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REAL-TIME ANALYSIS OF THERMAL DIFFUSIVITY
DATA FROM A PULSED LASER FACILITY

C. M. Davenport
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UNION
CARBIDE

OAK RIDGE Y-12 PLANT
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*prepared for the U.S. ATOMIC ENERGY COMMISSION
under U.S. GOVERNMENT Contract W-7405 eng 26*

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National Technical Information Service
U.S. Department of Commerce
5285 Port Royal Road, Springfield, Virginia 22151
Price: Printed Copy \$3.00; Microfiche \$0.95

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under Contract W-7405-eng-26

Date Issued - September 11, 1972

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ABSTRACT

A computer (PDP-15/35) has been used in conjunction with a pulsed laser facility to provide real-time analysis of thermal diffusivity data. Upon command of the operator, a transient recorder and other registers showing the device switch positions are scanned, the data are analyzed with FORTRAN routines, and the results are printed out at the laser station Teletype. The analysis includes finding an average and a standard deviation for thermal diffusivity at each temperature point. A report-form summary is printed out at the end of a run.

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SUMMARY

If a laser is used to fire a defocussed burst of energy at a thin material sample, a heat-transient signal may be picked up at the back side by a thermocouple. This heat transient may be graphically analyzed to yield the thermal diffusivity value of the sample. Real-time analysis of the data by computer would greatly reduce the work done by the operator, would provide more repeatable results, and would make practical more extensive runs. Accordingly, a PDP-15/35 computer has been used to provide real-time analysis of thermal diffusivity data. The laser facility shares the computer with other projects, involving process control and automated instrument analysis, on a multiprogramming basis.

The laser operator runs the experiment as before, obtaining an acceptable trace on the transient recorder. At this point, instead of plotting the trace out on an X-Y recorder and analyzing it graphically by hand, he merely pushes a button. The transient recorder and other registers showing the device switch positions are scanned by the computer, the data are analyzed using FORTRAN IV routines, and the results are printed out at the laser station Teletype. Provisions are made for finding an average and a standard deviation for thermal diffusivity at each temperature point. At the end of a run, involving up to 30 temperature points, a report form summary is printed out. Substantial running time with the new system has shown correct operation and has established that all the original objectives have been met.

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INTRODUCTION

The temperature distribution $T(\vec{x}, t)$ inside a homogeneous isotropic solid having no internal sources of heat is given by the solution of the equation of conduction:

$$\nabla^2 T - \frac{1}{\alpha} \frac{\partial T}{\partial t} = 0, \quad (1)$$

where α is a constant, the so-called "thermal diffusivity" constant. This equation can be applied very profitably in engineering calculations if the thermal diffusivity of the material in question is known.

One of the simplest and most direct ways of experimentally determining thermal diffusivity is to set up a one-dimensional heat conduction experiment for which a mathematical solution exists. The experimentally measured boundary conditions are then compared with the theoretical to yield a solution for α . This approach is the method used in the system described in this report. The experimental setup is indicated in Figure 1.

Figure 1. EXPERIMENTAL GEOMETRY FOR DETERMINING THERMAL DIFFUSIVITY.

The duration of the laser burst is short enough to be considered a heat impulse function at the front face. As this sharp pulse travels through the material it will become broadened due to the diffusive effect of the material. The thermocouple at the back face will see the pulse as a heat transient. It can be shown⁽¹⁾ that the thermal diffusivity of the material is given by:

$$\alpha = 0.139 d^2 / t_{1/2}, \quad (2)$$

where d represents the sample thickness, and $t_{1/2}$ the half rise time for the heat transient.

The half rise time cannot be measured directly but must be graphically determined from the heat transient. Figure 2 presents a typical heat transient curve along with the graphical analysis. Previously, before the graphical analysis could be done, the transient recorder trace

Figure 2. TYPICAL HEAT-TRANSIENT TRACE ON THE RECORDER.

had to be plotted out on an X-Y recorder each time. The purpose of the present project was to completely automate the data analysis. In addition, the task had to be tailored for the multiuser PDP-15/35 computer system. This report details how both requirements were met.

ANALYZING THERMAL DIFFUSIVITY DATA

THE PDP-15/35 REAL-TIME COMPUTER SYSTEM

The PDP-15/35 computer is especially designed for real-time operation. It has a minimum of 16K words of core of 18-bit length, a hardware priority interrupt system, a memory protect feature, and a real-time clock. Peripherals include a disc of 262K words capacity, DEC tapes (magnetic), a high-speed paper tape reader/punch, interfacing for additional Teletypes for communication with remote stations, and an oscilloscope display screen.

Real-time operation is supervised by the real-time executive (RSX) software supplied by the manufacturer. RSX is a multiprogramming system which schedules space available on a priority basis, queuing all requests. Currently executing jobs are not bumped by higher priority requests, and no swapping of jobs in and out of core occurs. All time spent waiting for I/O and similar delays is released for the use of other jobs. The configuration of the operating system in core is outlined in Figure 3.

