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HIGH-PRECISION THICKNESS MEASUREMENTS USING BETA BACKSCATTER

By R. V. Heckman

Published November 1978

Milestone Report

Prepared for the United States Department of Energy
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Bendix Kansas City Division

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Milestone Report
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HIGH-PRECISION THICKNESS MEASUREMENTS USING BETA BACKSCATTER

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A two-axis, automated fixture for use with a high-intensity Pm-147 source and a photomultiplier-scintillation beta-backscatter probe for making thickness measurements has been designed and built. A custom interface was built to connect the system to a minicomputer, and software was written to position the tables, control the probe, and make the measurements. Measurements can be made in less time with much greater precision than by the method previously used.

WPC-TR/2

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SUMMARY

In a previous report,[1] the development of a scintillation probe to be used with a high-intensity Pm-147 source for making nondestructive, highly precise thickness measurements of thin, laminated films was discussed. This report covers the design, fabrication, and evaluation of the automated fixture that was built to house the scintillation probe.

A two-axis, automated fixture using stepping motors was built and interfaced to a minicomputer. A custom interface was successfully designed and built, and the necessary software was written to position the tables, control the probe, and make the thickness measurements.

As a result of these efforts, the time required for inspecting parts can be significantly reduced. The accuracy and precision of the inspection technique has been improved. The system now is being evaluated in operation to establish its quantitative, overall capability.

The final phase of this project will investigate the use of eddy-current techniques to make the same thickness measurements on assembled units while simultaneously measuring other system components.

DISCUSSION

SCOPE AND PURPOSE

This report describes the semiautomatic fixture which was developed for use with the scintillation probe and high-activity Pm-147 source. A fixture of the type described was required, since the high-density flux associated with the new probe system necessitated minimizing exposure of the operator. Also, the shorter measurement times that were obtainable with the new probe could be used most effectively by an automated fixture. Furthermore, the existing fixture was totally inadequate for use with a probe that is capable of producing measurements having a precision of less than 0.5 percent.

The development efforts associated with the new fixture are divided into three distinct activities.

- Fixture Design and Fabrication
- Control-Mechanism Design and Fabrication
- Software Development

The fixture was designed for maximum accuracy and reliability. Stepping motors for positioning the probe were interfaced directly to the minicomputer, rather than using a tape numerical-control unit.

PRIOR WORK

A report describing the development of beta backscatter probes using high-intensity sources has been published.[1] This report is a continuation of that development effort.

ACTIVITY

Fixture Design and Fabrication

The fixture was designed at the Bendix Kansas City Division and fabricated at Universal Tool, Dayton, Ohio. The basic design concept involves the use of two precision milling-machine tables mounted at right angles to each other. The vertical table holds the part dish, while the horizontal table contains the detection probe (Figure 1).

