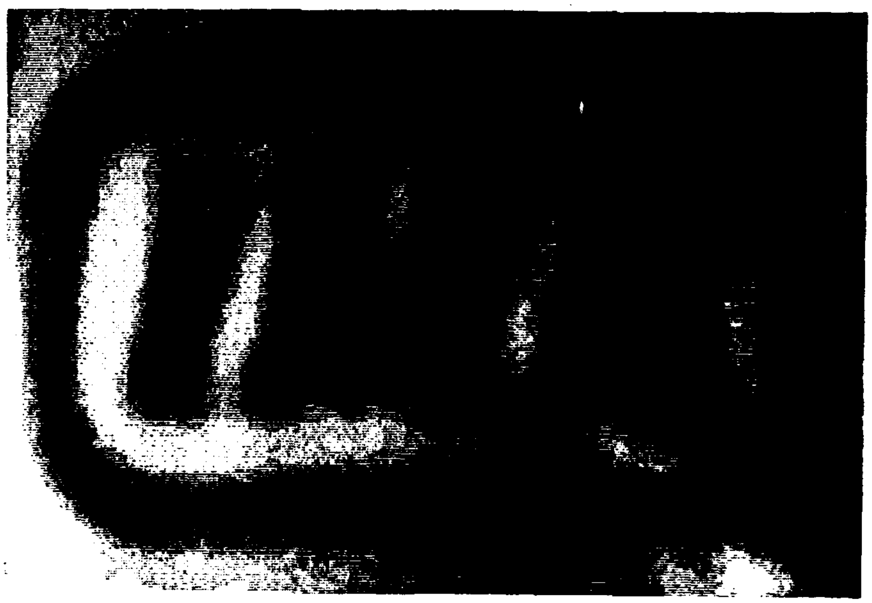

Figure 12. Box-car image of an adhesive pattern as seen through a 0.2 mm thick steel panel. Note the difference in resolution between Fig. 11 and Fig. 12.

Another pair of illustrative examples[10] is given in Fig. 13. These are box-car images of a plasma-sprayed coating on the top of a piston from an internal combustion engine. The left image is one of the piston before it was installed in the engine. The right is one after the engine had been run steadily for several weeks. The most obvious change between the "before" and "after" images is the large region on the upper right of the rim in which the coating has spalled off. (It should be noted that the color maps for the two are not the same; the second has a much grater dynamic range than the first.) Of more interest are the "hot spots" at the center and at various points around the rim. As demonstrated by subsequent sectioning of the sample, these represent regions in which the bonding of the coating to the substrate has failed, but not yet enough to cause spalling.

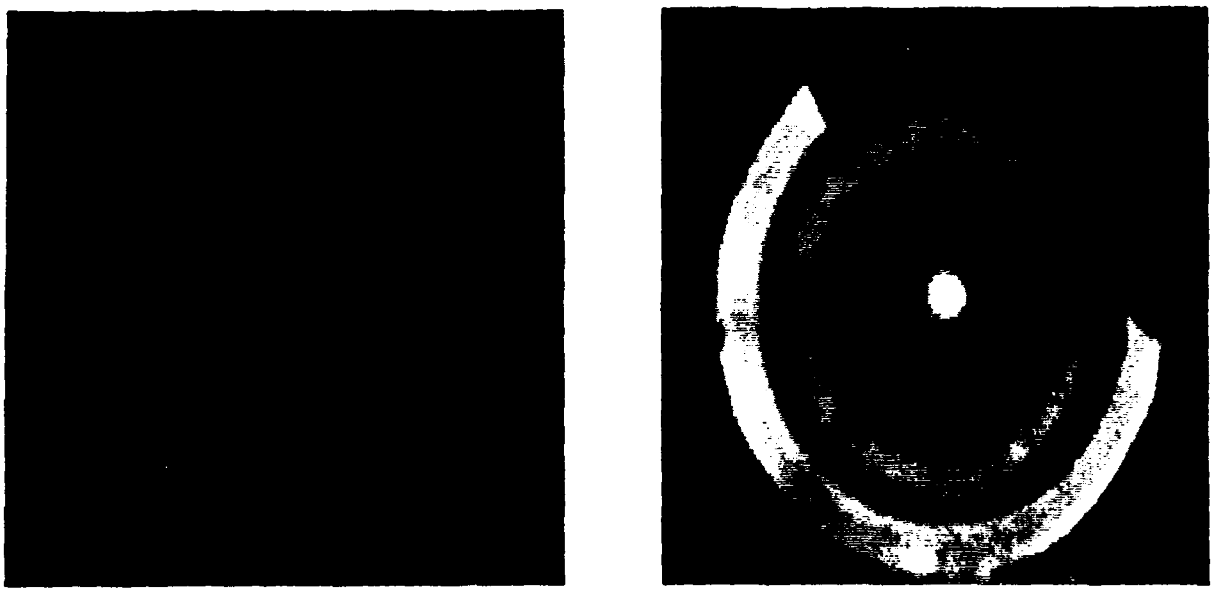

Figure 13. Left, box-car image of a thermal barrier coating on a piston cap *before* being run in an engine. Right, image of same piston *after* being run in an engine for several weeks.

