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Interim Report 64-MDC-A-77

A STUDY OF PRESSURE TIME CURVES FOR SMALL CALIBER AMMUNITION

Sep 69

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U.S. ARMY ARMAMENT COMMAND

Munitions Development and Engineering Directorate

U.S. ARMY ARMAMENT COMMAND
FRANKFORD ARSENAL
PHILADELPHIA, PENNSYLVANIA 19137

FINGERPRINTING AMMUNITION ON A HYBRID COMPUTER*

For

Frankford Arsenal
Philadelphia, Pennsylvania

F. J. Shinaly, Consultant

*Work performed by P.J. Dionne, Senior Development Engineer and L.E. Addison, Engineer of

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Fingerprinting Ammunition on a Hybrid Computer

INTRODUCTION

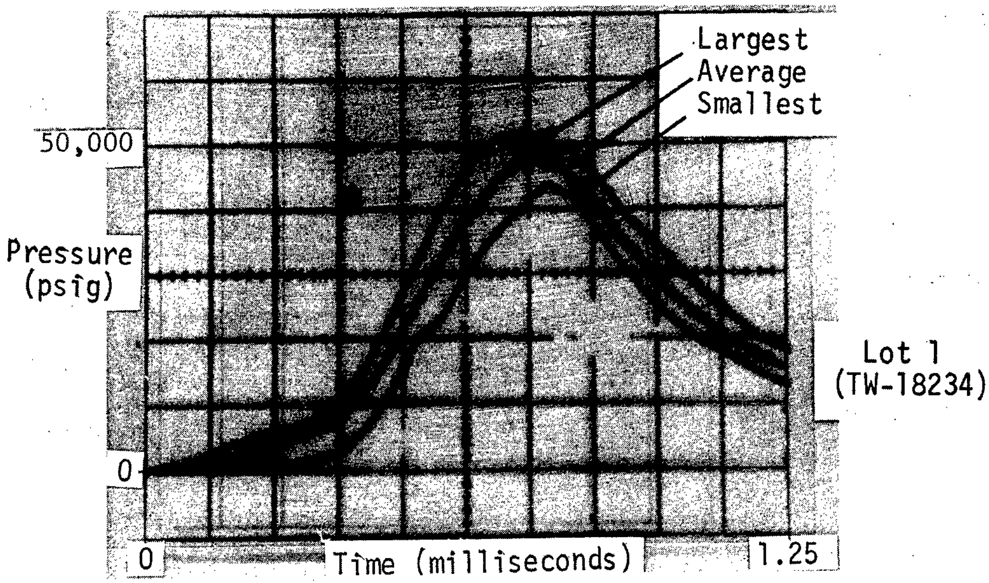
Computers have already been used to fingerprint ammunition. Geene[1] states that his model provides an "aid in defining more meaningful acceptance criteria for small arms propellants." Geene's study was aimed at illuminating the reasons for ammunition causing weapon performance failures after passing acceptance tests. Geene's "Energy Equation" model does provide some insights into propellant burn and projectile dynamics, however his model does not match the data very well.