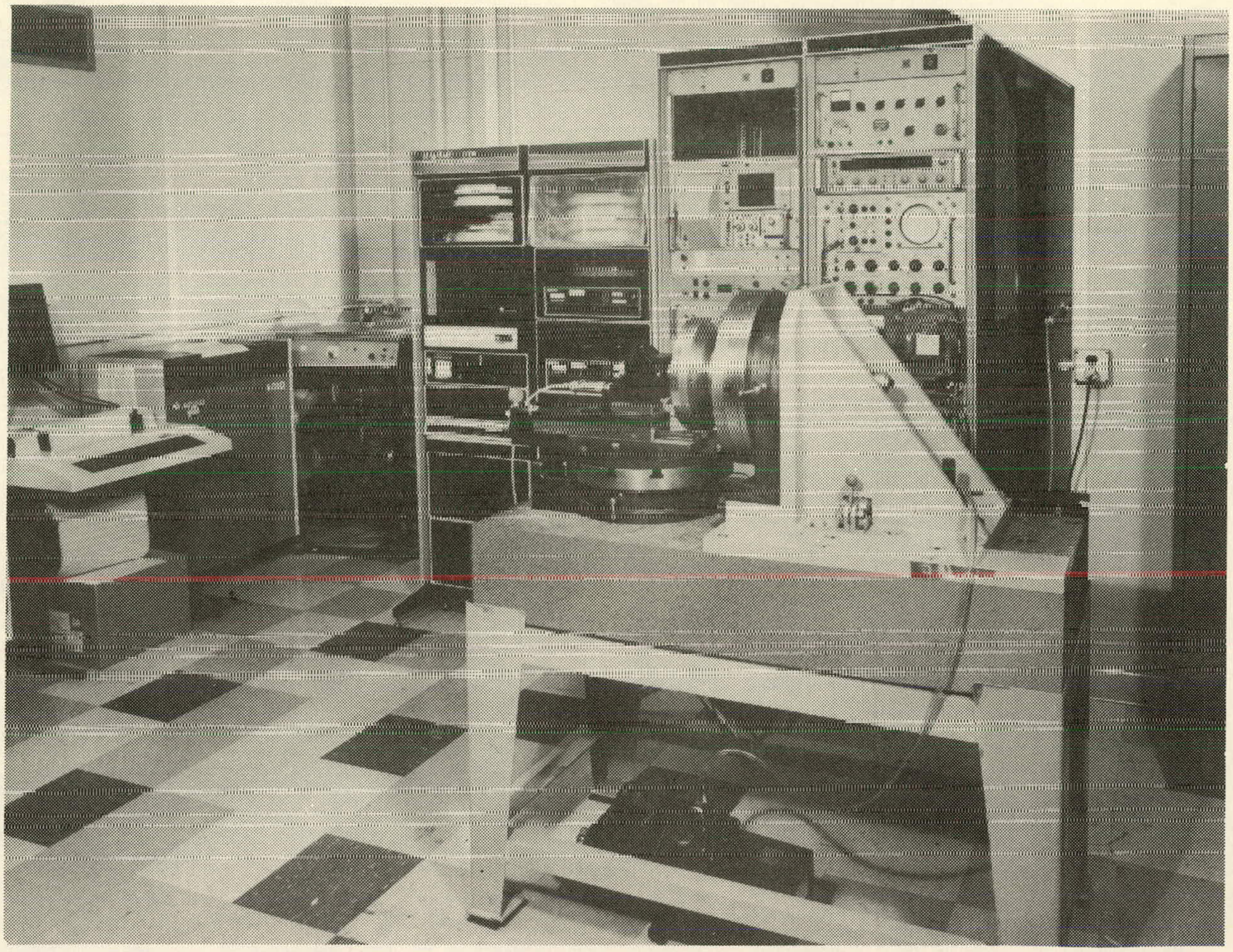

Figure 1. Semiautomatic Beta Backscatter Thickness-Measurement System

The fixture was designed for multipurpose use so that different sizes of laminates could be inspected by changing part holders, and both Geiger and scintillation probes could be used as detectors. To accommodate parts having different radii, the horizontal table slides back and forth. The entire assembly was mounted on a 203-mm granite slab to maintain alignment. Two stepping motors with 5.65-N·m of torque were chosen to position the tables.

The part holders were designed so that the calibration standards could be recessed around the outside rim (Figure 2). Vacuum chucks, which were designed to allow the laminates to be essentially unconstrained except at the measurement locations, were incorporated. A porous graphite material was used for the inspection locations (Figure 3).