A third illustrative example[13] is given in Figs. 14-17. Figure 14 shows a box-car image of a 3" x 5" x 0.25" laminated graphite-epoxy panel which had been subjected to an impact from the opposite side. This image is made by first flash heating the sample with a 10 kJ pulse from a pair of xenon flashlamps, and then grabbing two gated images at different delays after the flash. The first gate was set at 33 ms, and second was set several seconds out on the cooling curve. The image obtained in the second gate was subtracted pixel-by-pixel from the image from the first gate. The displayed image is the average of 16 repetitions of this process. It should be noted that, at this short (for this material) gate time, the image displays many of the details of the first ply of the sample. The 45° lines apparent in the image are bundles of graphite fibers in that ply. Also apparent is a near subsurface delamination, showing as a red patch in the image, resulting from the

13 "Noise Suppression in IR Thermal-Wave Video Images by Real-Time Processing in Synchronism with Active Stimulation of the Target," L.D. Favro, T. Ahmed, H.J. Jin, P.K. Kuo, and R.L. Thomas, SPIE Vol. 1313 Thermosense XII (1990), pp. 302-306.

impact on the opposite side. Figs. 15-17 are similar to Fig. 14, except that the first gate was set progressively later to display the increasing penetration depth of the thermal waves as time progresses. In this pulsed version of thermal wave imaging, the penetration depth reached by the thermal waves responsible for the image is proportional to the square-root of the first gate time. As the gate time increases, we see in Fig. 15 a first slight hint of a second, deeper, delamination in the form of a faint vertical band passing through the red area, indicating the shallower delamination. In Fig. 16 this band has become quite pronounced, and in Fig. 17 the deeper delamination has become quite clear. Imaging from the opposite side inverts the order of the appearances of these features.

Fig. 14. Synchronous box-car image of a quarter-inch thick graphite-epoxy laminate that had been impacted by a ball bearing. Gate delay is 33 ms. Some indications of surface ply structure (45° lines), and near subsurface delamination (red area) caused by the impact.

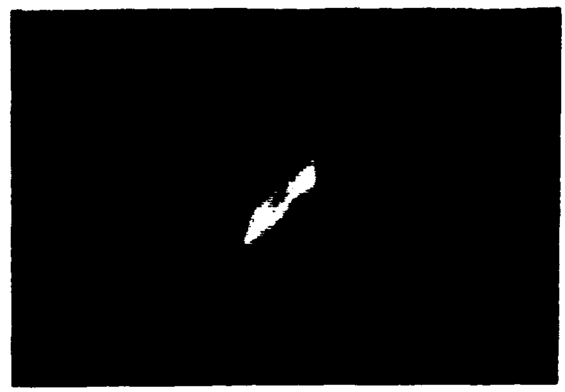

Fig. 15 Synchronous box-car image of the same sample as in Fig. 14, but at a gate delay of 83 ms. Note the disappearance of surface features and the faint indications of a deeper delamination (vertical band passing through the red area).

Fig. 16. Synchronous box-car image of the same sample as in Fig. 14, but at a gate delay of 500 ms. Note the emergence of the deeper delamination.

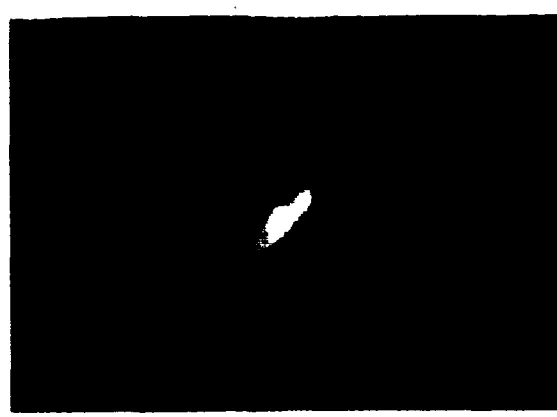

Fig. 17 Synchronous box-car image of the same sample as in Fig. 14, but at a gate delay of 1 s, now showing a clear image of the deeper delamination.