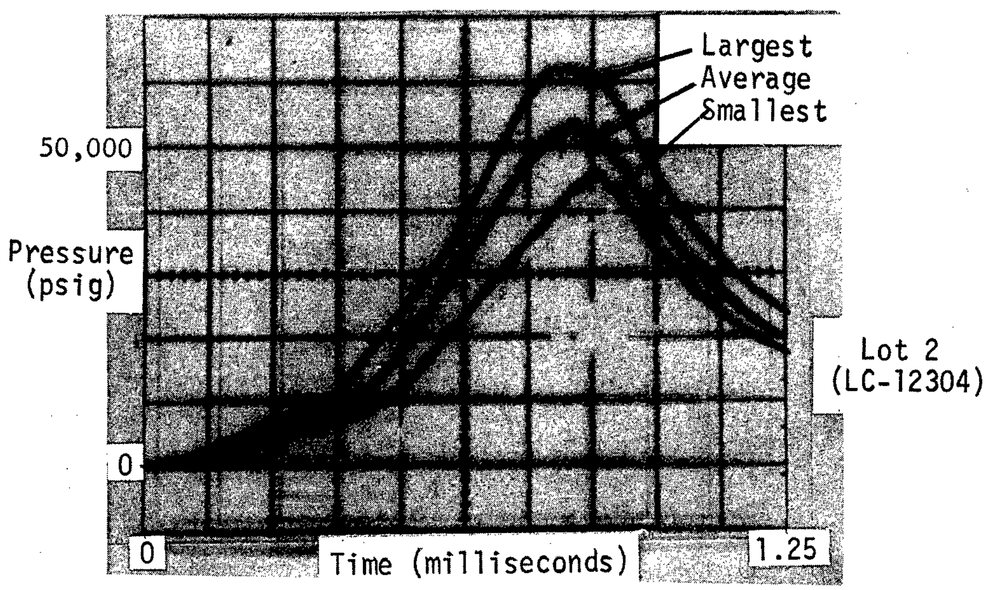
Instead of beginning our work by using Geene's model as a springboard, our approach has been to develop a set of non-linear differential equations which describe the dynamics of the physical system. The simulation of these differential equations was performed on an EASE 2133 analog computer and a PDP-7 digital computer connected through 24 channels of analog/digital and digital/analog converters.

SUMMARY

This report summarizes the techniques used and the results obtained by fingerprinting ammunition on a hybrid computer.

A FORTRAN program was used to calculate the average chamber pressure versus time as well as the largest and smallest pressure used for the average of ten lots of ammunition (20 rounds per lot). The data points were taken from 200 photographs furnished by Frankford Arsenal. Figures 1a-1e show the largest, average and smallest pressures versus time for each of the furnished lots. The variation between the largest and smallest pressures is greater for ball propellant (Lots 1, 2, 5-8, 10) than for the IMR propellant (Lots 3, 4, 9).


Largest
Average
Smallest
50,000
Pressure
(psig)
0
0
Time (milliseconds)
1.25
Lot 1
(TW-18234)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Pressure
(psig)
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Time (milliseconds)
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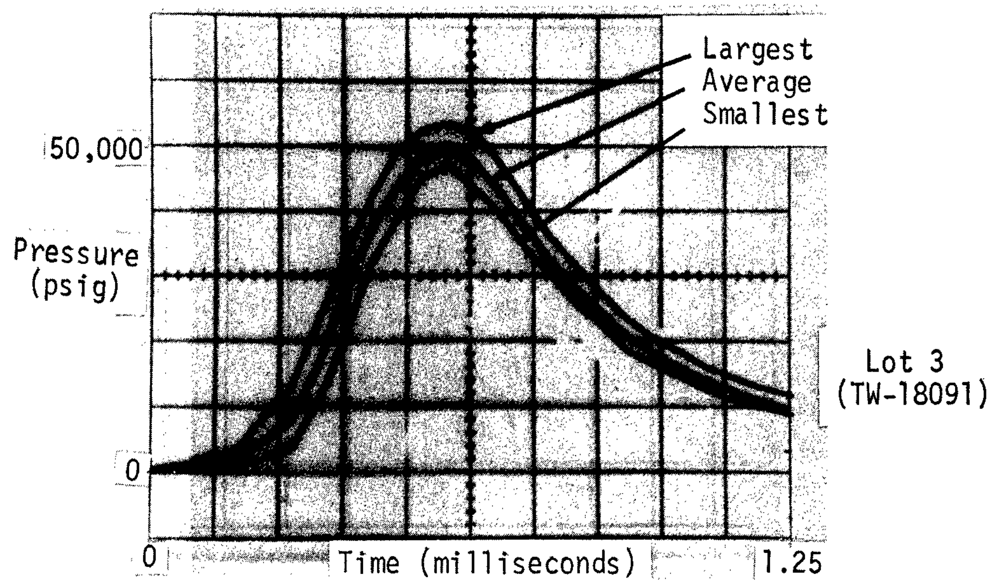
Lot 2
(LC-12304)