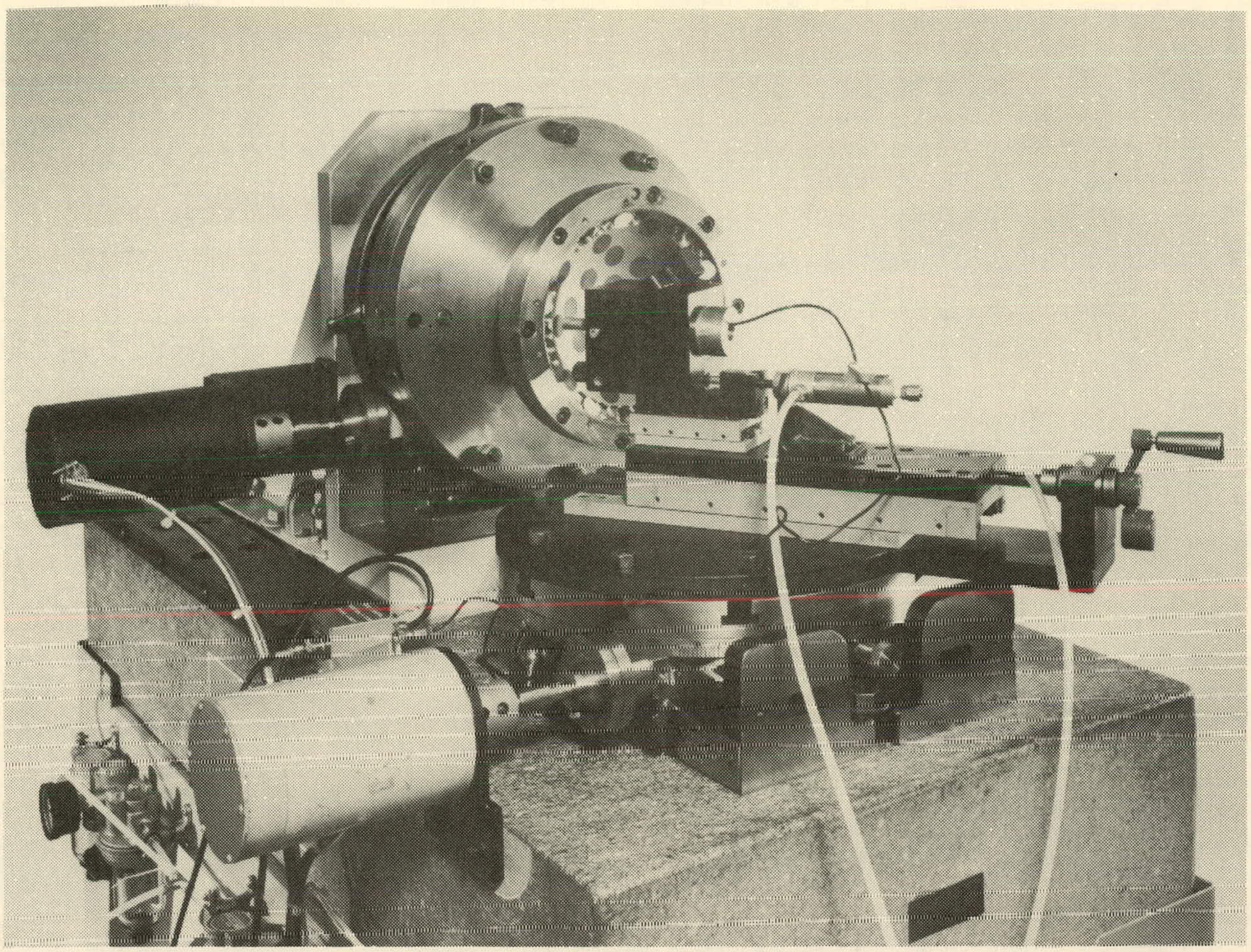

Figure 2. Precision Turntables, Stepping Motors, Vacuum Chuck, and Probe Holder of the Semiautomatic Beta Backscatter Thickness-Measurement System

The stepping motors are connected to the rotary tables through worm gears having reduction ratios of 90:1. Thus a 1.8-degree step at the motor turns a table 0.02 degree or 1.2 minutes, and 50 motor steps turn a table 1 degree.

Although the vacuum-chuck design appears to be adequate, the dishes are being redesigned to reduce their excessive weight (greater than 68.04 kg or 150 pounds). After rework, the fixture design was found to be sound, and the system functioned satisfactorily.

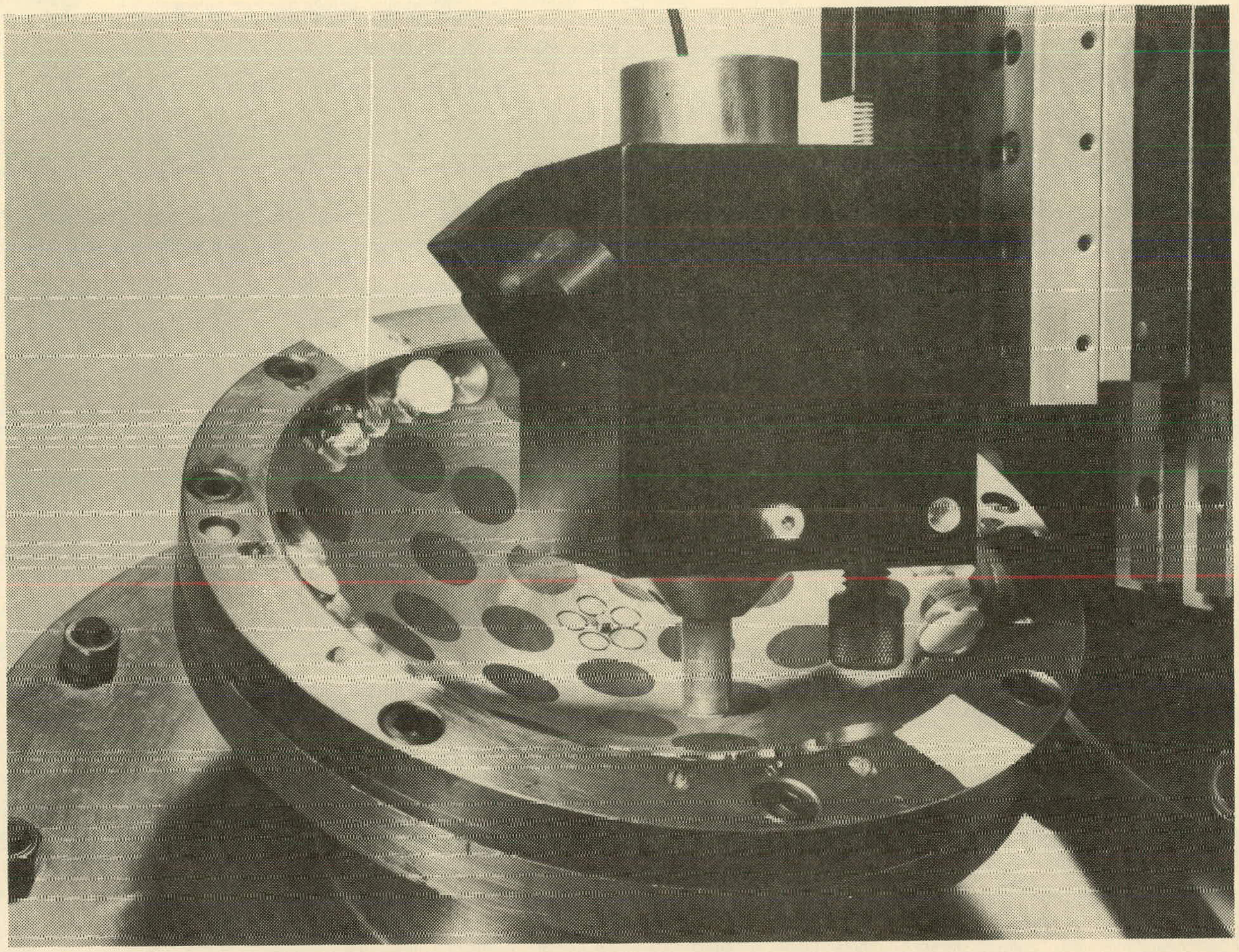

Figure 3. View of Vacuum Chuck Showing the Porous Graphite Inserts Along With the Thickness Standards Embedded in the Outer Rim

