NASA TECHNICAL MEMORANDUM

NASA TM-82471

THERMAL MONITORING, MEASUREMENT, AND CONTROL SYSTEM FOR A VOLATILE CONDENSABLE MATERIALS (VCM) TEST APPARATUS

By R. E. Ives
Materials and Processes Laboratory

April 1982

NASA

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama

(NASA-TM-82471) THERMAL MONITORING, MEASUREMENT, AND CONTROL SYSTEM FOR A VOLATILE CONDENSABLE MATERIALS (VCM) TEST APPARATUS (NASA) 33 p HC A03/MF A01 CSCL 14B G3/35

N82-24472

Unclas 09958

TECHNICAL REPORT STANDARD TITLE PAGE

1. REPORT NO.	2. GOVERNMENT ACCESSION NO.	3. RECIPIENT'S CATALOG NO.
NASA TM-82471		

4. TITLE AND SUBTITLE	5. REPORT DATE
Thermal Monitoring, Measurement, and Control System for a Volatile Condensable Materials (VCM) Test Apparatus	April 1982
	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) R. E. Ives	8. PERFORMING ORGANIZATION REPORT #
9. PERFORMING ORGANIZATION NAME AND ADDRESS George C. Marshall Space Flight Center Marshall Space Flight Center, AL 35812	10. WORK UNIT NO.
	11. CONTRACT OR GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS National Aeronautics and Space Administration Washington, D.C. 20546	13. TYPE OF REPORT & PERIOD COVERED Technical Memorandum
	14. SPONSORING AGENCY CODE

15. SUPPLEMENTARY NOTES

Prepared by Materials and Processes Laboratory, Science and Engineering

16. ABSTRACT

This report describes a unique thermal monitoring and control concept for a Volatile Condensable Materials (VCM) test apparatus where electric resistance heaters are employed per VCM test specification JSC SP-R-0022A or ASTM standard test method E-595-77. The technique is computer-based, but requires only proportioning ON/OFF relay control signals supplied through a programmable scanner and simple quadrac power controllers.

System uniqueness is derived from automatic temperature measurements and the averaging of these measurements in discrete overlapping temperature zones.

Overall control tolerance proves to be better than ±0.5°C from room ambient temperature to 150°C. Using precisely calibrated thermocouples, the method provides excellent temperature control of a small copper VCM heating plate at 125 ± 0.2°C over a 24 hr test period. For purposes of unattended operation, the programmable computer/controller provides a continual data printout of system operation. Real-time operator command is also provided for, as is automatic shutdown of the system and operator alarm in the event of malfunction.

This system has been incorporated into the MSFC Materials and Processes Laboratory VCM Test Facility located in Building 4711.

17. KEY WORDS	18. DISTRIBUTION STATEMENT
	Unclassified -- Unlimited

19. SECURITY CLASSIF. (of this report)	20. SECURITY CLASSIF. (of this page)	21. NO. OF PAGES	22. PRICE
Unclassified	Unclassified	31	NTIS

MSFC - Form 3292 (Rev. December 1972)

For sale by National Technical Information Service, Springfield, Virginia 22151

ACKNOWLEDGMENTS

The author gratefully acknowledges the efforts of Messrs. William A Wall, Leland K. Swaim, Evan S. Howell, and Ollie B. Toney, III, for technical support in bringing this effort to a successful conclusion.

TABLE OF CONTENTS

		Page
I.	INTRODUCTION	1
II.	VCM TEST SYSTEM	2
	A. General	2
	B. Test Hardware	4
	C. Test Measurement and Control Instrumentation	5
III.	COMPUTER CONTROL AND MONITOR SYSTEM	10
	A. General	10
	B. System Interface Technique	10
	C. Control System Functions	11
IV.	RESULTS AND CONCLUSIONS	13
BIBLIOGRAPHY		14
APPENDIX A – LIST OF EQUIPMENT		15
APPENDIX B – INTERFACE DESIGN DETAIL		16
APPENDIX C – CONTROL SYSTEM OPERATIONAL DETAIL		19
APPENDIX D – SOFTWARE THERMOCOUPLE LINEARIZATION		21
APPENDIX E – PROGRAM FLOW CHART		22

LIST OF ILLUSTRATIONS

Figure	Title	Page
1.	Typical VCM test station (cross section)	2
2.	VCM system operation timeline	3
3.	Thermocouple plan	4
4.	Hot and cold plates, close-up views	6
5.	Hot and cold plate support and vacuum system	7
6.	Constant temperature cold water bath	8
7.	Lab data acquisition system with controller	9
8.	System block diagram	10
B-1.	Typical heater control circuits	17
B-2.	Prototype interface chassis	18

LIST OF TABLES

Table	Title	Page
1.	Thermocouple Usage	12
2.	Typical Monitor Printout Data	12
3.	Unattended Computer Control/Monitor Functions	13
C-1.	Thermal Equivalences	19

TECHNICAL MEMORANDUM

THERMAL MONITORING, MEASUREMENT, AND CONTROL SYSTEM FOR A VOLATILE CONDENSABLE MATERIALS (VCM) TEST APPARATUS

I. INTRODUCTION

To implement a 24 hr unattended Volatile Condensable Materials (VCM) test facility operation within the Marshall Space Flight Center's Materials and Processes (M&P) Laboratory, a combined zone temperature control system and test monitor was developed by the M&P Laboratory Support Branch. Temperature control precision obtained by this unique system proved to be well within the stringent tolerance of ±1°C at 125°C for 24 hr as imposed by VCM test specification JSC SP-R-0022A, "Vacuum Stability Requirements of Polymeric Materials for Spacecraft Application."

The test apparatus is designed to have four independently operated electrical cartridge heaters mounted within a copper block, or hot plate, containing three special holders for material test specimens. Six strategically placed calibrated thermocouples are also mounted in this hot plate. A zone-averaging method of temperature monitoring and heater control is employed, whereby the hot plate surface is mapped into separate, overlapping thermal areas or zones. Each zone is monitored by one or more thermocouples and controlled by at least one cartridge heater. Each specimen holder is in turn affected by one or more of the monitor/control zones.

Thermocouple reading, dynamic averaging, and heater control is performed by a Hewlett-Packard (H-P) digital data acquisition system (DAS). The DAS is outfitted with the necessary peripheral interface electronics to match its calculated error signals with four proportional heater controllers which were developed in-house. The DAS is also programmed to monitor and average nine other thermocouples located within a nearby condensing (cold) plate required by the VCM specification. All thermocouple values can be linearized and printed out individually following (1) defined time periods, (2) the operator's manual command, or (3) detection of out-of-tolerance readings. The DAS also tags this data with date and time and terminates the test if programmed logic dictates. Under normal test conditions, the DAS continually flashes the last read temperatures onto its display. Once each hour, all thermocouple temperatures are printed out. Thus, a minimum of data printout is necessary to verify a successful 24-hr test run.

Not only does the accuracy of the digital control system developed for this application exceed that of a typical analog system, but it can also prove more cost effective in the long run. Details of the VCM test apparatus, the control concept, and the interfacing electronics are covered in the succeeding sections and appendices to this report.

II. VCM TEST SYSTEM

A. General

The general test procedure outlined in the referenced JSC SP-R-0022A document has now become an approved ASTM standard material test method E-595-77, "Total Mass Loss and Collected Volatile Condensable Materials from Outgassing in a Vacuum Environment." The test procedure requires the heating of candidate material test specimens, by highly controllable means, to a temperature which will evaporate the volatiles of interest. As many of the volatiles as possible are collected nearby the heated specimens by condensing the volatiles on a cold plate containing precisely weighed metal discs (collectors). Figure 1 shows a cross section of a typical VCM specimen test station.

A test run consists of elevating the test specimens to a defined temperature in 1 hr or less and holding them at that temperature for a defined time under high vacuum conditions of approximately 10^{-6} torr. Currently, the defined test temperature is 125 ± 1°C, and the defined time at temperature is 24 hr. The cold plate and its collectors are maintained at 25 ± 1°C for the duration of the test.

At the conclusion of the 24-hr period, the heaters are turned off and the specimens are allowed natural, uncontrolled cooling to ambient temperature. The cold plate collectors are precisely weighed before and after controlled specimen heating, and the difference in these weights becomes a measure of the volatiles lost by the test specimens. This test method is primarily a screening technique for spacecraft materials. Actual characterization of any collected volatiles is not a test goal.

In preparing for a test run, and before test specimens are installed, a thorough manual cleaning and vacuum bake of all critical hardware within the vacuum system is essential. To this end, a 4-hr equipment bakeout at a nominal 150°C was ascertained by the equipment developers to be adequate. This bakeout temperature is just below the point at which certain structural resins used in the test system assembly might, of themselves, outgas or break down. The overall system operation timeline is shown in Figure 2.

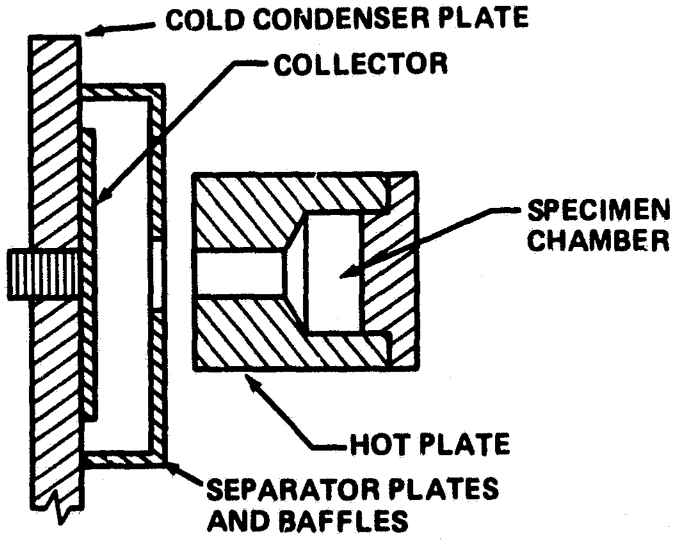


Figure 1. Typical VCM test station (cross section).

