1984

Comparison of the response of shape memory alloy actuators using air-cooling and water-cooling.

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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

COMPARISON OF THE RESPONSE OF SHAPE MEMORY ALLOY ACTUATORS USING AIR-COOLING AND WATER-COOLING

by

Robert E. Watson

December 1984

Thesis Advisor: W. G. Culbreth

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Date Entered)

REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) Comparison of the Response of Shape Memory Alloy Actuators Using Air-Cooling and Water-Cooling		5. TYPE OF REPORT & PERIOD COVERED Master's Thesis; December 1984
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Robert E. Watson		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Postgraduate School Monterey, California 93943		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS Naval Postgraduate School Monterey, California 93943		12. REPORT DATE December 1984
		13. NUMBER OF PAGES 119
14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)		15. SECURITY CLASS. (of this report) Unclassified
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Shape Memory Alloys
Titanium-Nickel Alloys
Shape Memory Actuators
Cooling Time Constant Comparisons of S.M. Actuators
Computer Aided Data Acquisition & Control of S.M. Actuators

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

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DD FORM 1473 1 JAN 73 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-LF-014-6601

Unclassified

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

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Comparison of the Response of Shape Memory Alloy Actuators Using Air-Cooling and Water-Cooling

by

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MASTER OF SCIENCE IN MECHANICAL ENGINEERING

from the

NAVAL POSTGRADUATE SCHOOL
December 1984

ABSTRACT

Titanium-Nickel (Ti-Ni) alloy specimens with induced shape memory were subjected to various single step current inputs under water-cooled, natural convective air-cooling, and stagnant air-cooling conditions to determine cooling time constants and subsequent delay time for successive actuation. Power input, specimen recovery and reextension displacement with various loads applied to the coil shaped actuator, and temperature distributions along the coil were recorded as functions of time. Results suggested that liquid cooling was a viable method for increased actuator response time. A brief review of the phase transformations that give rise to the shape memory effect is included. Recommendations for continued research and application are discussed.

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I. INTRODUCTION

A new group of actuators, or force-motion transducers, is being developed through use of alloys which exhibit shape memory behavior. The shape memory effect occurs when a part made from an alloy is deformed at one temperature and recovers its original shape when heated to a second temperature. This effect is shown in Figure 1. Numerous applications for these thermo-mechanical actuators exist; however, one area in which shape memory alloys, or SMA's, can assert a tremendous influence is robotics. Low weight and small size actuators are prime candidates to replace stepper motors and other hydraulic or mechanical actuating systems. Recent work by the Mechanical Engineering Research Lab of Hitachi, Ltd. of Japan illustrates the extent to which SMA can be employed to reduce volume and weight of small load robotic systems [1]. Their three finger 'hand' and its 'forearm' have a mass of only 4.5 kg and the entire system is only 700 mm in total length. The forearm containing the SMA actuators is only 400 mm long, 80 mm wide, and 50 mm high. The robot can manipulate a 2.5 kg load with nearly the dexterity of a human hand.

The present work involved the design and construction of a liquid-cooling SMA testing system. A subsequent experimental investigation of SMA response time was conducted using heated water to assist actuation and using water cooling to decrease actuator cycle time. The system was automated by using computer control of the SMA actuator and computer-aided data acquisition from the testing system.

An understanding of the basic mechanism of shape memory behavior has been included to introduce some of the working parameters used in the study of shape memory alloys.

II. MATERIALS ASPECTS OF SHAPE MEMORY ALLOYS

The shape memory effect is a behavior exhibited predominantly by titanium-nickel, copper-aluminum-nickel, and copper-zinc-aluminum alloys. Characteristic shape memory behavior occurs when an alloy is deformed from its original shape well beyond normal plastic deformation and then regains that original shape when moderately heated. Shape memory is the result of a reversible transformation, called a thermoelastic martensitic transformation, in which martensite plates form and grow continuously during cooling and then shrink by the reverse path to the parent phase of the alloy as the temperature is raised [2]. Figure 2 depicts shape memory behavior in a coiled wire and the temperature and phase transformations that the alloy undergoes during memory inducement and cycling. An alloy specimen, the coil, is prepared by annealing it at a high temperature while it is constrained in the desired shape. Rapid cooling to below the martensite finish temperature, M_f, will produce a coil of SMA in its martensitic phase. If the coil is mechanically deformed it will be able to recover that induced shape by heating it through the parent start P_s, to parent finish, P_f, temperature range.

The original shape can be recovered because internal deformations that occurred during straining will retreat along the same path by which they were introduced as the alloy is heated.

As the coil is stretched both temperature and stress will cause transformation to the SMA martensitic phase. If the coil is in the temperature range between M_d, the highest temperature at which martensite can be produced, and M_s, the martensite start temperature, stress will induce the martensitic phase. If the coil is cooled to the M_s to M_f temperature range, or below, the parent phase will transform spontaneously to martensite [2].

Only low levels of elastic strain are created during the structural change so that the elastic limits of the parent and martensite phases are not exceeded. Irreversible plastic deformations do not occur during deformation. Rather, deformation causes shear transformation of parent phase regions to stress-induced martensite. Growth and/or shrinkage of neighboring plates is such that they accommodate the small strains that do develop, and in these groups the net shape change is small [2]. Simple stacking of plates in which strain vectors cancel each other is one type of group accommodation. There are also more complex mechanisms of strain accommodation that will not be discussed in this work [3,4,5]. Also, in Ti-Ni alloys, individual martensite plates have a strain accommodating substructure known as twinning [2]. Figure 3 is a transmission electron photomicrograph of internally twinned martensite plates in 50 percent Ti-50 percent Ni. During deformation, martensite plates will detwin to accommodate stress.

Reversion stress and reversion strain are two parameters which characterize the shape memory phenomena. A SMA specimen constrained against recovery during heating through the P_s to P_f temperature range develops an internal stress, known as the reversion stress. When later deformed and heated while unconstrained, the reversion stress produces reversion strain that can be observed as a change in the shape of the deformed specimen. To increase reversion stress, and thus increase the work output of a specimen upon heating, a sample specimen to be formed for a particular use should be strained up to its strain limit. Figure 4 shows that the percentage of recoverable strain for a SMA specimen is a maximum for an induced strain of up to the strain limit, typically about 8 percent. If the initially induced strain is greater than the strain limit, the reversion stress and the recoverable strain, and consequently the useful work output, decreases [2].

The ambient temperature at which the SMA actuator resides is important to the design of actuators because of the temperature dependence of the parent to martensite transformation and its reverse, the martensite to parent transformation.

Figure 5 shows stress-strain diagrams for a SMA at two different ambient temperatures. Figure 5a is the stress-strain diagram for an actuator at an ambient temperature above M_s and below P_f. Two parameters are introduced to describe the transformation stresses and their values reflect the stability of the parent phase material. The stress required to stress induce martensite, s_{p-m}, is a function which linearly increases from a minimum at M_s to a maximum at P_f. When stress reaches s_{p-m} the alloy will begin to experience strain and will transform from the parent phase to the martensite phase. For the martensite-to-parent transformation to occur, the stress level must drop to s_{m-p}. If the stress level is decreased to s_{m-p} there will be an elastic recovery to a lower strain. This is called the pseudoelastic effect, PEE. Further recovery will occur on heating the actuator--the shape memory effect [2]. If the ambient temperature is below the martensite finish temperature, as in Figure 5b, no elastic behavior will occur on unloading the actuator. Recovery will occur on heating only.

Reversion stress has been found to be well approximated by the value of the flow stress s_{p-m} [2]. Flow stress is obtainable from simple tensile tests as a function of temperature and strain. Perkins [2] reported that reversion stress will be about 20 percent lower than flow stress for a given temperature and strain. This information can be used during the design of a functional SMA actuator.

The temperature dependencies discussed above must be taken into account by the designer of mechanical systems with SMA actuators. Particular attention must be paid to the temperature dependence of the flow stress and reversion stress. Reversion stress is a maximum over only a small temperature range near P_f [2]. If, during heating, the stress on the SMA actuator exceeds the parent phase yield strength so that yielding occurs there will be a decrease in reversion stress which will continue to decrease as the temperature continues to rise [2]. Accompanying the decrease in reversion stress may be a conversion of part of the initial strain into permanent damage in the form of plastic strain. A second problem situation occurs if a constant load is maintained on the SMA as the temperature approaches M_s. Since s_{p-m} is low at M_s the applied stress may produce true plastic deformation of stress-induced martensite [2].

A specimen, if cycled many times, may develop a partial two-way shape memory, that is, the SMA will have one remembered shape in the high temperature phase and a second remembered shape in the low temperature phase. A detailed review of the mechanisms of two-way shape memory may be found in references [6,7,8]. However, some observations on two-way shape memory (TWSM) training are appropriate.

From a study of TWSM training routines, Perkins and Sponholz [6] reported some factors which contribute to the improvement of TWSM. Deformation beyond the strain limit of the sample in its initial training cycle was a requirement for TWSM. As a sample undergoes an increasing number of work cycles, some martensite structures may be retained in the sample even in the parent phase. This retained martensite does not now have to be induced in later training cycles and the training process becomes easier. Perkins and Sponholz [6] postulated that the retained martensite may serve as nucleation sites for the thermoelastic martensitic transformation discussed above. Through plastic deformation and retained martensite, the parent phase matrix may adjust so as to nucleate and grow a particular and preferential variant of martensite. This substructural adjustment becomes more refined as cycling continues.

Optimum training for TWSM displacements will be realized when an SMA, initially in the parent phase, is subjected to some plastic deformation during the first cycle which is followed by approximately 15 training cycles. The training cycle displacements should be at least 2 times greater than the TWSM cool temperature working displacement [6]. Specific TWSM training routines are given in [2 and 6].

III. EXPERIMENTAL APPARATUS

The SMA testing apparatus consisted of an electrical heating system, a fluid flow system, and a data acquisition and control system. Each of these systems will be described. Letters in parentheses refer to Figure 6, which is a schematic diagram of the SMA testing apparatus.

A. ELECTRICAL HEATING SYSTEM

An electrical system was built to heat the SMA coil sample, control the amount of heat applied to it, and measure the power consumed by the coil during heating. The SMA test coil was resistively heated as electrical current was passed through it. A 25 VDC variable power supply (A) was used as the current source. A precision 2 ohm resistor (B) was connected in series with the SMA coil. Using the measured voltage drop through the resistor (V_8), the current through the coil was calculated. A switch (C) was installed in the circuit for manual control of power to the coil. A 125 VDC, 1 amp relay (D) was installed to permit computer control of power to the coil. The SMA coil was connected in the electrical circuit by two 3/8 inch diameter, 1/8 inch thick copper discs (E). The coil leading ends (F) fitted into a centered hole in the discs and were anchored by set screws. The positive electrode was fixed to an L bracket (G) which was attached to the supporting structure. The negative electrode (H) remained free to travel with the recovering SMA coil. It was sandwiched between two insulating phenol discs, each 1/2 inch diameter and 1/16 inch thick. The return wire (I) emerged from the copper disc through the center of the second phenol disc.

Displacement of the SMA coil during actuation was determined through the use of a 10 turn linear potentiometer (J). A soft rubber, center grooved, grommet (K) was mounted to the potentiometer arm on a teflon disk. A wire string (L) ran from the negative electrode (H), over the potentiometer arm, to a plate (M) which carried loads applied during test runs. Voltage across the variable resistor (V_7) was measured by the data acquisition system as the potentiometer arm turned as the SMA recovered or reextended.

B. FLUID FLOW SYSTEM

A constant flow rate fluid system using water was constructed to provide cooling water to the SMA coil. The head tank (N) was fitted with an overflow (O) to the system reservoir to maintain a constant head, and thus, constant flow rate. An immersion heater (P) was installed in the head tank, supported by the tank top to preheat the water. A type T thermocouple was installed in the head tank near the flow exit of the tank (T6). A Fisher-Porter rotometer (Q) with a ball float was installed in the system between head tank and the SMA cooling chamber.

The SMA chamber (R) served as a mechanical support for the SMA coil and as the cooling chamber when water cooling was applied during test runs. A photograph of the SMA chamber is provided in Figure 7. Referring to Figure 6, type-T thermocouples were installed near the inlet (T1) and outlet (T2) of the chamber through holes in the tubing. Three type-T thermocouples were affixed to the SMA coil (T3, T4, T5) with small strips of heat-shrinkable tubing, and emerged from the chamber through a Swagelok fitting (S).

After passing through the SMA chamber, water flowed into the system reservoir (T). A small electric submersible pump (U), capable of 1/70 HP, was sufficient to maintain the head tank water level for the flow rates used in the investigation.

C. DATA ACQUISITION AND CONTROL

The data acquisition and control system was centered around an HP-9826 computer, an HP-3497A data acquisition system, and an HP-6942A multiprogrammer. A block diagram of the data acquisition and control system, as well as a data reduction flow chart, is provided in Figure 8. All computer programs written for the HP-9826 used the Basic programming language and are included in Appendix B. Programs written for data reduction using the IBM 3033 used Fortran and are included in Appendix C.

Program 'SMA' directed electrical system control and data acquisition. Sets of data were taken by the HP-3497A as directed by 'SMA'. Data accumulated in each set included coil position, coil current and voltage drop, and all thermocouple outputs. As indicated in Figure 8, the initial portion of 'SMA' was interactive, requiring operator input of the total number of samples, TT, for each test run and the interval between each sample set, t. The total time between sets of data, including data acquisition, the programming loop and the wait interval, was measured as 2.075 seconds by the HP-9826 internal clock.

Program 'SMA' directed electrical power to the coil by closing the relay installed in the electrical system (see Figure 6). This was accomplished through a relay card on the HP-6942A multiprogrammer. 'SMA' directed closing of the HP-6942A relay which, in turn, completed the required circuit to close the electrical system relay. With that relay closed, power was available to the test coil. Power to the coil was disconnected when 'SMA' directed the multiprogrammer to open its relay.

Program 'SMA' directed the HP-3497A data acquisition system to sample each of the nine system voltages every t seconds. The sampling time for each channel of the HP-3497A was 0.04 seconds, for a total sampling duration of 0.44 seconds. After sampling, the HP-3497A was directed to send the data to the HP-9826 for storage. The type-t thermocouple voltages were converted to temperature in degrees Celcius using the fourth order least squares coefficients given by Beckwith and Buck [10]. Potentiometer voltage, V_7, was converted into distance using the linear relation developed as a result of calibration of the potentiometer. Appendix D contains the calibration coefficients for this potentiometer. Current through the circuit was calculated using the voltage drop, V_8, across the precision 2 ohm resistor. Power to the coil was calculated using the voltage drop across the coil, V_9, multiplied by the calculated current. This data was written to a disk file by the HP-9826.

IV. EXPERIMENTAL PROCEDURE

The experimental procedure consisted of three basic steps: SMA sample preparation, SMA sample testing for response, and the measurement of temperature distributions along the sample.

A. SMA COIL PREPARATION

A SMA spring-like coil shape was chosen for testing because of the anticipated use of this shape in a robot arm. For use in the SMA chamber the coil was required to have a section of straight wire at both ends leading to the coil. The straight coil ends were required so that they would travel freely through the SMA chamber ends.

Raychem Corporation of Menlo Park, California, provided samples of 50 percent Ti-50 percent Ni wire of various diameters. Wire with a diameter of 0.53 mm (0.030 inch) was chosen for use because its malleability allowed for easy coil formation. Also, less power was required to heat wire of this diameter than larger diameter wire.

The Ti-Ni wire was locked into spring-like coils with straight sections at both ends by using a specially designed mandrel. The mandrel was a threaded rod, with special nuts used for locking the wire during the shaping process. The coil forming rod can be seen in Figure 9a. The rod formed a 1 inch long coil with 20 turns per inch and lead sections of 3.5 inches long at either end of the coil. Wire was wound on the rod as the rod was hand turned on a lathe. The coil was locked at both ends with the set nuts. The leading ends were strained to approximately 4% then locked in place at the end of the rod. Leads were pressed into grooves cut into the rod with plates as seen in Figure 9b. During the heat-treating process, the plates were clamped tight into the grooves to prevent recovery to the factory-induced shape of the Ti-Ni wire that existed as it was first heated.

To heat-treat the wire, the entire assembly was placed into a 320°C oven for 15 minutes. After removing the assembly from the oven the assembly was quenched in ice water.

After heat-treating the SMA coil leading ends were checked for the proper straight shape. The locking nuts on the end of the rod were removed and those at the end of the coil remained in place. The leads were bent out of the rod groove, then heated to review their recovery. If the leads did not recover a straight configuration that would slide through the SMA chamber end readily, the shaping process was repeated for the leads. With the coil still locked in place, the leads were further strained and then locked in. Heat-treating and shape checking were repeated as discussed. Satisfactory coils and leads were generally obtained after repeating the process two or three times.

B. SMA COIL EXTENSION, ACTUATION, AND DATA ACQUISITION

Tests were conducted with single-cycle and repeated-cycle runs. Single-cycle extension runs included extension of the SMA coil, actuation and recovery of the coil, and cooling. Repeated-cycle runs merely repeated this sequence more than one time during a sample run.

1. Single-Cycle Tests

The primary purpose of the single-cycle runs was to identify the maximum temperatures reached during SMA recovery and to compare coil rate of recovery at various current inputs. Work done by the coil was also of interest and was easily calculated from data taken during the single-cycle runs.

A single-cycle of a test run contained the following steps.

a. Apply the load. The desired load was placed on the load plate. The applied load varied from no load on the plate to 1.96 Newtons. The mass of the plate (refer to Figure 6) and wire string was 31 grams.

b. Extend the SMA coil. The coil was extended by the operator until the coil reached the end of the cooling chamber. Figure 6 shows the coil in its extended, deformed, position.

c. Set desired current. The desired current input was adjusted by the operator at the power supply.

d. Initiate computer control. For this phase of the tests a single step, constant current input heated the SMA sample. Program SMA (refer again to Figure 7) was configured to take two sample sets, then close the relay to apply power to the SMA coil. The relay was not opened by computer control until the final sample was taken.

e. Cut power-off. Power was manually cut off by the operator, using the installed switch, when the coil reached maximum recovery. Data acquisition continued whether power was applied to the coil or not. The total number of sample cycles for each run could be varied by interactive computer control, but generally, 100 samples of each parameter were taken. Sufficient data was obtained from the recovery phase and cool-down period.

2. <u>Multiple-Cycle Tests</u>

This phase of the testing involved a repetition of the single-cycle tests within the same run period. The most effective use of the multiple cycle tests occurred when no cooling water was present in the cooling chamber at the start of the run. The cycle was initiated as above, then when the actuator reached full recovery the operator cut off power to the system and initiated fluid flow through the chamber to cool the actuator. Once the actuator had cooled, as recognized by its reextension, coolant was cut off and power reinitiated to start the next recovery cycle. The cycle was repeated as often as possible during the run period. Once again, 100 sample sets was used as the total number of samples taken.

V. DATA REDUCTION

Data reduction included transferring data obtained during runs of the SMA testing system from floppy disk storage on the HP-9826 microcomputer to the IBM 3033 computer and then obtaining data listings or graphic output. Refer to Figure 8 during the following discussion. Programs written in the Basic programming language are included in Appendix B. Programs written in Fortran are included in Appendix C.

Transfer of data from floppy disk to the IBM 3033 was accomplished by two terminal programs. Program SEND_DATA utilized the Binary Enhancement Basic program available on the HP-9826 to communicate with the IBM 3033 via modem. This program read data files from disk and transmitted data, one number at a time, to the IBM 3033. Fortran program GRAB, run on the IBM 3033, received the transmitted data and wrote it to a disk data file for storage.

Program REARRANGE was then used to reorganized the data file from a single string of numbers to nine columns of numbers corresponding to the nine measured parameters of the SMA testing system. After rearranging, the data files were easily used as input to other data reducing programs.

Three programs were used for producing graphic output of the data. SMA3, LOGGRPH, and TEMGRPH were Fortran programs that used the Display Integrated Software System and Plotting

Language (DISSPLA), by Integrated Software Systems Corporation of San Diego, CA, resident on the IBM 3033. DISSPLA is a library of Fortran subroutines that can be used in Fortran source code to generate graphical output. Since DISSPLA is computer and device independent, programs developed in this work may be converted for use at other installations having DISSPLA.

Program SMA3 was written to present data from different test runs side by side (see Figure 10). Generally, for each run two data plots were presented. The first was a plot of temperatures along the SMA coil. It included T3, T4 and T5, and the cooling water temperature, or ambient temperature, T2, if water cooling was not used, as functions of time (Fig. 11a). The second was a plot of current, power, and SMA coil displacement as a function of time (Fig. 11b). These plots were used to identify the cooling period of each test run for further data reduction. Figures 12, 13, and 14 have been annotated to identify the cooling period which became the focus of further data reduction.