Control-Mechanism Design and Fabrication

The control mechanism consists of the stepping motors, a parallel digital input-output (I/O) card, a control interface, and a dual-axis translator (DAT). All of these items are commercial hardware except for the control interface. It was designed and built at Bendix Kansas City as a part of this project. A schematic of the interface is shown in Figure 4; values of the resistors and capacitors are shown in Table 1.

The I/O card accepts program commands and generates transistor-to-transistor logic (TTL) signals, as commanded. Each of 16 output lines may be latched high or low, while 16 input lines can be sampled for highs and lows.

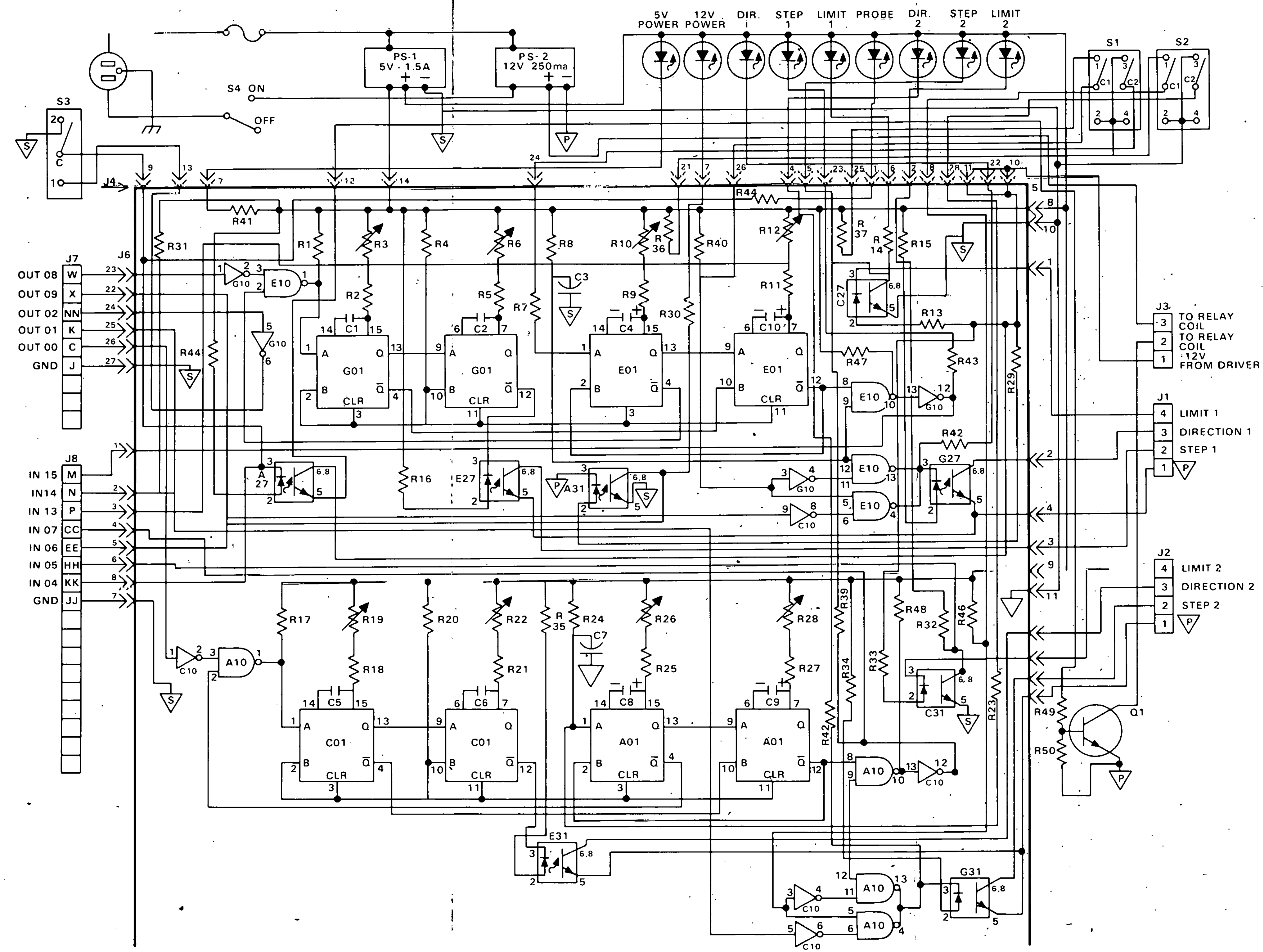

Figure 4. Schematic of the Open-Collector Interface Used for Interfacing the Standard Parallel Interface to the Stepping-Motor Dual-Axis Translator