Thermal Wave Tomography:

A recent development in the time-domain thermal wave technology has been our demonstration[14] of real-time (10 Hz rate) tomography, in which the pixel-by-pixel thermal wave "echo" time is determined for sub-surface planar scatterers, and stored in an image buffer for viewing immediately following the cooling of the sample surface. This technique has now been installed in a "Beta Site" system which is being evaluated by Lockheed at their Marietta, GA facility, for possible use in characterizing and testing composite materials and parts to be used in the F-22 Advanced Tactical Fighter development program. That system has been running successfully since November 12, 1991.

Thermal Wave Tomography:

Another recent development in the time-domain thermal wave technology has been our demonstration[15] that it is possible to simulate the heat flow and in fact carry out numerical inverse scattering calculations to determine the shapes and sizes of subsurface scatterers.

14 "Real-Time Thermal Wave Tomography," L.D. Favro, H.J. Jin, P.K. Kuo, R.L. Thomas, and Y.X. Wang, accepted for Proc. 7th Int. Topical Meeting on Photoacoustic and Photothermal Phenomena, Doowerth, The Netherlands, August 26-30, 1991.

15 "Analytic Calculations and Numerical Simulations of Box-Car Thermal Wave Images of Planar Subsurface Scatterers,"D. Crowther, L.D. Favro and R.L. Thomas, Proc. 18th Annual Review of Progress in Quantitative NDE, Brunswick, ME, July 28-Aug. 2, 1991, to be published in *Review of Progress in Quantitative NDE*, Vol. 11, edited by D.O. Thompson and D. Chimenti, Plenum New York, (to be published).

Velocity domain (Flying spot imaging)

In work which we also reported at the 6th International Topical Meeting on Photoacoustic and Photothermal Phenomena,[16] we have described the development of a "Flying-Spot" laser-source/IR-detector camera in which an unmodulated laser heating spot scans the sample in a raster. The detector tracks the heating spot in the same raster, but with a time delay, thus forming an image with a very short time between the application of the heat source and the detection of the thermal waves. The *same* pair of scanning mirrors is used to scan both the camera's IR detector focal spot and the heating laser's focal spot (see schematic diagram, Fig. 18, below), thereby maintaining complete synchronism between the two focal spots in both the horizontal and vertical directions. A more recent description, with comparison between theory and experiment, was presented at the 1991 QNDE Meeting in Maine.[17]

16 "A Novel "Flying-Spot" Infrared Camera for Imaging Very Fast Thermal-Wave Phenomena,"Y.Q. Wang, P.K. Kuo, L.D. Favro, and R.L. Thomas, in Springer Series in Optical Sciences, Vol. 62, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 24-26.

17 "Flying Laser Spot Thermal Wave IR Imaging," Y.Q. Wang, P.Chen, P.K. Kuo, L.D. Favro, and R.L. Thomas, Proc. 18th Annual Review of Progress in Quantitative NDE, Brunswick, ME, July 28-Aug. 2, 1991, to be published in *Review of Progress in Quantitative NDE*, Vol. 11, edited by D.O. Thompson and D. Chimenti, Plenum New York, (to be published).