Since the SMA test system was a thermal system, and SMA coil displacement versus time curve was exponential in appearance, the system was considered to be a first order system. Output of this system was SMA coil displacement, in recovery or in reextension, according to the relation:

$$c(t) = 1 - e^{-t/T} \quad (t > 0)$$

where $c(t)$ = coil displacement divided by maximum displacement

T = the system time constant

t = time since zero

In order to verify that cooling of the SMA coil was, indeed, first order, and to compare water and air cooled coil performance, the coil time constant was calculated for each test run. The natural logarithm of normalized displacement during the cooling period was plotted as a function of time and the first order system time constant, T, was determined from such a plot as:

$$T = -1/\text{slope}$$

Fortran program POLYFIT was used at this point to determine a linear fit to the natural logarithm of normalized data during the cooling period. Displacement was normalized by dividing the displacement value at time t by the maximum displacement at recovery. In the cooling phase, then, normalized data would decrease from 1.0 to some value which is a percentage of the total possible recovery displacement. The percentage of possible reextension is one minus that value.

Data points were determined for each run using SMA3 graphs and the data listings from which they were generated. Figures 12b, 13b, and 14b, indicate that the coil did not immediately begin to reextend when power was cut-off. These represent coil recovery by stagnant air, natural convection to air, and water cooling, respectively. As can be seen from the corresponding temperature versus time graphs, the temperature decreased prior to reextension. With that in mind, the data files were examined to isolate the beginning and end of the coil reextension period. For RUN 81 and RUN 85, Figures 12 and 13, respectively, the cooling period included the remaining time of the run after power to the coil was turned off. In Figure 14 of RUN 194, and similarily in other test runs which used water cooling, the cooling period included only four data points. The final data point for inclusion in the linearity calculation was determined as the last data point to be 0.05 cm greater than the following point. At that point the SMA coil had nearly reached its limit of reextension determined by the load and the temperature of the cooling water. This data was fed into POLYFIT which normalized the displacement and then calculated the natural logarithm. POLYFIT then used these numbers to make a first order curve approximation to the data and output the coefficients of the curve fit:

$$\ln(X/X)_{max} = A_1 + A_2 t$$

where A_1 = the y intercept

A_2 = the slope of the curve and is equal to 1/T

X = the displacement

t = the time

POLYFIT also output a set of data points which corresponds to the curve fit described above.

Program LOGGRPH was used to compare POLYFIT output for different SMA test system runs. LOGGRPH used the raw log normalized data and the curve fit data developed in POLYFIT to produce graphic output of the type seen in Figure 15. The linear nature of these curves confirms that the SMA test system is a first order system [11]. And from the curves, the time constants of the system under different cooling conditions were easily compared.

Program TEMGRPH was written to examine the recovery or reextension displacement of the SMA coil as a function of the coil temperature. The temperature dependence of coil recovery and reextension displacement is a characteristic that must be used in the development of feedback control of future SMA systems. Figure 18 is a displacement-temperature graph produced by TEMGRPH.

VI. RESULTS

The results of this investigation into different methods of cooling the SMA coil after coil recovery can best be seen graphically in Figures 10, 11, 15 and 19. A description of these figures and some additional observations follow.

A. SMA COIL IMMERSED IN WATER

Electrical heating of the SMA coil immersed in water produced no coil recovery. Figures 10 and 11 represent data obtained from two SMA test runs in which the coil was immersed in stagnant water during the entire time of the run. During RUN 82 shown on Figures 10a and 10b, 6 watts of electrical power at 2 amperes was applied for 200 seconds. The water temperature was initially at the room temperature of 22.8^{o}C and rose to 27.3^{o}C by the end of the run. During RUN 138 shown on Figures 11a and 11b, 2.5 watts of power at 1.25 amps was applied for 200 seconds. The water in the chamber had been preheated to 45^{o}C and rose to 47^{o}C during the run. In each case, it can be seen that no coil recovery displacement resulted from the electrical heating. Due to the large amount of heat transferred from a coil to a surrounding liquid, it was not possible to actuate an SMA coil immersed in water. The technique employed in later experiments was to initially heat the coil with only air present in the chamber. Water was then added to quickly cool the coil causing it to revert to its original shape. This technique dramatically increased SMA coil cycle time.

B. SMA COIL COOLED UNDER THREE CONDITIONS

Data was compiled as described in the experimental procedure using three different cooling conditions for the SMA coil. The primary goal of the data reduction was to determine the coil cooling time constant, T, for the SMA coil as it is cooled in the chamber with no coolant, by natural air convection, and by water cooling. This time constant reflects the displacement of the coil with respect to time. Figure 15 is a plot of the natural logarithm of the normalized coil reextension displacement versus time for three test runs, each of which used one of the three cooling conditions. For each run the applied load on the SMA coil was 1.3 N. The time constant for each cooling configuration can be read from the graph. For the three runs shown, the time constant of the chamber-cooled SMA system with stagnant air as the coolant was 25 times as long as the water cooled SMA system. The time constant for the natural convection air-cooled system was 15 times as long as that for the water-cooled system.

Figure 17 shows time constant data for some additional SMA test system runs conducted with various cooling conditions and various loads. A comparison of time constants for RUN 196

(Figure 17) and RUN 85 (Figure 15), both cooled by natural air convection, and the SMA coil loaded with 1.3 N, shows a difference of 66 seconds between the two. A primary factor in this difference may be the ambient temperature at the time of the run. From Figure 16, it can be seen that the ambient temperature at the time of RUN 196 was 27 C, whereas during RUN 85 the ambient temperature was 22 C. Also from Figure 16, it can be seen that the time constant of the water-cooled system load with 2.0 N, RUN 191, was 2.2 times larger than the time constant for a water-cooled system loaded with only 0.8 N.

In general, the time constant of a water-cooled SMA system was 15 to 25 times faster than a natural air cooled system and 20 to 30 times as fast a closed-chamber system.

It can be seen from Figures 12 and 14 that reextension of the SMA coil did not begin immediately when power was turned off. Note the constant displacement ledge in each figure. Reextension began only when the temperature at the midsection of the coil decreased below 60 C. Also, in Figure 13, where the coil did not reach such high temperatures, reextension still did not begin immediately but accompanied a decrease in temperature below 50 C. However, the delay in this case was much less. By examining the heating portion of the temperature and displacement versus time graphs of Figures 12, 13, and 14 it can be seen that the rate of work output from the coil decreased dramatically after the coil reached approximately 50 C. This could be expected as a characteristic of this first order system and, also, it corresponded to the approximate austenite finish temperature referred to in the discussion on the material aspects of SMA's. The delay in reextension after recovery is indication that the M_d for this SMA (refer to Fig. 2) was in the 55-60 C temperature range. By plotting displacement as a function of temperature, as in Figure 18, it can be seen that very little displacement per degree was yielded when the coil temperature was above 45 C. This was true for both recovery or reextension.

VII. CONCLUSION

This work has involved the construction of a system for testing SMA actuators under different loads, different actuating electrical current, and different cooling conditions after actuation. Computer control of the SMA testing system and data acquisition system was implemented. Experimentation proved that a SMA system equipped with water cooling provided an actuator cycle time 15 to 30 times faster than a natural air-cooled system or a stagnant air-cooled system.

Recommendations for further study are numerous, and included three major areas of SMA use and control. The first area for study is that of the alloys themselves. For most applications, specific knowledge may be required of the alloy transformation temperature range, the maximum reversion stress, and other alloy characteristics. This information was not available from the alloy manufacturer at the outset of this investigation but could be obtained in local laboratory testing. Also, a more thorough knowledge of two-way shape memory training and strengthening routines is needed to efficienctly use SMA actuators. This is required since one-way shape memory induced devices gain two-way shape memory after only a few cycles.

The second area of continuing work would involve adaptation and expansion of the computer control portion of the

SMA testing system for additional modes of control. Current input frequency, step size, and signal types such as a ramp input, may be used to vary the heating of the SMA and, consequently, the performance of the actuator. Computer control of the system using temperature feedback should be tried to prevent overheating of the coil and obtain maximum work output for a given electrical power input.

Finally, the efficiency of the mechanical structures of the testing system should be improved. A more precise potentiometer should be installed. Different actuator shapes and combinations of actuators should be tried. For example, a cluster of small diameter SMA wires may have the same load capacity as one wire of larger diameter, but the cluster will have a time constant many times faster than the single wire [12]. In that case, water cooling or forced air convective cooling is an appropriate consideration for cooling in the system. Study of forced air convection cooling compared to water-cooling and to natural air-cooling should be investigated.

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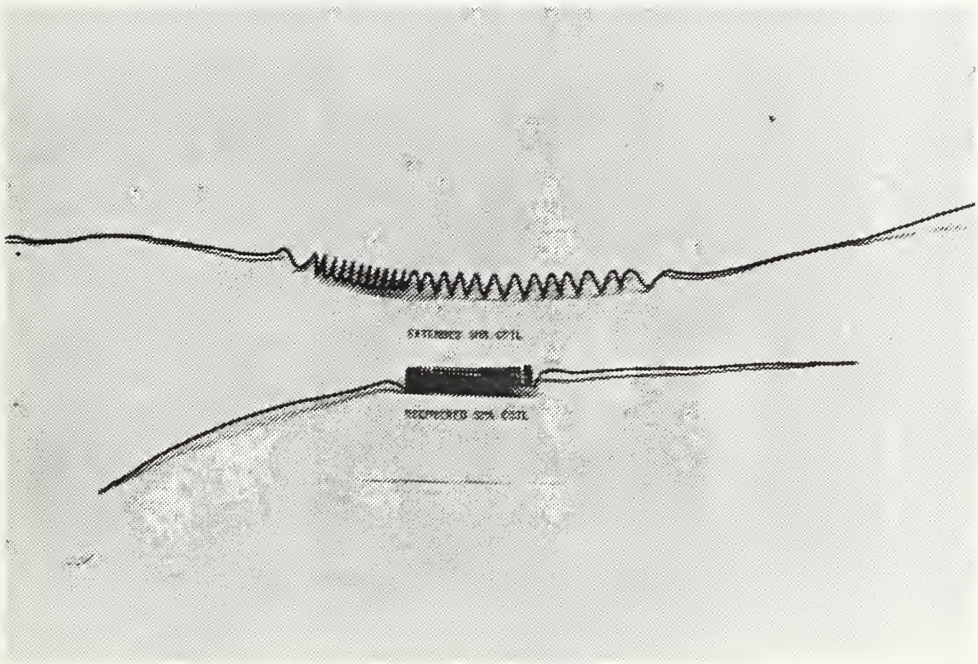


Figure 1. Shape Memory Behavior. A SMA Coil Deformed Will Recover Its Original Shape When Heated

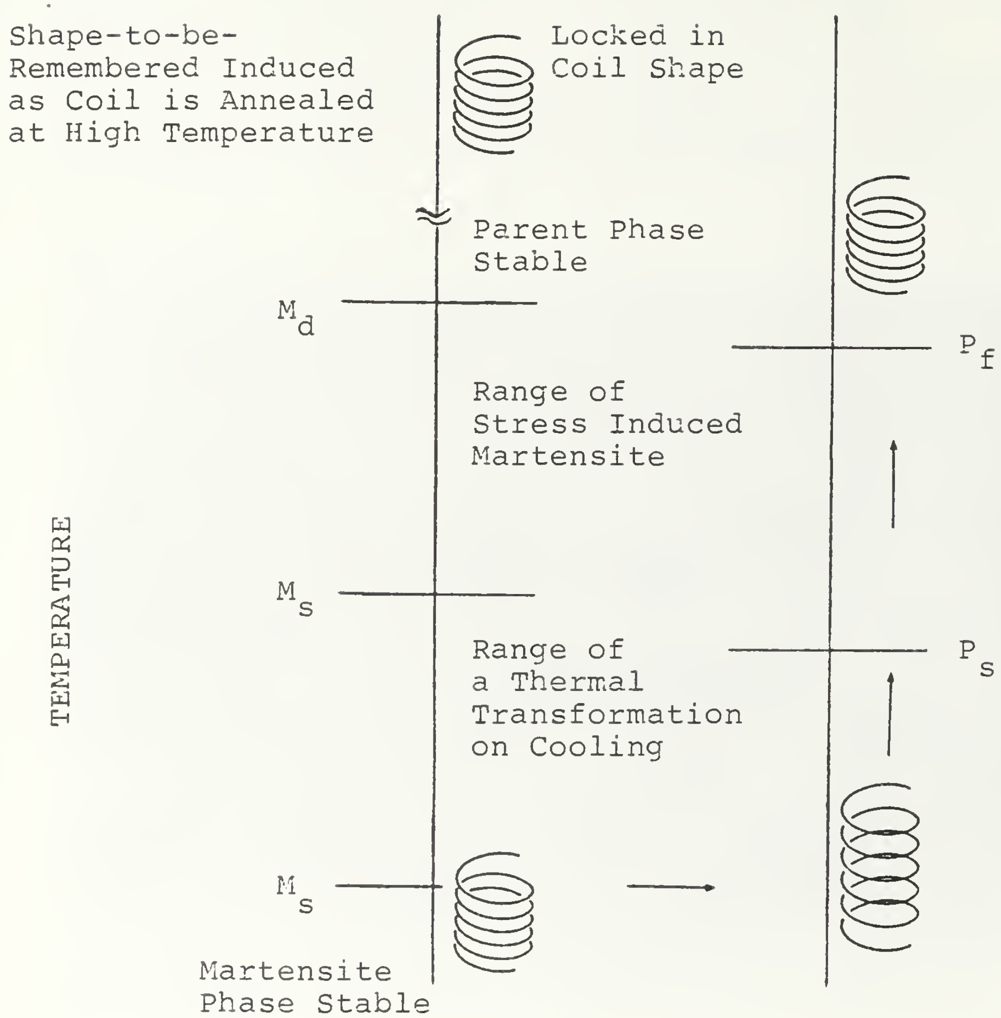


Figure 2. A Schematic Description of the Shape Memory Effect (Adapted from Perkins [2])

Figure 3. A Transmission Electron Microscopy Photomicrograph of Internally Twinned Martensite Plates (Reprinted with permission [2])

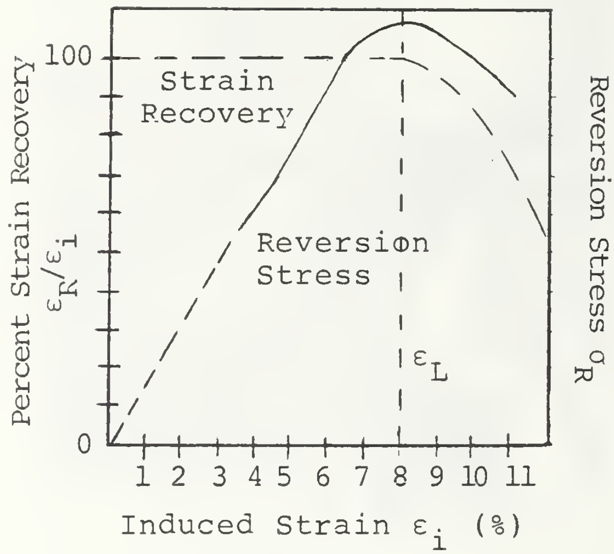


Figure 4. Percent Strain Recovery and Reversion Stress as a Function of Induced Strain (Adapted from [2])

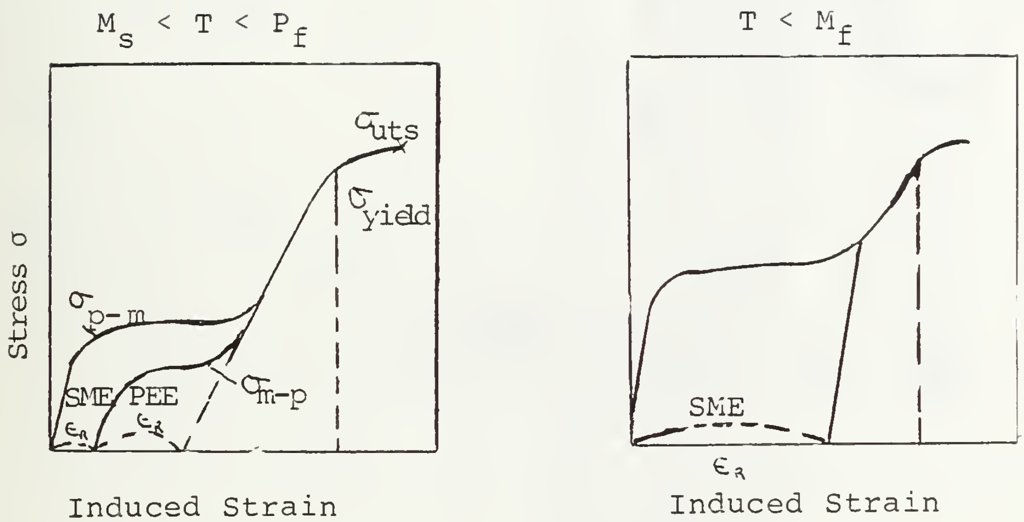


Figure 5. Schematic Stress-Strain Curves for a Shape Memory Alloy at Two Different Temperatures (Adapted from [2])