Table 1. Resistor and Capacitor Values for the Open-Collector Interface

Resistor Designation	Resistor Value (kΩ)	Capacitor Designation	Capacitor Value (μF)
R-1	1.0	C-1	0.022
R-2	0.680	C-2	0.047
R-3	10.0	C-3	16.0
R-4	1.0	C-4	2.2
R-5	3.3	C-5	0.022
R-6	10.0	C-6	0.047
R-7	0.100	C-7	16.0
R-8	8.2	C-8	2.2
R-9	1.8	C-9	1.0
R-10	20.0	C-10	1.0
R-11	34.0		
R-12	20.0		
R-13	2.7		
R-14	0.220		
R-15	0.470		
R-16	0.470		
R-17	1.0		
R-18	0.680		
R-19	10.0		
R-20	1.0		
R-21	3.3		
R-22	10.0		
R-23	0.100		
R-24	8.2		
R-25	1.8		
R-26	20.0		
R-27	3.9		
R-28	20.0		

Table 1 Continued. Resistor and Capacitor Values for the Open-Collector Interface

Resistor Designation	Resistor Value (kΩ)	Capacitor Designation	Capacitor Value (μF)
R-29	2.2		
R-30	0.220		
R-31	1.0		
R-32	0.220		
R-33	2.2		
R-34	0.470		
R-35	0.470		
R-36	1.0		
R-37	1.0		
R-38	1.0		
R-39	0.390		
R-40	1.0		
R-41	0.390		
R-42	0.390		
R-43	0.390		
R-44	0.470		
R-45	0.470		
R-46	1.0		
R-47	1.0		
R-48	1.0		
R-49	2.0		
R-50	1.0		

The control interface electrically connects the standard parallel interface (which uses TTL levels) with the DAT (which uses complimentary-metal-oxide-semiconductor, or CMOS, conventions: open-collector outputs; and inputs which, in effect, look for contact closures). The interface also generates timing signals suited to the maximum motor-run rates, and, through the use of switches, permits manual control of the stepper motors.

The DAT accepts timing and direction signals from the interface and sends limit signals to the interface. The DAT, when it receives a strobe timing signal for a motor, begins to pulse the several motor-stepper windings in forward or reverse order to rotate the motor forward or backward one step.

A 100-μs strobe pulse is the first timing signal that is generated by the interface. The next signal is a delay signal of approximately 5 ms which allows time for the motor step to be completed at the maximum run rate.

When the motor is being started or stopped, the strobe pulses must be timed to accelerate or decelerate the motor smoothly. If this timing is inaccurate, some of the step pulses will fail to step the motor, thus producing errors in positioning.

A variety of acceleration/deceleration techniques may be employed. For example, controllers which use a given step count to accelerate, run, and decelerate motors are available. However, the method described in this report uses simpler equipment in which the acceleration/deceleration timing is controlled by the software. The algorithms that are used to carry out the control functions are briefly described in the next section of this report, and they are fully defined in Appendix A.

Software Development

Software was developed to control the location of the part and probe, to calibrate the nuclear counting system, and to perform thickness measurements of the part. In addition, software now is being developed to maintain both a general directory and a file of the data.

The motor-control software consists of a series of algorithms to accelerate and decelerate the tables, raise and lower the probe, and move the probe to a specific position (angles ϕ and θ) on the part. The details of these algorithms, together with examples, are given in Appendix A.

The software that has been developed for the acquisition and reduction of the beta-backscatter data closely parallels the software that is already in use for the Geiger-tube-based system. Two levels of files control the measurement of elements and standards. At the top level, a Control File specifies which tests or processes should be performed, while, at the lower level, Location Files give information about points to be measured within a test or process. Control files are read and interpreted by a routine which is essentially a general-purpose program. The measurement of standards or elements is started by a control-file entry (STDS or ELTS).

The STDS and ELTS routines access files with entry lines which include sequence numbers, identification numbers, ϕ- and θ-angle locations, the number of counts to take, the standard thickness, and the element row/column keys.

As information is read from a file, or after all necessary information has been read, the tables are positioned (Appendix A), counter readings are taken, and counter information is stored. This general process repeats for each element or standard which is specified in a Location File. Once all elements or standards have been processed, repeat or closure measurements are then taken (Appendices B and C).

ACCOMPLISHMENTS

A two-axis, automated fixture has been designed, built, and then interfaced to a minicomputer which controls both the fixture positioning and the beta-backscatter measurements. This latter activity required the design and fabrication of an open-collector interface to interconnect the stepping-motor and probe-positioning controls. Software has been written to control table positioning, calibration of the beta-backscatter system, and thickness measurements.