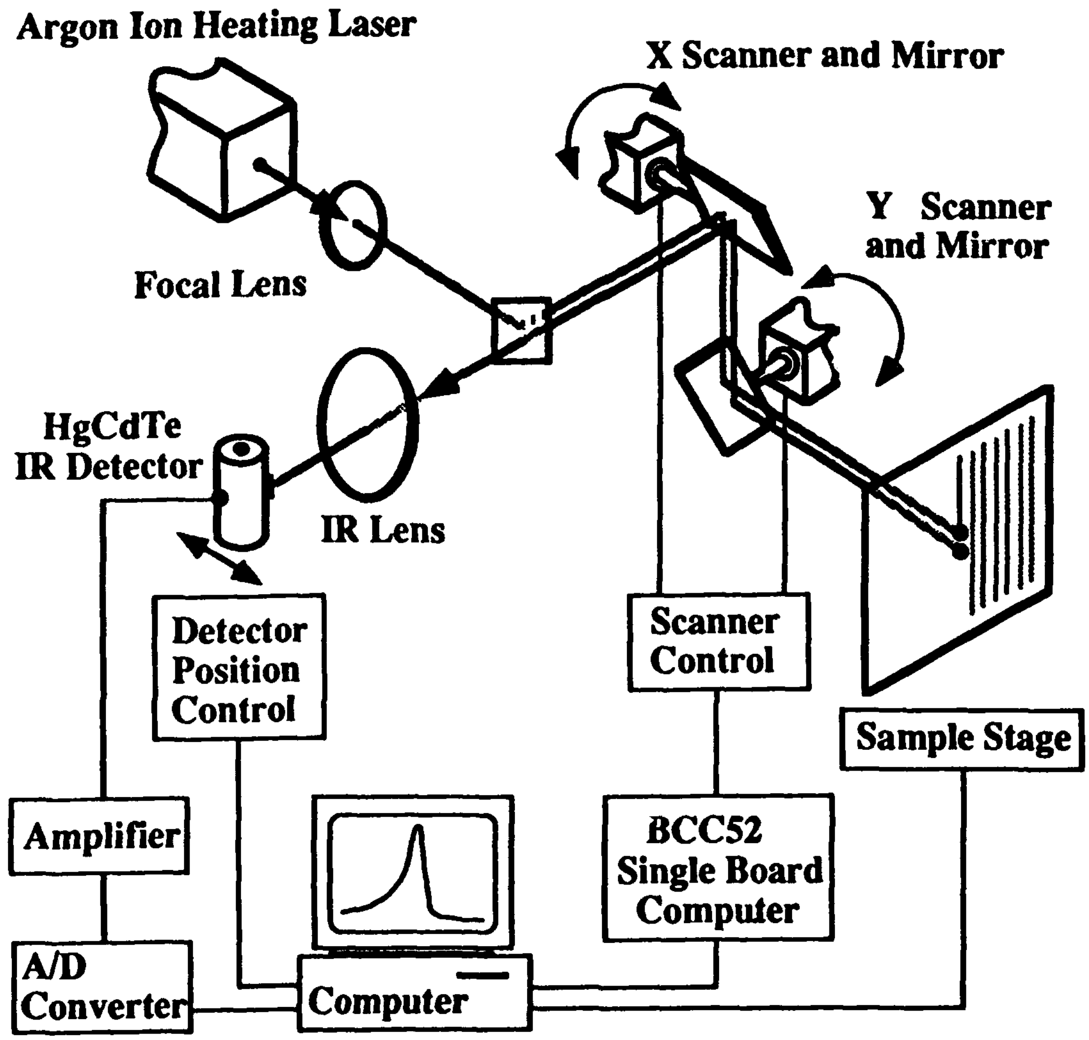

Figure 18. Schematic diagram of the "Flying-Spot" Thermal Wave Camera.

C. LIST OF ALL PUBLICATIONS AND TECHNICAL REPORTS

"Parallel Vector Lock-In Thermal Wave IR Video Imaging of Microcracks in Cu Foils Deposited on Polyimide", T. Ahmed, P.K. Kuo, L.D. Favro, H-J Jin, R.L. Thomas, C.M. Woods and G.L. Houston, *Review of Progress in Quantitative NDE,* **Vol. 8**, edited by D.O. Thompson and D. Chimenti, Plenum New York pp. 607-611 (1989).

"Parallel Thermal Wave IR Video Imaging of Polymer Coatings and Adhesive Bonds", T. Ahmed, P.K. Kuo, L.D. Favro, H-J Jin, R.L. Thomas, and R. Dickie, *Review of Progress in Quantitative NDE,* Vol. 8, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 1385-1392 (1989).

"Phase-locked Image Acquisition in Thermography", P.K. Kuo, T. Ahmed, Hijia Jin, and R.L. Thomas, Proc. SPIE Symposium on Advances in Intelligent Robotics Systems, Cambridge, MA, Nov. 6-11, 1988, *SPIE Vol. 1004* Automated Inspection and High Speed Vision Architectures II (1988), pp. 41-45.

"Characterization of Plasma-Sprayed Coatings using Thermal Wave Infrared Video Imaging", T. Ahmed, Z.J. Feng, P.K. Kuo, J. Jaarinen and J. Hartikainen, *J. Nondestr. Eval.*, Vol. 6, No. 4 (1987), pp. 169-175.

"Thermal Wave Microscopy", R.L. Thomas, L.D. Favro and P.K. Kuo, *Proc. 11th Triennial World Congress of the International Measurement Confederation* (accepted for publication).

"Infrared Thermal Wave Imaging of Adhesion Defects", P.K. Kuo, T. Ahmed, L.D. Favro, H.J. Jin, and R.L. Thomas, Proc. 17th Symposium on Nondestructive Evaluation, San Antonio, Texas, April 17-20, 1989, NTIAC, Southwest Research Institute, San Antonio, pp. 238-242..

"Synchronous Thermal Wave IR Video Imaging for NDE", P.K. Kuo, T. Ahmed, L.D. Favro, H-J Jin, and R.L. Thomas, *J. Nondestr. Eval.* **8**, 97-106 (1989).