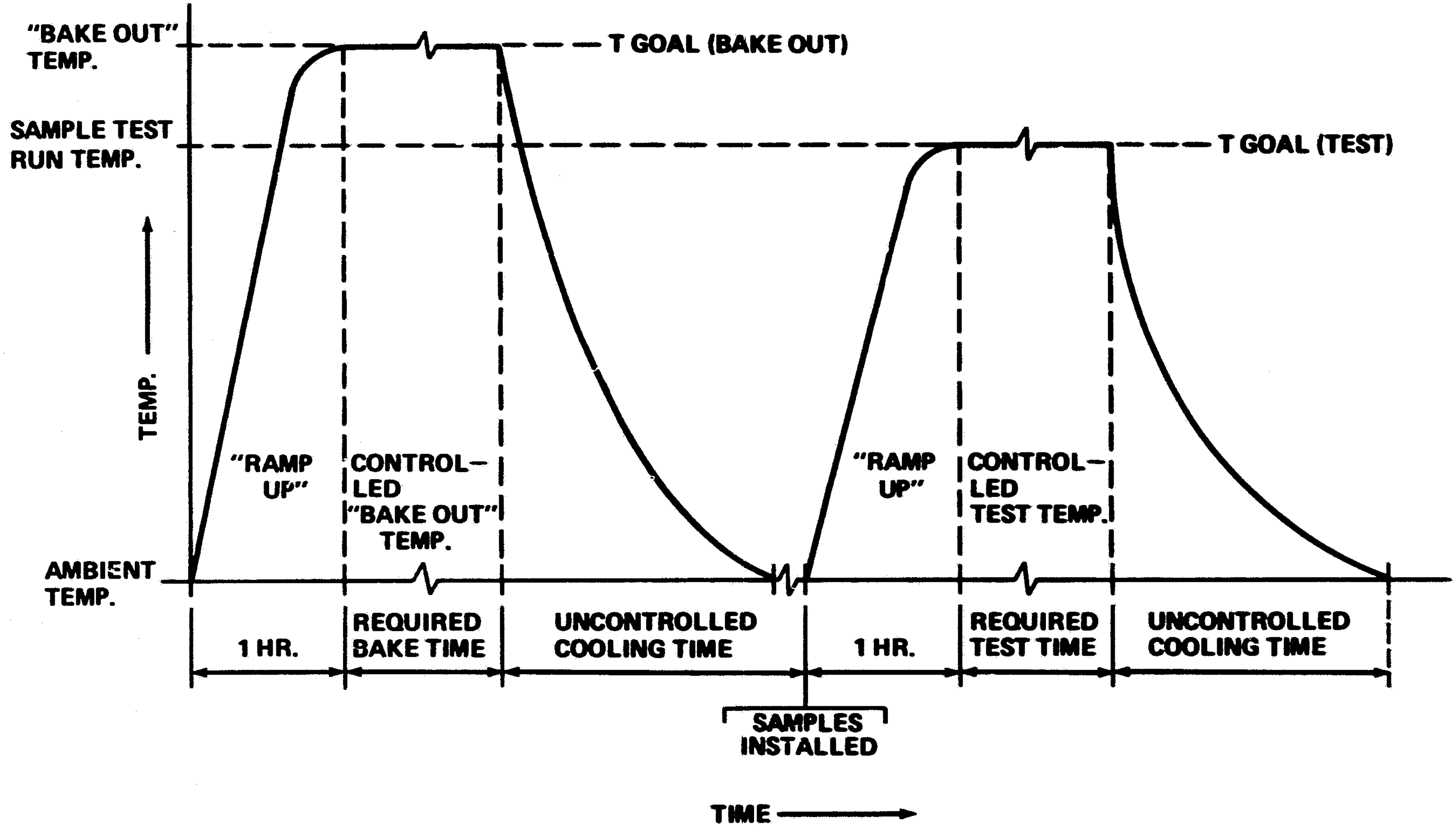


Figure 2. VCM system operation timeline.

B. Test Hardware

VCM system test equipment will be considered separately from the monitor and control operation which is described in Section III and detailed in the appendices. The system hot plate consists of a solid copper block, approximately 20.3 × 2.5 × 2.5 cm (8 × 1 × 1 in.), which offers good thermal conductivity and predictable thermal inertia. Three large holes bored in this block accommodate the specimen holders. Four smaller holes hold four 120 V, 125 W, electric cartridge heaters. Six calibrated copper-constantan (Type T) thermocouples are also located in this block, within appropriately drilled holes, between each specimen location and an adjacent heater [Fig. 3(a)]. The block is firmly supported within a laboratory-type vacuum bell jar by a thermally isolated fixture. All electric leads, having vacuum compatible insulation, are brought out of the chamber through a multi-pin vacuum connector.

The system cold plate, or condenser plate, consists of a second, thinner, copper block mounted upon the same fixture which supports the hot plate. This block is approximately 20.3 × 7 × 0.63 cm (8 × 2.75 × 0.25 in.). Three precision-machined condensing discs, or collectors, are attached to the front face of the block in a

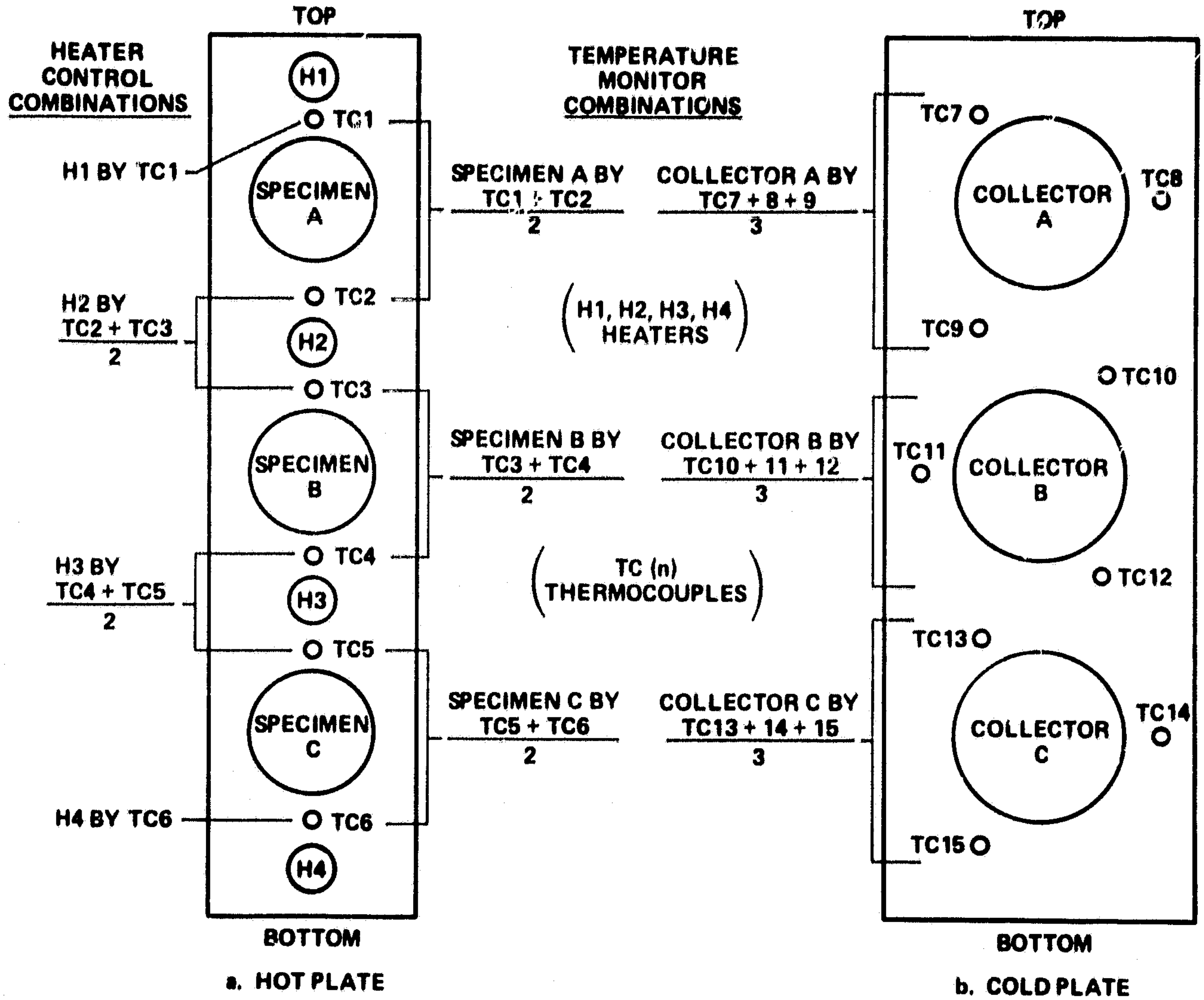


Figure 3. Thermocouple plan.

manner so that each collector is directly opposite a hot plate specimen test station. Each collector mounting surface was properly prepared, and attachment hardware was carefully selected, to maintain good thermal contact with the block. Nine calibrated Type T thermocouples are also installed in this block [as in Fig. 3(b)], along with appropriate masks and baffles to control and direct molecular streaming. Soft drawn 1/4-in. copper tubing was brazed in a gentle loop-back pattern to the rear face of the block through which cooling water flows from an external water bath. The water bath unit is independently controlled to maintain a 25 ± 1°C cold plate temperature.

Figures 4(a) and 4(b) show closeups of the hot and cold plates. Figure 5(a) also shows both plates along with their mounting fixture and the vacuum feedthroughs. Figure 5(b) shows the laboratory-vacuum bell jar system by Vactronic Lab Equipment, Inc. Figure 6 shows the constant temperature water bath by Forma Scientific, Inc.

C. Test Measurement and Control Instrumentation

For efficient spacecraft material screening according to the VCM procedure, a high degree of automation is desirable. This includes unattended system management and a record of system behavior over the 24-hr test cycle. Either a desk-top programmable calculator or a computer having flexible input/output (I/O) capability is well suited as a system controller/monitor. Such a device allows automatic:

1) Scanning and reading of many thermocouple signals

2) Averaging of these readings in different sets at will

3) Linearization and conversion of the readings to equivalent temperatures for human operator convenience

4) Logical decision-making through easily modifiable software routines

5) Dynamic system control output based on rapid analytical results

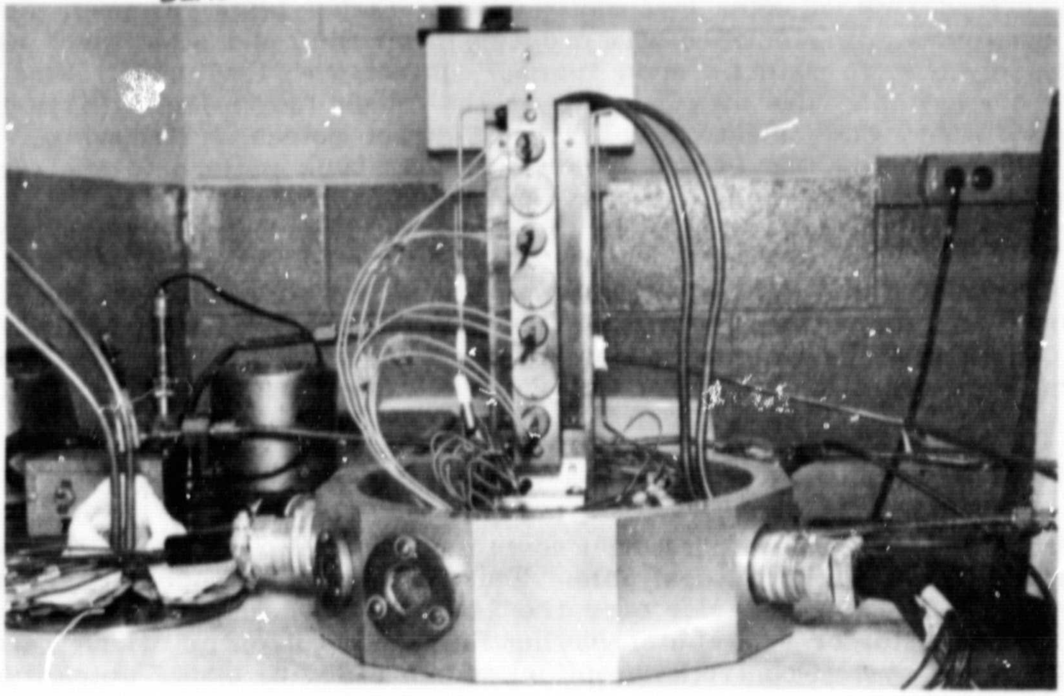
6) Test cycle timing

7) Record printout of overall system operation.