Jobs are especially prepared and compiled for particular user partitions in core. Since a partition is typically 4K in size, and user programs are usually much larger, the programs must be broken up into several smaller tasks to be executed one at a time. Each succeeding task completely overlays the previous one, and the tasks themselves issue requests for succeeding tasks. Intermediate variables are maintained in the user common area which remains resident. The foregoing provides a very powerful chaining capability in comparison with ordinary chaining within a partition, which is also available.

The computer system is designated as an unclassified operation so that information protection and security measures⁽²⁾ imposed on classified automatic data processing systems do not apply. Administrative control via software reviews and system operating features ensure that no classified information enters the computer. Control over the operating system is exercised only from the console Teletype. Since there are more users than user partitions, some scheduling is necessary. Prepared user programs are maintained on disc or magnetic tape and are loaded, run, scheduled for future times, or otherwise directed via commands entered on the console Teletype. Communication between the computer operator and the remote device operators is by way of a direct-line two-way intercom system. Further information on the system is given in material supplied by the manufacturer.^(3, 4)

Figure 3. CORE MAP FOR THE RSX OPERATING SYSTEM.

THERMAL DIFFUSIVITY HARDWARE DESCRIPTION

Figure 4 gives a block diagram of the system. The system hardware is divided into two distinct parts: (1) the remote station instruments and associated interface, and (2) the local

Figure 4. THERMAL DIFFUSIVITY SYSTEM.

computer interface. The remote and local interfaces are connected by approximately six hundred feet of digital data transmission cable.

The remote station contains a transient recorder, a digital voltmeter, control switches, an X-Y recorder, an oscilloscope for the transient recorder, and a Teletype for computer input/output. The output of the thermocouple is sensed continuously by the digital voltmeter, and the temperature transient which occurs when the laser is fired is recorded. The recorder contains an eight-bit by 1,024-word memory and can record over a time interval from 50 microseconds to 20 seconds, selectable by front panel switches. The recorder also has the capability of changing the recording speed after a selected number of words. This feature is useful when the first part of a temperature transient has a fast rise time followed by a slower temperature decay, and both parts of the

transient are of interest. The transient recorder provides a continuous display on the oscilloscope of the stored information and can plot the stored data on an X-Y recorder on command.

The system can generate three computer program interrupts. The temperature-read request is a push-button switch which causes a computer program interrupt. It directs the computer program to read and update the sample ambient temperature by selecting and reading the digital voltmeter. A new temperature value is stored in computer memory each time the button is pressed. Similarly, a data-scan request causes a computer program interrupt which directs the computer to a routine which scans the memory of the recorder and stores the information in computer memory. The third program interrupt is from the transient recorder and occurs each time a new word is available on the recorder data lines as they are being scanned by the computer.

The interface at the computer consists of flag receiver circuitry to post and decode program interrupt requests to the computer, a command generator to control the digital

recorder and clear the flags, and data reading logic. (For detailed logic diagrams, see Appendix A.)

SOFTWARE DESCRIPTION

The work to be done by the software falls into two major divisions: data acquisition and data analysis. Data acquisition must be done using MACRO assembler level language because it involves servicing a remote device through the hardware interrupt system. Data analysis and Teletype interaction with remote users can be done in FORTRAN. The version used is standard FORTRAN IV which is expanded to include commands which make available the time-scheduling and time-conserving features of RSX.

Data Acquisition

The interfacing hardware provides for a single interrupt line into the computer so that the device service routine may have a single interrupt entry point. However, the remote interface may then be interrogated via special MACRO commands to identify which of three sources within the interface generated the interrupt. Interrupt 1 represents a command by the laser operator for the computer to read the buffer which contains the current sample temperature voltage. Interrupt 2 represents a command by the laser operator for the computer to read the buffer which contains a code identifying the laser electronic equipment switch positions; and, additionally, to initialize and set in motion the scanning of the transient storage device. This device provides digital storage and readout of 1,000 X-Y pairs. It is read by having the computer to command that it send the first word; periodically, thereafter, it automatically generates an interrupt to signal that it is ready to send the next word until all 1,000 have been sent. This command is Interrupt 3. (Only the Y value is sent; the time base is derived from the switch position code read under Interrupt 2.) At the end of the reading of the transient storage device, the computer must command that the Interrupt 3 generator be disabled.

The device service routine is assembled just as an ordinary subroutine and is brought into core along with the proper task of the laser program. That is, input from the laser station is restricted to certain specified times during which the service routine is in core. The device service routine has two FORTRAN-callable entry points—one for initialization and the other for closeout operations.