FUTURE WORK

Two additional phases of this program are planned. The third phase, now in progress, will determine the quantitative accuracy and precision of the entire system. A capability study will be made, and the contribution of each component to the overall system error will be evaluated.

The fourth phase of the project will evaluate eddy-current-measurement techniques. For this purpose, the use of multifrequency, multiphase eddy-current equipment is planned.

REFERENCE

[1]R. V. Heckman, Development of Beta Backscatter Probes Using High-Intensity Sources (Milestone Report). Bendix Kansas City: BDX-613-1903 (Rev.), December, 1977 (Available from NTIS).

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Appendix A

TABLE-POSITION TRACKING AND CONTROL

In this description of the algorithms that are used for Motor Central, the following notation is used:

N_a = number of acceleration steps;

N_d = number of deceleration steps;

N = total step count;

r = maximum run rate (steps/second);

t = 1/r;

d = rate-change parameter (t/8); and

f = last delay used in acceleration.

N_a and N_d are first initialized to default values. If this results in $N_a + N_d > N$, N_a and N_d are changed to N/2 (for an even N) or (N-1)/2 and (N+1)/2 (for an odd N). This substitution causes $N_a + N_d$ to equal N, rather than being less than N. Whenever $N_a + N_d = N$, the motor is decelerated immediately after acceleration, and it may or may not reach full running speed.

The Acceleration Phase begins after Na and Nd have been initialized: a step (strobe) pulse is sent; the central processor unit (CPU) waits $N_a d$ seconds; a second step pulse is sent; the CPU waits $(N_a-1)d$ seconds; etc. After Acceleration Step j, the CPU waits $(N_a-j-1)d$ seconds or t seconds, whichever is greater. (See Examples for Motors in Beta-Backscatter System.) The last delay value for this phase is f.

The Run Phase begins after the acceleration has been completed. For each step in the Run Phase, the CPU sends a step pulse and waits for the busy signal to disappear. The maximum run rate therefore is controlled by a delay signal generated by the hardware. The number of run steps is $N - N_a - N_d$, which may equal zero.

Deceleration begins after $N - N_d$ steps have been taken. After sending the first deceleration-step pulse, the CPU waits f seconds; after the second pulse, the CPS waits f - d seconds; etc. Thus for the jth step from the end, the CPU waits $d(N - N_a + j)$ seconds or t seconds, whichever is greater.

EXAMPLES FOR MOTORS IN BETA-BACKSCATTER SYSTEM

Motors used in the beta-backscatter system were found to run reliably under manual control at 187 steps/second. This rate makes t = 5.3 ms. The values d = t/8, N_a = 20, and N_d = 20 were found to work consistently. (Test sequences of approximately 100,000 steps in runs of 25, 50, 100, . . . steps were used for verification.) With these values of d, N_a, and N_d, acceleration/deceleration timing is as shown in Tables A-1 and A-2. Table A-1 shows acceleration timing for a long run, while Table A-2 illustrates a 19-step acceleration/deceleration sequence.

ERROR AVOIDANCE

A simple algorithm is used to avoid two errors to which other algorithms may be subject: (1) round-off error, and (2) truncation error. The following examples will illustrate these possible errors.

Example 1

Suppose that Algorithm B1 uses two variables: Current Angle c, and Desired Angle d. B1 computes the number of steps as N = 50(d-c) if d > c, or as N = 50(c-d) if c > d, and it sets a forward or reverse direction flag. B1 then sets c = d.

Now suppose that angles of 0.001, 0.002, 0.003, . . . 0.999, and 1.000 degree are called for. For each angle, d - c = 0.001, so N = 0.050 = 0. Thus both the initial and final table angles are zero. This illustrates errors caused by the truncation of information about the actual table position.

Example 2

Assume that Algorithm B2 uses two variables: Current Angle c, and Desired Angle d. In a manner similar to that of B1, B2 computes the number of steps as N = 50(d-c) or N = 50(c-d), and it sets a direction flag. While B1 had set c = d, B2 now sets c = c + N/50.

In this case, if angles of 0.001, 0.002, . . . 0.999, and 1.000 degree are called for, c will remain zero for angles d = 0.001 through d = 0.019. When d = 0.020, a step will be taken, thus causing c to change to 0.020. In a similar manner, steps will be taken for angles d = 0.040, d = 0.060, etc. After 1000 angles, the table position would be 1.000 degree as desired; however, because of round-off error in computer arithmetic, the current-position Variable c could be as small as 0.99998 or as large as 1.00002.

Table A-1. Acceleration Timing for a Long Run

Step	Approximate CPU Delay (ms)	Additional Hardware Delay (ms)	Total Delay (ms)
1	13.20		13.20
2	12.54		12.54
3	11.88		11.88
4	11.22		11.22
5	10.56		10.56
6	9.90		9.90
7	9.24		9.24
8	8.58		8.58
9	7.92		7.92
10	7.26		7.26
11	6.60		6.60
12	5.94		5.94
13	5.28	0.02	5.30
14	4.62	0.68	5.30
15	3.96	1.34	5.30
16	3.30	2.00	5.30
17	2.64	2.66	5.30
18	1.98	3.36	5.3
19	1.32	3.98	5.3
20	0.66	4.64	5.3
21	0.00	5.3	5.3
22	0.00	5.3	5.3
23	0.00	5.3	5.3

Plainly, a one-step error could occur if 50,000 of these 1000-angle sequences were executed. Algorithm A1 avoids this problem by using integer arithmetic.