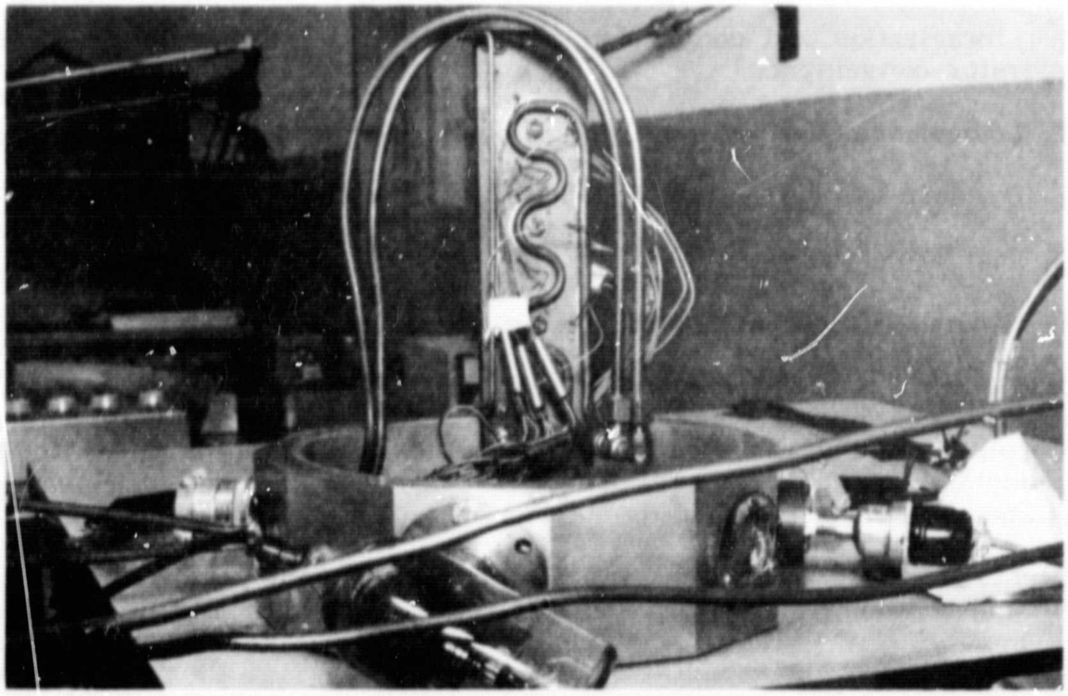
Included in such a measurement and control software package can be emergency equipment shutdown procedures, monitoring of other related activities (with or without control outputs), and a variety of human operator conveniences. Unattended housekeeping functions can also be monitored and controlled such as emergency backup power equipment.

Industrial analog controllers appeared lacking in one or more respects for this particular control/monitor system development. Since a H-P model 3050B laboratory DAS with a model H-P 9821A desk-top programmable digital controller was already available with the desired capabilities, the prototype system development centered on it. The DAS and its controller is shown in Figure 7. A system block diagram is shown in Figure 8.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

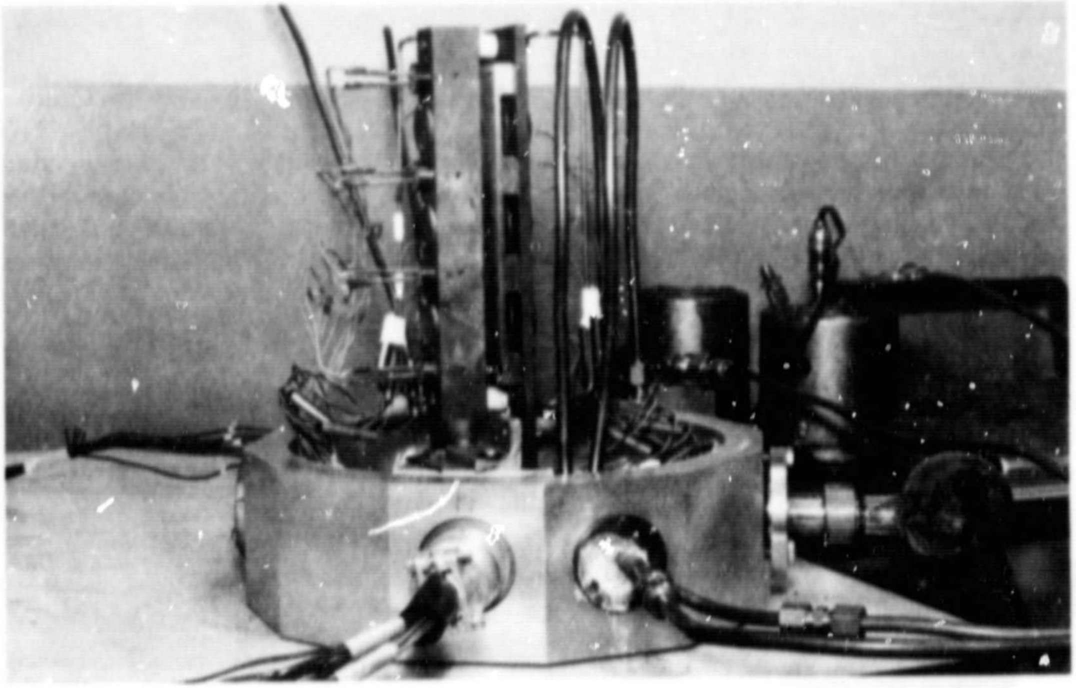


a. Hot plate.



b. Cold plate.

Figure 4. Hot and cold plates, close-up views.



a. Hot and cold plate support.

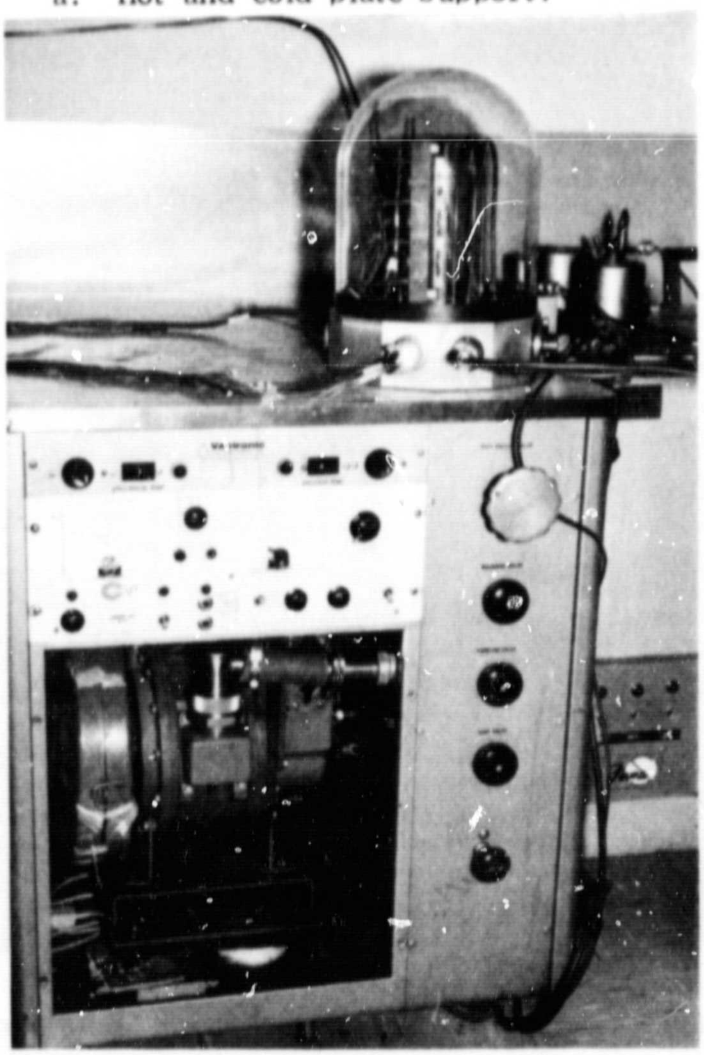


Figure 5. Hot and cold plate support and vacuum system.