Briefly, the data input sequence is as follows: when the FORTRAN program is ready for data, it prints a message to that effect on the operator's Teletype and then waits for the device service routine to set a software flag to indicate that input is completed. (The service routine was previously initialized.) The service routine waits for the operator to push the "temperature send" button on his interface, causing Interrupt 1. This interrupt is identified as a command to read the sample temperature buffer, which the service routine does. The information in the buffer is the binary coded decimal (BCD) form of the emf from a thermocouple at the back face of the sample. This information is converted to octal code and is made available to the FORTRAN program where it will be converted directly to temperature in degrees centigrade. Now, the service routine waits while the operator fires the laser and obtains a trace on his transient recorder. If this action is satisfactory, he pushes the "data send" (Interrupt 2) button on his interface. The service routine sees this step as a

command to read the laser interface buffer containing coded switch position information. This information is decoded to yield scale factors for the transient recorder data. The scale factors are passed to the FORTRAN routine. Upon completion of the scale factor decoding, and on the same interrupt, the service routine enables the readout circuitry on the transient recorder and commands it to send a word.

The service routine now gets a series of Interrupt 3's at equally spaced intervals, each denoting that another word is ready to be sent. These words are read, but not stored, until the transient recorder is cycled back to the beginning of the transient; then, they are read in and are packed two per computer word in 500 contiguous locations in core. As soon as 1,000 have been received, the service routine disables the recorder readout circuitry and clears any remaining flag. Data input is then complete, and a software flag is set to denote that fact. Note that any and all time spent waiting for this sequence to complete was released for the use of other jobs in other partitions of core.

Appendix B contains program flow charts, a description of program variables, and a typical Teletype printout.

Data Analysis

The bulk of the FORTRAN data analysis is concerned with doing the graphical analysis for the half rise time, as seen in Figure 2. The problem is compounded by the requirement that any feature(s) of the trace must be allowed to be distorted in relationship with any other(s) as long as all the general features of Figure 2 still appear. In fact, the program as completed requires nothing of the input trace except those things which are essential for accurate analysis by hand. Specifically, enough points must be taken before the laser burst marker to establish a reference level, the laser burst marker must appear, the half rise time point must occur before the time-base change, at least 200 points must be taken after the time-base change, and a local maximum must occur after the time-base change. The operator sees that these requirements are met before he sends a trace; and, if a trace is obviously not acceptable, the operator adjusts his equipment and refires the laser until he gets one that is. Figure 5 presents a block diagram of the calculation of the half rise time by the computer.

One feature which has not heretofore been mentioned is that the computer has a display panel with several lights which indicate the status of each remote job interfaced to the computer. It is the responsibility of the user program to correctly instruct the light panel interface on which lights are to be on at any given time. This instruction is done from FORTRAN by means of the subroutine LIGHTS, which controls the lights individually. Other FORTRAN calls with no corresponding subroutine listings are calls to the RSX monitor. (3)

RESULTS

A comparison with the hand graphical method showed comparable average values of diffusivity, but a standard deviation only about one third as large. Results are printed out at the operator's station beginning within five seconds of the pressing of the "data send" button. The whole software package for this project executes in 4K of core plus about 500 words of the user COMMON area. Total CPU time required over a two-hour experiment

Figure 5. A TYPICAL HALF-RISE TIME ANALYSIS.

time, for example, is on the order of seconds. Appendix B contains an example of the Teletype interaction with the laser operator and printout of typical results.

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ACKNOWLEDGEMENTS

J. D. Lore of the Y-12 Laboratory Development Department performed the final acceptance checkout and suggested several useful refinements.

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APPENDIX A

ENGINEERING DRAWINGS

Figure A-1. PULSED LASER SPECIMEN ANALYZER. (LTA Computer Interface)

		(PIN SIDE VIEW)																	
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16		
A	M	0	0	0	2	0	5	8	8	0	4	4	4	4	4	4	6	J2	J5
	L	0	0	0	2	0	5	8	8	0	4	4	4	4	4	4	6		
B	M	0	3	6	1	1	1	1	1	1	1	1	1	1	1	1	1	J1	J4
	L	0	5	0	0	2	2	1	1	1	1	1	1	1	1	1	1		

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Figure A-2. PULSED LASER SPECIMEN ANALYZER. (Biomation Recorder Interface Module Locations)

Figure A-3. PULSED LASER SPECIMEN ANALYZER. (Biomation Recorder Remote Interface)