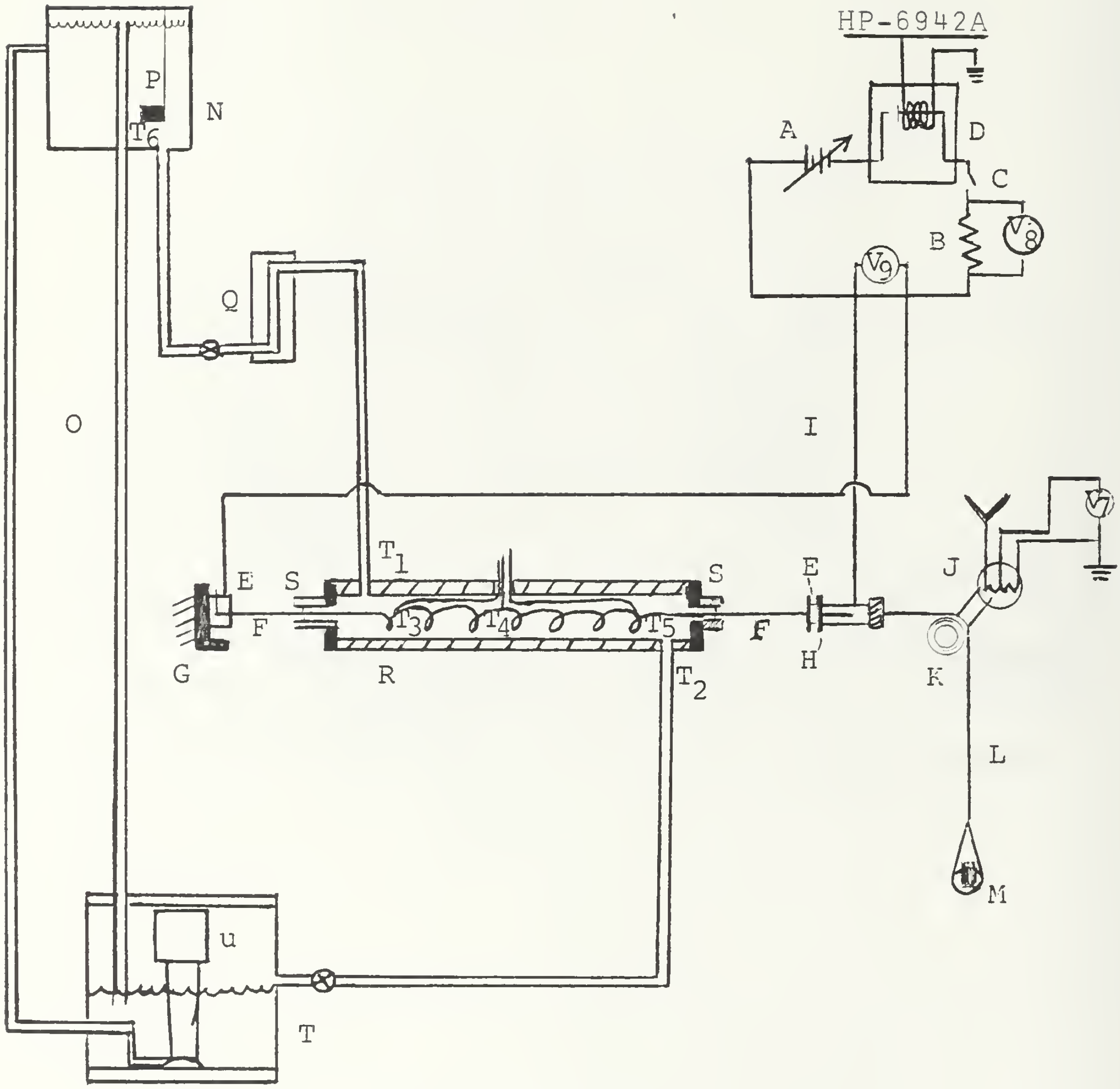


Figure 6. Schematic Diagram of SMA Testing Apparatus

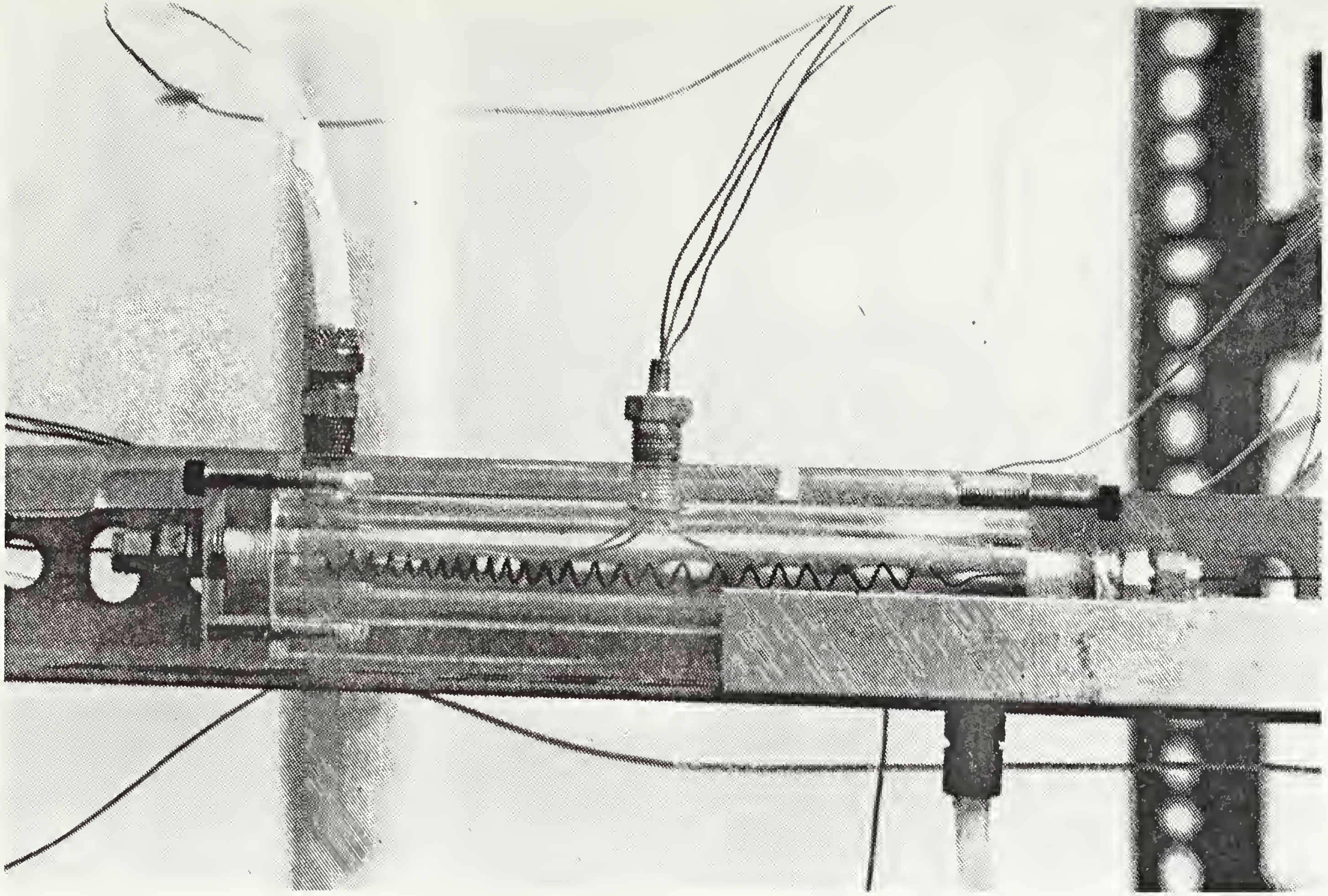


Figure 7. SMA Cooling Chamber

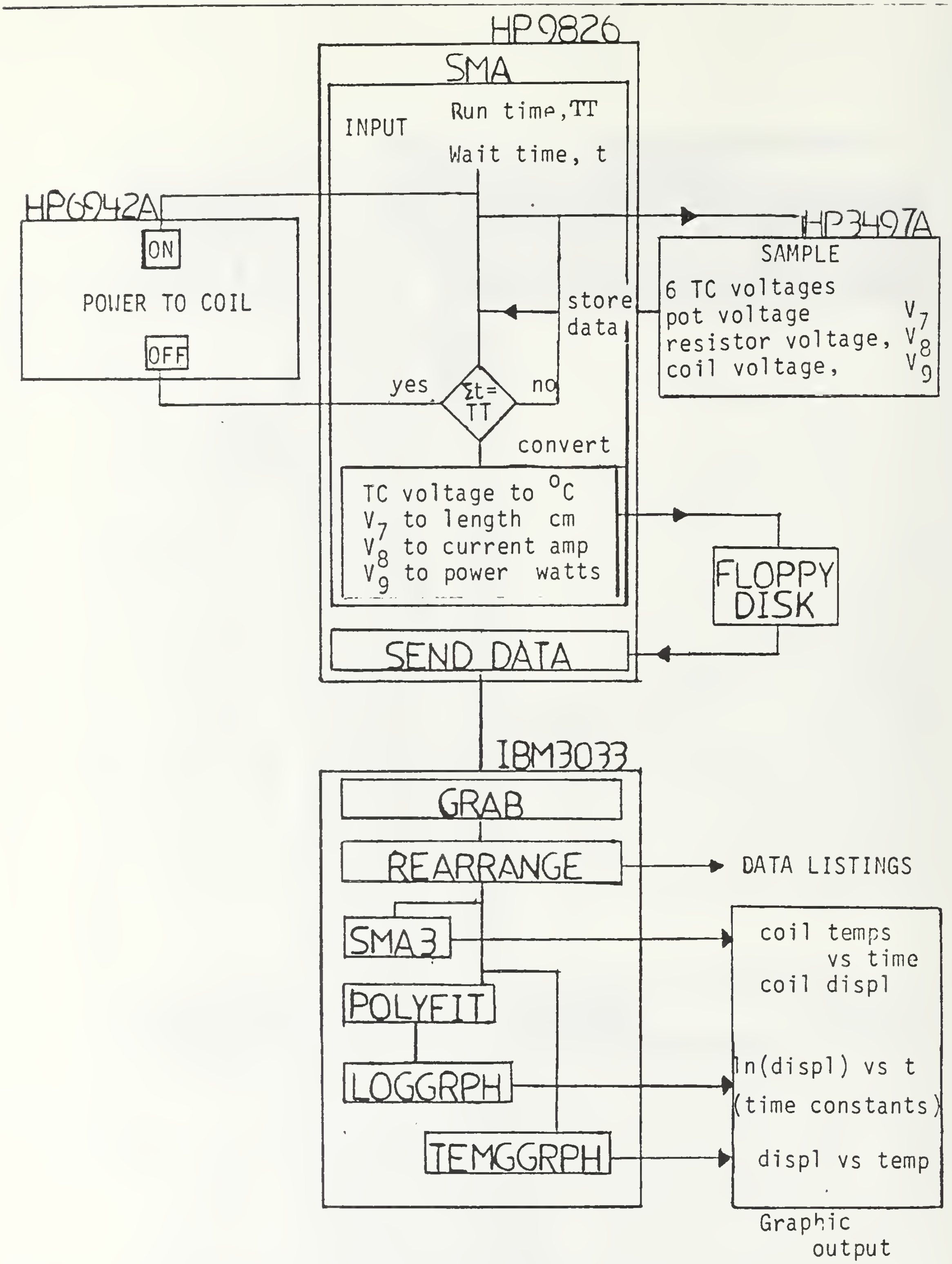


Figure 8. Block Diagram of SMA Data Acquisition and Control System with Data Reduction Process

(a)

(b)

Figure 9. SMA Coil Form Shape Locking Rod

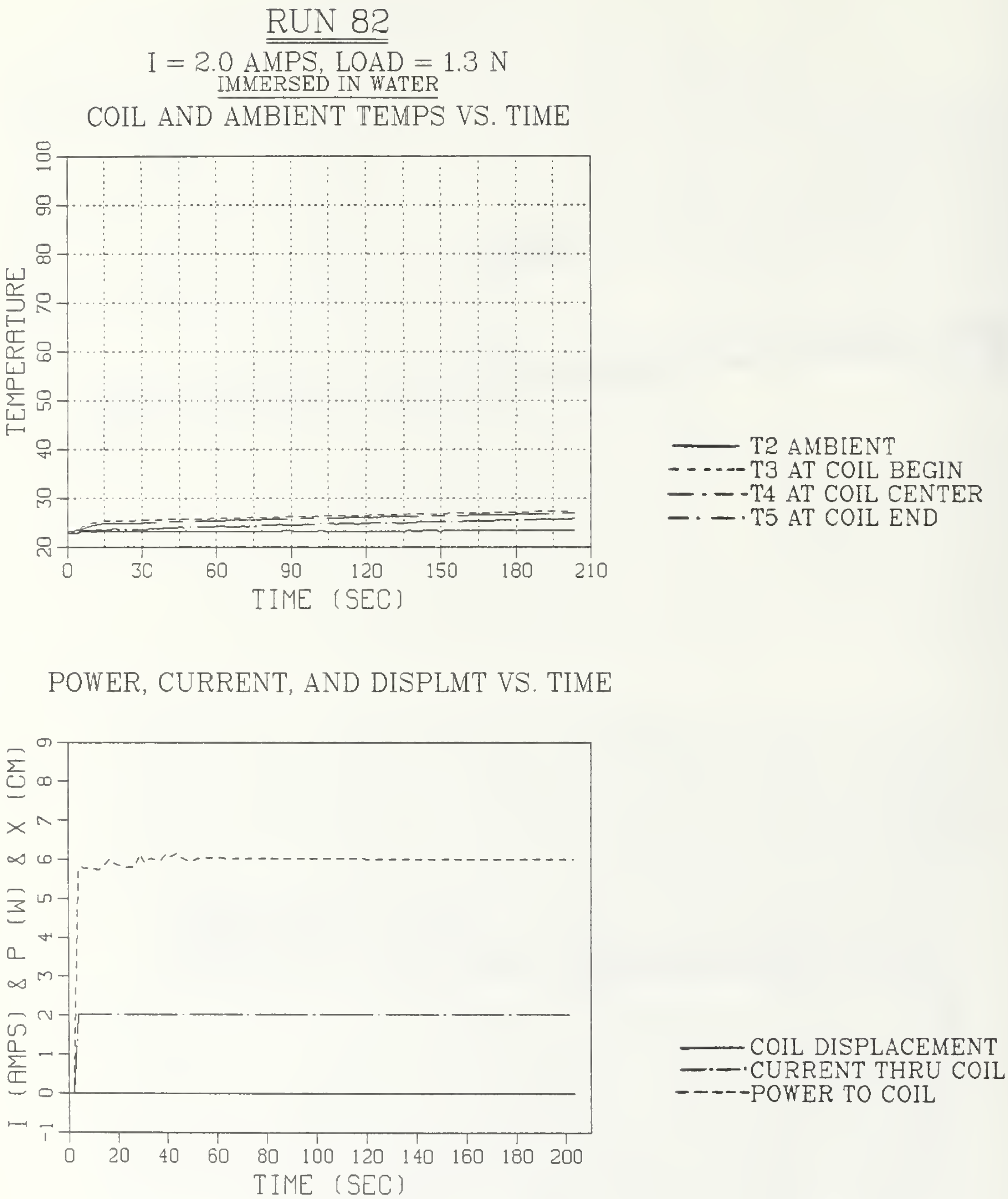


Figure 10. SMA Coil Temperature and Coil Displacement as Functions Run Time for RUN 82

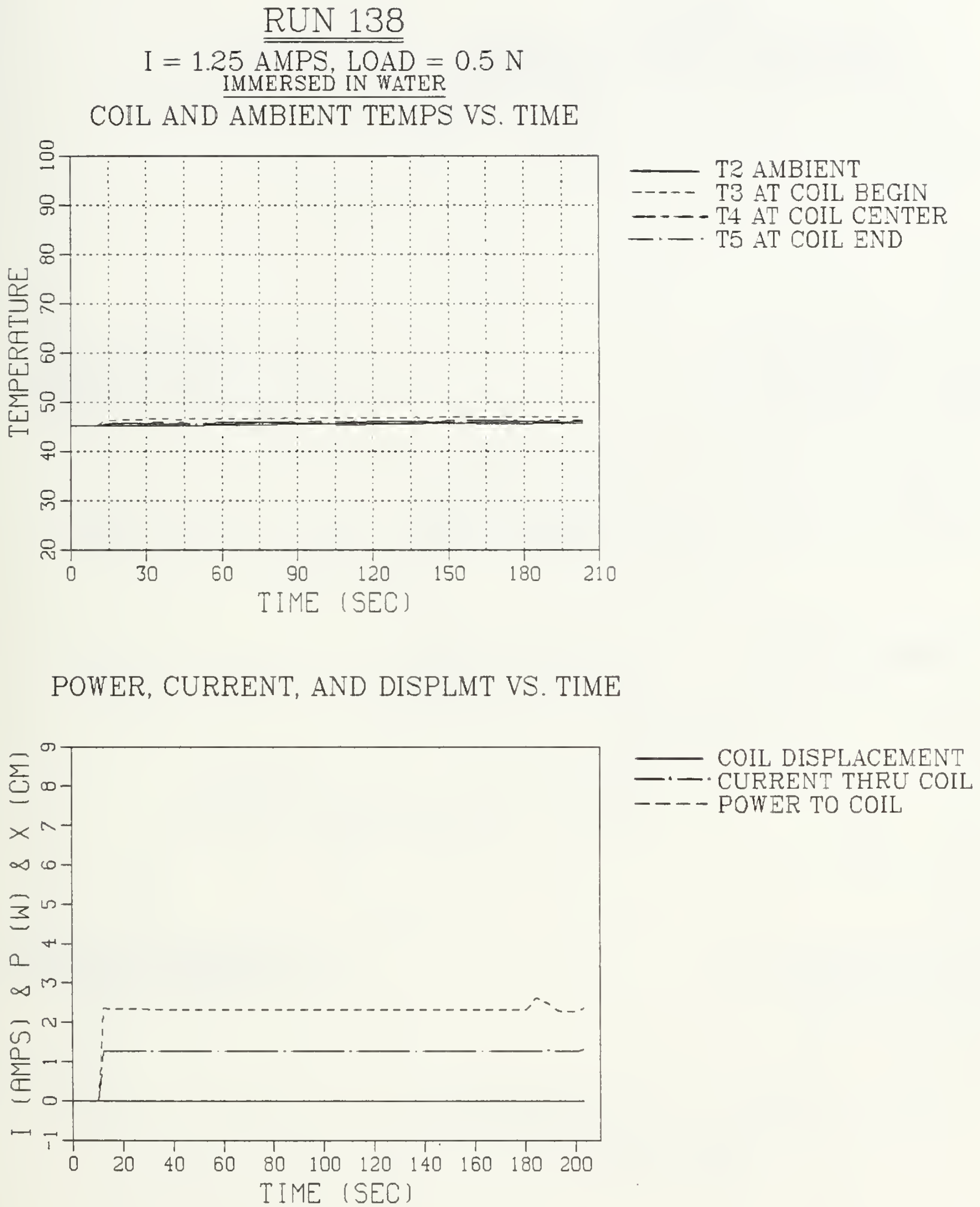
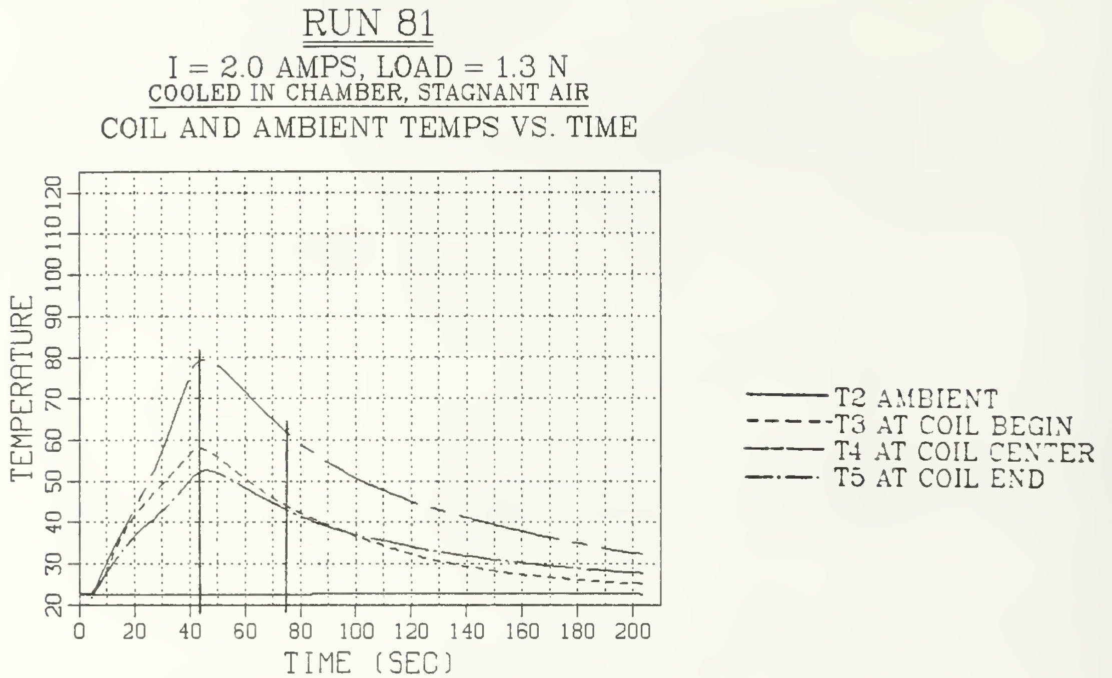


Figure 11. SMA Coil Temperature and Coil Displacement as Functions of Time for RUN 138



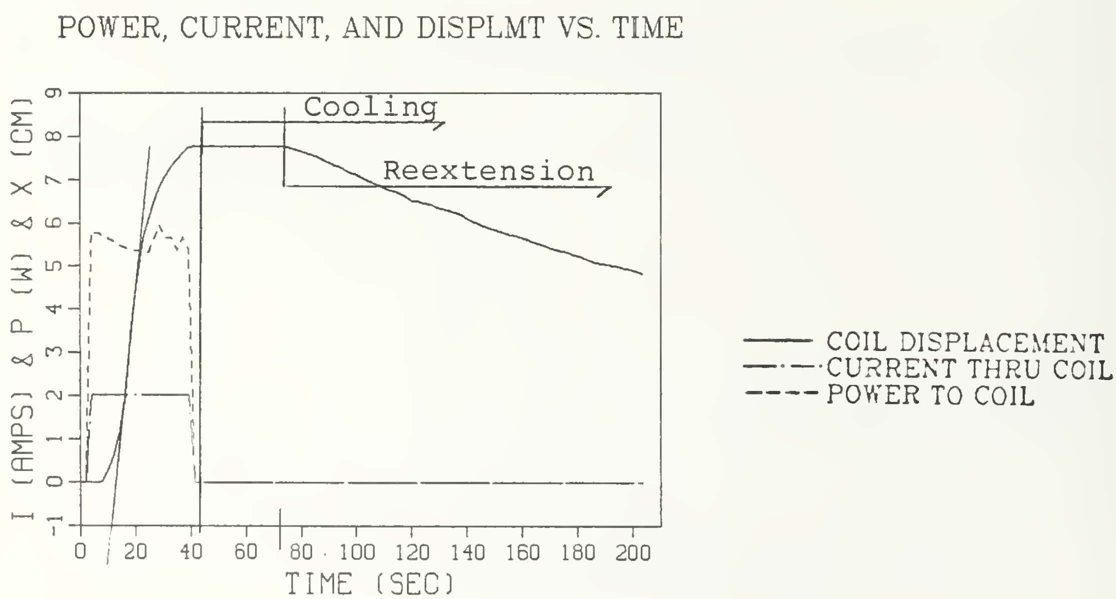


Figure 12. SMA Coil Temperature and Coil Displacement as Functions of Time for RUN 81