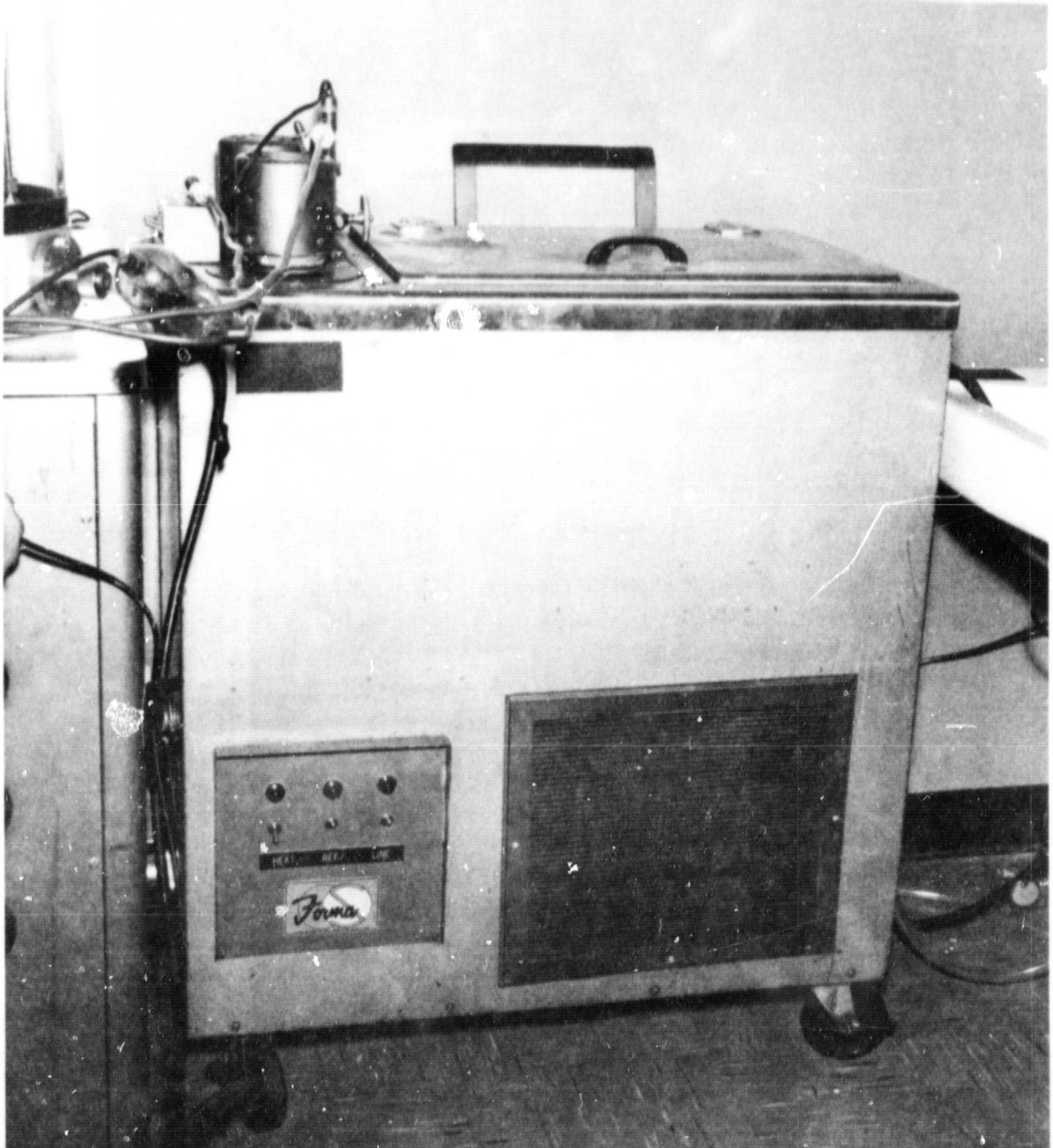


Figure 6. Constant temperature cold water bath.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

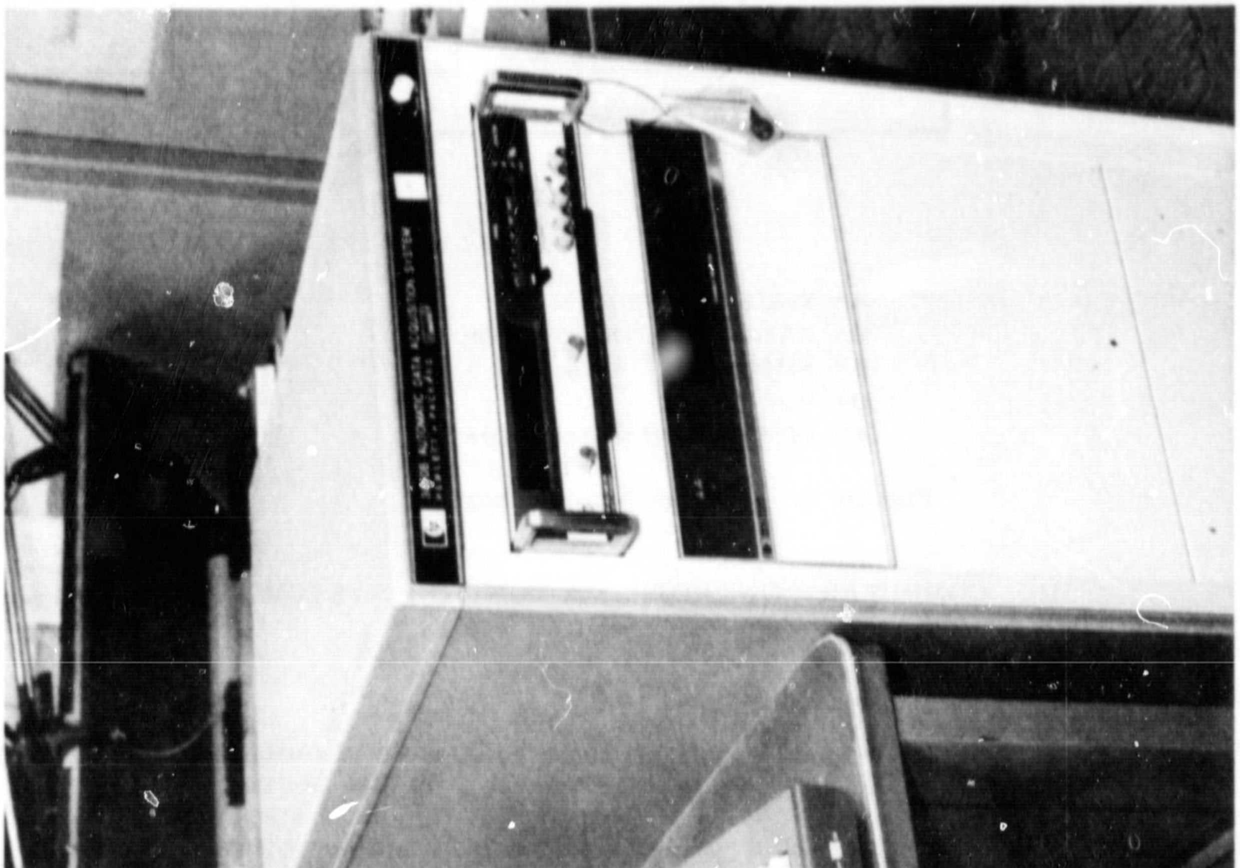
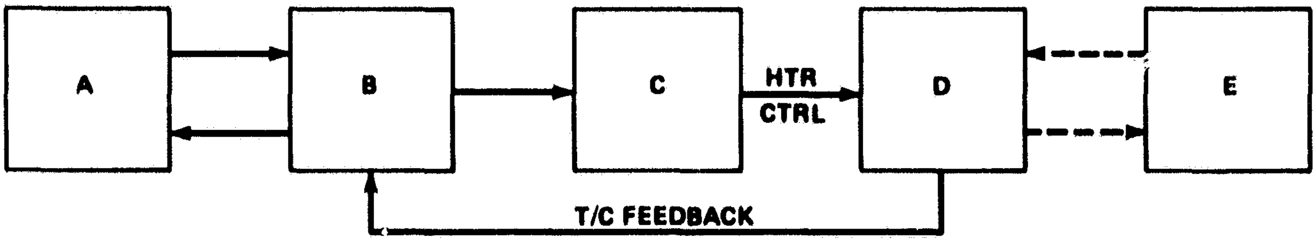


Figure 7. Lab data acquisition system with controller.

ORIGINAL PAGE IS
OF POOR QUALITY



A = SYSTEM CONTROLLER
B = DATA ACQUISITION SYSTEM
C = INTERFACE HARDWARE
D = VCM SYSTEM
E = INDEPENDENT WATER BATH

Figure 8. System block diagram.

III. COMPUTER CONTROL AND MONITOR SYSTEM

A. General

Requirements for DAS software broadly include input and output signal management, decision making, and timing. Both the bakeout and test sequences of Figure 2 involve the same control elements: system power turn-on, clock start, ramp up to operating temperature within one hour or less, timed maintenance of the operating temperature to close tolerance, operator printouts of system behavior, and power turn-off. An emergency shutdown routine was deemed essential in the event equipment defects caused either an over-temperature or an under-temperature condition. Provisions were also made for possible future control of a proportioning flow valve in the cooling water and automatic monitoring and maintenance of a back-up battery/ inverter power unit.

B. System Interface Technique

The H-P 3050B DAS scanner is equipped with normally-open (NO) double-pole single-throw (DPST) relays for output interface purposes. Therefore, interface circuitry was devised to convert this limited configuration into a pseudo-proportional controller for the four cartridge heaters. With appropriate interfacing, the scanner output relays can then be used to slightly step-change input power to each heater, independently. More specifically, the relay interface is wired to switch resistors in or out of the phase control circuits of four quadracs (back-to-back silicon controlled rectifiers) supplying power to the four heaters. Thus, the firing angle of each quadrac can be modified a predictable amount to either slightly reduce or slightly increase power delivered to its respective heater. Each heater sees the output of only one quadrac through a step down transformer. This arrangement allows wide latitude in quadrac triggering and stability for small power changes.

Computer logic is structured to anticipate all control action well ahead of time. Heater power control steps are established large enough to compensate for approximately ±10 percent power line voltage variations. However, the steps are also small enough to maintain test temperature tolerances. Complementary circuits implement differing equipment bakeout and specimen test temperatures, rapid initial temperature ramp up, and emergency power shutdown. Appendix A lists major components and equipment used in the control system. Appendix B further discusses interface design detail.

C. Control System Functions

The computer/controller is basically used to command three programmable instruments within the DAS: a digital clock and calendar unit, a digital voltmeter, and a multi-channel scanner having both low-thermal input channels and DPST relay output channels. Software functions consist of clocking (timing), thermocouple and auxiliary channel reading (input), data processing and error signal normalization (computation), and final equipment control (output). These functions are repeated in a cycle every 30 sec, which is a time duration offering the best results with minimum compromise due to equipment idiosyncrasies.

Throughout each 30-sec cycle, the controller displays the hottest thermocouple temperature last read from the hot plate and the last calculated average cold plate temperature. An audio alarm alerts the operator of any abnormal cold plate temperature since the cold plate is not presently computer controlled. To save central processor time, absolute thermocouple voltages, referenced to 150°F, are utilized for all internal decision-making operations. As an operator convenience, thermocouple readings are linearized and converted to equivalent temperatures for printout purposes only. Table 1 summarizes one common configuration for dynamically combining and averaging thermocouple inputs. Nomenclature for each thermocouple, heater, specimen, and collector in this table refers to Figure 3.

An option was incorporated in the software to print out individual thermocouple conversions, as well as averages, as a convenience during initial engineering development. However, linearizing temperatures and driving the printer are actions which slow the controller cycle time considerably and use excessive paper. Conversions and printouts are, therefore, limited to once each hour unless the operator requests them during any one clocking cycle by pressing a control (FLAG) key on the controller keyboard. The controller visual display does, however, continually convey relevant hot and cold plate temperature information which requires minimum algorithmic temperature conversion by the controller's central processor.

Certain file messages and questions for the operator, concerning equipment preparedness, occur at the start of the program after initialization. Following this step, an automatic check is made by the controller for the presence of proper data files (numerical constants, maximum and minimum temperature values for comparisons, linearization polynominal coefficients, etc.). Such operator interaction is a normal part of a system control program, and the software can be flexibly structured to suit the operator. Table 2 presents a typical operator initialization and information summary printed out before and during bakeout or test.