"Thermal Wave Measurement of Diamond Films", P.K. Kuo, Lanhua Wei, R.L. Thomas, and R.W. Pryor, Proceedings of the 6th International Topical Meeting on Photoacoustic and Photothermal Phenomena, Baltimore, MD, July 31 - August 3, 1989, *Photoacoustic and Photothermal Phenomena II*, J.C. Murphy, J.W. Maclachlan Spicer, L.C. Aamodt, and B.S.H. Royce (Eds.) Springer Series in Optical Sciences 62, 124-126, Springer-Verlag, Heidelberg (1990).

"Real-Time Asynchronous/Synchronous Lock-In Thermal-Wave Imaging With an IR Video Camera", L.D. Favro, T. Ahmed, H.J. Jin, P. Chen, P.K. Kuo, and R.L. Thomas, Proceedings of the 6th International Topical Meeting on Photoacoustic and Photothermal Phenomena, Baltimore, MD, July 31 - August 3, 1989, *Photoacoustic and Photothermal Phenomena II*, J.C. Murphy, J.W. Maclachlan Spicer, L.C. Aamodt, and B.S.H. Royce (Eds.) Springer Series in Optical Sciences **62**, 30-32, Springer-Verlag, Heidelberg (1990).

"A Novel "Flying-Spot" Infrared Camera for Imaging Very Fast Thermal-Wave Phenomena", Y.Q. Wang, P.K. Kuo, L.D. Favro, and R.L. Thomas, Proceedings of the 6th International Topical Meeting on Photoacoustic and Photothermal Phenomena, Baltimore, MD, July 31 - August 3, 1989, *Photoacoustic and Photothermal Phenomena II*, J.C. Murphy, J.W. Maclachlan Spicer, L.C. Aamodt, and B.S.H. Royce (Eds.) Springer Series in Optical Sciences **62**, 24-26, Springer-Verlag, Heidelberg (1990).

"Flying Laser Spot Thermal Wave IR Imaging of Horizontal and Vertical Cracks", Y.Q. Wang, P.K. Kuo, L.D. Favro, and R.L. Thomas, *Review of Progress in Quantitative NDE*, **Vol. 9**, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 511-516 (1990).

"Recent Developments in Growth and Characterization of Thin Diamond Films", R.W. Pryor, R.L. Thomas, P.K. Kuo, and L.D. Favro, *Proc. SPIE Conference 1146 (Diamond OpticsII)*, San Diego, CA, Aug.7-8, 1989 (accepted for publication).

"Mirage Effect Thermal Wave Measurements on Thin Polycrystalline Diamond Films", R.W. Pryor, P.K. Kuo, L. Wei, R.L. Thomas, and P.L. Talley, Proceedings of the Fourth Annual SDIO/IST-ONR Diamond Technology Initiative Symposium, Crystal City,VA, July 11-13, 1989

"Non-Contact Measurement of Thermal Properties of Diamond Films", Materials Research Society, P.K. Kuo, Lanhua Wei, R.L. Thomas, and R.W. Pryor, Diamond Films, Symposium Q (Extended Abstracts), Spring 1989, Apr. 24-29 (to be published)

"In-Situ Characterization of Thin Polycrystalline Diamond Film Quality by Thermal Wave and Raman Techniques," R.W. Pryor , P,K. Kuo, L. Wei, R.L. Thomas, and P.L. Talley, Materials Research Society, Diamond for Electronics, Symposium F4 (Extended Abstracts), Diamond, Boron Nitride, Silicon Carbide and Related Wide Bandgap Semiconductors, Fall 1989, Boston, MA, Nov.27-Dec.2, 1989 (to be published).

"Thermal Characterization of Diamond Materials," R.W. Pryor, R.L. Thomas, P.K. Kuo, and L.D. Favro, Proc. 1st Annual Diamond Technology Workshop, Engineering Society of Detroit, Sept. 18, 1989 (published by the Institute for Manufacturing Research, Wayne State University, 1989).

"Thermal Wave Measurement of Diamond Films", P.K. Kuo, Lanhua Wei, R.L. Thomas, "Real-Time Thermal-Wave Imaging of Plasma-Sprayed Coatings and Adhesive Bonds Using a Box-Car Video Technique,"T. Ahmed, H.J. Jin, P. Chen, P.K. Kuo, L.D. Favro, and R.L. Thomas, in Springer Series in Optical Sciences, **Vol. 62**, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 30-32.

"Thermal Wave and Raman Characterization of Diamond Films", R.W. Pryor, P.K. Kuo, Lanhua Wei, and R.L. Thomas, *Review of Progress in Quantitative NDE*, **Vol. 9**, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 1123-1128 (1990).