Figure 1a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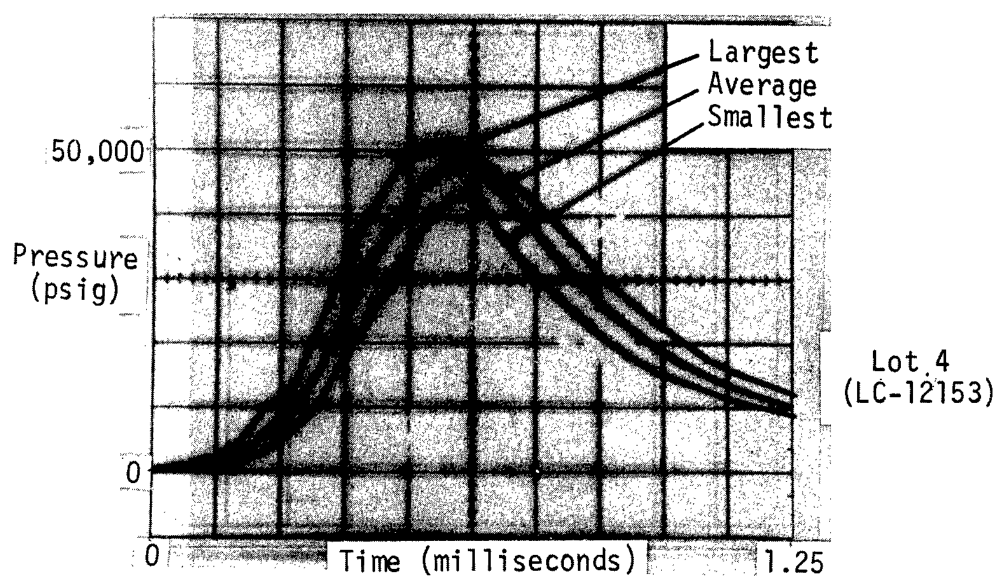
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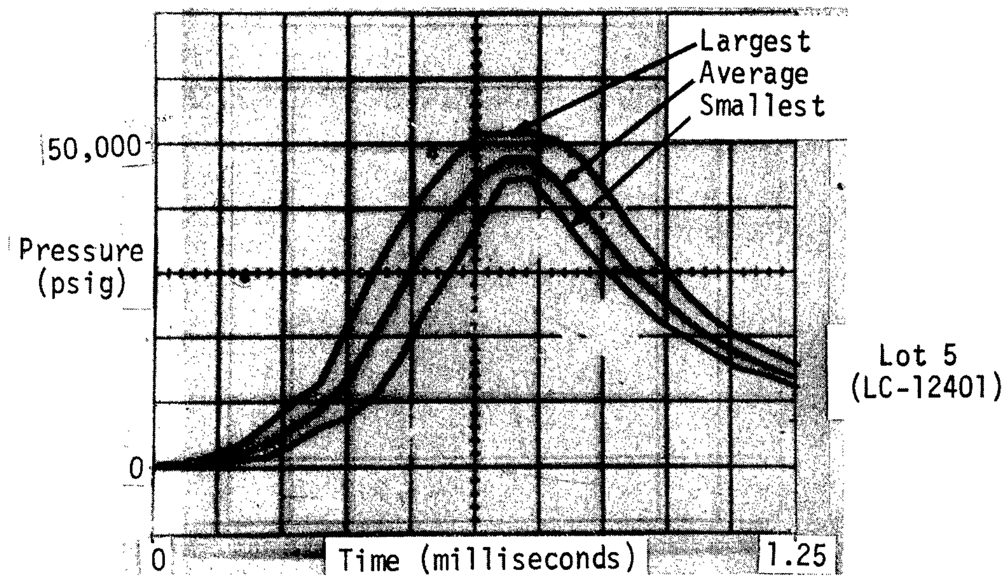
Average
Smallest
50,000
Pressure (psig)
0
0
Time (milliseconds)
1.25
Lot 4 (LC-12153)

Figure 1b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Average
Smallest
50,000
Pressure (psig)
0
0
Time (milliseconds)
1.25
Lot 5 (LC-12401)