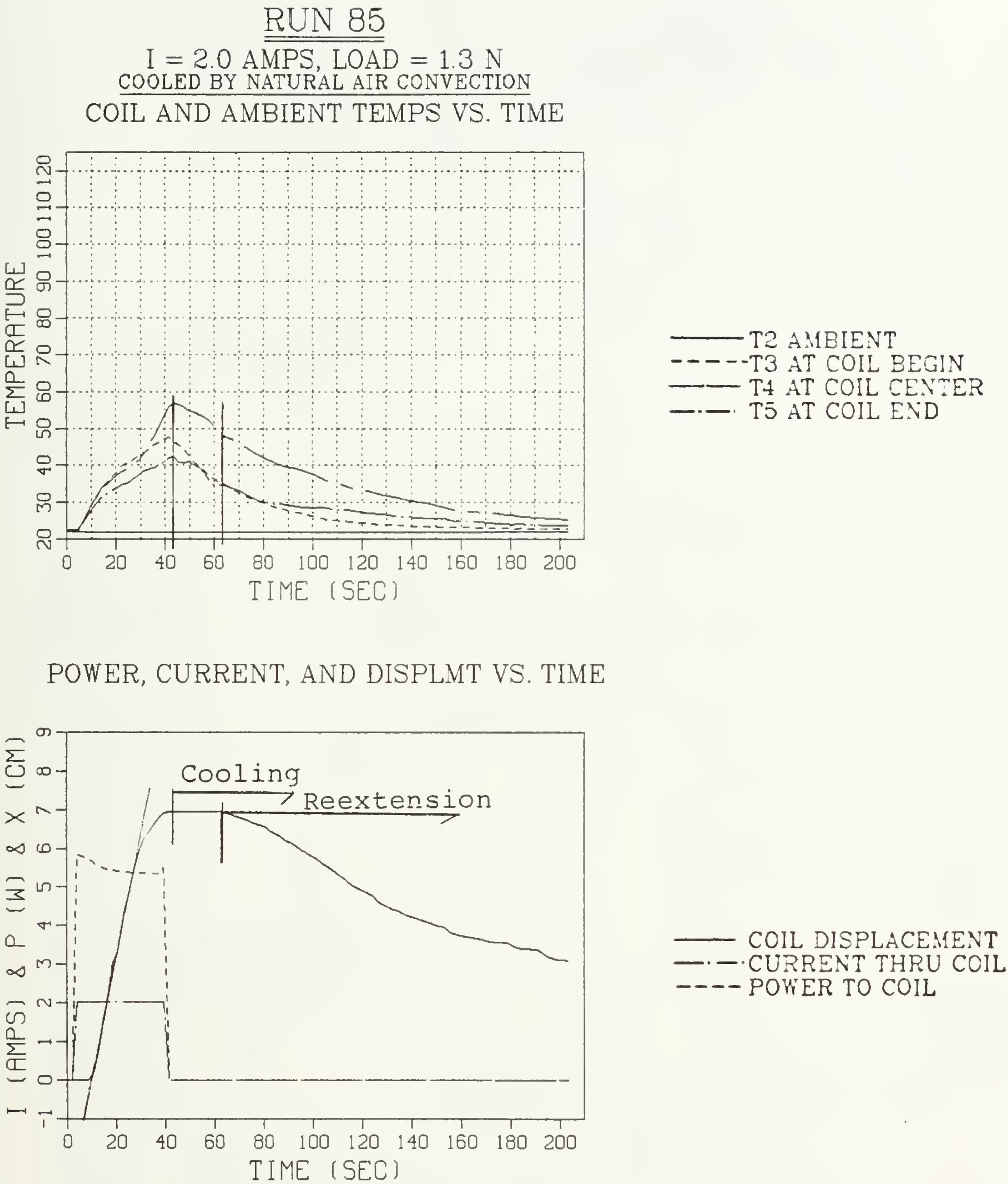


Figure 13. SMA Coil Temperature and Coil Displacement as Functions of Time for Run 85

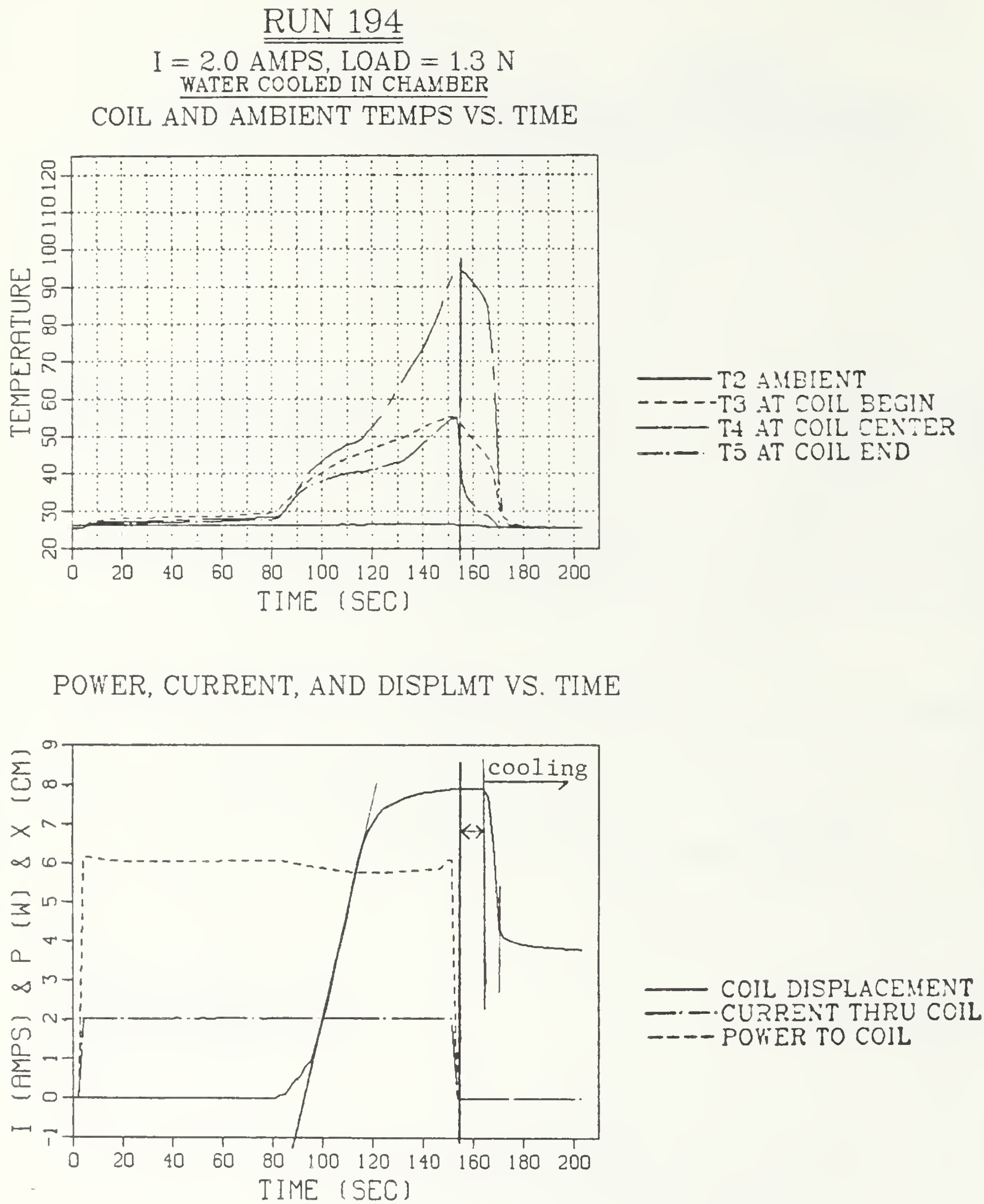


Figure 14. SMA Coil Temperature and Coil Displacement as Functions of Time for RUN 194

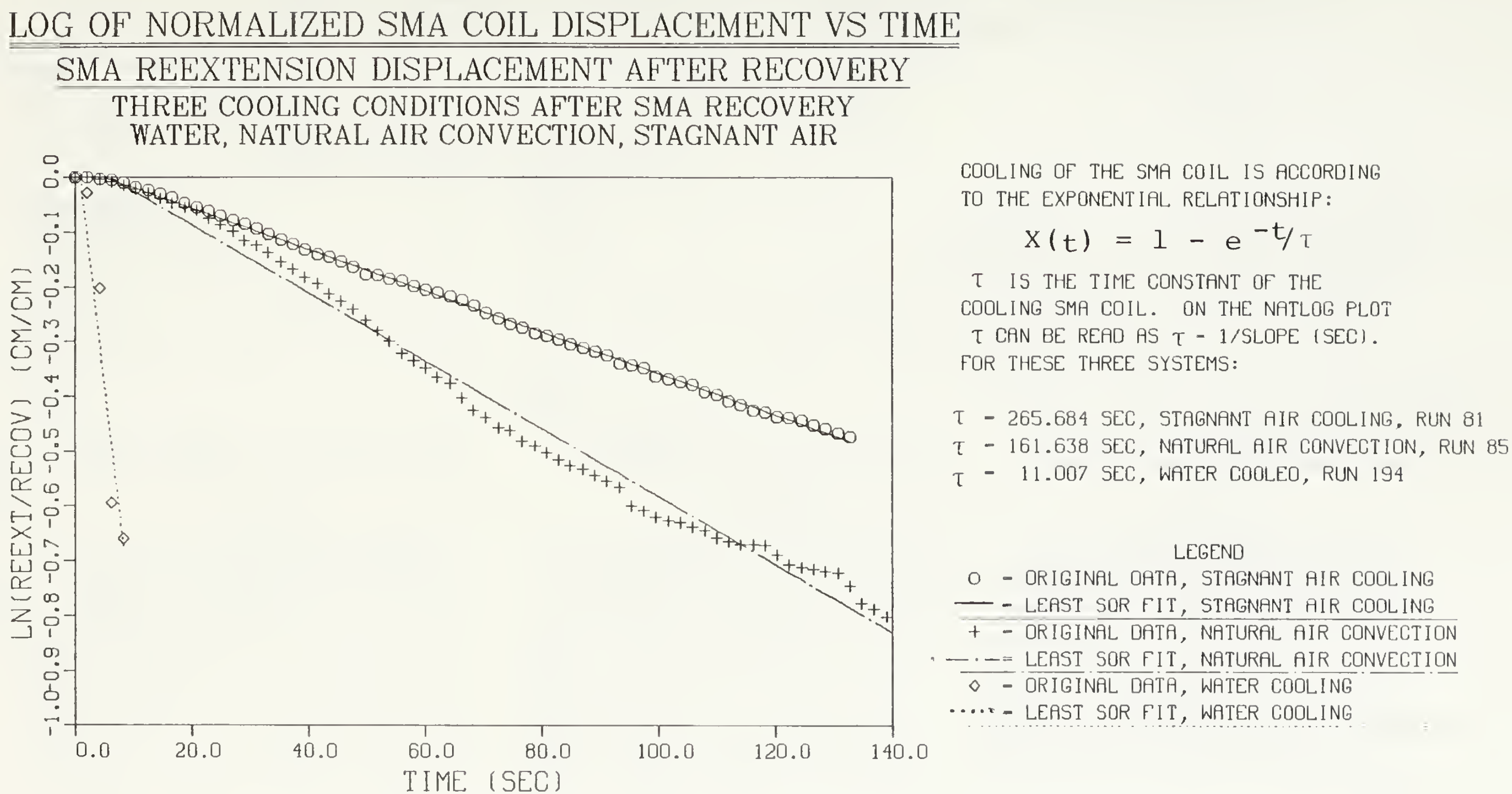


Figure 15. Natural Logarithm of the Normalized SMA Coil Reextension Displacement Using Chamber Cooling, Natural Air Convection Cooling, and Water Cooling

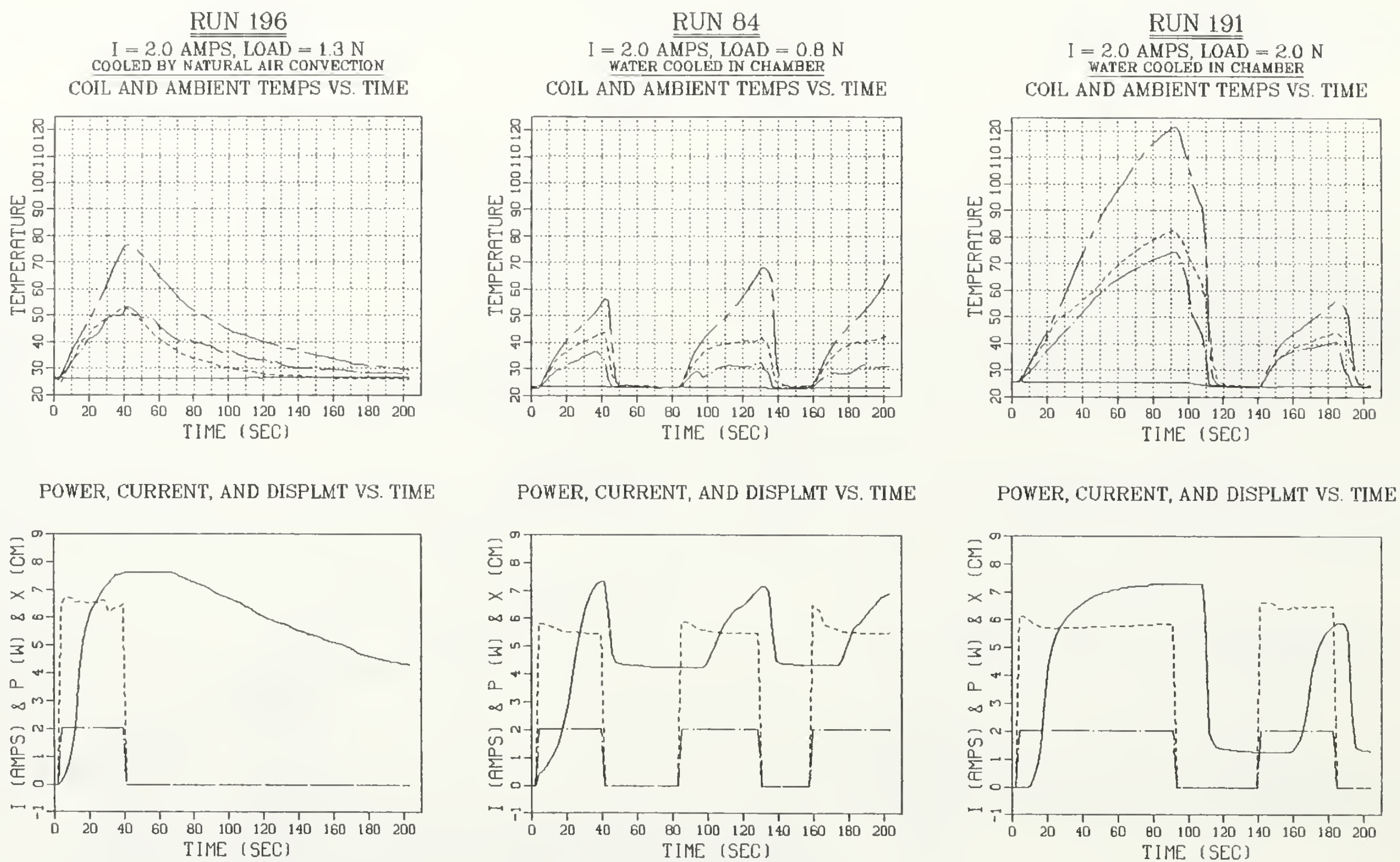


Figure 16. SMA Coil Temperature and Coil Displacement as Functions of Time for RUN 196, RUN 84, and RUN 191

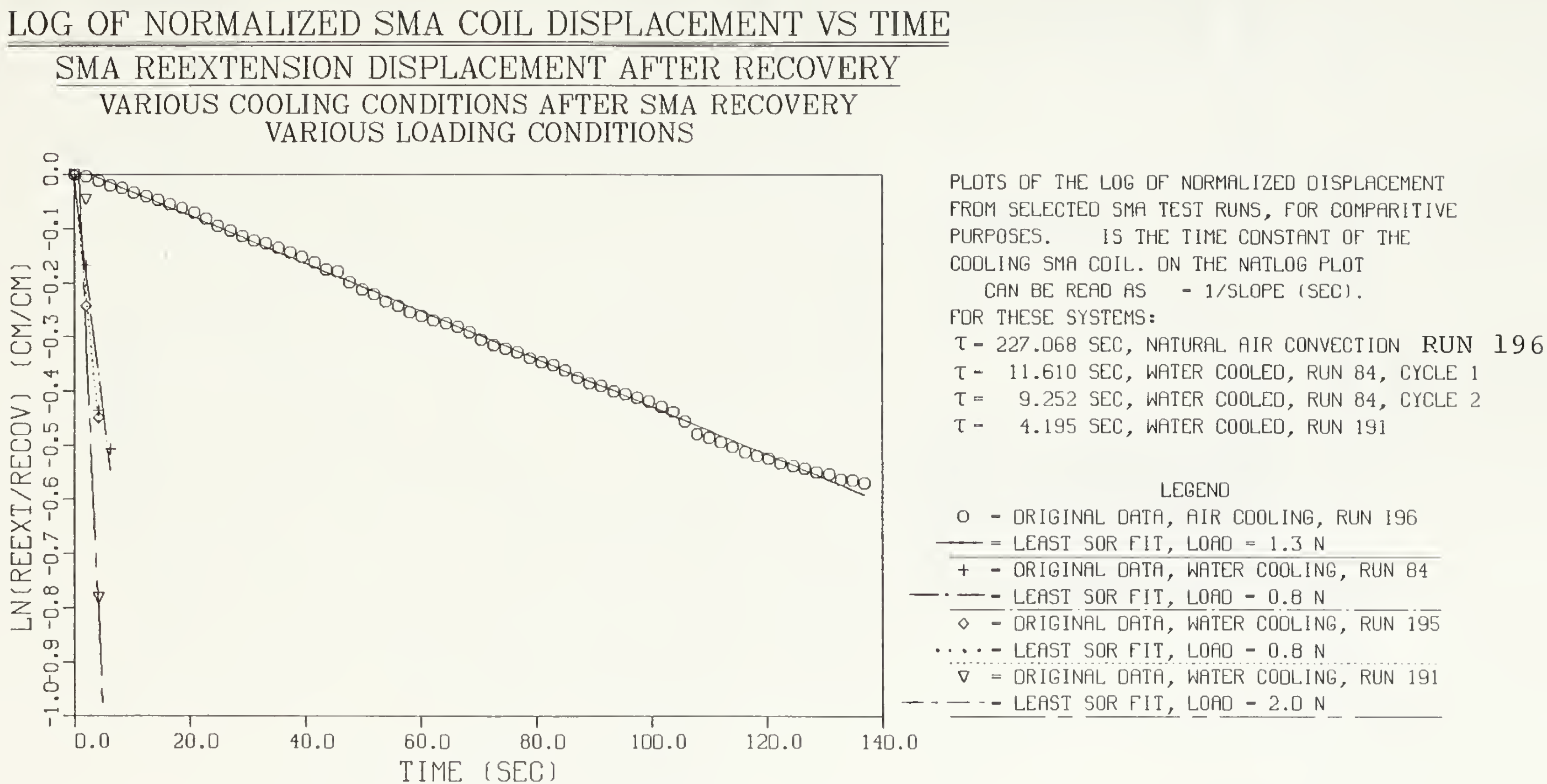


Figure 17. Natural Logarithm of the Normalized SMA Coil Reextension Displacement for Various Cooling and Loading Conditions