"Noise Suppression in IR Thermal-Wave Video Images by Real-Time Processing in Synchronism with Active Stimulation of the Target," L.D. Favro, T. Ahmed, H.J. Jin, P.K. Kuo, and R.L. Thomas, Proc.*SPIE Thermosense XII*, Orlando, FL, April 17-20, 1990 SPIE Vol. 1313 pp. 302-306 (1990).

"Infrared Thermal Wave Studies of Composites," T. Ahmed, H.J. Jin, X. Wang, L.D. Favro, P.K. Kuo, and R.L. Thomas, *Review of Progress in Quantitative NDE*, **Vol. 10B**, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 2173-2179 (1991).

"Measurement of the Thermal Diffusivity of Diamond Single Crystals," Lanhua Wei, P.K. Kuo, R.W. Pryor, and R.L. Thomas, presented at the *Review of Progress in Quantitative NDE, LaJolla, CA, July 15-20, 1990*.

"NDE Applications of Synchronous Video Lock-In Averaging," P.Chen, Y.X. Wang, T. Ahmed, H.J. Jin, X. Wang, L.D. Favro, P.K. Kuo, and R.L. Thomas, presented at the *Review of Progress in Quantitative NDE, LaJolla, CA, July 15-20, 1990*.

"A Thermal Wave Technique to Determine Thermal Diffusivities of Polymer Foils," J. Rantala, J. Jaarinen, Lanhua Wei , P.K. Kuo, and R.L. Thomas, *Review of Progress in Quantitative NDE*, Vol. 10B, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 2165-2172 (1991).

"Thermal Wave and Raman Measurement of Polycrystalline Diamond Film Quality," R.W. Pryor, L. Wei, P.K. Kuo, and R.L. Thomas, to be presented at the *NATO Advanced Study Institute onDiamond and Diamond-like Films and Coatings, Pascoli, Italy, July 22 - August 3 (1990).*

"The Thermal Diffusivity of Isotopically Enriched C_{12} Diamond," T.R. Anthony, W.F. Banholzer , J.F. Fleischer, Lanhua Wei, P.K. Kuo, R.L. Thomas and R.W. Pryor, *Phys. Rev.* **B42**, pp.1104-1111 (1990).

"Thermal Wave Measurement of Isotopic Effects in Polycrystalline and Bulk Diamond Materials," R.W. Pryor, Lanhua. Wei, P.K. Kuo, and R.L. Thomas, Proc. Second Int. Conf. on the New Diamond Science and Technology, Washington, D.C., Sept. 24-27, 1990, "New Diamond Science and Technology," Proceedings of ICNDST-2, Publications Dept., Materials Research Society, Pittsburgh (1991), pp. 863-868.

"Infrared Thermal Wave Studies of Composites," T. Ahmed, H.J. Jin, X. Wang, L.D. Favro, P.K. Kuo, and R.L. Thomas, *Review of Progress in Quantitative NDE*, Vol. 10B, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 2173-2179 (1991).

"IR Thermal Wave Imaging of Ceramics," R.L. Thomas, T. Ahmed, L.D. Favro, H.J. Jin, P.K. Kuo, and X. Wang, Proc. 37th Sagamore Army Materials Research Conf., Plymouth, MA, October 1-4, 1990, 489-495 (1990).

"Temperature Dependence of the Thermal Conductivity of Type IIA Diamond Crystals," Lanhua Wei, P.K. Kuo, R.L. Thomas, T.R. Anthony and W.F. Banholzer, Proc. Second Int. Conf. on the New Diamond Science and Technology, Washington, D.C., Sept. 24-27, 1990 "New Diamond Science and Technology," Proceedings of ICNDST-2, Publications Dept., Materials Research Society, Pittsburgh (1991), pp. 875-880.

"Infrared thermal-wave studies of coatings and composites," L.D. Favro, T. Ahmed, D. Crowther, H.J. Jin, P.K. Kuo, R.L. Thomas, and X. Wang, Proc.*SPIE Thermosense XIII*, Orlando, FL, April, 1991, SPIE Vol. 1467 Thermosense XIII, pp. 290-294, and p.132.

"Real-Time Thermal Wave Tomography," L.D. Favro, H.J. Jin, P.K. Kuo, R.L. Thomas, and Y.X. Wang, accepted for Proc. 7th Int. Topical Meeting on Photoacoustic and Photothermal Phenomena, Doowerth, The Netherlands, August 26-30, 1991.