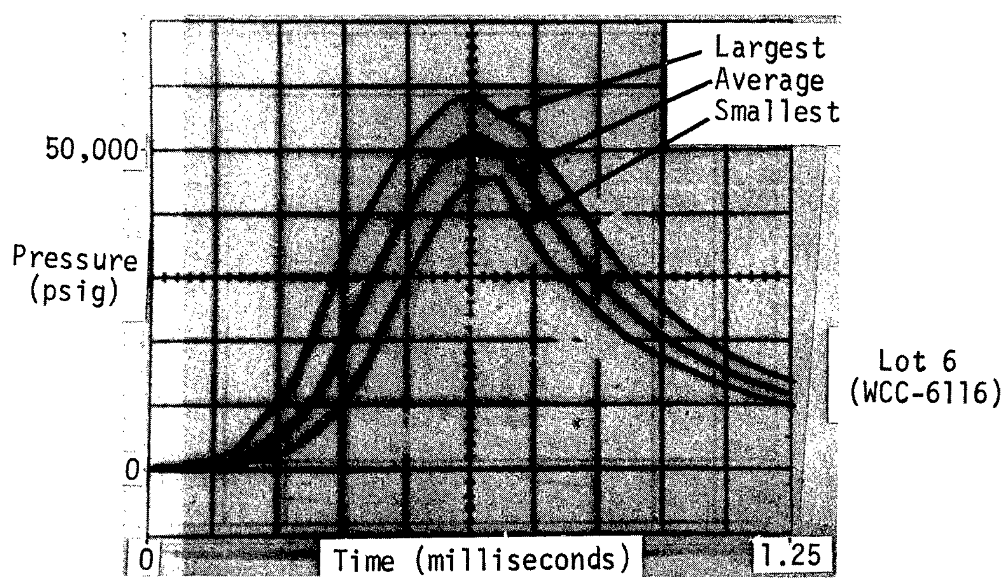
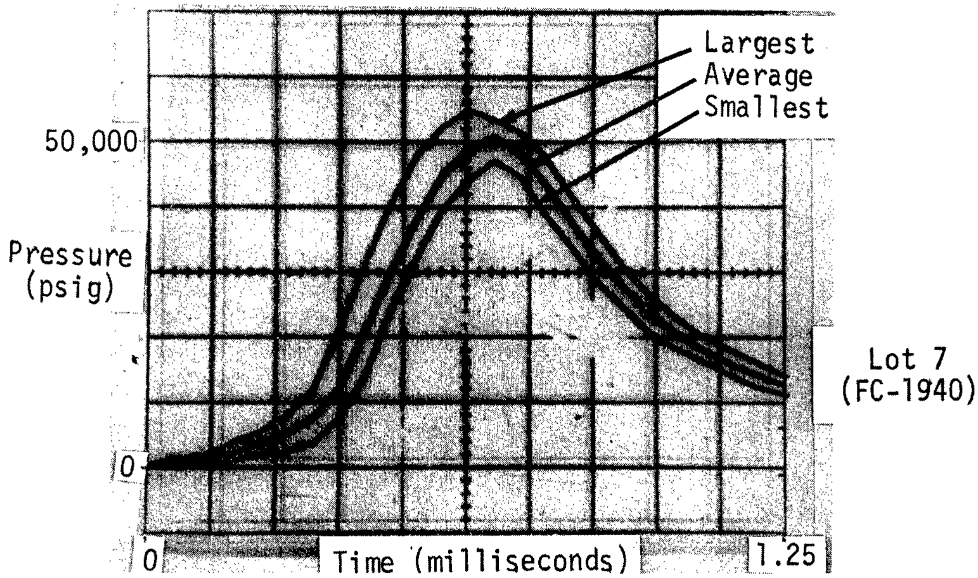
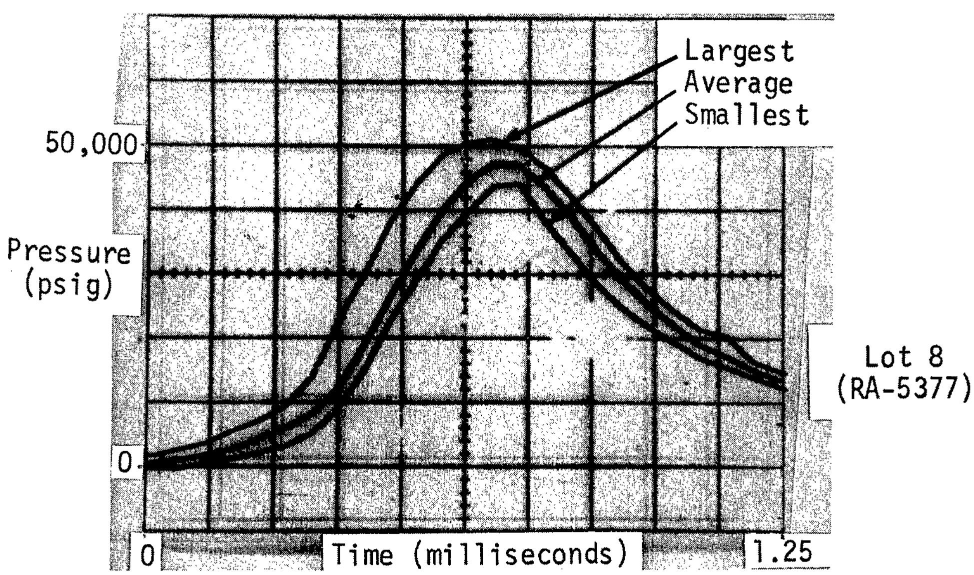