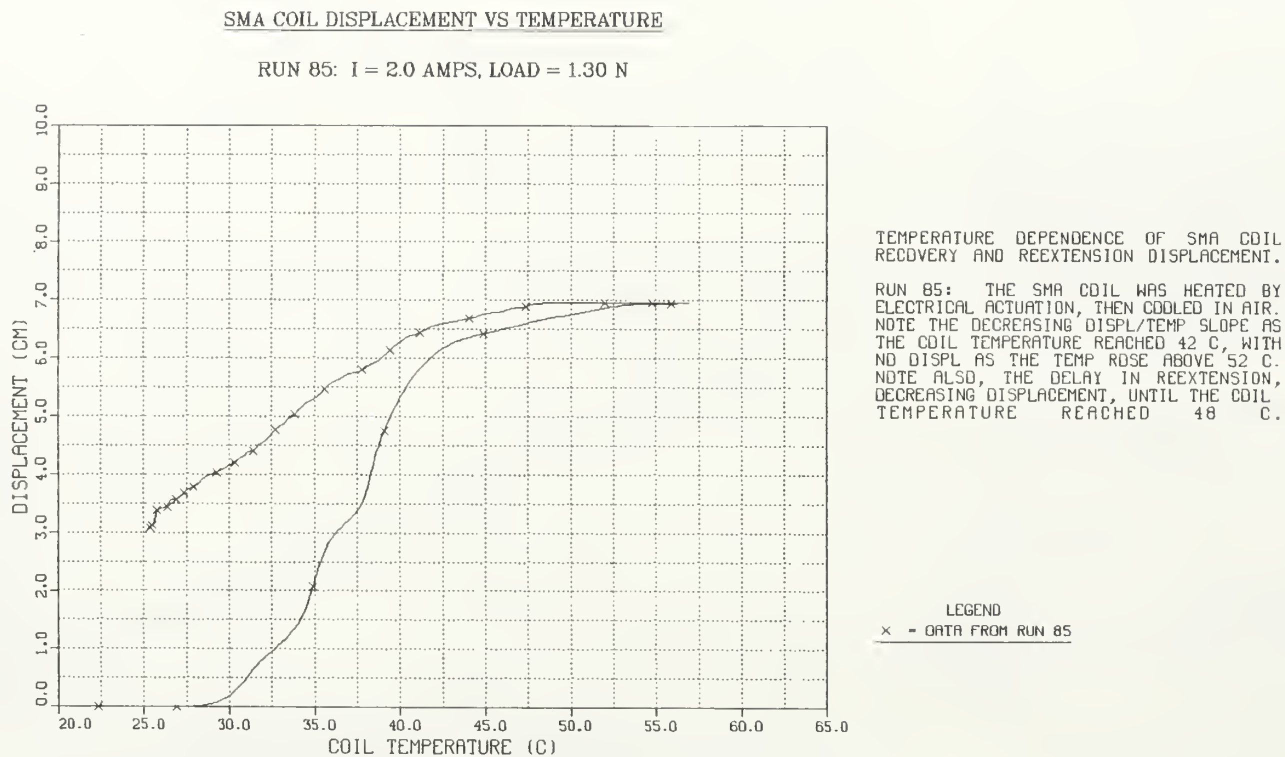


Figure 18. SMA Coil Displacement as a Function of Temperature

APPENDIX A

SMA TEST SYSTEM UNCERTAINTIES

1. Thermocouples: ± $0.023^{\circ}C$

2. Current: = 0.005 AMPS

3. Voltage: ± 1×10^{-6} V

4. Time: ± 1×10^{-3} sec

5. Position: ± 5.0%

6. Load: ± 0.10 Newtons

APPENDIX B

BASIC LANGUAGE PROGRAMS USED ON THE HP 9826 COMPUTER

```
10    !Program_sma
20    !
30    !     GOALS:  1.  READ NEARLY SIMULTANEOUSLY
40    !                  a. 6 THERMOCOUPLES
50    !                  b. 1 POTENTIOMETER
60    !                  c. CURRENT (DELTA V)
70    !                  d. VOLTAGE
80    !
90    !               2.  STORE DATA IN ARRAYS
100   !
110   !               3.  CORRECT FOR TYPE T-C BIAS
120   !
130   !BEGIN HP 9826 PROGRAM
140   !
150   OPTION BASE 1
160   DIM Data(900,9)
170   PRINTER IS 1
180   !
190   PRINT "time between samples?  (sec)"
200   INPUT Delta_t
210   !
220   PRINT "File to dump data to?"
230   INPUT File_name$
240   CREATE BDAT File_name$,50
250   ASSIGN @File TO File_name$
260   !
270   !
280   PRINT "Number of sample sets?"
290   INPUT I_finish
300   PRINT "NOMINAL INITIAL CURRENT IS?"
310   INPUT I_v
320   PRINT "HEATING APPLIED (0=NO, YES,ENTER TEMP)"
330   INPUT Ht
340   PRINT "FLOW RATE IS?"
350   INPUT Fr
360   PRINT "LOAD CONDITION?  (MASS ADDED TO PLATE)"
370   INPUT Load$
371   PRINT "MAX EXTENSION AT THIS TEMP?"
372   INPUT Max_ext
380   PRINTER IS 701
390   PRINT "     SAMPLE NO. 1"
400   PRINT "     RUN NUMBER   ";File_name$,
410   PRINT "     INITIAL CURRENT =";I_v,"AMPS"
420   PRINT "     HEATING CONDITION ";Ht,"C"
430   PRINT "     FLOW RATE = ";Fr,"ml/sec"
440   PRINT "     LOAD CONDITION IS  ";Load$,"GRAMS"
450   PRINT "     NO. OF SAMPLE SETS =";I_finish
460   PRINT "     TIME BETWEEN SAMPLES =";Delta_t,"SECS"
461   PRINT "     MAX EXT OF WIRE AT THIS TEMP = ";Max_ext,"cm"
470   PRINTER IS 1
480   !
490   !
500 Loop:      ! A.  Data Acquisition.
510            !
520            K=K+1
530            BEEP
540            IF K=3 THEN
550            BEEP
560            OUTPUT 723;"OB,1,15,1T"
570            END IF
580            PRINT "Now working on loop ";K
590            !
```

```
600            ! B.  Sample all thermocouples.
610            !
620            FOR J=1 TO 9
630                OUTPUT 709;"AI";J
640                ENTER 709;Data(K,J)
650                    PRINT "CH";J,"=";Data(K,J)
660            NEXT J
670                !
680                WAIT Delta_t  !pause dt secs
690                !
700 IF K<I_finish THEN GOTO Loop
710 OUTPUT 723;"OB,1,15,0T"
720 !
730 !   C.  Convert to engineering units
740 !
750 !     1.  Read chnl 18-bias for Type E T-C
760 !     2.  Read chnl 19-terminal temp(convert to celsius)
770 !
780 OUTPUT 709;"AI18VT1"
790 ENTER 709;Bias_voltage
800 Bias_voltage=Bias_voltage*1000
810 PRINT "BIAS VOLTAGE =";Bias_voltage,"mV"
820 !
830 OUTPUT 709;"AI19Vt1"
840 ENTER 709;V_terminal
850 PRINT "V TERMINAL";V_terminal
860     Emf=V_terminal      !(V)
870     !
880     !Convert Emf to temperature (C) for type E TC.
890     !
900     V=Emf*1000.      !(mV)
910     PRINT "V=";V,"mV"
920     T=1.7022525E+1*V-2.2097240E-1*V*V+5.4809314E-3*V`3-5.7669892E-5*V`4.0
  !(C)
930     PRINT "T Terminal =";T,"(C)"
940     !
950     !  3. Convert Type-T TC voltage to temperature (C).
960     !
970     !   a.  Find the Emf(mV) corresponding to a given temperature.
980     !
990     Emf=3.8740773840E+1*T+3.3190198092E-2*T^2+2.0714183645E-4*T`3-2.19458348
23E-6*T´4.
1000    Emf=Emf+1.1031900550E-8*T^5-3.0927581898E-11*T^6+4.5653337165E-14*T 7.
1010    Emf=Emf-2.7616878040E-17*T^8.
1020    Emf=Emf*.001
1030    !
1040    !   a.  Find the EMF for a Type-T TC for the terminal strip temperature.
1050    !
1060    Emf_correct=Emf
1070    !
1080    FOR K=1 TO I_finish
1090      FOR J=1 TO 6
1100        Emf=Emf_correct+Data(K,J)*1000.-Bias_voltage
1110    !
1120    !Convert Emf(V) to temperature(C) for type T TC.
1130    !
1140        V=Emf
1150        T=2.5661297E+1*V-6.1954869E-1*V*V+2.2181644E-2*V`3-3.550090E-4*V 4.
```

```
1160        Data(K,J)=T
1170      NEXT J
1180    NEXT K
1190!
1200!   4. Correct remaining lines for Type-E TC bias.
1210 !SET FLAG FOR VOLTS FROM POT (J=7)  TO X DISTANCE
1220 Flag=0
1230!
1240    FOR K=1 TO I_finish
1250        FOR J=7 TO 9
1260            Data(K,J)=Data(K,J)-Bias_voltage/1000
1270            IF J=7 THEN
1280            Data(K,J)=3.022260*Data(K,J)+.00227  !VOLTAGE TO DISTANCE
1290            IF Flag=0 THEN
1300            Initial_x=Data(1,7)
1310            END IF
1320            Flag=1
1330            Data(K,J)=(Data(K,J)-Initial_x)*2.54  !X IN CENTIMETERS
1340            END IF
1350            IF J=8 THEN
1360            Data(K,J)=Data(K,J)/2.  !I=V/R R=2OHMS .
1370            END IF
1380            IF J=9 THEN
1390            Data(K,J)=Data(K,J)*Data(K,8) !P=V*I
1400            END IF
1410        NEXT J
1420    NEXT K
1430!
1440!
1450!  C.  Now print out all the data and write to disk.
1460!PRINTER IS 701
1470!
1480 !PRINT   !SPACE LINE
1490!
1500 FOR K=1 TO I_finish
1510    PRINTER IS 1
1520    PRINT "LOOP";K
1530    FOR J=1 TO 9
1540        OUTPUT @File;Data(K,J)
1550        PRINT "CH";J,"=";Data(K,J)
1560    NEXT J
1570 NEXT K
1580 PRINTER IS 701
1590 PRINT "     FLUID TEMP AT START IS = ";Data(1,6),"C"
1600 PRINT "     FLUID TEMP AT END IS = ";Data(I_finish,6),"C"
1610 PRINT
1620 ASSIGN @File TO File_name$   !close the file descriptor.
1630 !
1640 !
1650 PRINTER IS 1
1660 BEEP
1670 PRINT File_name$;" is written and closed."
1680 END
```

```
10      !       PROGRAM "SEND_DATA"
20      !
30      !    To VAX,IBM,TRS-80.
40      !
50      !  HP-9826 TERMINAL PROGRAM
60      !  [REQUIRES BINARY ENHANCEMENT PROGRAM
70      !   "BEB"!]
80      !
90      !  JUNE 30, 1982
100     !  updated 1/5/83
110     !  updated 1/16/84
120     !
130     !  BILL CULBRETH
140     !
150     !
160     Sc=9     ! RS-232 IS SELECT CODE 9.
170     PRINTER IS 1   ! PRINTER IS CRT.
180     Pr=1           ! DEFAULT PRINTER IS CRT
190     Printer_choice=701 ! MY PRINTER IS 701.
200     Bits=7         ! BITS PER CHARACTER
210     Duplex=0       ! FULL DUPLEX
220     Baud=300       ! BAUD RATE
230     Computer=1     ! ASSUME IBM COMPUTER
240     !
250     OUTPUT Pr;"(300 BAUD. IBM assumed."
260     OUTPUT Pr;" Load the binary program BEB first"
270     OUTPUT Pr;" unless you have BASIC 2.0"
280     OUTPUT Pr;" SET MODEM ON <FULL DUPLEX> }"
290     OUTPUT Pr;" "
300     !
310     DIM Name$[200],Hp_file$[30],Aa(1500),Numb$[30]
320     INTEGER Isend
330     !
340     CONTROL Sc,3;Baud
350     CONTROL Sc,4;Bits-5+4 ! BITS/CHAR & #STOP BITS.
360     !
370     !
380     To_disk=0
390     Datadump=0
400     I_data=1
410     I=1
420     J=1
430     K=1
440     L=1
450     !
460     ON ERROR GOTO Errors
470     ON KEY 0 LABEL "Line Mode" GOTO Line_mode
480     ON KEY 5 LABEL "Terminal" GOTO Terminal
490     ON KEY 6 LABEL "To Crt" GOTO Pr_crt
500     ON KEY 7 LABEL "To Prt" GOTO Pr_prt
510     ON KEY 8 LABEL "DATA" GOTO Data_dump
520     !
530     !
540 Line_mode:     !
550         OUTPUT Pr;"{LINE RECEPTION MODE}"
560 Begin: STATUS Sc,10;Y ! CHECK FOR FULL BUFFER
570*
580         IF BIT(Y,0)=0 THEN GOTO Begin
590     !
```

```
600    !  RECEIVE ROUTINE.
610    !
620 Receive:     STATUS Sc,6;A
630        B=A
640        OUTPUT Pr USING "#,A";CHR$(B)
650        IF B=63 AND Datadump=1 THEN GOTO Data_dump
660        IF B=13 AND Computer=3 THEN OUTPUT Pr;CHR$(13)
670        GOTO Begin
680    !
690    !  TRANSMIT ROUTINE.
700    !
710*
720              IF Duplex=0 THEN
730                  IF NUM(Key$)<>255 THEN OUTPUT Pr USING "#,A";Key$
740                  IF NUM(Key$)=255 THEN OUTPUT Pr;" "
750              END IF
760              IF Computer=1 AND NUM(Key$)=8 THEN Key$=CHR$(64)
770              !
780              !  the previous line gives an @
790              !  for a backspace for the IBM.
800              !
810              IF Computer=5 AND NUM(Key$)=8 THEN Key$=CHR$(127)
820              !
830              !  THE VAX/VMS REQUIRES A DELETE
840              !  SYMBOL FOR A BACKSPACE.
850              !
860              IF NUM(Key$)=255 THEN Key$=CHR$(13)
870              OUTPUT Sc USING "#,A";Key$
880              GOTO Begin
890   !
900   !
910   !
920   !   DATA FILE OUT TO THE HOST COMPUTER.
930   !
940   !
950   !
960 Data_dump:   !
970              IF I_data=1 THEN GOSUB Open_file
980              !
990              IF Datadump=0 THEN GOTO Begin
1000                IF Computer=1 THEN WAIT .3
1010                ! wait for the slow IBM.
1020                BEEP 1000+RND*1500,.05
1030                OUTPUT Pr;"A(";I_data;")=";
1040                OUTPUT Pr;Aa(I_data)
1050                GOSUB Send_number
1060             IF Aa(I_data)=-200 THEN
1070                   I_data=1
1080                   Datadump=0
1090             END IF
1100             I_data=I_data+1
1110 GOTO Begin
1120 !
1130 !
1140 !  ERROR HANDLING SUBROUTINE
1150 !
1160 Errors:  OFF ERROR
1170          Close_file=-200
1180          !  FIRST, END OF FILE ERROR.
1190          IF ERRN=59 THEN
1200             Aa(I)=-200
```

```
1210             GOTO 2000 ! RETURN AFTER ERROR.
1220          END IF
1230          !
1240          IF ERRN<>59 THEN OUTPUT Pr;"<error #";ERRN;" generated.>"
1250          IF ERRN=54 THEN OUTPUT Pr;"{FILE <";Hp_file$;"> ALREADY THERE}"
1260          IF ERRN=54 THEN GOTO Created
1270          IF ERRN=56 THEN OUTPUT Pr;"<FILE (";Hp_file$;" IS NOT ON DISK.>"
1280          ASSIGN @File TO *
1290 GOTO Line_mode
1300 !
1310 !
1320 !  OUTPUT TO CRT.
1330 !
1340 Pr_crt:  Pr=1
1350          GOTO Line_mode
1360 !
1370 !
1380 !  OUTPUT TO PRINTER.
1390 !
1400 Pr_prt:  Pr=Printer_choice
1410 GOTO Line_mode
1420 !
1430 !
1440 !  CHANGE THE TERMINAL CHARACTERISTICS.
1450 !
1460 Terminal:  !
1470             OUTPUT Pr;"     1.  Baud Rate =";Baud
1480             OUTPUT Pr;"     2.  Bits/Char =";Bits
1490             OUTPUT Pr;"     3.  Duplex    =";Duplex
1500             OUTPUT Pr;"         [1=full,0=half]"
1510             OUTPUT Pr;"     4.  Computer  =";Computer
1520             OUTPUT Pr;"         [IBM=1, VAX/UNIX=2, "
1530             OUTPUT Pr;"          TRS-80=3, Cyber=4, vax/vms=5]"
1540             OUTPUT Pr;" "
1550             INPUT "Change which one?",Which
1560             IF Which=1 THEN INPUT "To?",Baud
1570             IF Which=2 THEN INPUT "To?",Bits
1580             IF Which=3 THEN INPUT "To?",Duplex
1590             IF Which=4 THEN INPUT "To?",Computer
1600             IF Computer=1 THEN Duplex=0
1610             IF Computer=3 THEN Duplex=0
1620             IF Computer=3 THEN Bits=8
1630             IF Computer=5 THEN Duplex=1
1640 GOTO Line_mode
1650 !
1660 !
1670 !
1680 Open_file:  !
1690             !  Open a file to read data from
1700             !  disk.
1710             !
1720      Datadump=1
1730      !
1740        INPUT "Is this LDV data? (1=YES)",Ldv$
1750        IF Ldv$="1" THEN
1760          INPUT "Experiment #?",Experiment$
1770        ELSE
1780          OUTPUT Pr;"Data file out of HP to host."
1790          INPUT "File name?",Hp_file$
1800        END IF
```

```
1810      !
1820     IF Ldv$="1" THEN
1830       Hp_file$=Experiment$&"_RESULT"
1840     END IF
1850     !
1860     !  Read the file off of disk.
1870     !
1880     ASSIGN @File TO Hp_file$
1890     I=1
1900     Check=0
1910     BEEP
1920     BEEP
1930     OUTPUT Pr;"{Working on file <";Hp_file$;">.}"
1940     !
1950*
1960       ENTER @File;Aa(I)
1970       Check=Aa(I)
1980       I=I+1
1990*
2000     !
2010     ASSIGN @File TO *
2020       Datadump=1
2030 RETURN
2040 !
2050 !
2060 !
2070 Send_number: !
2080              ! SEND A NUMBER ONE CHARACTER AT
2090              ! A TIME TO THE HOST COMPUTER.
2100              !
2110          Numb$=VAL$(Aa(I_data))
2120          Length=LEN(Numb$)
2130          !
2140          IF ((Ldv$="1") AND (I_data>13)) THEN
2150            Posit=POS(Numb$,".")
2160            IF (Posit<>0) THEN Length=Posit+2
2170          END IF
2180          !
2190          FOR I=1 TO Length
2200            Numeric=NUM(Numb$[I,I])
2210            OUTPUT Sc USING "#,A";Numb$[I,I]
2220          NEXT I
2230          !
2240          OUTPUT Sc USING "#,A";CHR$(13)
2250 RETURN
2260 !
2270 !
2280 !
2290 END
```

APPENDIX C

FORTRAN PROGRAMS USED ON THE IBM 3033

```
FILE: GRAB      FORTRAN  A1

C
C        PROGRAM GRAB
C
C       TEST PROGRAM FOR DATA TRANSFER FROM THE HP-9826
C       TO THE IBM.
C
C       BY BILL CULBRETH
C       FOR ME2410, FALL QUARTER, 1982
C
C       FILEDEF 05 TERMINAL
C       FILEDEF 06 TERMINAL
C       FILEDEF 07 DISK MYDATA DATA (PERM)
C
C       GLOBAL TXTLIB FORTMOD2 MOD2EEH
C
C             TYPE IN THE ABOVE 4 LINES TO MAKE THIS
C                   FORTRAN PROGRAM RUN.
C
C
        DIMENSION DATA(3000)
        I=1
        WRITE(6,80)
80      FORMAT(2X,'BEGIN INPUTING DATA FROM THE HP-9826')
C
C
10      CONTINUE
        READ(5,*) DATA(I)
        I=I+1
        IF(DATA(I-1).NE.-200) GOTO 10
C
        NITEMS = I-1
6       FORMAT(2X,I5,'  DATA POINTS WERE ENTERED.')
        WRITE(6,6) NITEMS
C
C       NOW THAT ALL DATA HAS BEEN ENTERED, WRITE IT OUT ON
C       DISK.
C
5       FORMAT(2X,'DATA(',I5,') = ',1F15.5)
        I=1
20      WRITE(7,*) DATA(I)
        I=I+1
        IF(DATA(I-1).NE.-200) GOTO 20
C
C             ALL DATA HAS BEEN WRITTEN ONTO DISK.
C
        STOP
        END
```

```
FILE: WATARRNG FORTRAN  A1

C       PROGRAM REARRANGE
C
C       BY BILL CULBRETH
C       22 JUNE 1984
C       NAVAL POSTGRADUATE SCHOOL
C       REVISED BY R. WATSON 1 SEP 84 TO HANDLE 9 CHANNELS OF DATA
C
C       PURPOSE:  TAKE IN DATA AQUIRED ON THE HP-9826 AND PLACE IT
C           IN ORDERED ARRAYS.
C
C
C       FILEDEF 20 -- INPUT
C       FILEDEF 21 -- OUTPUT
C
        DIMENSION X(1000),Y(1000),Z(1000),A(1000),B(1000),C(1000),
      * D(1000),E(1000),F(1000),G(1000)
        I=1
 100    CONTINUE
          READ(20,*) X(I)
                CHECK=X(I)
        IF(CHECK.EQ.-200.0)  GOTO 5
          READ(20,*)  Y(I)
          READ(20,*)  Z(I)
          READ(20,*)  A(I)
          READ(20,*)  B(I)
          READ(20,*)  C(I)
          READ(20,*)  D(I)
          READ(20,*)  E(I)
          READ(20,*)  F(I)
          I=I+1
        GOTO 100
 5      CONTINUE
        NITEMS = I-2
        WRITE(5,*)  NITEMS
        WRITE(21,*) NITEMS
C
C
C     WRITE ALL DATA TO A DISK FILE.
C
        DO 91 I=1,NITEMS
C       MULTIPLY E(I) TIMES F(I) = CURRENT *VOLTAGE = POWER
C           G(I)=E(I)*F(I)
C
            WRITE(21,*) X(I),Y(I),Z(I),A(I),B(I),C(I),D(I),E(I),F(I)
            WRITE(5,10) I,X(I),Y(I),Z(I),A(I),B(I),C(I),D(I),E(I),F(I)
 10         FORMAT (I5,9(1X,F6.2))
 91     CONTINUE
C
        STOP
        END
```