APPENDIX B

PROGRAM FLOW CHARTS

DESCRIPTION OF PROGRAM VARIABLES

AVGDIF	Temporary storage for the accumulation of the average diffusivity at a particular temperature point.
AVGT	Temporary storage for the accumulation of the average temperature.
AVT12	Temporary storage for the accumulation of the average half rise time at a particular temperature point.
DENS	Density of the sample, in grams per cubic centimeter.
IBU	Temporary variable.
IBURST	Indicates at which point in the transient recorder data that the laser burst occurs.
ICHNG	Indicates at which point in the transient recorder data that the time base change occurs.
IDENT(28)	Array; holds the two-line identification which is entered by the operator.
IYH	Indicates at which point the rough half maximum occurs, excluding the laser burst.
IYM	Indicates at which point the absolute maximum occurs, excluding the laser burst.
IL	Temporary variable; usually the lower index of a range of points.
INVG	Counter for averaging results of NAVG shots.
IPREV	Temporary variable.
ISUM	Accumulates sum when averaging several values to obtain REFLVL.
IU	Temporary variable; usually the upper index of a range of points.
IUADJ	Temporary variable.
IXHH	An X offset for the transient recorder data which roughly centers the half maximum data about the origin.
IY	Ith Y-axis value from the transient recorder data.
IYHH	A Y offset for the transient recorder data which roughly centers the half maximum data about the origin.

IYMAX	Absolute maximum of the recorder data, excluding the laser burst.
IYMAXP	Similar to IYHH, except that it is used for data prints about the absolute maximum.
LSEND	Index of a point which is just past all laser burst effects.
LSEV	Event variable used for the RSX monitor.
MULTX	Scale multiplier for the time base (X axis).
NAVG	Number of shots to be averaged at each temperature.
NEWSCL	Indicates at which point a time base change has been detected.
NHLF	Number of points to be used in quadratic least squares determination of the half rise time X coordinate.
NO	Contains alphanumeric N.
NPT	Counter which allows the accumulation of values for up to 30 separate points, to be printed out in report form at the end of a run.
OPTION	Indicates which temperature sensor is being used.
PMPDLY	Indicates time delay between the laser burst spike in the recorder data and the actual laser burst.
REFLVL	Y-axis reference level for the recorder data.
RFLAG	Indicates to the FORTRAN analysis routine the completion of data readin.
SCL	Scale factor; used in temporarily scaling recorder data so that a more accurate quadratic least-squares fit may be obtained.
SCLFTX	X-axis scale factor for the recorder data.
SSQ	Accumulates sum in calculating the standard deviation.
STDEV(30)	Array; holds standard deviation values.
S1 (3)	Array; holds coefficients of fitted quadratics.
TEMPMV	Sample thermocouple voltage; to be converted to sample temperature.
TDIFU	Temporary variable; holds diffusivity value for present shot.
THK	Sample thickness, in centimeters.

TMV	Same as TEMPMV, except converted to millivolts.
TN	Sample temperature, in degrees centigrade.
T12	Half rise time, in seconds.
XDIF(30)	Array; holds diffusivity values.
XMAX	X coordinate of the fitted maximum.
XNAVG	Floating-point representation of NAVG.
XT(30)	Array; holds temperature values.
XTC(30)	Array; holds thermal conductivity values.
YES	Contains alphanumeric Y.
YHLF	Y coordinate of the half maximum.
YM	Temporary variable.
YNS	Temporary variable.
YSPH(30)	Array; holds specific heat values.

TYPICAL REMOTE TELETYPE PRINTOUT

LASER REMOTE DATA SERVICE IN OPERATION.
PLEASE WAIT FOR COMPUTER INSTRUCTIONS BEFORE ENTERING DATA.

ENTER DATE AND SAMPLE IDENTIFICATION (2 LINES).

ARMCO IRON

AR38.20. 3-29-72

ENTER SAMPLE THICKNESS IN CM

.218

ENTER TIME DELAY CORRECTION IN MILLISEC

.30

ASSUME END OF LASER BURST

AT WHICH BIOMATION POINT

300

WHICH TEMPERATURE SENSOR ARE YOU USING/ (CODES 1-7)

1

CALCULATE THERMAL CONDUCTIVITY

N

HOW MANY SHOTS WILL BE AVERAGED AT EACH POINT (UP TO 99)

4

START OVER

N

	SHOT	TEMP	DIFFUS	T 1/2	
READY FOR DATA.	1	25.1	0.1874E+00	0.3526E-01	
KEEP Y					
READY FOR DATA.	2	24.9	0.1878E+00	0.3518E-01	
KEEP Y					
READY FOR DATA.	3	25.1	0.1828E+00	0.3613E-01	
KEEP Y					
READY FOR DATA.	4	24.9	0.1822E+00	0.3625E-01	
KEEP Y					
AVERAGES		25.0	0.1850E+00	0.3571E-01	0.2919E-02
DO ANOTHER PT					
N					

ARMCO IRON

AR38.20. 3-29-72

TEMPERATURE DEG C	DIFFUSIVITY CM**2/SEC	STD DEVIATION CM**2/SEC
25.0	0.1850E+00	0.2919E-02

START NEW RUN

Y

Y-1841

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