Largest
Average
Smallest
50,000
Pressure (psig)
0
0
Time (milliseconds)
1.25
Lot 6 (WCC-6116)

Figure 1c


Largest
Average
Smallest
50,000
Pressure
(psig)
0
0
Time (milliseconds)
1.25
Lot 7
(FC-1940)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Average
Smallest
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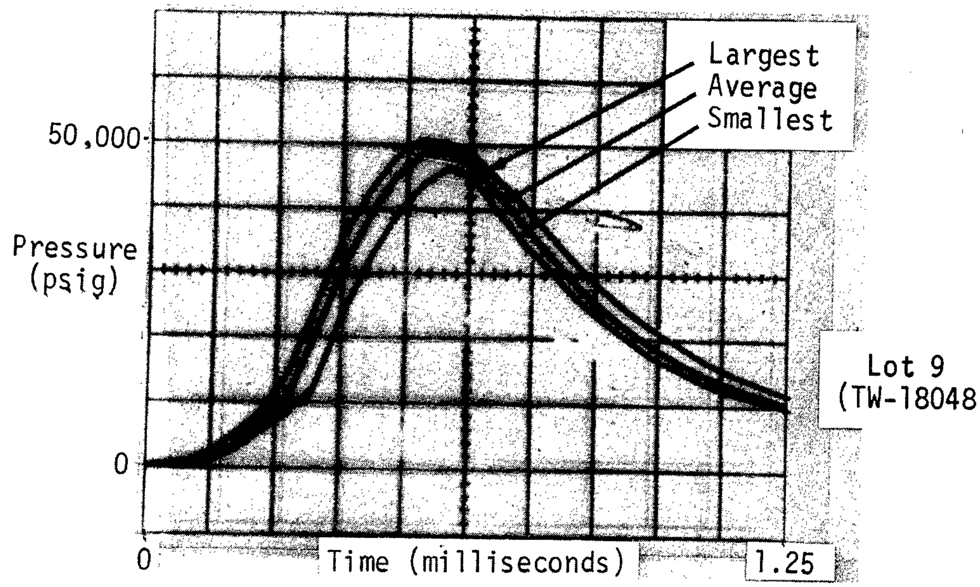
Pressure
(psig)
0
0
Time (milliseconds)
1.25
Lot 8
(RA-5377)

Figure 1d


Largest
Average
Smallest
50,000
Pressure
(psig)
0
Lot 9
(TW-18048)
0
Time (milliseconds)
1.25