FILE: SMA3   FORTRAN A1

```
C PROGRAM BY LT. R. WATSON,  SEPTEMBER 10,1984
C THE PURPOSE OF THE PROGRAM IS CONTRAST TEMPERATURE AND
C DISPLACEMENT OF A SMA COIL AS IT RECOVERS UNDER THE APPLIED
C POWER.  DATA WAS OBTAINED FROM THE DATA AQUISITION SYSTEM OF
C THE SHAPE MEMORY ALLOY TESTING SYSTEM, CONSTRUCTED BY
C LT. WATSON.
C THIS PROGRAM WILL PLOT DATA FROM 2 FILES SIDE BY SIDE.
C TWO GRAPHS FOR EACH FILE ARE PLOT ONE UNDER THE OTHER.
C CURRENTLY, THE TOP LEVEL GRAPHS PLOT TEMPERATURE OF THE
C A SMA COIL AT ITS TWO ENDS AND MIDPOINT.  THE BOTTOM GRAPHS
C PLOT CURRENT AND POWER APPLIED DURING THE PARTICULAR TEST RUN
C AND THE RECOVERY DISPLACEMENT OF THE COIL AS A FUNTION OF TIME.
C*****************************************************************
C   DATA FILE DIMENSION VARIABLE       SMA TESTING SYSTEM PARAMETER
C             X                        T1   CHAMBER INLET TEMPERATURE
C             Y                        T2   CHAMBER OUTLET TEMPERATURE
C             Z                        T3   COIL FRONT END TEMPERATURE
C             A                        T4   COIL MIDPOINTTEMPERATURE
C             B                        T5   COIL END TEMPERATURE
C             C                        T6   WATER TEMPERATURE
C             D                        X    COIL RECOVERY DISPLACEMENT
C             E                        I    CURRENT THROUGH SMA COIL
C             F                        P    POWER TO THE SMA COIL
C*****************************************************************
C
      DIMENSION X(100),Y(100),Z(100),A(100),B(100),C(100),
     * D(100),E(100),F(100),G(100),T(100),TEMPAK(500),POWPAK(500)
C READ DATA INTO THE ARRAYS
      NDATA=2
      XPHYS=.50
      CALL COMPRS
C      CALL TEK618
      CALL PAGE(14.0,10.0)
      CALL BLOWUP(1.00)
      CALL NOBRDR
      DO 99 ISET=1,NDATA
      IF(ISET.EQ.2) GO TO 45
      READ(21,*) NITEMS
      DO 51 I=1,NITEMS
C        READ(21,*)  X(I),Y(I),Z(I),A(I),B(I),C(I),D(I),E(I),F(I)
        READ(21,*)  X(I),Y(I),Z(I),A(I),B(I),C(I),D(I),E(I),F(I),G(I)
 51    CONTINUE
      REWIND 21
      GO TO 52
   45 CONTINUE
      READ(22,*) NITEMS
      DO 52 I=1,NITEMS
        READ(22,*)  X(I),Y(I),Z(I),A(I),B(I),C(I),D(I),E(I),F(I)
 52    CONTINUE
      DO 92 K=1,NITEMS
  92  T(K)=FLOAT(K)*2.075
C     TIMAX=FLOAT(NITEMS)
C  LEVEL 1
      CALL PHYSOR(XPHYS,5.5)
      CALL AREA2D(4.0,3.0)
      CALL XNAME('TIME (SEC)$',100)
      CALL YNAME('TEMPERATURE$',100)
      CALL INTAXS
      CALL GRAF(0.0,30,210.,20.0,10,125.)
      CALL DOT
      CALL GRID (02,01)
      CALL RESET ('DOT')
C PLOT TEMPS
      CALL THKCRV(.01)
      CALL CURVE (T,X,NITEMS,0)
      CALL CHNDOT
      CALL CURVE(T,Z,NITEMS,0)
      CALL CHNDSH
      CALL CURVE(T,A,NITEMS,0)
      CALL DASH
      CALL CURVE(T,B,NITEMS,0)
      CALL THKFRM(.015)
```

FILE: SMA3 FORTRAN A1

```
      CALL FRAME
      CALL COMPLX
C
      IF(ISET.EQ.2) GO TO 998
         CALL HEADIN('RUN 194$ ',-100,-1.25,4)
         CALL HEADIN('I = 1.25 AMPS, LOAD =1.3 N$',100,1.,4)
         CALL HEADIN('COOLED IN CHAMBER, NO WATER$',-100,.75,4)
       GO TO 999
 998  CONTINUE
         CALL HEADIN('RUN 196$ ',-100,-1.25,4)
         CALL HEADIN('I = 2.0 AMPS, LOAD = 1.3 N$',100,1.,4)
         CALL HEADIN('COOLED IN AIR$',-100,.75,4)
 999  CONTINUE
C
      CALL HEADIN('COIL AND AMBIENT TEMPS VS. TIMES',100,
     * 1.,4)
C
C     SET UP LEGEND FOR THE SECOND CALL
      IF (ISET.EQ.1) GO TO 888
          CALL HEIGHT (.12)
         MAXLIN=LINEST(TEMPAK,500,33)
          CALL LINES('  T2 AMBIENT$',TEMPAK,1)
          CALL LINES('  T3 AT COIL BEGINS',TEMPAK,2)
          CALL LINES('  T4 AT COIL CENTER$',TEMPAK,3)
          CALL LINES('  T5 AT COIL END$',TEMPAK,4)
          CALL LSTORY(TEMPAK,4,4.75,2.3)
C
 888  CONTINUE
      CALL RESET(3HALL)
      CALL ENDGR(0)
C PLOT VOLTAGES
      CALL PHYSOR(XPHYS,1.)
      CALL AREA2D(4.0,3.0)
      CALL XNAME('TIME (SEC)$',100)
      CALL YNAME('I (AMPS) & P (W) & X (CM)$',100)
      CALL INTAXS
      CALL GRAF(0.0,20,210.,-1.0,1.,9.)
      CALL CURVE(T,D,NITEMS,0)
      CALL RESET('CHNDOT')
      CALL CHNDOT
      CALL CURVE(T,E,NITEMS,0)
      CALL DASH
      CALL CURVE(T,F,NITEMS,0)
C     CALL CURVE(T,G,NITEMS,0)
      CALL RESET(3HALL)
      CALL COMPLX
      CALL THKFRM(.015)
      CALL FRAME
      CALL HEADIN ('POWER, CURRENT, AND DISPLMT VS. TIMES',
     * 100,1.,1)
C
C SET UP LEGEND FOR SECOND CALL
      IF (ISET.EQ.1) GO TO 889
          CALL HEIGHT (.12)
       MAXLIN=LINEST(POWPAK,500,33)
          CALL LINES('  COIL DISPLACEMENTS',POWPAK,1)
          CALL LINES('  CURRENT THRU COILS',POWPAK,2)
          CALL LINES('  POWER TO COIL$',POWPAK,3)
          CALL LSTORY(POWPAK,3,4.75,2.5)
 889  CONTINUE
C
      CALL RESET ('COMPLEX')
      CALL ENDGR(0)
      XPHYS=XPHYS+5.5
   99 CONTINUE
      CALL ENDPL(0)
      CALL DONEPL
      STOP
      END
```

```
FILE: LOGGRPH   FORTRAN A1

C  LOGGRPH, WRITTEN BY D. WATSON, 10 OCT 84
C  THIS PROGRAM USES INPUT FROM PROGRAM POLYFIT TO PLOT
C  THE LOG OF NORMALIZED DISPLACEMENT OF THE SMALL TEST COIL AS
C  IT IS COOLED.  THE INTENT OF THE PLOT IS TO DETERMINE THE COOLING
C  TIME CONSTANT OF THE COIL UNDER VARIOUS COOLING CONDITIONS.
C  THIS PROGRAM PLOTS DATA FROM 3 DIFFERENT FILES CORRESPONDING
C  TO THREE DIFFERENT COOLING CONDITIONS.
CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C
      DIMENSION X(100),Y(100),Z(100),A(5),ABAB(100),
     * XX(100),YY(100),ZZ(100),AA(5),ABABA(100),
     * XXX(100),YYY(100),ZZZ(100),AAA(5),ABABB(100),
     * LGPAK(1000),IPAK(1000)
      COMMON DY(1000)
      INTEGER N,NN,NNN,I,J
C
C  SET UP THE TEK GRAPHICS SCREEN FOR PLOTTING
      CALL COMPRS
C     CALL TEK618
C     CALL PRTPLT(72,6)
      CALL BLOWUP (1.2)
      CALL HWRCT('COMIC')
      CALL HWSCAL('SCRN')
C     TEK618 SCREEN DIMENSIONS (14.0,10.5)
      CALL PAGE(14.0,11.)
      CALL NOBRDR
C     CALL RESET ('ALL')
      CALL GRACE(0.00)
C
C DATA IS FROM THREE POLYFIT CREATED DATA FILES INTO THE ARRAYS
C X IS TIME, Y IS NORMALIZED DISPLACEMENT OF ORIGINAL DATA FILE
C Z IS DATA FROM POLYFIT LEAST SQUARES 1ST ORDER CURVE FIT
C
C NOW READ THE DATA INTO ARRAYS.
C THE FIRST TWO NUMBERS ARE THE COEFFICIENTS OF THE LEAST SQUARES
C FIT.  1 IS THE Y INTERCEPT.  2 IS THE SLOPE.  1/SLOPE IS THE TIME
C CONSTANT OF THE SYSTEM.
C
C  FIRST FILE
      IJUNK=2
      DO 92 I=1,IJUNK
          READ(21,*) L,A(I)
          WRITE(6,*) L,A(I)
 92   CONTINUE
C
      READ(21,*) N
C
      DO 93 J=1,N
         READ(21,*)   X(J),Y(J),Z(J),ABAB(J)
C        WRITE(6,*)   X(J),Y(J),Z(J),ABAB(J)
 93   CONTINUE
C
C  SECOND FILE
      DO 94 I=1,IJUNK
          READ(22,*) LL,AA(I)
          WRITE(6,*) LL,AA(I)
 94   CONTINUE
C
      READ(22,*) NN
C
      DO 95 J=1,NN
         READ(22,*)   XX(J),YY(J),ZZ(J),ABABA(J)
C        WRITE(6,*)   XX(J),YY(J),ZZ(J),ABABA(J)
 95   CONTINUE
C
C  THIRD FILE
      DO 96 I=1,IJUNK
          READ(23,*) LLL,AAA(I)
          WRITE(6,*) LLL,AAA(I)
 96   CONTINUE
C
      READ(23,*) NNN
```

FILE: LEGGRPH FORTRAN A1

```
C
      DO 97 J=1,NNN
         READ(25,*) XXX(J),YYY(J),ZZZ(J),ABABB(J)
C        WRITE(6,*)  XXX(J),YYY(J),ZZZ(J),ABABB(J)
 97   CONTINUE
C
      CALL PHYSOR(0.75,0.60)
      CALL AREA2D(8.0,6.0)
      CALL THKFRM(.015)
      CALL FRAME
      CALL COMPLX
C     CALL INTAXS
C
      CALL HEADIN('LOG OF NORMALIZED SMA COIL DISPLACEMENT VS TIME$',
     * -100,-1.25,4)
      CALL HEADIN('SMA PREXTENSION DISPLACEMENT AFTER RECOVERY$',
     * -100,1.15,4)
      CALL HEADIN('THREE COOLING CONDITIONS AFTER SMA RECOVERY$',
     * 100,1.,4)
      CALL HEADIN('WATER, NATURAL AIR CONVECTION, CHAMBER-NO COOLANT$',
     * 100,1.,4)
C
      CALL RESET ('COMPLEX')
      CALL XNAME('TIME (SEC)$',100)
      CALL YNAME('LN(REXT/RECOV)$',100)
      CALL GRAF(00.0,20.,150.,-1.0,-.10,-0.0)
      CALL THKCRV(.01)
C
C  PLOT FILE NUMBER ONE
C  PLOT LOG (DISPLMT) OF ORIGINAL DATA AS INDIVIDUAL DATA POINTS
      CALL MARKER (1)
      CALL LEGLIN
      CALL CURVE (X,Y,N,-1)
C
C   PLOT LEAST SQUARES DATA AS SMOOTH LINE
      CALL LEGLIN
      CALL CURVE (X,Z,N,0)
C
C  PLOT FILE NUMBER TWO
C  PLOT LOG (DISPLMT) OF ORIGINAL DATA AS INDIVIDUAL DATA POINTS
      CALL MARKER (3)
      CALL LEGLIN
      CALL CURVE (XX,YY,NN,-1)
C
C   PLOT LEAST SQUARES DATA AS SMOOTH LINE
      CALL CHNDOT
      CALL LEGLIN
      CALL CURVE (XX,ZZ,NN,0)
C
C  PLOT FILE NUMBER THREE
C  PLOT LOG (DISPLMT) OF ORIGINAL DATA AS INDIVIDUAL DATA POINTS
      CALL MARKER (5)
      CALL LEGLIN
      CALL CURVE (XXX,YYY,NNN,-1)
C
C   PLOT LEAST SQUARES DATA AS SMOOTH LINE
      CALL CHNDSH
      CALL LEGLIN
      CALL CURVE (XXX,ZZZ,NNN,0)
C
C     CALL DOT
C     CALL BLNK1 (5.20,7.60,.800,1.6,1)
C     CALL DOT
C     CALL GRID(05,02)
C     CALL RESET('DOT')
C     CALL RESET('BLNK1')
C
C
C     SET UP LEGEND
      CALL LINESP (2.0)
      CALL HEIGHT (.11)
      MAXLIN=LINEST(LEGPAK,500,40)
```

```
      CALL LINES('= ORIGINAL DATA, COOLING IN CHAMBER$',LEGPAK,1)
      CALL LINES('= LEAST SQR FIT, COOLING IN CHAMBER$',LEGPAK,2)
      CALL LINES('= ORIGINAL DATA, AIR COOLING$',LEGPAK,3)
      CALL LINES('= LEAST SQR FIT, AIR COOLING$',LEGPAK,4)
      CALL LINES('= ORIGINAL DATA, WATER COOLING$',LEGPAK,5)
      CALL LINES('= LEAST SQR FIT, WATER COOLING $',LEGPAK,6)
C     CALL LINES('$',LEGPAK,5)
      CALL LEGEND(LEGPAK,6,8.5,.6)
C
      CALL HEIGHT (.12)
      MAXLIN=LINEST(IPAK,500,50)
      CALL LINES('COOLING OF THE SMA COIL IS ACCORDING$',IPAK,1)
      CALL LINES('TO THE EXPONENTIAL RELATIONSHIP:$',IPAK,2)
      CALL LINES('             $',IPAK,3)
      CALL LINES('             $',IPAK,4)
      CALL LINES('    IS THE TIME CONSTANT OF THE$',IPAK,5)
      CALL LINES('COOLING SMA COIL. ON THE NATLOG PLOTS$',IPAK,6)
      CALL LINES('    CAN BE READ AS   = 1/SLOPE (SEC).$',IPAK,7)
      CALL LINES('FOR THESE THREE SYSTEMS; RUNS 81, 85, & 194 $',IPAK,8
      CALL LINES('      $',IPAK,9)
      CALL LINES('  = 265.664 SEC, CHAMBER-NO COOLANT $',IPAK,10)
      CALL LINES('  = 161.638 SEC, NATURAL AIR CONVECTION$',IPAK,11)
      CALL LINES('  =  11.007 SEC, WATER COOLED$',IPAK,12)
C      CALL LINES('1.3 .$',IPAK,9)
      CALL LSTORY(IPAK,12,8.5,3.1)
C
      CALL ENDGR(0)
      CALL ENDPL(0)
      CALL DONEPL
      STOP
      END
```

FILE: TEMGRPH FORTRAN A1

```
C   PROGRAM TEMPGRP,  WRITTEN BY R. WATSON,  10 OCT 1984.
C   WRITTEN FOR USE ON THE IBM 3033.
CCC CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
C   THIS PROGRAM PLOTS THE DISPLACEMENT OF THE SMA COIL
C   DURING A COMPLETE RUN VS. THE TEMPERATURE IN THE CENTER OF THE COIL.
C   DATA FILES FROM THE SMA DATA AQUISITION SYSTEM WHICH HAVE BEEN
C   TRANSFERRED TO THE IBM 3033 ARE READ IN THIS PROGRAM.
C   THE DISPLACEMENT, ARRAY D, AND TEMPERATURE ARRAYS, Z, B,& C ARE USED
C   THE PURPOSE OF THE PLOT IS TO SHOW THE TEMPERATURE DEPENDENCE OF THE
C   SMA COIL ACTUATION.
C
C
CCC CCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCCC
       DIMENSION X(100),Y(100),Z(100),A(100),B(100),C(100),IPAK(500),
     * D(100),E(100),F(100),T(100),LEGPAK(500),COMMON(2000),FF(100),
     * ZZ(100),AA(100),BB(100),CC(100),DD(100),XX(100),YY(100),EE(100)
       INTEGER NNITEM,NNITEM,I
       CALL TEK618
C      CALL COMPRS
C      CALL PRTPLT(72,0)
       CALL HWRCT('COMIC')
       CALL HWSCAL('DOWN')
C      TEK618 SCREEN DIMENSIONS (14.0,10.5)
       CALL PAGE(14.0,10.5)
       CALL BLOWUP(.75)
       CALL NOBRDR
       CALL GRACE(0.00)
C
C READ DATA FROM BOAT FILES INTO THE ARRAYS USED FOR PLOTTING.
C ARRAY D IS DISPLACEMENT OF SMA COIL.
C ARRAY T IS TIME OF RUN.
C
       READ(21,*) NITEM
          DO 52 I=1,NITEM
             READ(21,*)  X(I),Y(I),Z(I),A(I),B(I),C(I),D(I),E(I),F(I)
                T(II)=FLOAT(I-1)*2.075
 52       CONTINUE
C
       READ(22,*) NNITEM
          DO 53 I=1,NNITEM
             READ(22,*)  XX(I),YY(I),ZZ(I),AA(I),BB(I),CC(I),
     *       DD(I),EE(I),FF(I)
 53       CONTINUE
C
C   SET UP GRAPH AREA AND HEADINGS
       CALL PHYSOR(0.75,0.60)
       CALL AREA2D(3.0,6.0)
       CALL COMPLX
C
C      CALL HEADIN('$ ',-100,-1.25,4)
C      CALL HEADIN('$',100,1.,4)
C      CALL HEADIN('     $',100,1.,4)
       CALL HEADIN('SMA COIL DISPLACEMENT VS TEMPERATURE$',-100,1.,1)
C      CALL HEADIN('                    $',100,1.,2)
       CALL RESET ('COMPLEX')
       CALL XNAME('COIL TEMPERATURE (C)$',100)
       CALL YNAME('DISPLACEMENT (CM)$',100)
       CALL GRAF(20.,5.,80.,0,1.,10.0)
C            CALL BLNK1 (4.95,7.8,.90,2.15,1)
             CALL DOT
             CALL GRID(02,02)
             CALL RESET('DOT')
C            CALL RESET('BLNK1')
       CALL THKFRM(.017)
       CALL FRAME
       CALL THKCRV(.01)
       CALL SMOOTH
C
C
C   PLOT DISPLACEMENT VS. TEMP OF FIRST FILE
C
C        CALL CURVE (ZZ,DD,NITEM,0)
C      CALL CURVE (AA,DD,NITEM,0)
```

```
      CALL RASPLN (1)
      CALL MARKER(4)
      CALL LEGLIN
      CALL CURVE (A,B,NITEM,-3)
C
C   SET UP CURVE FROM SECOND FILE
C
C     CALL MARKER(4)
C     CALL LEGLIN
C     CALL CURVE (AA,BB,NNITEM,3)
C
C     SET UP STORY
      CALL TYPSET
      CALL HEIGHT (.12)
      CALL MIXALF('INSTRU')
      MAXLIN=LINEST(LEGPAK,500,45)
C          CALL LINES('$',LEGPAK,1)
      CALL LINES('TEMPERATURE DEPENDENCE OF SMA COIL$',LEGPAK,1)
      CALL LINES('RECOVERY AND REEXTENSION DISPLACEMENT.$',LEGPAK,2)
      CALL LINES('                   $',LEGPAK,3)
      CALL LINES('RUN 85:  THE SMA COIL WAS HEATED BY$',LEGPAK,4)
      CALL LINES('ELECTRICAL ACTUATION, THEN COOLED IN AIR.$',LEGPAK,5)
      CALL LINES('NOTE THE DECREASING DISPL/TEMP SLOPE AS$',LEGPAK,6)
      CALL LINES('THE COIL TEMPERATURE REACHED 42 C, WITH$',LEGPAK,7)
      CALL LINES('NO DISPL AS THE TEMP RISES ABOVE 52 C.$',LEGPAK,8)
      CALL LINES('NOTE, ALSO, THE DELAY IN REEXTENSION $',LEGPAK,9)
      CALL LINES('--DECREASING DISPLACEMENT--UNTIL THE $',LEGPAK,10)
      CALL LINES('COIL TEMPERATURE REACHED 46 C.(1)$',LEGPAK,11)
C          CALL LINES('OF COIL RECOVERY DISPLACEMENT$',LEGPAK,2)
           CALL LSTORY(LEGPAK,11,8.5,3.0)
C
C   SET UP LEGEND
C
       CALL LINESP(2.2)
       CALL HEIGHT(.11)
       MAXLIN=LINEST(IPAK,500,50)
          CALL LINES('= DATA FROM RUN 85$',
    * IPAK,1)
C         CALL LINES('= DATA FROM RUN 81$',
C    * IPAK,2)
          CALL LEGEND(IPAK,1,6.5,.7)
C
      CALL ENDGR(0)
      CALL ENDPL(0)
      CALL DONEPL
      STOP
      END
```