TABLE 1. THERMOCOUPLE USAGE

I.	Hot Plate Heater and Sample Thermocouples
	A. Heater Temperatures for Control (with averaging)
	T/C 1 alone controls H1
	T/C (2 + 3)/2 controls H2
	T/C (4 + 5)/2 controls H3
	T/C 6 alone controls H5
	B. Sample Temperatures for Printout (with averaging)
	T/C (1 + 2)/2 gives T average for sample A
	T/C (3 + 4)/2 gives T average for sample B
	T/C (5 + 6)/2 gives T average for sample C
II.	Cold Plate Collector Thermocouples
	T/C (7 + 8 + 9)/3 gives T average for Collector A
	T/C (10 + 11 + 12)/3 gives T average for Collector B
	T/C (13 + 14 + 15)/3 gives T average for Collector C

TABLE 2. TYPICAL MONITOR PRINTOUT DATA

TITLE OF PROGRAM

↓

QUESTIONS FOR OPERATOR RESPONSE
(E.G., IS THIS THE DESIRED PROGRAM? IS EQUIPMENT READY?)

↓

DATE AND TIME COMPUTER TURNS POWER ON AND INITIAL
TEMPERATURES OF ALL T/Cs AND ZONE AVERAGES

↓

DATE AND TIME "RAMP-UP" IS COMPLETE
AND MAIN CONTROL PROGRAM STARTS

↓

TEMPERATURE DATA HOURLY OR ON OPERATOR DEMAND

↓

EQUIPMENT STATUS MESSAGES
(E.G., COLD PLATE OUT OF SPEC; LOSS OF A T/C INPUT)

↓

DATE AND TIME COMPUTER TURNS POWER OFF, AND FINAL
TEMPERATURES OF ALL T/Cs AND ZONE AVERAGES

IV. RESULTS AND CONCLUSIONS

A stable, steady-state hot plate temperature of 125 ± 0.2°C can be maintained by the system. The close tolerance is partly caused by the measurement and control of discrete, overlapping thermal zones throughout the copper block. This unique zonal concept is made plausible by today's small, inexpensive laboratory-type computer/controller. Such a controller, with appropriate peripheral components, can rapidly and automatically scan strategically placed precision thermocouples. These readings can then be used either single or in multiple group averages. Through software flexibility, control zones can even be dynamically changed, or redefined, to optimize system response to changing conditions throughout a test run.

Overall results of the control development exceeded expectations. Manual presetting of controls proved to be non-critical for achieving controllable temperature trends in the hot plate. Also, automatic stepped power proportioning adjustments by the quadrac circuits are simple and effective. The temperature tolerance of ±0.2°C generally exceeds the precision of industrial thermostatic control techniques. Table 3 summarizes performance results for unattended computer control/monitor functioning.

TABLE 3. UNATTENDED COMPUTER CONTROL/MONITOR FUNCTIONS

VCM Specification Items	Requirement	System Performance
1. Specimen test temperature	125 ± 1°C over 24 hr	125 ± 0.2°C automatic shutoff after 24 hr
2. Temperature ramp-up to test value	≤1 hr with overshoot ≤1°C	≤1 hr with overshoot ≤0.2°C
User Specification Item		
3. Bakeout temperature	150 ± 1°C for 4 hr	150 ± 1°C automatic shutoff after 4 hr

It has been shown that an effective and inexpensive pseudo-proportional controller can be fabricated from common electrical/electronic components using a simple design philosophy. Although the availability of a small computer/controller with I/O capability is requisite, small computer-based laboratory data acquisition systems are becoming quite commonplace for process control. Within this design philosophy, successful thermal measurement and control by dynamic averaging of thermocouples in discrete temperature zones has been demonstrated in a small VCM apparatus. The computer/controller allows convenient real-time and historical records of total system behavior throughout a test run in addition to unattended automatic operation.

It is concluded that the system is highly successful. The overlapping zonal averaging concept, plus associated computerized recordkeeping, can certainly be envisioned for other applications where precise temperature control, along with comprehensive operator assistance, is essential.

BIBLIOGRAPHY

Healy, B., Dir., "Introduction to Logic Design," Educational Systems Division, Data Technology Corp., California, 1965.

Keister, Ritchie, and Washburn, "Design of Switching Circuits," Van Nostrand, New Jersey, 1951.

Wilson, E. B., Jr., "An Introduction to Scientific Research," McGraw-Hill, New York, 1952.

APPENDIX A

LIST OF EQUIPMENT

1. Laboratory vacuum system, Vactronic Lab Equip., Inc., NY.

2. Vacuum gauges/power supplies, F. J. Cooke, Inc., CN.

3. Constant temperature water bath, Forma Scientific, Inc., OH.

4. Laboratory data acquisition system, Hewlett-Packard (H-P) Model 3050B containing: H-P Model 3490A programmable multimeter, and H-P Model 3495A programmable scanner.

5. Controller, Hewlett-Packard (H-P) Model 9821A.

6. Solid state AC quadrac controls, Leviton Model 6681, 600 Watt.

7. Thermocouple reference junction, Hy-Cal Engineering, CA, 150°F "Ref-Cel" Model 205-T.

8. Relay coil power supply, "Plug-In" Instruments, Inc., TN, Model SPS-2011.

9. Heater interface transformers, Edwards Co., Inc., CN, "Tri-volt" Model 998 (Class 2): 8V/16V/24V secondaries; 120V primary.

10. Power control relay, Potter & Brumfield Div. of AMF, Inc., IN, 24 VDC Model KRP11D.

11. Rampup relay, Babcock Control Products, CA, 24 VDC Model AG805.

12. Precision thermocouples, Medtherm Corp., AL, Type T, ±0.05°C at 125°C.

13. Quadrac stepping relays, ES/Portland R805, hermetically sealed, can-type.

APPENDIX B

INTERFACE DESIGN DETAIL

Due to the scanner's actuator relay characteristics, a separate relay interface unit was constructed having several selectable relay options. Referring to Figure B-1 which shows a typical heater circuit, the two-key stepping resistors in each quadrac control loop are R_p and R_s. The circuit resistance in each quadrac trigger control circuit is stepped down or up (respectively) from the nominal preset value required to allow approximate long term stability of the hot plate at temperature goal (TGOAL) in Figure 2 under normal high-vacuum operating conditions. Since R_p and R_s are actually small multi-turn potentiometers, initial system calibration is straightforward.

Cost effectiveness is a major goal in most projects such as this one. Therefore, as many laboratory stock items as possible were employed: relays, sockets, switches, chassis of various sizes, transformers, cabling, etc. The only items requiring special local procurement were inexpensive 120 Vac Leviton No. 6681 quadrac controllers designed for a 600 W resistive load.

Since a quadrac is basically a triac accompanied by a matched trigger device in the same package, in normal operation its output contains a significant dc component. For this reason, a transformer T1 (Fig. B-1) used to step down the output voltage to the heater, must be able to withstand the extra I^2R heating which will result.

The rating of the transformers actually employed is 30 V/A on bothe the 24-V and 16-V taps. The effective ac power dissipation of each heater during normal system operation steps between 8 V/A and 18 V/A, while the extra I^2R heating in the T1 primary winding due to the dc component approximates 8 W. Therefore, the maximum total power handled by each transformer is well within its rating, and transformer core temperatures consistently remain within acceptable limits. The transformer reduction scheme yields precise power control at each transformer secondary over conveniently coarse quadrac power adjustment ranges at each primary. Reliable triggering and excellent stability of each quadrac is maintained.

A main power relay, K6, and a ramping relay, K5, for switching the 16-V and 24-V transformer secondaries, complete the complement of interface relays. Relay power supplies are independent of computer control and have their own manual power switch.

Figure B-2 shows an overview of the prototype interface chassis.

ORIGINAL PAGE IS
OF POOR QUALITY

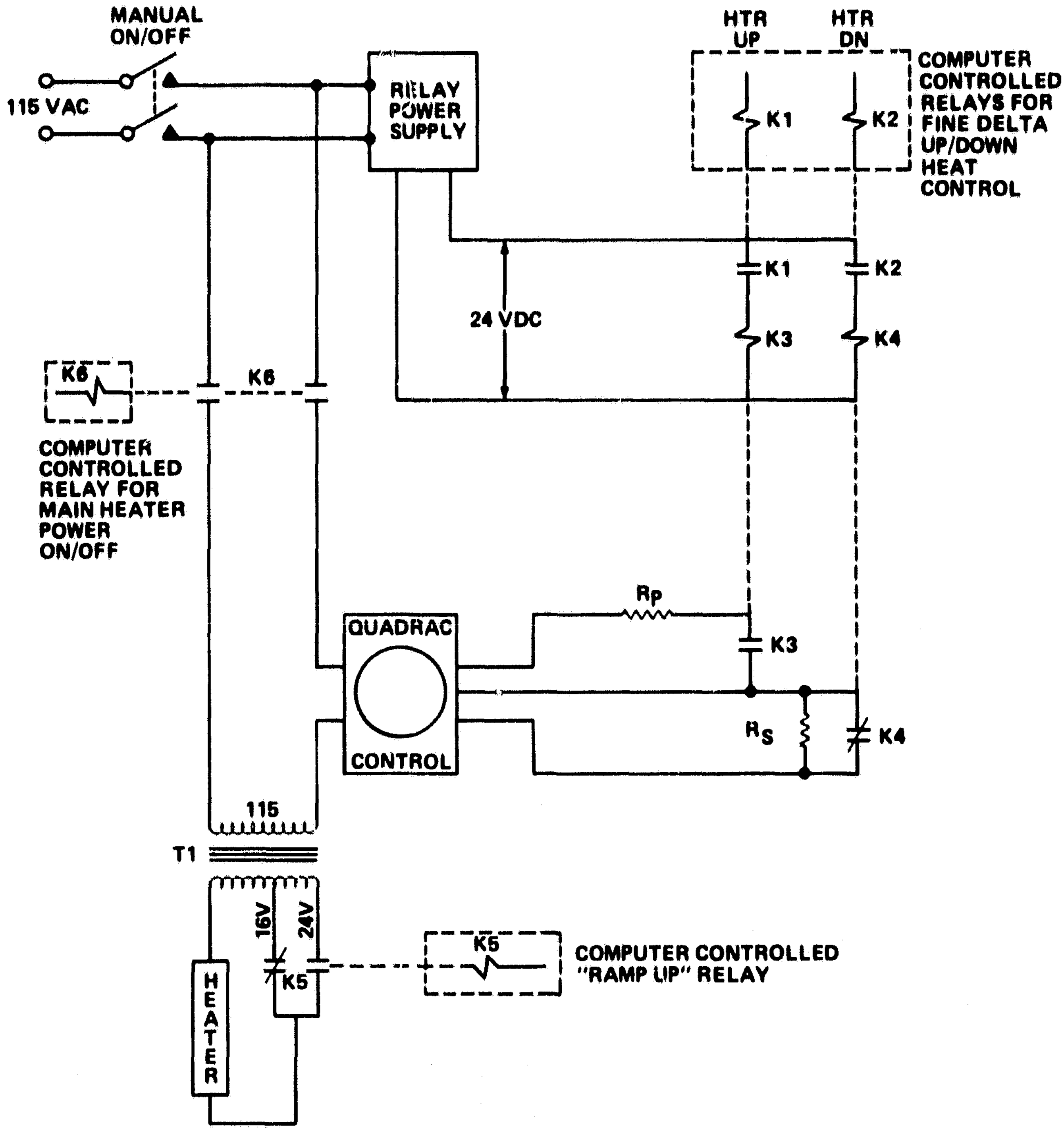


Figure B-1. Typical heater control circuits.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