"Thermal Diffusivity Measurements of Diamond Materials, "P.K. Kuo, Lanhua Wei, and R.L.Thomas, accepted for Proc. 7th Int. Topical Meeting on Photoacoustic and Photothermal

Phenomena, Doowerth, The Netherlands, August 26-30, 1991.

"Thermal Wave Imaging for Structural Analysis," P.K. Kuo, L.D. Favro, and R. L. Thomas, Proc. 1991 SEM Spring Conf. on Exptl. Mechanics, Milwaukee, June 10-13, 1991, SEM Publications, Bethel, CT (1991), pp. 244-247.

"Thermal Diffusivity Measurements of Diamond Materials", Lanhua Wei, P.K. Kuo, And R.L.Thomas, Proc. 18th Annual Review of Progress in Quantitative NDE, Brunswick, ME, July 28-Aug. 2, 1991, to be published in *Review of Progress in Quantitative NDE*, Vol. 11, edited by D.O. Thompson and D. Chimenti, Plenum New York, (to be published).

"Flying Laser Spot Thermal Wave IR Imaging," Y.Q. Wang, P.Chen, P.K. Kuo, L.D. Favro, and R.L. Thomas, Proc. 18th Annual Review of Progress in Quantitative NDE, Brunswick, ME, July 28-Aug. 2, 1991, to be published in *Review of Progress in Quantitative NDE*, Vol. 11, edited by D.O. Thompson and D. Chimenti, Plenum New York, (to be published).

"Thermal Wave Imaging for Nondestructive Evaluation of Coatings and Interfaces," R.L. Thomas, L.D. Favro and P.K. Kuo, invited talk to be presented at the First Annual ASNT Symposium: NDE of Interfaces, to be held in Orlando, Florida, March 31 - April 1, 1992.

"Tomographic Infrared Thermal Wave Imaging," R.L. Thomas, invited talk to be presented at the American Physical Society Meeting in Inianapolis, March 16-20, 1992

D. LIST OF ALL PARTICIPATING SCIENTIFIC PERSONNEL SHOWING ANY ADVANCED DEGREES EARNED BY THEM WHILE EMPLOYED ON THE PROJECT

Prof. R.L. Thomas
Prof. L.D. Favro
Prof. P.K. Kuo
Dr. Tasdiq Ahmed (Postdoctoral Research Associate)
Y. Wang
Y.Q. Wang ; M.S. (Physics), 1991 "Thermal Wave Imaging Techniques on NuVision Image Processing System"
Ms. Peggy Talley (Graduate Research Assistant)
Dr. Celeste B. Reyes (Ph.D., 1988 "Thermal Wave Measurement of Thermal Diffusivities of Solids")

REPORT OF INVENTIONS (BY TITLE ONLY)

"Vector Lock-in Imaging System"

"Synchronous Imaging System"

"A Dynamic Offset to Increase the Range of Digitization of Video Images"

BIBLIOGRAPHY

1. "Photothermal Deflection (mirage) Detection of Diffusivities and Surface and Subsurface Defects in Solids", by P.K. Kuo, L.D. Favro, and R.L.Thomas, in *Photothermal Deflection Spectroscopy and Applications"*, ed. J.A. Sell, Academic Press, New York (1988), Chapter 6, pp. 191-212.

2. "Thermal Diffusivity of Isotopically Enriched ^{12}C Diamond", T.R. Anthony, W.F. Banholzer, J.F. Fleischer, Lanhua Wei, P.K. Kuo, R.L. Thomas, and R.W. Pryor, Phys. Rev. **B42**, pp.1104-1111 (1990).

3. "Thermal Diffusivity Measurements of Diamond Materials, "P.K. Kuo, Lanhua Wei, and R.L.Thomas, accepted for Proc. 7th Int. Topical Meeting on Photoacoustic and Photothermal Phenomena, Doowerth, The Netherlands, August 26-30, 1991.

4. "Temperature Dependence of the Thermal Conductivity of Type IIA Diamond Crystals," Lanhua Wei, P.K. Kuo, R.L. Thomas, T.R. Anthony and W.F. Banholzer, Proc. Second Int. Conf. on the New Diamond Science and Technology, Washington, D.C., Sept. 24-27, 1990, "New Diamond Science and Technology," Proceedings of ICNDST-2, Publications Dept., Materials Research Society, Pittsburgh (1991), pp. 875-880.

5. "Thermal Wave Measurement of Diamond Films," P.K. Kuo, Lanhua Wei, R.L. Thomas, and R.W. Pryor, in Springer Series in Optical Sciences, Vol. 62, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 124-126.