APPENDIX D

CALIBRATION DATA

D.1 Potentiometer Calibration

The following relation was used in Basic program SMA to convert the 10 turn linear potentiometer voltage read by the HP 3497A to displacement:

$$X = 3.02260V + 0.0027$$

where X = SMA coil displacement from zero

V = potentiometer voltage output to the HP 3497A

D.2 Flow System Rotometer Calibration

The following relation converts the rotometer reading to volumetric flow rate:

$$M = 0.03419R + 1.6411$$

where M = volumetric flow rate through the system

R = the face plate reading on the rotometer

APPENDIX E

DATA LISTINGS

BDAT files are to be read as follows:

Col.	1	2	3	4
row 1	T1	T2	T3	T4
row 2	T5	T6	Displacement	Current
row 3	Power			

LBDAT files are to be read as follows:

Col.	1	2	3	4
	Time	ln (normalized displacement)	Fitted Data Points	normalized displacement

```
FILE: BDAT81   DATA      A

         99
  22.6096344         22.4866333         22.6834412         22.7572174
  22.6834412         22.0189362         .0001             .300000011E-05
 -.330000055E-10
  22.6096344         22.4620209         22.6588440         22.7572174
  22.6834412         22.0435638         .153530855E-04     .300000011E-05
 -.330000055E-10
  22.6342468         22.4620209         22.7326202         22.8063965
  21.4768982         22.0189362         .383826991E-04     2.02358818
  5.78984451
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23.1004486	22.2642059	4.25080776	.195000030E-04
.175500003E-09			
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.151999996E-09			
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23.1004486	22.2395782	4.24750614	.189999992E-04
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22.8546295	23.0267181	22.9283905	23.0021362
23.1250305	22.2642059	4.24719906	.189999992E-04
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23.1004486	22.2642059	4.24643230	.189999992E-04
.208999998E-09			
23.2478943	22.9775543	23.4935303	24.1562042
24.2052612	22.7316742	4.24412918	2.02004528
5.89710045			
22.9038086	22.9775543	25.0630035	27.4330750
26.6523437	22.6578979	4.24405193	2.01989555
5.89100742			
22.9038086	23.0021362	26.6035004	30.9324951
28.8452759	22.6824799	4.24412918	2.01974583
5.83745003			
22.9038086	23.0267181	27.5961029	34.0433704
30.8598328	22.6086834	4.24420547	2.01954596
5.77169037			
22.9283905	23.0267181	28.8939209	36.7392426
32.7703705	22.5594940	4.24453981	2.01999569
5.67879486			
22.9283905	23.0267181	28.7236786	38.9874573
34.3132324	22.5840912	4.24528027	2.01989555
5.62579441			
22.9283905	23.0267181	26.7938129	40.9887390
36.1157532	22.6086884	4.24765968	2.01999569

FILE: BDAT84 DATA A

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37.1225739	22.6824799	4.36257744	2.02004523
5.55571270			
22.8792114	23.0267181	28.1639862	44.2608032
37.8405914	22.6086884	4.66664600	2.02009533
5.53362942			
22.9038036	23.0267181	28.8939209	45.5594940
38.4143219	22.5594940	4.94192600	2.01994514
5.51564503			
22.9038086	23.0267131	30.3508301	46.8080750
38.8919830	22.5594940	5.28291798	2.01994514
5.49807167			
22.9283905	23.0267181	30.6659851	47.9364319
39.1783752	22.6333008	5.60932446	2.01999569
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22.9233905	23.0513000	31.0051727	49.1562347
39.3692169	22.6333008	5.85850525	2.02009583
5.48231838			
22.9283905	23.0513000	31.2957306	50.7005920
39.5123138	22.5840912	6.01710224	2.02009533
5.48009682			
23.0513000	23.0758607	31.2473145	52.3338928
39.6553650	22.5348969	6.21592522	2.02024555
5.48353386			
22.9529724	23.0758667	31.0778198	54.0785522
39.9175415	22.6333008	6.35502188	2.02009533
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22.9529724	23.0513000	30.7386780	55.8177795
40.2748413	22.6333008	6.41666698	2.02014542
5.47841454			
22.9529724	23.0513000	30.7144470	57.6670380
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23.0267131	23.0021362	31.0051727	59.5102234
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.26950000 0E-08			
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38.3426361	22.1657257	6.98196697	.27000001 9E-04
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22.7070770	23.3215942	23.1987457	62.3324280
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23.4444122	22.2642059	4.35321236	.215000036E-04
.451499949E-09			
22.7808685	23.2478943	23.0758667	23.6163177
23.4444122	22.1657257	4.35305882	.209999998E-04
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22.7808685	23.0758667	23.0513000	24.0580902
23.3461609	22.7070770	4.33471203	2.02029514
6.49422169			
22.8300476	23.1004486	24.3033600	26.0416107
25.6748352	22.7316742	4.33540249	2.02039528
6.36887455			
22.8300476	23.1250305	25.7726746	29.4042816
28.0422363	22.6578979	4.33540249	2.02044582
6.27447510			
22.8300476	23.1250305	26.8476257	32.5771942
30.2780762	22.5840912	4.33532619	2.02064514
5.80974197			
22.8546295	23.1250305	27.6524506	35.4194946
32.1906586	22.6086884	4.33517265	2.02089596
5.74639797			
22.8546295	23.1004486	28.1396332	37.8405914
33.8074646	22.6333008	4.33455849	2.02099514
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22.8792114	23.1004486	28.4804077	39.9175415
35.4915619	22.6578979	4.33432865	2.02104553
5.64051723			
22.8546295	23.1495972	28.3830719	41.7492065
36.7392426	22.6578979	4.33673807	2.02099514
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22.8792114	23.1741791	28.4560699	43.2670135
37.8405914	22.5840912	4.52532101	2.02114582
5.56217534			
22.9038086	23.1741791	28.3830719	44.9223328
38.6532135	22.5840912	4.93386650	2.02124596
5.53455639			
22.8792114	23.1495972	28.2126770	46.3843384
39.2976685	22.6578979	5.27032852	2.02119541
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39.8222198	22.6578979	5.64079857	2.02119541
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22.9038086	23.1495972	30.1082764	48.8515320
40.0843048	22.6824799	5.73596210	2.02119541
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22.8792114	23.1495972	31.0293884	50.2096710
40.1557617	22.6333008	5.34315205	2.02124596
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22.8792114	23.1495972	31.6587219	51.5878296
40.2748413	22.5594940	5.99921608	2.02134514
5.48571110			
22.8792114	23.1250305	31.1504669	53.1487427
40.4653015	22.5340912	6.17347336	2.02124596
5.47674647			
22.8792114	23.1250305	30.7871399	54.7748871
40.7270813	22.7070770	6.34657955	2.02129555
5.47102261			
22.8792114	23.1004436	30.5690308	56.5813293
41.0363007	22.7070770	6.48091888	2.02134514
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FILE: BDAT84 DATA A

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   22.8792114      23.0267131      31.1262512      63.4071350
   42.3683177      22.5594940      6.86106110      2.02114582
   5.46435070
   22.9038086      22.9775543      31.2230988      65.8917236
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FILE: LBDT84B DATA A

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 2.07499981       -.242019951      -.230184615       .214959502
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FILE: BDAT85 DATA A

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   21.9854534         22.2563019         .0001              .145000004E-04
 -.145000002E-10
   21.9854584         19.8138733         22.5023956         22.4039612
   21.7144928         22.6499939         .230296209E-03     2.02093029
   5.83333683
   21.9608307         19.7891388         24.1973377         24.2219238
   24.2219238         22.6745911         .767653983E-04     2.02073097
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   21.9362030         19.7391388         30.0277100         31.5783691
   32.1345673         22.5762024         .707393169         2.02073097
   5.56481075
   21.9362030         19.7891388         31.7477112         33.9442902
   33.9442902         22.6745911         1.39666939         2.02083015
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   21.9362030         19.7891388         32.3520508         34.9070292
   35.3637233         22.6499939         2.03103371         2.02083015
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   21.9115753         19.7891388         33.3399384         36.3719330
   36.8992920         22.6499939         3.03983307         2.02083015
   5.42847824
   21.9115753         19.7644196         34.0888062         37.4261475
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   5.40624905
   21.9115753         19.7644196         35.0512848         38.4783325
   40.0051880         22.6253967         4.23353481         2.02083015
   5.39068890
   21.8869476         19.7396851         35.2195435         39.0752716
   40.6242676         22.6253967         4.74709606         2.02083015
   5.38199902
   21.8869476         19.7396851         36.2280121         40.0523412
   41.3852336         22.5762024         5.34816933         2.02083015
   5.37371349
   21.8376770         19.7149506         37.2106781         41.2901764
   42.4298706         22.6253967         5.35635567         2.02088070
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   21.8623047         19.7149506         38.5022278         42.9514465
   43.4488525         22.7237854         6.24632454         2.02088070
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   21.8376770         19.6902161         38.8365734         44.8675232
   44.3004913         22.6991882         6.41904640         2.02098083
   5.35855105
   21.8376770         19.6902161         39.4331207         47.6470184
   45.4811554         22.6007996         6.61786842         2.02103043
   5.35464101
   21.8130493         19.6654968         39.8622284         50.1086121
   46.2354534         22.5762024         6.75372337         2.02103043
   5.35403538
   21.8130493         19.6902161         40.8383942         52.7689056
   47.0357819         22.6253967         6.90497112         2.02093029
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   21.7884064         19.6654968         42.0502319         55.9029541
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   46.5180664         22.2070616         6.94872761         .244999974E-04
   .218050000E-03
   21.7637634         19.6902161         40.3621326         56.5276642
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   .169200010E-03
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39.5235034	22.2070618	6.94872761	.224999967E-04
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21.7637634	19.7149506	37.6807526	52.9551239
38.3538715	22.2809143	6.94872761	.219999929E-04
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33.7997234	22.2563019	6.89192104	.219999929E-04
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32.9798431	22.3301392	6.84816456	.219999929E-04
.241999976E-09			
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31.6993256	22.2316895	6.75834942	.219999929E-04
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29.6393433	22.3055267	6.54724407	.209999998E-04
.209999934E-10			
21.7391357	19.7149506	29.6150665	41.1950989
29.1291962	22.2563019	6.44361115	.209999998E-04
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21.7391357	19.7149506	29.3721924	40.5766754
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28.3509216	22.2316895	6.29545403	.209999998E-04
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26.8641968	22.2316895	5.95615101	.204999960E-04
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21.7391357	19.7644196	27.9369965	35.2195435
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23.7066345	22.2316895	4.33169289	.189999992E-04
-.189999960E-10			
21.8130493	19.8138733	26.1070862	30.7793579
23.6329803	22.2809143	4.28957367	.184999953E-04
-.184999932E-10			
21.7884064	19.8385925	26.0093231	30.5127716
23.5838776	22.2563019	4.26040268	.184999953E-04
-.184999932E-10			
21.8376770	19.8138733	25.8381605	30.3137866
23.5347595	22.2316895	4.20589924	.184999953E-04
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21.8376770	19.8385925	25.7403564	29.9547103
23.4610901	22.3301392	4.15369892	.184999953E-04
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21.8376770	19.8385925	25.6425323	29.7607422
23.4119720	22.2070618	4.10994339	.184999953E-04
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FILE: bDAT85 DATA A

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.184999932E-10			
21.8623047	19.8633270	25.4712677	28.9347382
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23.2400055	22.3301392	3.95103836	.184999953E-04
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21.8869476	19.8880463	25.1286011	28.1561737
23.2400055	22.2316895	3.82053757	.180000061E-04
.180000043E-10			
21.8869476	19.8880463	24.9816742	27.9369965
23.2400055	22.3055267	3.73292274	.180000051E-04
.180000043E-10			
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23.1908569	22.2070618	3.71460152	.175000023E-04
.350000029E-10			
21.9362030	19.8880463	24.8347015	27.4252472
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23.0925598	22.2316895	3.67468357	.164999947E-04
.495000013E-10			
21.9362030	19.8880463	24.6386871	27.2301636
23.0925598	22.3055267	3.65088558	.169999985E-04
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21.9608307	19.9375000	23.9520721	25.8870850
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21.9608307	19.9375000	23.8293610	25.7892761
22.8221436	22.2809143	3.37990379	.164999947E-04
.659999971E-10			
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22.7975616	22.3301392	3.29853249	.164999947E-04
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22.7975616	22.2563019	3.19873714	.160000054E-04
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21.9854584      19.9375000      23.6820831      25.3978577
22.7729645      22.2316895      3.11659908      .160000054E-04
.639999997E-10
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6.22499943	-.854009390E-02	-.214163051E-02	.850372761E-02
8.29999924	-.149092398E-01	-.149789788E-01	.147986934E-01
10.3749990	-.214320235E-01	-.278163254E-01	.212039612E-01
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14.5249987	-.385014266E-01	-.534910224E-01	.377696417E-01
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18.6749878	-.545833558E-01	-.791656375E-01	.531204231E-01
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31.1249847	-.124502122	-.156189680	.117063642
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35.2749939	-.154465377	-.181864440	.143126905
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101.674988	-.626618445	-.592659593	.465604186
103.749985	-.629930675	-.605496943	.467371235
105.824982	-.637422860	-.618334293	.471346915
107.899979	-.643920183	-.631171584	.474770606
109.974976	-.657255175	-.644008934	.481725077
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114.124985	-.669259965	-.669683695	.487912595
116.199982	-.669475675	-.682521045	.488023043
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134.874985	-.776133776	-.798057199	.539818287
136.949982	-.786991775	-.810894549	.544737884
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99

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.949999975E-11	.902499841E-16		
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46.2433319	47.5138855	.0	1.28042221
2.34514904	3.00273091		
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46.2668915	47.0671092	-.767653983E-04	1.28042221
2.34253842	2.99950218		
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46.3610992	47.5603826	-.153530811E-03	1.28032207
2.34048462	2.99657345		
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46.3375549	48.3987427	-.153530811E-03	1.28027153
2.33744907	2.99250897		
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46.3610992	48.3627515	-.230296209E-03	1.28027153
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46.4082031	47.3728485	-.230296209E-03	1.28037167
2.33391857	2.98828316		
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2.33101082	2.98444366		
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46.4788513	47.7958221	-.307061709E-03	1.28042221
2.32760715	2.98031902		
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46.4788513	48.7815094	-.307061709E-03	1.28017235
2.32433701	2.97555161		
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46.4552917	48.0071869	-.307061709E-03	1.28042221
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46.4788513	47.4903717	-.383826904E-03	1.28037167
2.32009029	2.97057724		
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46.4552917	48.3592834	-.383826904E-03	1.28037167
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46.4552917	48.8752899	-.383826904E-03	1.28027153
2.31722069	2.96667099		
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46.4788513	48.2184753	-.307061709E-03	1.28042221
2.31693036	2.96671295		
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2.31587315	2.96633720		
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46.5259399	47.7488403	-.307061709E-03	1.28067207
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2.31105232	2.95923710		
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2.31099129	2.95973587		
45.3475037	45.1587219	45.6069794	45.8663177
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45.3946838	45.2059174	45.6305542	45.8898926
46.6201019	48.7111664	.0	1.28062153
2.30978584	2.95796108		
45.3946839	45.2059174	45.6305542	45.9134674
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2.30965805	2.95779705		
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46.6436310	46.9965973	.0	1.28047130
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46.6436310	48.6408081	.0	1.28067207
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45.4182739	45.2531128	45.6777191	45.9606018
46.6436310	48.6408081	.0	1.28042221
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2.31160831	2.96098900		
45.3946838	45.2295227	45.6777191	45.9370270
46.6907196	47.5843811	.0	1.28077221
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45.3946838	45.2295227	45.6541290	45.9606018
46.7142487	49.1331177	.0	1.28067207
2.31435871	2.96393394		
45.3710937	45.2295227	45.6541290	45.9370270
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2.31456947	2.96512990		
45.3475037	45.2295227	45.6541290	45.9370270
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2.31350040	2.96271301		
45.3710937	45.2531128	45.6541290	45.9134674
46.7142487	47.3023224	.0	1.28057194
2.31323201	2.96232319		
45.3475037	45.2295227	45.6305542	45.9370270
46.7142487	48.8752399	.0	1.28062153
2.31311607	2.96222591		
45.3710937	45.2295227	45.6305542	45.9134674
46.7377777	49.2971191	.0	1.28077221
2.31351471	2.96308517		
45.3710937	45.2531128	45.6305542	45.9134674
46.7142487	48.4062195	.0	1.28067207
2.31340226	2.96278572		
45.3946838	45.2531128	45.6305542	45.9370270
46.7377777	47.1377258	.0	1.28037167
2.31215191	2.96041298		
45.4182739	45.2531128	45.6541290	45.9370270
46.7142487	47.9602203	.0	1.28042221
2.31249809	2.96097374		
45.4182739	45.2295227	45.6777191	45.9370270
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46.7142487	49.2034149	.0	1.28047130
2.31169224	2.96005630		
45.4654541	45.2295227	45.7012939	45.9606018
46.7377777	47.6078796	.0	1.28062153
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2.31227207	2.96137619		
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46.8083801	48.4296875	.0	1.28057194
2.31200123	2.96068382		
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46.8319092	47.6513782	-.767653983E-04	1.28062153
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46.8083801	47.7488403	.0	1.28062153
2.31157875	2.96025658		
45.5833893	45.3003082	45.8427429	46.0784302
46.7613220	48.4296875	.0	1.28082180
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45.6069794	45.3239136	45.8427429	46.0784302
46.8083801	48.6077136	-.767653983E-04	1.28067207
2.31166935	2.96049023		
45.6069794	45.3239136	45.8663177	46.1255493
46.8789673	47.6078796	.0	1.28097153
2.31246662	2.96220303		
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46.8554382	46.9260254	-.767653983E-04	1.28077221

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2.31175995	2.96072102		
45.6069794	45.4182739	45.3663177	46.1491089
46.9024963	48.5000610	-.767653983E-04	1.28082180
2.31155586	2.96069050		
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46.9260254	48.9221802	-.767653983E-04	1.28087234
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45.5833893	45.4418640	45.3898926	46.1726685
46.9024963	48.0776215	.0	1.28077221
2.31082535	2.95964050		
45.5833893	45.4654541	45.3427429	46.1255493
46.9260254	47.3728485	.0	1.28067207
2.31090069	2.95950503		
45.5833893	45.4654541	45.3427429	46.1726685
46.9495544	48.1011047	.0	1.28072166
2.31047916	2.95906070		
45.5597992	45.4654541	45.3427429	46.1491089
46.9260254	48.5939026	-.767653983E-04	1.28082180
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2.31334659	2.96527782		
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46.9260254	48.8283997	.0	1.28087234
2.31420803	2.96420479		
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46.9260254	49.0393829	.0	1.28097153
2.31438828	2.96466541		
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46.9024963	48.1950073	.0	1.28082160
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2.32816887	2.98208618		
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2.50646210	3.21785069		
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2.28362274	2.92457104		
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46.9730835	47.2317810	.767653983F-04	1.28062153
2.28302097	2.92366507		
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2.36278915	3.08313560		