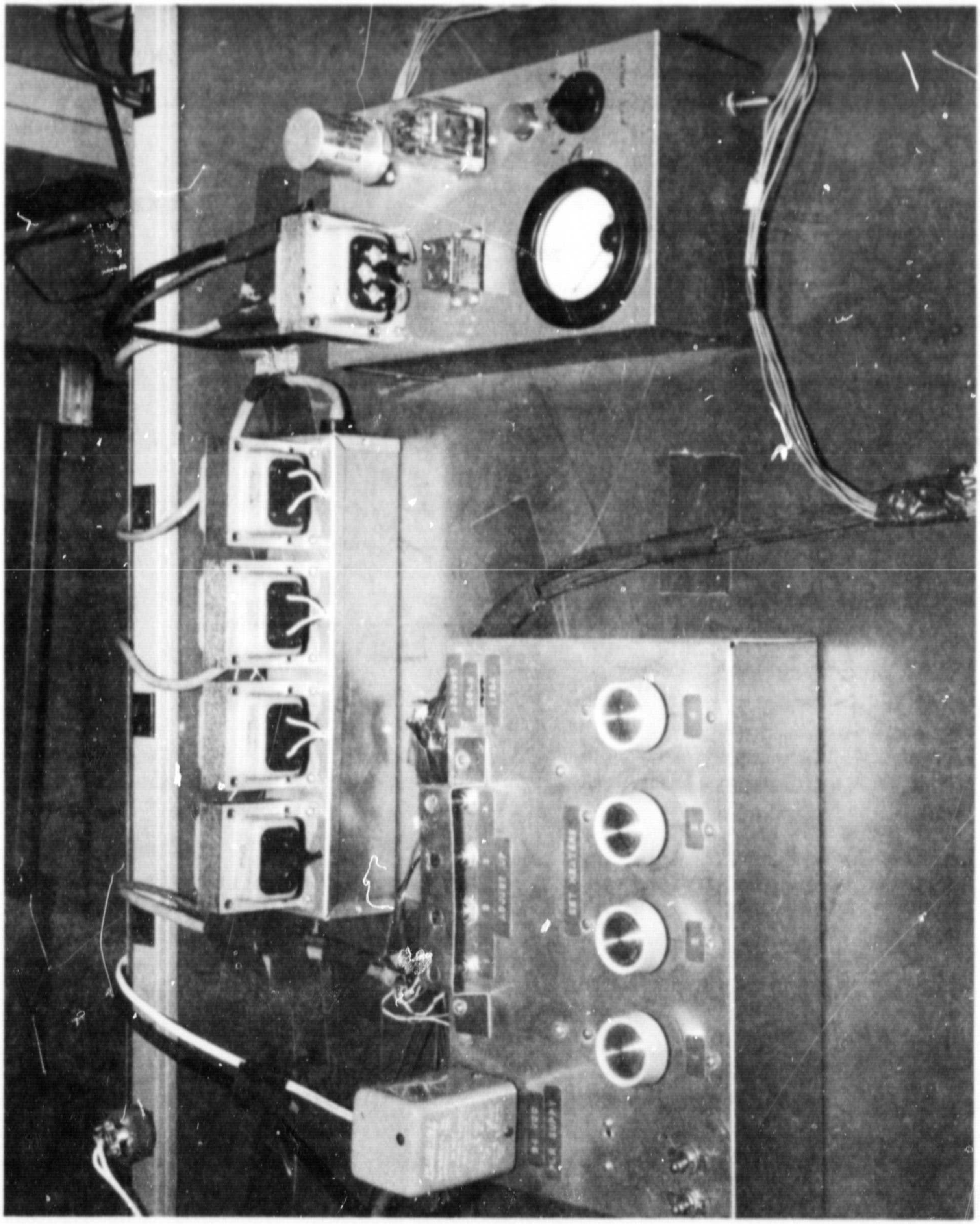


Figure B-2. Prototype interface chassis.

APPENDIX C

CONTROL SYSTEM OPERATIONAL DETAIL

The four electric cartridge heaters used in the VCM hot plate are controlled in such a way that, during operation, the heaters are neither completely OFF nor fully ON, unlike most thermostatically-controlled devices. Therefore, heat is continuously being introduced to the copper block to balance fixed losses during system operation. Heat losses are due mainly to surface radiation and conduction through the hot plate supports. Optimal quadrac control settings and stepping resistor values necessary to achieve thermal balance were empirically determined during system development. A nominal 125°C is maintainable in the copper hot plate with an effective voltage (V_{eff})* to each heater of approximately 12 Vac. For an optimal "step down" to lower heat, the V_{eff} to each heater is about 8 Vac. An optimal "step up" to higher heat yields a V_{eff} of about 16 Vac. Table C-1 reflects approximate conversion to equivalent heat input.

TABLE C-1. THERMAL EQUIVALENCES

Heater Power Modes	Approximate V_{eff} Meter Reading (Vac)	Approximate Heat Input Per Heater (Btu/min)	Approximate Total Heat Input To Four Heaters (Btu/min)
High Heat	16	1.0	4
"Normal"	12	0.75	3
Low Heat	8	0.5	2

Under high-vacuum conditions and with a stable cold-plate temperature, ramp-up of the hot plate from ambient to test temperature (TGOAL of Fig. 2) takes between 40 and 50 min. This is well within the 1 hr required by the VCM test specification. The control system allows a linear ascent curve until a point about 4°C below TGOAL, where the ramp-up relay is dropped out. This action creates a gradual tapering off of the ascent curve as TGOAL is approached. When TGOAL -0.5°C is reached for the 125°C program, or TGOAL -1.0°C for the 150°C program, the computer "steps" the quadracs, in cooperation with normal thermal inertia, to stabilize the hot plate. During this stabilization period, the maximum temperature reached at any point in the hot plate has been measured as TGOAL +0.2°C. When a subtle downward temperature trend is sensed in the hot plate caused by heat being lost faster than the preset heater control settings allowed, automatic heater control commences. The master clocking cycle, either 4 hr or 24 hr, is automatically initialized upon detection of TGOAL anywhere in the hot plate following ramp-up relay cutoff.

*The term V_{eff} reflects comparative measurements of the non-sinusoidal ac at each heater (due to the nature of quadrac output) by a standard ac voltmeter having a d'Arsonval movement. The meter proves more convenient than an oscilloscope during system calibration.

Although the control system can handle extreme long-term line voltage variations, the ±0.2°C tolerance may not always be maintainable. If, for example, excessive 120 Vac supply line voltage or an internal system defect were to cause the temperature to climb uncontrollably, the main power relay would be automatically de-energized. In the opposite case, if heater power were to become inadequate, even with all appropriate power called for, the ramp-up relay would again be energized. This action would essentially call for a new voltage reference (24 Vac instead of 16 Vac) from which the control system could continue to temporarily function. Under extended abnormal conditions, the operator would presumably abort the run and correct the deficiency. For a test run with no operator in attendance, the emergency power cutoff capability would (1) protect the specimens and the equipment from over-temperature and (2) terminate the test for extended under-temperature conditions.

APPENDIX D

SOFTWARE THERMOCOUPLE LINEARIZATION

Linearization of the Type T thermocouple readings, and conversion to equivalent temperatures, is accomplished using an active polynomial routine. This method saves much limited memory over a resident, passive "lookup" table. A ninth-order polynomial is used for high linearization accuracy. The polynomial takes the form:

$$T_{eq.} = k_0 + k_1E + k_2E^2 + k_3E^3 + \ldots + k_9E^9 \quad ,$$

where $T_{eq.}$ is the equivalent temperature in degrees Celsius, k_n are predetermined polynomial coefficients stored in memory, and E is either an individual or an average thermocouple voltage in millivolts.

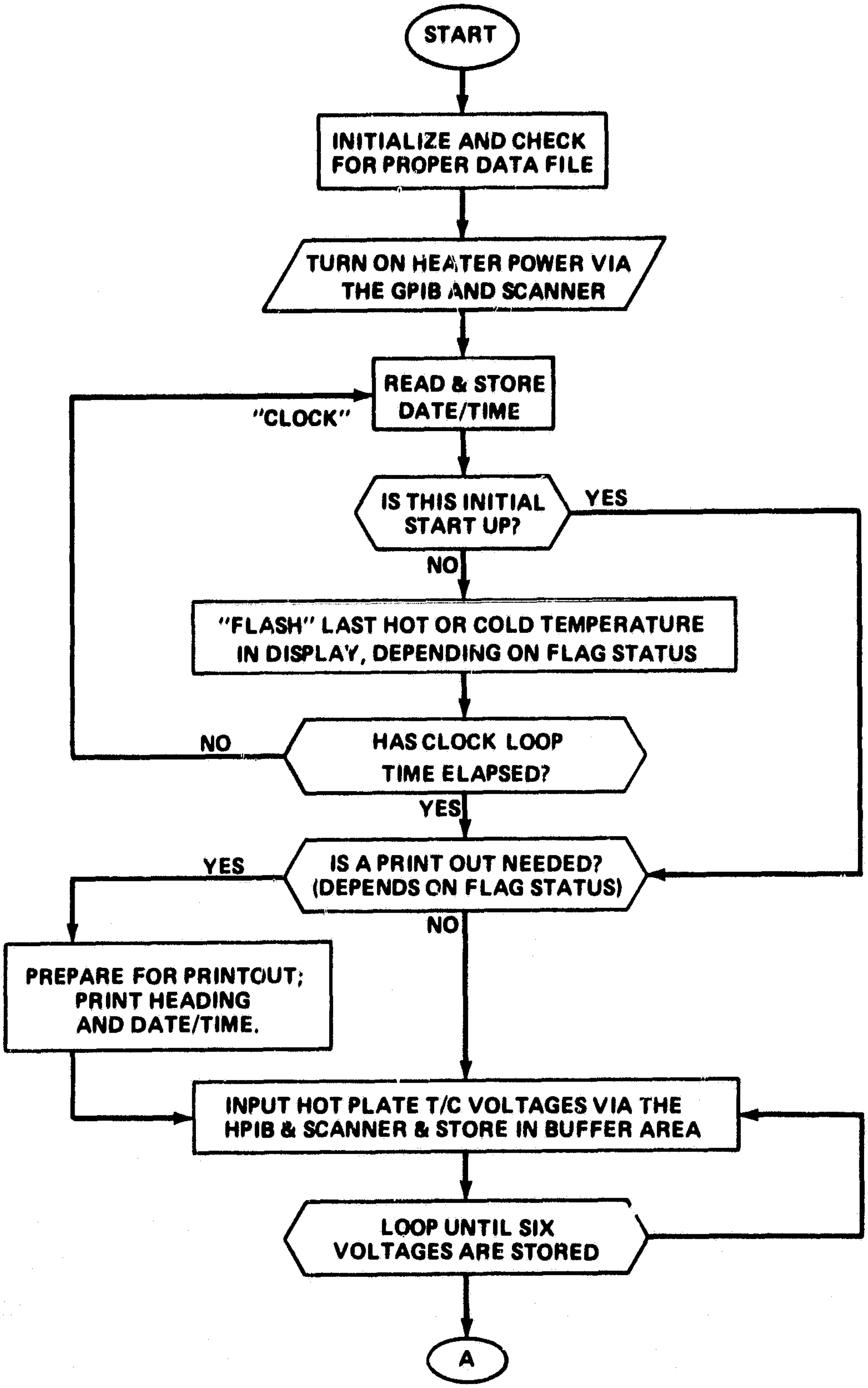
In evaluating the terms of the polynomial by the computer/controller, significant central processor time is saved by avoiding the individual exponentiations involved. The terms are "nested" into a simpler and faster series of successive multiplications. The equation actually used is structured as follows:

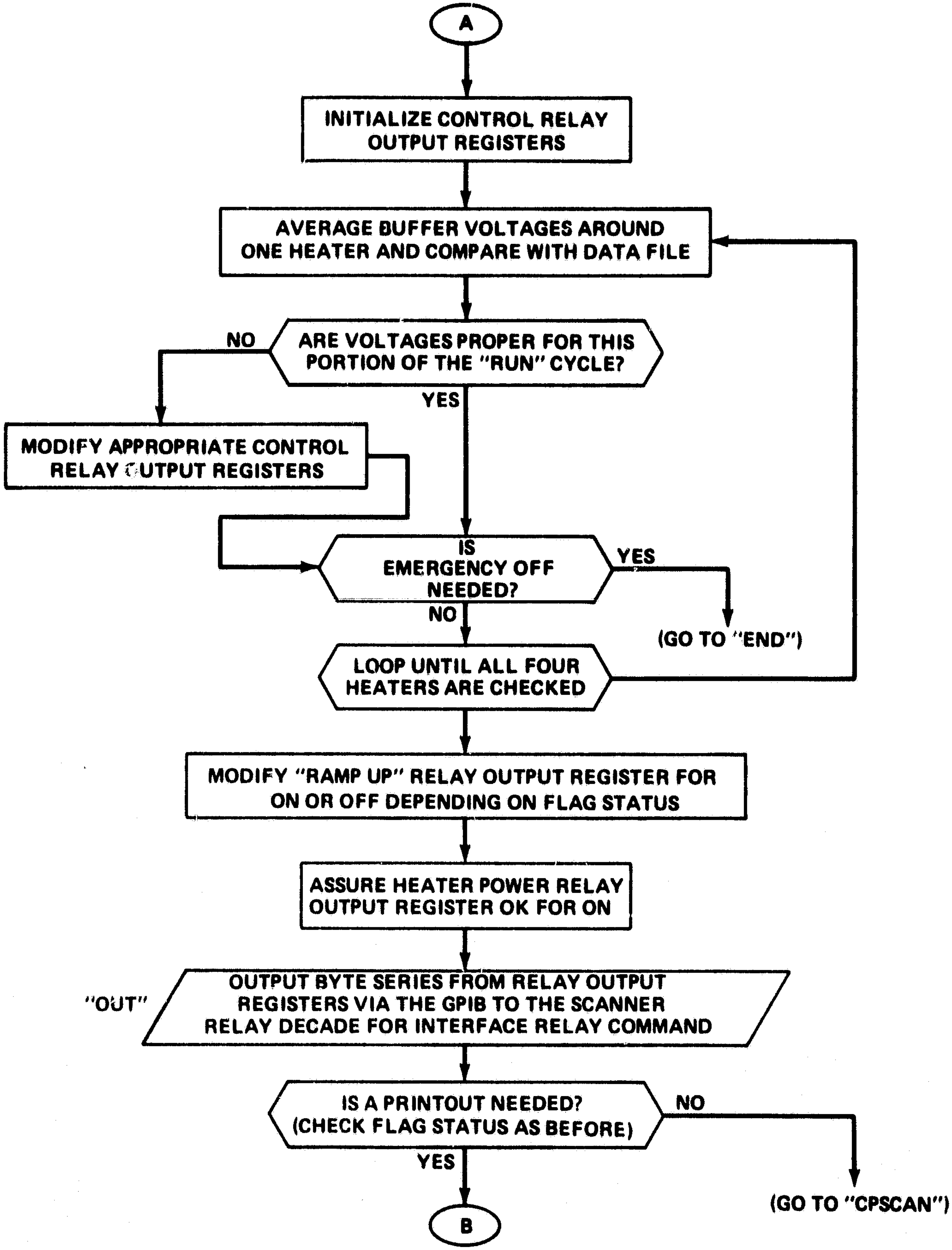
$$T_{eq.} = k_0 + E(k_1 + E(k_2 + \ldots + E(k_8 + Ek_9))) \ldots)_9 \quad .$$

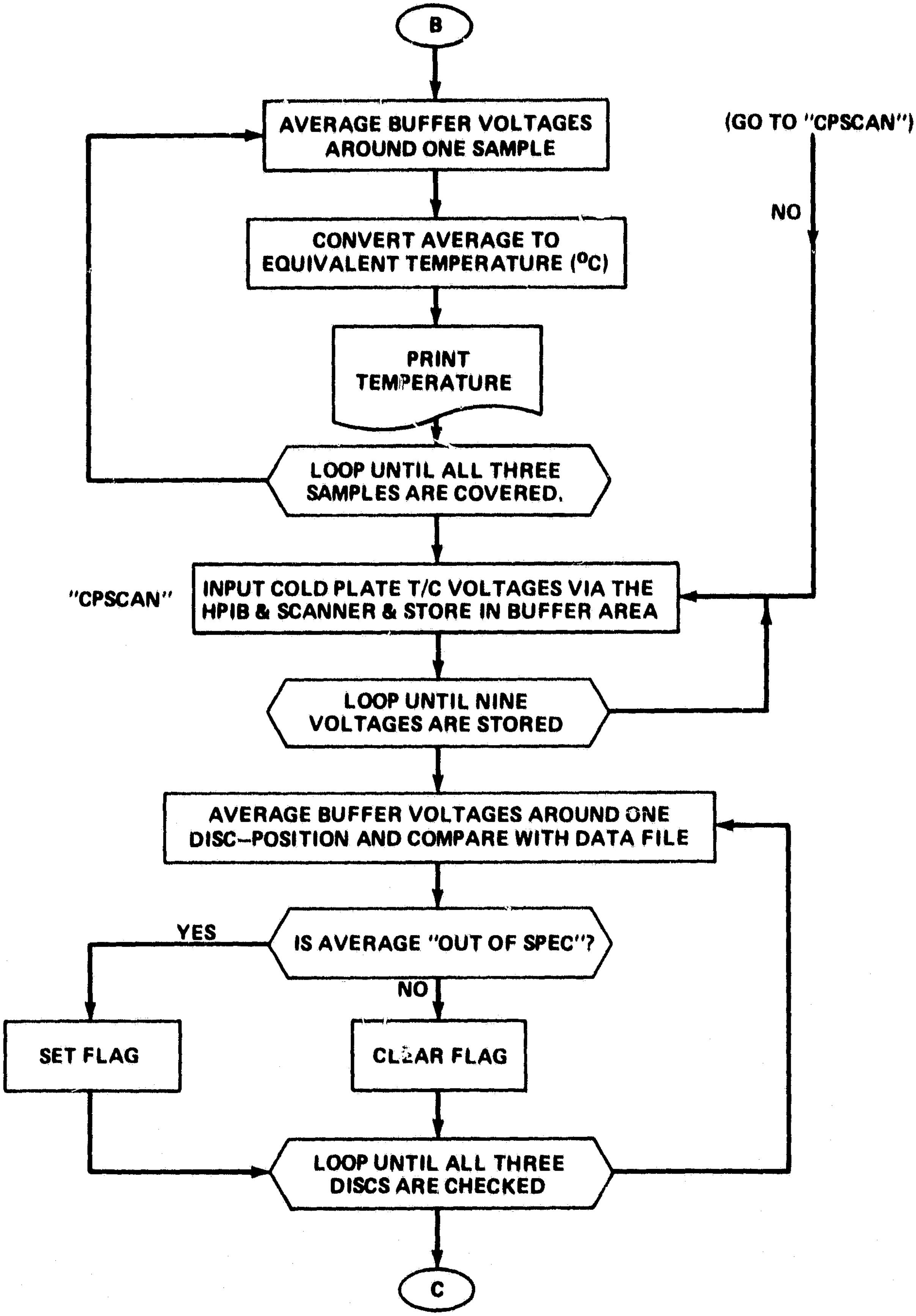
This polynomial can easily be optimized, over the limited temperature range of interest here, to within ±0.1°C in conversion accuracy.