6. "Thermal Diffusivity Measurements of Diamond Materials", Lanhua Wei, P.K. Kuo, And R.L.Thomas, Proc. 18th Annual Review of Progress in Quantitative NDE, Brunswick, ME, July 28-Aug. 2, 1991, to be published in *Review of Progress in Quantitative NDE*, **Vol. 11**, edited by D.O. Thompson and D. Chimenti, Plenum New York, (to be published).

7. "Thermal Diffusivity Measurements of Diamond Materials, "P.K. Kuo, Lanhua Wei, and R.L.Thomas, accepted for Proc. 7th Int. Topical Meeting on Photoacoustic and Photothermal Phenomena, Doowerth, The Netherlands, August 26-30, 1991.

8. "A Thermal Wave Technique to Determine Thermal Diffusivities of Polymer Foils," J. Rantala, J. Jaarinen, Lanhua Wei , P.K. Kuo, and R.L. Thomas, *Review of Progress in Quantitative NDE*, **Vol. 10B**, edited by D.O. Thompson and D. Chimenti, Plenum New York, pp. 2165-2172 (1991).

9. "Real-Time Asynchronous/Synchronous Lock-In Thermal-Wave Imaging With an IR Video Camera," L.D. Favro, T. Ahmed, H.J. Jin, P. Chen, P.K. Kuo, and R.L. Thomas, in Springer Series in Optical Sciences, Vol. 62, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 490-492.

10. "Synchronous Thermal Wave IR Video Imaging for NDE", P.K. Kuo, T. Ahmed, L.D. Favro, H-J Jin, and R.L. Thomas, *J. Nondestr. Eval.*8, 97-106 (1989); "IR Thermal Wave Imaging of Ceramics," R.L. Thomas, T. Ahmed, L.D. Favro, H.J. Jin, P.K. Kuo, and X. Wang, Proc. 37th Sagamore Army Materials Research Conf., Plymouth, MA, October 1-4,

1990, 489-495 (1990).

11. "Real-Time Thermal-Wave Imaging of Plasma-Sprayed Coatings and Adhesive Bonds Using a Box-Car Video Technique,"T. Ahmed, H.J. Jin, P. Chen, P.K. Kuo, L.D. Favro, and R.L. Thomas, in Springer Series in Optical Sciences, Vol. 62, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 30-32.

12. "Infrared thermal-wave studies of coatings and composites," L.D. Favro, T. Ahmed, D. Crowther, H.J. Jin, P.K. Kuo, R.L. Thomas, and X. Wang, Proc.*SPIE Thermosense XIII, Orlando, FL, April 3-5, 1991, Vol. 1467 Thermosense XIII (1991), pp. 290-294, and 132 (1991).*

13. "Noise Suppression in IR Thermal-Wave Video Images by Real-Time Processing in Synchronism with Active Stimulation of the Target," L.D. Favro, T. Ahmed, H.J. Jin, P.K. Kuo, and R.L. Thomas, SPIE Vol. 1313 Thermosense XII (1990), pp. 302-306.

14. "Real-Time Thermal Wave Tomography," L.D. Favro, H.J. Jin, P.K. Kuo, R.L. Thomas, and Y.X. Wang, accepted for Proc. 7th Int. Topical Meeting on Photoacoustic and Photothermal Phenomena, Doowerth, The Netherlands, August 26-30, 1991.

15. "Analytic Calculations and Numerical Simulations of Box-Car Thermal Wave Images of Planar Subsurface Scatterers,"D. Crowther, L.D. Favro and R.L. Thomas, Proc. 18th Annual Review of Progress in Quantitative NDE, Brunswick, ME, July 28-Aug. 2, 1991, to be published in *Review of Progress in Quantitative NDE*, Vol. 11, edited by D.O. Thompson and D. Chimenti, Plenum New York, (to be published).

16. "A Novel "Flying-Spot" Infrared Camera for Imaging Very Fast Thermal-Wave Phenomena,"Y.Q. Wang, P.K. Kuo, L.D. Favro, and R.L. Thomas, in Springer Series in Optical Sciences, Vol. 62, *Photoacoustic and Photothermal Phenomena II*, Eds. J.C. Murphy, J. W. Maclachlan-Spicer, L. Aamodt, and B.S.H. Royce, Springer-Verlag Berlin, Heidelberg 1990, pp. 24-26.

17. "Flying Laser Spot Thermal Wave IR Imaging," Y.Q. Wang, P.Chen, P.K. Kuo, L.D. Favro, and R.L. Thomas, Proc. 18th Annual Review of Progress in Quantitative NDE, Brunswick, ME, July 28-Aug. 2, 1991, to be published in *Review of Progress in Quantitative NDE*, Vol. 11, edited by D.O. Thompson and D. Chimenti, Plenum New York, (to be published).