Table A-2. Timing for a 19-Step Acceleration-Deceleration Sequence

Step	Approximate CPU Delay (ms)
1	13.20
2	12.54
3	11.88
4	11.22
5	10.56
6	9.90
7	9.24
8	8.58
9	7.92
10	7.92
11	8.58
12	9.24
13	9.90
14	10.56
15	11.22
16	11.88
17	12.54
18	13.20
19	13.86

Algorithm A1

Algorithm A1 uses two variables: Current-Step-Count k, and Desired Angle d. Letting j = 50d: when j > k, N is set to N = j - k forward steps; when j < k, N is set to N = k - j reverse steps. Then, k is updated to k + N (forward) or k - N (reverse).

This algorithm acts, in general, the same as B2, except that no error accumulates. When the table is at 1 degree, k = 50. Note that provisions are needed to avoid integer overflow. The simplest approach is to maintain k in the range of -9000 to +9000, which corresponds to the range of -180 to +180 degrees. Also, j should be computed in the same range.

Angle changes (d - c) of more than 180 degrees are equivalent to changes of 360 - c + d; so a workable algorithm should incorporate checks for this case. (See A2.4 of Algorithm A2.) Also, Algorithms A1 and B1 may yield table errors of up to 0.0199 degree, while positioning to the nearest step would give a maximum error of 0.00999. . . degree. (See additions of +1/2 in A2.3 of Algorithm A2.)

<u>Algorithm A2</u>

Algorithm A2 uses two variables: Current-Step-Count k, and Desired Angle d. The constant 9000 is the number of steps that rotate a table 180 degrees, while the constant 18000 corresponds to a 360-degree rotation. As before, the constant 50 is the number of motor steps per table degree.

A2.1

Put k in the range of -9000 to +9000. If k is not between -9000 and +9000, add or subtract 18000 to put k within this range.

A2.2

Compute Angle p in the range of -180 to +180 degrees:

$$p = d - 360\left(\frac{d + 180}{360}\right). \qquad \text{(A-1)}$$

A2.3

If 50p > k, let

$$N = 50p - k + 1/2. \qquad \text{(A-2)}$$

If 50p < k, let

$$N = 18000 - (k - 50p + 1/2). \qquad \text{(A-3)}$$

(Note that in both cases $0 \leq N \leq 18000$.)

A2.4

Compute the direction for acute-angle rotation:

If N < 9000, Count = N,
Direction = Forward;

If N > 9000, Count = 18000 - N,
Direction = Forward.

A2.5

With the number of steps that has been computed in A2.4, for each forward step taken, add 1 to k; for each reverse step taken, substract 1 from k. This maintains the position in real time.

Appendix B

PROCESSING OF STANDARDS

When the Control-File processor invokes Standards (STDS), it also tells STDS the name of a file (specified by an entry in the Control File) which contains entry lines for standards. STDS reads all of the information into arrays and closes the file. While reading the file, STDS verifies that sequence numbers are in order, that the number of readings to be taken is stored in the Standard Repetition (SREP) array, that ϕ angles are stored in the Standard Place 1 (SPL1) array, that θ angles are stored in the Standard Place 2 (SPL2) array, and that actual (calibrated) thicknesses are stored in the Standard Thickness (STH) array.

Next, STDS goes through all of the standards in the order specified by the file. For the jth standard, STDS uses the PLACE routine to put the tables at angles SPL1 (j) and SPL2 (j). STDS then uses the Counter (COUNTR) routine to count SREP j times. As the counts are taken, STDS keeps track of the maximum and minimum counts.

After the set of counts for the standard has been completed, the results are printed, and the set is checked for internal consistency as follows, where

σ = standard deviation of the average count, C_a,

$\underline{c}$ = minimum count, and

$\bar{c}$ = maximum count:

$$\sigma = \sqrt{C_a}. \tag{B-1}$$

If $C_a - \underline{c} > 2\sigma$, the count set is repeated;

If $\bar{c} - C_a > 2\sigma$, the count set is repeated.

Thus if any reading deviates from the average by more than two standard deviations, the set of readings is repeated after a rejection message has been printed.

After all standards have been counted, the counts for different standards are compared through the use of a Thickness-Consistency Check. Each standard's average count is compared to the average count for every other standard having a different thickness. (This check does not apply to standards having nearly equal thicknesses.) The thicker standards should produce more counts than the thinner standards. If a pair of standards has anomalous counts (that is, the thicker standard has fewer counts than the thinner standard), the pair is rerun.