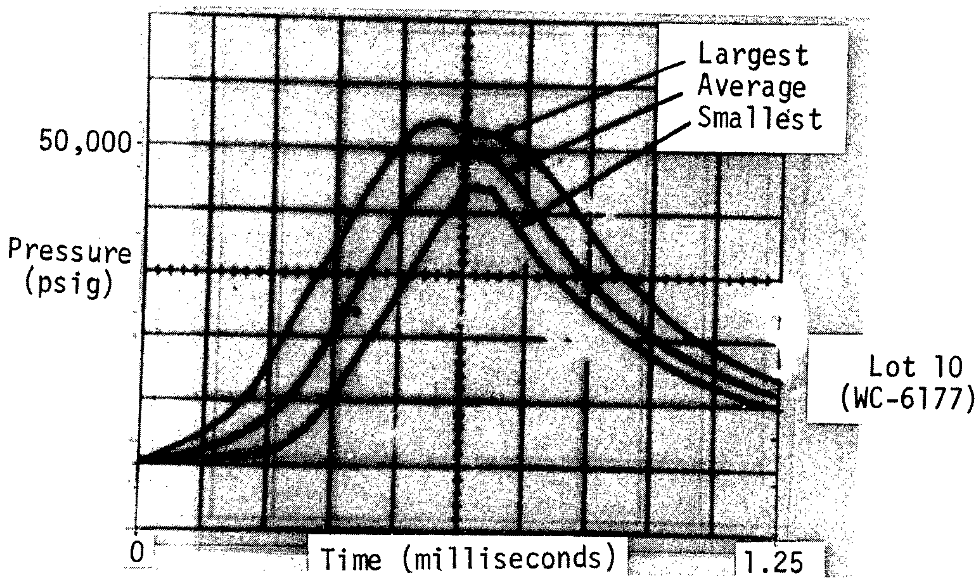

Largest
Average
Smallest
50,000
Pressure
(psig)
Lot 10
(WC-6177)
0
Time (milliseconds)
1.25

Figure 1e

A hybrid computer model was developed using differential equations to describe the amount of propellant burned, the pressure buildup and decay, the volume behind the projectile, and the acceleration, velocity and position of the projectile within the muzzle. The coefficients of the terms of the differential equations were then adjusted so that the model curve matched the average data curves for the ten lots. Table 1 shows the value of the coefficients or parameters of the model for each lot.

Frankford Arsenal furnished seven unknown pressure-time curves to test the fingerprinting capability of our approach. Unfortunately, the unknown data did not come from the same lots that the averages were computed from. Nor were the data taken at the same ambient temperatures. Also, it would have been desirable to test our approach more thoroughly through many more unknown pressure-time curves, but the contract time expired. The results of the unknown mathcings are shown in Figures 2a-2c.

CONCLUSIONS

The fact that the model was matched to each lot, as verified by the results shown in Table 1, demonstrates the feasibility of our approach.

Although the unknowns were not from the same lots as furnished originally by Frankford Arsenal, some interesting observations can be made.

Figures 2a and 2b show that ambient temperature does effect the pressure-time curve. The 155^{O}F ambient temperature curve of Figure 2a made a very good match with Lot 9. The 0^{O}F curve fitted Lot 9 best but not nearly as well as the 155^{O}F curve. The 70^{O}F curve fitted Lot 3 better than Lot 9. Lots 3, 4, and 9 of the original data were IMR tracer lots so unknown TW-18179 is an IMR propellant lot.

Lot No.	$10^4\ k_1$ (sec^{-1})	$10^7\ k_2$ $(in^5/lb\text{-}sec)$	$.5\ k_3$ (lb/in^2)	$.0005\ k_4$ (lb/in^5)	$.1\ P_0$ (psig)	$10^5\ k_x$	$.001\ P_{sw}$ (psig)	$10^4\ k_a$ $(in/lb\text{-}sec^2)$
1 (TW-18234)	83.84	25.27	61.66	64.73	34.09	31.25	25.44	43.47
2 (LC-12304)	83.84	25.27	62.37	57.34	34.11	31.82	31.40	39.54
3 (TW-18091)	83.84	36.12	93.75	78.69	34.11	31.53	14.66	52.53
4 (LC-12153)	83.84	36.12	92.15	77.85	34.09	31.34	14.66	52.53
5 (LC-12401)	83.85	28.64	52.16	65.61	34.11	25.39	24.50	63.51
6 (WCC-6116)	83.85	32.31	64.83	69.30	34.11	26.28	23.84	63.87
7 (FC-1940)	83.84	30.94	60.19	68.35	34.09	25.93	23.84	63.41
8 (RA-5377)	83.84	29.58	54.87	65.72	34.09	25.97	23.84	62.58
9 (TW-18048)	83.85	47.88	89.29	65.72	34.11	27.34	13.06	62.66
10 (WC-6177)	83.85	43.93	67.25	58.90	34.38	23.83	17.08	65.84