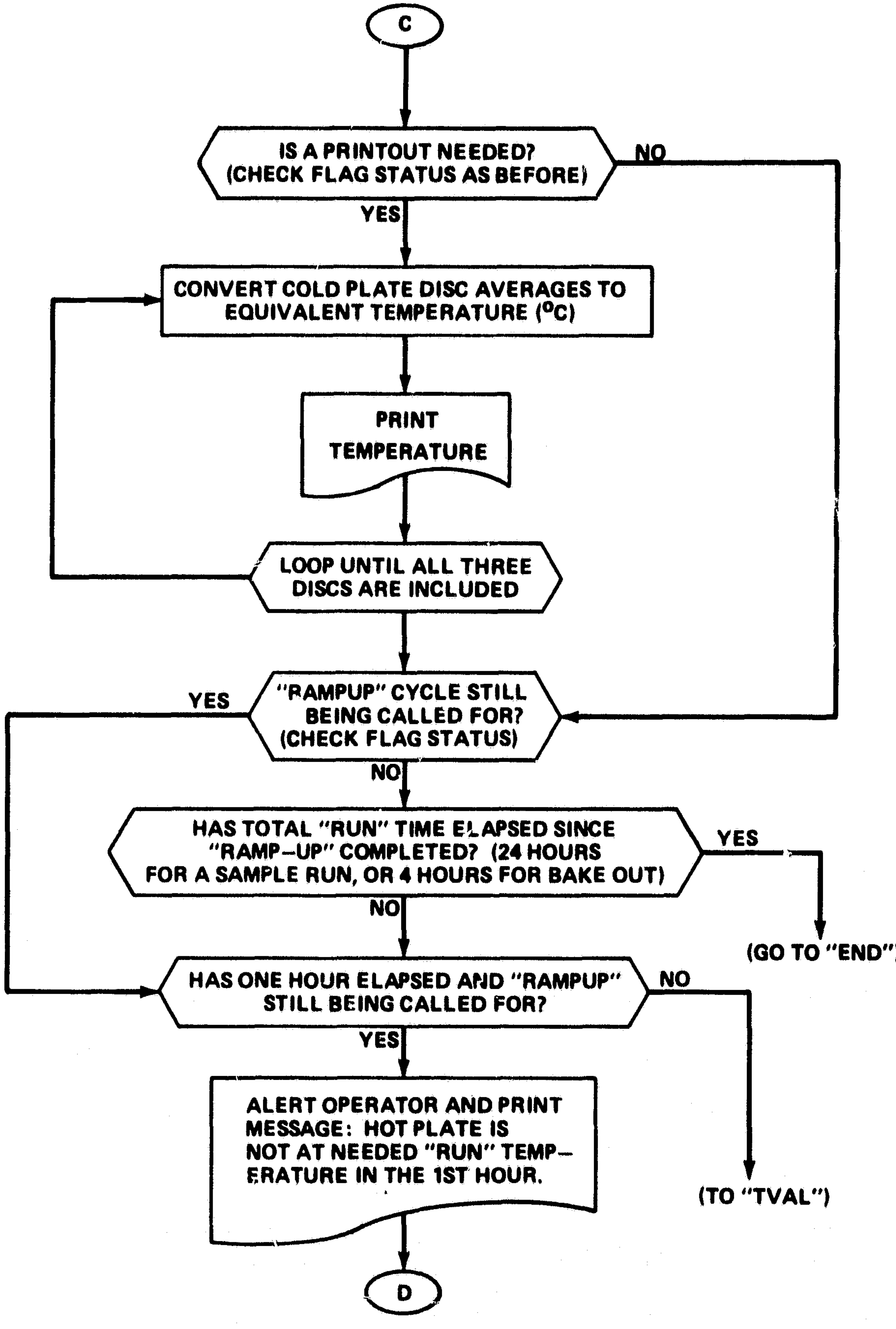
APPENDIX E

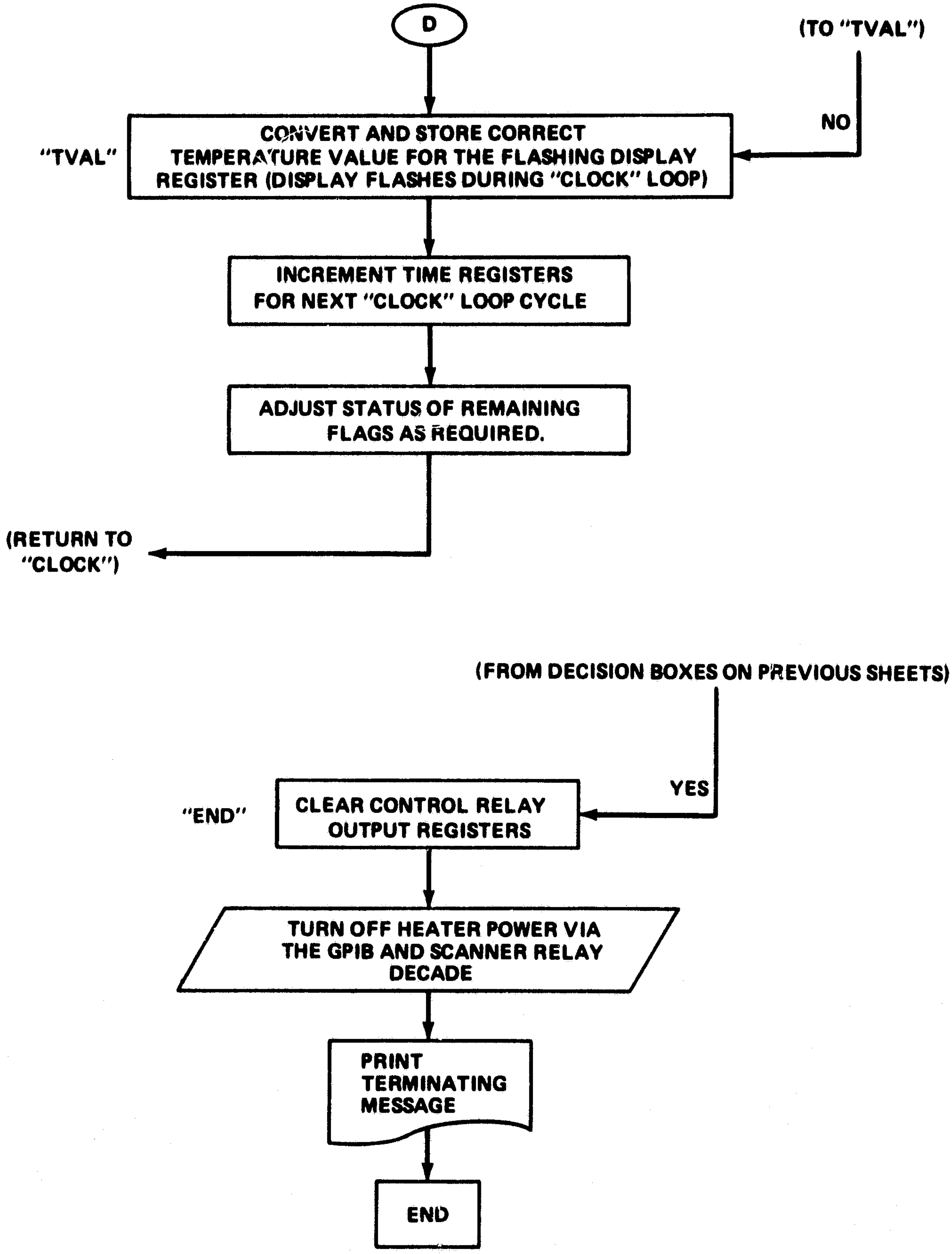
PROGRAM FLOW CHART




A
INITIALIZE CONTROL RELAY OUTPUT REGISTERS
AVERAGE BUFFER VOLTAGES AROUND ONE HEATER AND COMPARE WITH DATA FILE
ARE VOLTAGES PROPER FOR THIS PORTION OF THE "RUN" CYCLE?
NO
YES
MODIFY APPROPRIATE CONTROL RELAY OUTPUT REGISTERS
IS EMERGENCY OFF NEEDED?
YES
NO
(GO TO "END")
LOOP UNTIL ALL FOUR HEATERS ARE CHECKED
MODIFY "RAMP UP" RELAY OUTPUT REGISTER FOR ON OR OFF DEPENDING ON FLAG STATUS
ASSURE HEATER POWER RELAY OUTPUT REGISTER OK FOR ON
"OUT"
OUTPUT BYTE SERIES FROM RELAY OUTPUT REGISTERS VIA THE GPIB TO THE SCANNER RELAY DECADE FOR INTERFACE RELAY COMMAND
IS A PRINTOUT NEEDED? (CHECK FLAG STATUS AS BEFORE)
NO
YES
(GO TO "CPSCAN")
B


B
AVERAGE BUFFER VOLTAGES AROUND ONE SAMPLE
(GO TO "CPSCAN")
NO
CONVERT AVERAGE TO EQUIVALENT TEMPERATURE (°C)
PRINT TEMPERATURE
LOOP UNTIL ALL THREE SAMPLES ARE COVERED.
"CPSCAN"
INPUT COLD PLATE T/C VOLTAGES VIA THE HPIB & SCANNER & STORE IN BUFFER AREA
LOOP UNTIL NINE VOLTAGES ARE STORED
AVERAGE BUFFER VOLTAGES AROUND ONE DISC–POSITION AND COMPARE WITH DATA FILE
YES
IS AVERAGE "OUT OF SPEC"?
NO
SET FLAG
CLEAR FLAG
LOOP UNTIL ALL THREE DISCS ARE CHECKED
C


C
IS A PRINTOUT NEEDED? (CHECK FLAG STATUS AS BEFORE)
NO
YES
CONVERT COLD PLATE DISC AVERAGES TO EQUIVALENT TEMPERATURE (°C)
PRINT TEMPERATURE
LOOP UNTIL ALL THREE DISCS ARE INCLUDED
YES
"RAMPUP" CYCLE STILL BEING CALLED FOR? (CHECK FLAG STATUS)
NO
HAS TOTAL "RUN" TIME ELAPSED SINCE "RAMP-UP" COMPLETED? (24 HOURS FOR A SAMPLE RUN, OR 4 HOURS FOR BAKE OUT)
YES
(GO TO "END")
NO
HAS ONE HOUR ELAPSED AND "RAMPUP" STILL BEING CALLED FOR?
NO
YES
ALERT OPERATOR AND PRINT MESSAGE: HOT PLATE IS NOT AT NEEDED "RUN" TEMPERATURE IN THE 1ST HOUR.
(TO "TVAL")
D


D
(TO "TVAL")
NO
"TVAL"
CONVERT AND STORE CORRECT TEMPERATURE VALUE FOR THE FLASHING DISPLAY REGISTER (DISPLAY FLASHES DURING "CLOCK" LOOP)
INCREMENT TIME REGISTERS FOR NEXT "CLOCK" LOOP CYCLE
ADJUST STATUS OF REMAINING FLAGS AS REQUIRED.
(RETURN TO "CLOCK")
(FROM DECISION BOXES ON PREVIOUS SHEETS)
YES
"END"
CLEAR CONTROL RELAY OUTPUT REGISTERS
TURN OFF HEATER POWER VIA THE GPIB AND SCANNER RELAY DECADE
PRINT TERMINATING MESSAGE
END

APPROVAL

THERMAL MONITORING, MEASUREMENT, AND CONTROL SYSTEM FOR A VOLATILE CONDENSABLE MATERIALS (VCM) TEST APPARATUS

By R. E. Ives

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

R. J. Schwinghamer

R. J. Schwinghamer
Director, Materials and Processes
Laboratory

☆U.S. GOVERNMENT PRINTING OFFICE 1982—546-071/195