Twice the specified number of readings is taken when a pair of standards is rerun. After the new data have become available, the thickness-consistency check starts again from the beginning. If the consistency check repeatedly fails, the program will return the tables to their zero-angle positions and stop. An internal limit controls the number of failures that is allowed.

After the thickness-consistency check has been completed, a Linear-Regression-Routine (LINREG) is used to compute a and b for the model

$$t = \frac{c - a}{b}, \qquad \text{(B-2)}$$

where

t = thickness (in the same units as the standard thicknesses), and

c = counts.

Note that the model shown is equivalent to a + bt = c, which is a linear-regression model. LINREG solves for a and b in the a + bt = c model, and it also computes R^2 for the same form. Regression results are printed at the console.

Closure readings also are taken for each of the standards. Each standard is read; the standard's thickness is computed, using the t = (c-a)/b model; and the error (or residual) is computed. The new count, the actual thickness, the computed thickness, and the error are printed after each closure check.

If the new count for the standard differs from the original count by more than two standard deviations, a second count is taken. Again, thickness and error are computed and printed, and a 2-σ check is made. A second failure causes a complete restart of the calibration. If more than the limited number of restarts occur, STDS will return the tables to their zero-angle positions and stop.

After the closure checks have been completed, STDS zeroes the tables and returns to the main program. Subsequently, a WRITES command in the Control File can be used to copy the calibration results to a disk file. Later runs can retrieve calibration results from the disk for use in the measurement of elements through the use of the READS command.

A final note on the processing of standards: the COUNTR routine responds to the "Attention" button on the communications interface by printing the request, "CON?" The operator may type "Y" to continue, or "N" not to continue. In the latter case, COUNTR exits with an abort flag set to "N." In the STDS routine, each call to COUNTR is followed by a flag check. When the flag is "N," STDS prints the message, "STDS RUN ABORTED BY ATTENTION INPUT," zeroes the tables, and returns to the Control-File processor. This allows the operator to terminate a run in case of equipment failure or operator error.

Appendix C

PROCESSING OF ELEMENTS

When the Control-File processor invokes Elements (ELTS), it also tells ELTS the name of a file (specified by an entry in the Control File) which contains entry lines for elements. ELTS prints a heading at the console and begins its first file pass. A single line is read at a time. Each line includes a sequence number, the number of readings to be taken, the location angles, the row and column keys, and the element-identification number. After the sequence number has been checked, the tables are positioned, and ELTS discards the location angles so that they cannot be printed out. ELTS then prints the sequence number and the element number, and it calls COUNTR the number of times specified.

Like STDS, ELTS, after every COUNTR call, checks the abort flag which may have been set by COUNTR. If the flag is "N," ELTS zeroes the tables, prints the message, "RUN ABORTED BY ATTENTION INPUT," and returns to the Control-File processor.

When the specified number of readings for an element has been completed, ELTS computes and prints the average count and the computed thickness, after which it proceeds to the next element, if one or more elements remain. Otherwise, Rerun Processing begins.

The Rerun-Processing section of ELTS conforms to the project specifications that are supplied to the programmers. In Stage 1 of Rerun Processing, row averages, column averages, and standard deviations are computed. Row and column keys from the Elements File associate each element with one row and one column. An element's computed thickness contributes to the statistics for both the row and the column with which it is associated.

In Stage 2, if an element's computed thickness differs from the average for the element's row by more than 2 percent, the element is marked to be rerun because of row deviance. If the value differs from the average for the element's column by more than 1 percent, the element is marked to be rerun because of column deviance. After an element has been marked, the element's location is read from the Element File, the tables are positioned, and the location data are discarded (zeroed).

Twice as many readings then are taken as were taken at the start. If the average of the second set of readings is within 2 percent of the average of the first set of readings, the two sets of readings are averaged together according to the following formula.

$$C_f = \frac{2C_n + C_o}{3} , \qquad \text{(C-1)}$$

where

C_f = final average,

C_n = new average, and

C_o = old average.

A weighted average is used, since C_n is the average of twice as many readings as C_o. An Average (AVG) flag is printed. In other words, if

$$\left| C_n - C_o \right| < 2 \text{ percent of } C_n,$$

a final average, which is the average of all readings for the element, is computed. When

$$\left| C_n - C_o \right| > 0.02C_n,$$

C_n replaces C_o completely; C_f is set to C_n. A Replace (REP) flag is printed, together with the rerun information.

After the reruns have been completed, ELTS writes element-thickness data into a disk file so that they can be retrieved for future analysis. For example, if a MATRIX keyword follows the ELTS keyword in the Control File, measurement data will be printed in matrix form with row, column, and overall statistics. When a matrix is printed, data are printed in the row and column specified by each element's row and column keys in the Element File.

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A two-axis, automated fixture for use with a high-intensity Pm-147 source and a photomultiplier-scintillation beta-backscatter probe for making thickness measurements has been designed and built. A custom interface was built to connect the system to a minicomputer, and software was written to position the tables, control the probe, and make the measurements. Measurements can be made in less time with much greater precision than by the method previously used.

SPECIAL PROJECTS: Nondestructive Testing

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