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.150000012E-10
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25.9763641          24.4095612          -.307061709E-03     2.02085400
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28.1963959          22.6168365          .767653983E-04      2.02095413
6.10774326
25.4872234          25.3159180          28.2937622          30.0677948
30.5043335          22.7152252          .307061709E-03      2.02145386
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36.7232056          22.4938354          .865146101          2.02125359
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25.4872284          25.2914429          34.5378265          40.2350922
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25.4872234          25.2914429          48.1320343          66.4675751
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25.4872284          25.3648682          51.2921906          72.7496643
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25.5116882          25.3648682          54.2487946          78.7195282
58.4337147          23.2805939          6.76180363          2.02130413
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25.5361633	25.3403931	65.1026306	99.5064697
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25.5361633	25.3893433	68.3730316	108.190353
74.9703674	23.7226410	7.22700214	2.02255440
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76.9149170	24.0907440	7.22853756	2.02285385
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78.5192871	22.8135986	7.29609108	2.02305412
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79.2976074	24.5560406	7.29609103	2.02245426
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25.5606232	25.4627533	74.3655701	121.319000
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.132599993E-08			
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68.0105743	23.2063787	7.30223274	.139999992E-04
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24.4340668	24.9241638	42.9668884	91.2430267
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.47250039E-09
23.9680634      24.6301575      24.1888530      27.0509136
27.9772339      23.3297272      1.44142437      .22499967E-04
.24750020E-09
23.9189911      24.6056519      24.1643372      24.8261871
25.5159180      24.2624359      1.36166477      .20999998E-04
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FILE: BDAT191   DATA      A

    .146999996E-09
    23.8699188         24.4585876        24.1398010        24.4585876
    24.7526855         24.3605194        1.33410549        .209999998E-04
    .126000002E-09
    23.8208313         24.4831085        24.0662079        24.3850403
    24.5560406         25.1200367        1.31706429        .209999993E-04
    .146999996E-09
    23.7962799         24.3850403        23.9680634        24.2133789
    24.4095612         21.3361969        1.29979229        .204999960E-04
    .184499999E-09
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FILE: LDT191   DATA      A

          1   .134094378941631762
          2  -.238353699778213274
          4
   .999999975E-05   .999999975E-05   .184092462       .999999975E-05
   2.07499981      -.459381044E-01  -.310488999       .448988676E-01
   4.14999962      -.731928241      -.805072904       .542477071
   6.22499943      -1.40326977      -1.29965591       .754208326
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FILE: BDAT104 DATA A

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         99
  26.3218231        24.1921344        25.5150146        25.4660797
  25.4416199        24.8050079        .0001             .900000032E-05
 -.450000037E-10
  26.2973938        24.2167206        25.5150146        25.4660797
  25.4416199        26.4683838        .767654041E-03    .900000032E-05
 -.539999989E-10
  26.3951111        24.2167206        25.5394897        25.5394897
  25.6862640        25.6373444        .0001             2.03146839
  6.14424601
  26.3462524        24.2412415        26.1996613        26.3705818
  26.7857971        24.8050079        .0001             2.03146839
  6.13693523
  26.3462524        24.2412415        26.4683838        26.7369843
  27.2006073        26.4683838        .767654041E-03    2.03131339
  6.12458229
  26.3706818        24.2412415        26.5904846        26.9810333
  27.4932098        26.0774689        .153530808E-02    2.03166771
  6.09792137
  26.3462524        24.2657623        26.6881561        27.1518250
  27.7125702        24.0204773        .767654041E-03    2.03166771
  6.07613237
  26.3462524        24.2412415        26.7369843        27.2493744
  27.9074707        24.0940704        .0001             2.03136826
  6.05903435
  26.3462524        24.2657623        26.7369843        27.2493744
  28.0048931        25.3681946        .0001             2.03151798
  6.05155849
  26.3706818        24.2412415        26.7125702        27.2249908
  28.0536041        26.5172272        .153530808E-02    2.03171825
  6.04727540
  26.3462524        24.2657623        26.7125702        27.1762085
  28.0779572        24.9764862        .767654041E-03    2.03136798
  6.04486087
  26.3462524        24.2412415        26.7369843        27.2006073
  28.0779572        23.6277771        .0001             2.03221798
  6.04348273
  26.3462524        24.2657623        26.7613831        27.2493744
  28.0536041        24.6580048        .0001             2.03171825
  6.03955841
  26.3462524        24.3393250        26.8102112        27.2981567
  28.1023102        26.1263425        .767654041E-03    2.03211734
  6.04013729
  26.3462524        25.0744324        26.8346100        27.3225403
  28.1266632        26.2240906        .153530808E-02    2.03196812
  6.03867531
  26.3462524        25.1478832        26.8834229        27.3713074
  28.1999916        25.0499420        .767654041E-03    2.03196812
  6.03634711
  26.3462524        25.1968536        26.9322357        27.3956909
  28.2970734        23.9468689        .0001             2.03186798
  6.03634957
  26.3462524        25.2213287        26.9566345        27.4444580
  28.3944244        25.2702942        .0001             2.03221798
  6.03880682
  26.3218231        25.2458191        26.9810333        27.4932098
  28.4674377        26.9322357        .153530808E-02    2.03196812
  6.03725338
  26.3218231        25.2702942        27.0298462        27.5419617
  28.5160980        25.7107239        .767654041E-03    2.03146839
  6.03373623
  26.3462524        25.3192444        27.0542297        27.5907135
  28.5890961        24.1676636        .0001             2.03261757
  6.03979397
  26.3218231        25.3437195        27.0786285        27.6394501
  28.6134136        24.4864349        .0001             2.03216839
  6.03763499
  26.3218231        25.3437195        27.1030273        27.6882019
  28.6377411        25.9306014        .767654041E-03    2.03231812
  6.03788662
  26.3218231        25.3681946        27.1518250        27.7612915
  28.6620636        26.1996613        .153530808E-02    2.03171825
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FILE: BDAT194   DATA   A

6.03569794			
26.3462524	25.3437195	27.1762085	27.7856598
28.6864014	24.7805176	.767654041E-03	2.03221793
6.03921509			
26.3462524	25.3192444	27.2249908	27.8100231
28.6864014	23.6487091	.0001	2.03271770
6.04212379			
26.3462524	25.2947693	27.2249908	27.8343811
28.6864014	24.8785095	.0001	2.03191757
6.04055882			
26.3462524	25.2947693	27.2737732	27.8587494
28.7107239	26.3951111	.767654041E-03	2.03216839
6.04272461			
26.3462524	25.2947693	27.2981567	27.8831177
28.7107239	25.5150146	.767654041E-03	2.03246784
6.04585266			
26.3462524	25.2947693	27.3469238	27.9074707
28.7350464	24.3883667	.767654041E-03	2.03271770
6.04883194			
26.3706818	25.6574524	27.3713074	27.8587494
28.6377411	24.6580048	.0001	2.03271770
6.05106831			
26.3462524	26.0530243	27.3956909	27.8100281
28.6620636	26.3706818	.767654041E-03	2.03251839
6.05087943			
26.3462524	25.9063416	27.5175934	27.9074707
28.9052582	26.1507874	.153530808E-02	2.03266811
6.05396343			
26.3462524	25.8329926	27.5907135	28.0292511
29.0754395	24.5354614	.767654041E-03	2.03286839
6.05497074			
26.3706818	25.8329926	27.6638336	28.1266632
29.1726532	24.3638458	.0001	2.03271770
6.05635357			
26.3706818	25.7840881	27.6882019	28.2240448
29.2455597	26.2973938	.767654041E-03	2.03281784
6.05705733			
26.3706818	25.7840881	27.7369385	28.2727356
29.3427429	26.2973938	.153530808E-02	2.03236839
6.05944252			
26.3706818	25.7840881	27.7612915	28.3214111
29.3913269	24.6089783	.767654041E-03	2.03241825
6.05830479			
26.3951111	25.7351685	27.7856598	28.3457489
29.4642029	24.2902832	.0001	2.03251839
6.06063557			
26.3706818	26.4439545	27.9074707	28.3700867
29.7798615	26.4195404	.767654041E-03	2.03281734
6.06193633			
26.3951111	26.6637421	28.3944244	28.6809509
30.7257533	26.4633838	.306036592E-01	2.03301811
6.06029701			
26.3706818	26.8834229	30.1438599	30.0710907
32.1294403	24.3148041	.105168581	2.03271770
6.04314041			
26.3951111	26.9506345	31.9360352	32.2502747
33.6018219	23.7996216	.304758668	2.03281734
6.02026367			
26.3951111	26.3951111	33.5777130	34.6373291
35.1422340	24.7560120	.462127745	2.03311825
5.99268818			
26.3951111	26.3218231	34.9500122	36.3942108
36.4387817	27.1513250	.577275613	2.03261784
5.96436119			
26.3951111	26.2973938	36.0549774	38.9270020
37.5407410	26.6881561	.821389794	2.03311825
5.93901443			
26.3951111	26.2729645	36.8702393	40.6905975
38.5449371	23.7505188	.944982111	2.03296757
5.91621304			
26.3951111	26.2485199	37.4923741	42.0689392
39.4042053	24.0450134	1.40327163	2.03316784

FILE: BDAT194 DATA A

5.89585400 26.3951111 40.0954235	26.2240906 25.5684094	37.9952393 1.83699603	43.2070150 2.03291798
5.87276649 26.3951111 40.8095551	26.1996613 27.0054474	38.4732666 2.30142639	44.2245636 2.03306770
5.85327625 26.3951111 41.9739838	26.1752167 24.9274902	38.9747467 2.93934727	45.2402191 2.03316784
5.83546829 26.3951111 42.8042145	26.1507874 23.5295563	39.4042053 3.61181259	46.1126709 2.03321833
5.81853294 26.4195404 43.4674938	26.1263428 24.1676036	39.7856750 4.09082794	46.9131775 2.03331757
5.80377293 26.3951111 44.0353851	26.1263428 26.0530243	40.0954285 4.64277172	47.8064728 2.03331757
5.78730297 26.4195404 44.6026917	26.0774689 26.2973938	40.3097687 5.37050724	48.1352234 2.03288839
5.77240181 26.3951111 45.1458130	26.0774689 24.3638458	40.4526062 6.01764011	48.5576172 2.03341770
5.76847563 26.3951111 45.6884155	26.0774689 23.8977814	40.5954132 6.45904064	49.4248657 2.03331757
5.76371670 26.4195404 46.2069092	26.0530243 25.9063416	40.7357666 6.79680920	51.2253265 2.03336811
5.76080799 26.4195404 46.8601194	26.0285797 26.7613831	41.1425013 7.02556992	52.8570862 2.03336811
5.76019764 26.4195404 47.3365021	26.0041351 25.0009766	41.5702820 7.23667431	54.5537109 2.03341770
5.76257610 26.4439545 47.8534546	26.0041351 23.8732452	42.0214691 7.09250851	56.5227661 2.03346325
5.76617527 26.4195404 48.5186904	25.9796906 25.8085480	42.4722748 7.46236515	58.7613831 2.03376770
5.77170372 26.4195404 49.0500051	25.9308014 26.8834229	42.3753204 7.52608013	61.1287842 2.03346325
5.77654552 26.4439545 49.2140350	25.9063416 25.5394897	43.1359558 7.59133053	63.5091553 2.03351784
5.78563493 26.4439545 49.9164734	25.9308014 23.7996216	43.3698120 7.65504646	65.7836047 2.03351784
5.79315948 26.4195404 50.6414032	25.9063416 24.4374034	44.6371393 7.68191433	67.9683228 2.03346825
5.79993057 26.4439545 51.3137103	25.8818970 26.4439545	45.7005737 7.72797298	70.0946198 2.03316784
5.80842781 26.4439545 52.0884247	25.8574524 26.8834229	47.2659607 7.75789093	72.0555878 2.03341770
5.81991863 26.4439545 52.7639771	25.8818970 25.0744324	48.5748962 7.79706192	74.5478821 2.03346825
5.83063916 26.4439545 53.3224335	25.8574524 23.6763799	50.0100708 7.80243587	77.3766327 2.03321833
5.84028816 26.4439545 53.9267883	25.8329926 25.7340881	51.2486725 7.83237457	80.8093297 2.03326797
5.85324192 26.4439545 54.4144440	25.8574524 26.8590240	52.4146576 7.85310078	84.2795363 2.03316784

FILE: BDAT194 DATA A

5.87003231			
26.4195404	25.8329926	53.6479340	88.6704407
54.9248810	26.6149139	7.85617161	2.03291798
6.07829475			
26.4439545	25.8574524	54.9248810	92.3992310
55.3885040	25.2213237	7.88341248	2.03281784
6.07271004			
26.3951111	25.8329926	55.1799164	94.3525238
54.6929321	23.5050049	7.89608955	.370000052E-04
.562399904E-08			
26.2240906	26.3951111	37.4450073	94.0707703
53.0605436	26.3102112	7.89455414	.365000014E-04
.500050135E-08			
26.2729645	26.2485199	33.6741180	93.1378784
51.2253265	23.9959412	7.89532185	.359999976E-04
.421200141E-08			
26.3462524	26.3462524	32.1294403	91.4419703
49.3780212	23.5295563	7.89608955	.354999938E-04
.365649999E-08			
26.1752167	26.3462524	30.0468292	89.6321106
47.5480347	25.9552460	7.89608955	.354999938E-04
.326599991E-08			
26.0041351	26.1507874	29.0754395	87.7510376
45.8534393	27.0298462	7.89532185	.350000046E-04
.297500002E-08			
25.9063416	26.1018982	28.8809509	84.5879974
44.2718353	24.9274902	7.67730808	.350000046E-04
.206499995E-08			
25.8329926	26.1018982	27.5663452	70.7941284
40.2621460	23.2593536	6.45136452	.339999970E-04
.190400007E-08			
25.7596283	26.1018982	25.9063416	38.6882324
32.4918671	23.9959412	4.35566902	.334999932E-04
.140700007E-08			
25.7107239	26.1507874	25.8329926	27.6633336
28.3457439	26.6393230	4.08391953	.334999932E-04
.140700007E-08			
25.6862640	26.2485199	25.7840831	26.2729645
27.0786285	26.3951111	4.02097225	.330000039E-04
.132000011E-08			
25.6618042	26.2729645	25.7596283	26.0530243
26.5416565	23.8732452	3.97951889	.325000001E-04
.120250010E-08			
25.6128693	26.2240906	25.7351685	25.9552460
26.2973938	23.7505188	3.94113541	.319999963E-04
.115200005E-08			
25.6128693	26.0774689	25.7351685	25.9063416
26.0530243	25.5639496	3.91042995	.315000070E-04
.110250009E-08			
25.5884094	25.9552460	25.6862640	25.8574524
25.9063416	27.0786285	3.89584446	.315000070E-04
.107099996E-08			
25.5639496	25.8329926	25.6618042	25.7596283
25.8329926	25.9552460	3.87511730	.310000032E-04
.102299991E-08			
25.5639496	25.7840831	25.6373444	25.7107239
25.7840831	23.6523235	3.86897659	.304999994E-04
.100649999E-08			
25.5394897	25.7596283	25.6128693	25.6862640
25.7351685	23.9468689	3.85399639	.304999994E-04
.975999946E-09			
25.5639496	25.7107239	25.6128693	25.6618042
25.7107239	26.3951111	3.84517860	.299999956E-04
.930000077E-09			
25.5394897	25.6862640	25.5884094	25.5884094
25.6862640	26.6834229	3.83057406	.299999956E-04
.900000074E-09			
25.5394897	25.6373444	25.5639496	25.5884094
25.6618042	25.2458191	3.82368469	.295000063E-04
.885000073E-09			
25.5394897	25.6373444	25.5639496	25.5884094
25.6373444	23.6032257	3.81370544	.290000025E-04

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FILE: BDAT194   DATA      A

  .840999936E-09
  25.5639496          25.6128693          25.5639496          25.5884094
  25.6128693          24.9519806          3.30602837          .234999937E-04
  .826499980E-09
  25.5394897          25.5884094          25.5394897          25.5639496
  25.5884094          26.9073369          3.79988766          .279999949E-04
  .812000023E-09
  25.5394897          25.5639496          25.5394897          25.5639496
  25.5884094          26.4683838          3.79221058          .275000057E-04
  .797500066E-09
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FILE: LBDT194   DATA      A

          1    .802528999780172392E-01
          2   -.908548909572918506E-01
          5
   .999999975E-05   .999999975E-05   .802519321E-01   .999999975E-05
   2.07499981       -.230014426E-01  -.108270943       .276130289E-01
   4.14999962       -.201978683      -.296794832       .182887673
   6.22499943       -.594792068      -.465318720       .448322773
   8.29999924       -.659213066      -.673842609       .482741833
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FILE: BDAT196   DATA      A

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  26.2843170        25.1347961        26.3820343        26.2354534
  25.6487122        38.9142303        .0                .120000004E-04
-.840000014E-10
  26.2843170        25.1103058        26.3576202        26.2354584
  25.6487122        38.9142303        .0                .120000004E-04
-.720000032E-10
  26.3576202        25.1347961        27.1875610        27.6751556
  24.5223389        38.9380951        .116218720        2.03567410
  6.36687133
  26.3331909        25.1347961        29.0381317        30.6400909
  27.3338776        38.9142303        .396877110        2.03562355
  6.72233368
  26.3331909        25.1592712        30.7612610        33.7576294
  30.3976746        38.7709808        .792986631        2.03552437
  6.72892952
  26.3087463        25.1592712        32.6233556        36.6417389
  33.4442749        38.9142303        1.25511456        2.03547382
  6.68011665
  26.3087463        25.1592712        34.3838196        39.2960358
  34.5522766        38.8426056        2.03888693        2.03592396
  6.54376125
  26.3087463        25.1347961        35.6820526        41.7476044
  39.6775818        38.8664856        4.02557755        2.03607363
  6.56256771
  26.3087463        25.1592712        37.3603821        44.0936390
  41.0584564        38.9380951        5.12639332        2.03587437
  6.58961135
  26.3087463        25.1592712        40.4398604        46.3827362
  41.8425751        38.8426056        5.71595192        2.03597355
  6.52315521
  26.3087463        25.1592712        41.3912506        49.0140223
  43.5021320        38.8664856        6.13662624        2.03562355
  6.51796246
  26.2843170        25.1837616        42.1274414        51.6795654
  44.9679413        38.7471008        6.40684032        2.03597355
  6.54229259
  26.2843170        25.1592712        42.9574432        54.2859650
  46.3120380        38.8187408        6.62485400        2.03562355
  6.53078651
  26.3087463        25.1592712        44.3262634        57.0651245
  47.6294556        38.6993408        6.39430046        2.03587437
  6.62014961
  26.2843170        25.1592712        47.8643799        60.1933032
  48.6858063        38.7471008        7.10156727        2.03572369
  6.62800789
  26.2843170        25.1592712        49.5294189        63.5654602
  49.2952118        38.6993408        7.22669506        2.03627396
  6.20421696
  26.2843170        25.1592712        49.6889160        66.7765350
  49.9975586        38.8277008        7.40246775        2.03597355
  6.28861454
  26.3087463        25.1837616        49.6699066        69.6082001
  51.0960999        38.6038208        7.50995922        2.03592396
  6.34077930
  26.3087463        25.1592712        49.6464996        72.6058350
  52.0293427        38.6993408        7.54987717        2.03627396
  6.37750435
  26.2843170        25.1592712        50.6990051        75.4090424
  52.7960304        38.6993408        7.58902740        2.03607368
  6.48031044
  26.3087463        25.1347961        53.1936798        76.5711975
  52.7282410        38.4365997        7.60608373        .255000050E-04
  .400349975E-08
  26.2843170        25.1592712        52.9377239        76.2535449
  51.3995819        38.5321503        7.60663373        .250000012E-04
  .292500002E-08
  26.2843170        25.1592712        51.9593964        75.5879822
  50.1379089        38.5799255        7.60663373        .244999974E-04
  .237650011E-08
  26.2843170        25.1592712        50.7924652        74.4014435
  49.0608978        38.5082703        7.60663373        .244999974E-04
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FILE: BDAT196 DATA A

.208249995E-08 26.2843170 47.9113464	25.1592712 38.6038208	49.1780701 7.60668373	73.0777130 .239999936E-04
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.155100000E-08 26.2598877 44.9443359	25.1837616 38.5321503	49.1077728 7.60668373	69.8567047 .235000043E-04
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.835999936E-09 26.2598877 39.0574341	25.1837616 38.5082703	43.4785156 7.60668373	61.7354736 .215000036E-04
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.292500024E-09 26.3087463 33.2272186	25.2082367 38.3649139	39.6060638 7.19829173	50.7924652 .189999992E-04
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26.3331909	25.2082367	34.9131012	43.1706696
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26.4064636	25.3061523	30.2270205	37.0733438
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27.0899811	38.1259003	5.55167389	.160000054E-04
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27.0411835	38.0780945	5.51712990	.160000054E-04
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26.4064636	25.3306274	30.0338440	36.2340851
26.9679871	38.0780945	5.47797966	.160000054E-04
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26.4308929	25.3551025	29.8397064	34.7637983
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26.4308929	25.3306274	29.3783264	34.4800873
26.5041656	37.9107056	5.23002720	.160000054E-04
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26.4553223	37.9585419	5.17782683	.164999947E-04
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26.3820343	37.9824524	5.15019131	.160000054E-04
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8.29999924	-.251444168E-01	-.244386643E-01	.248309113E-01
10.3749990	-.330422111E-01	-.335768797E-01	.325022899E-01
12.4499989	-.404772274E-01	-.427150987E-01	.396639400E-01
14.5249987	-.473326745E-01	-.513533140E-01	.462299176E-01
16.5999908	-.549817035E-01	-.609914996E-01	.534975119E-01
18.6749878	-.615081340E-01	-.701296926E-01	.596547052E-01
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