TABLE 1 - Equation Coefficients

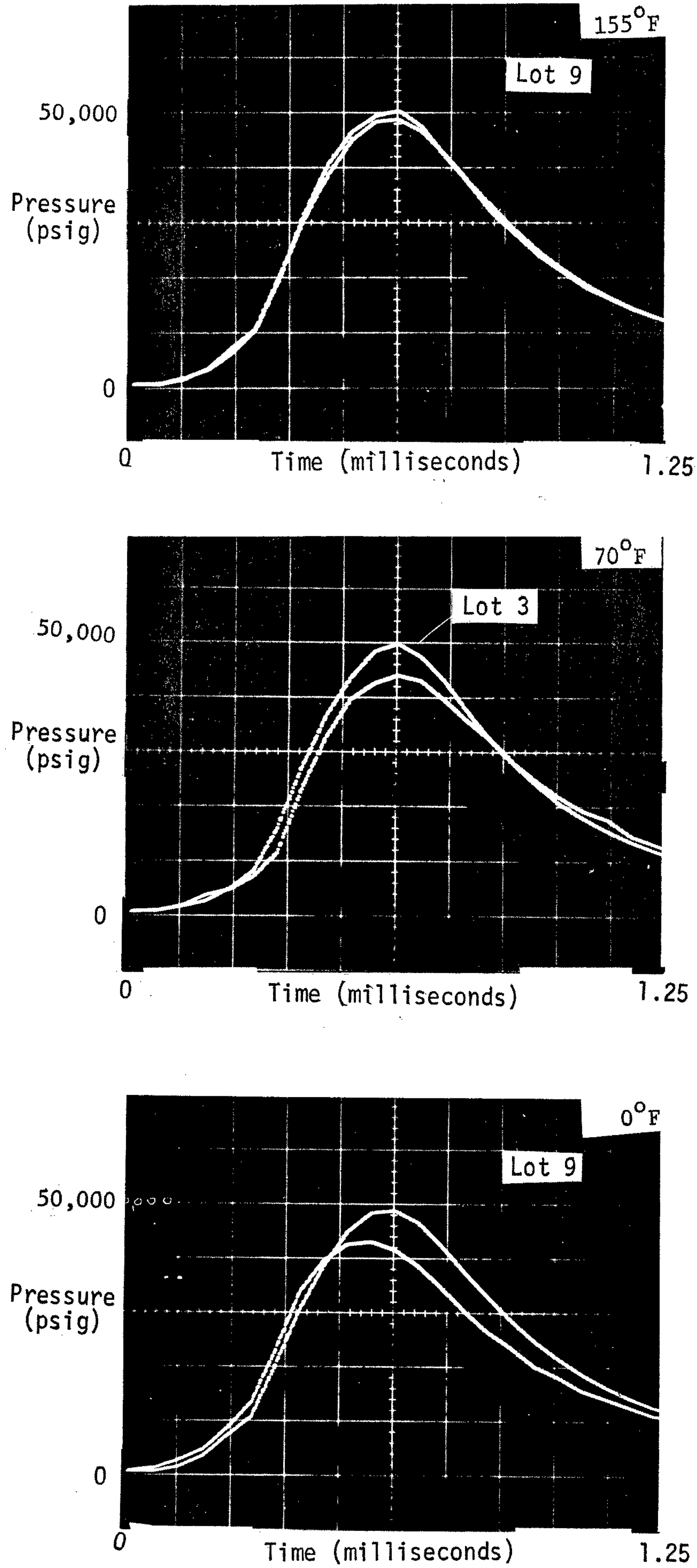


Figure 2a
Unknown Lot TW-18179

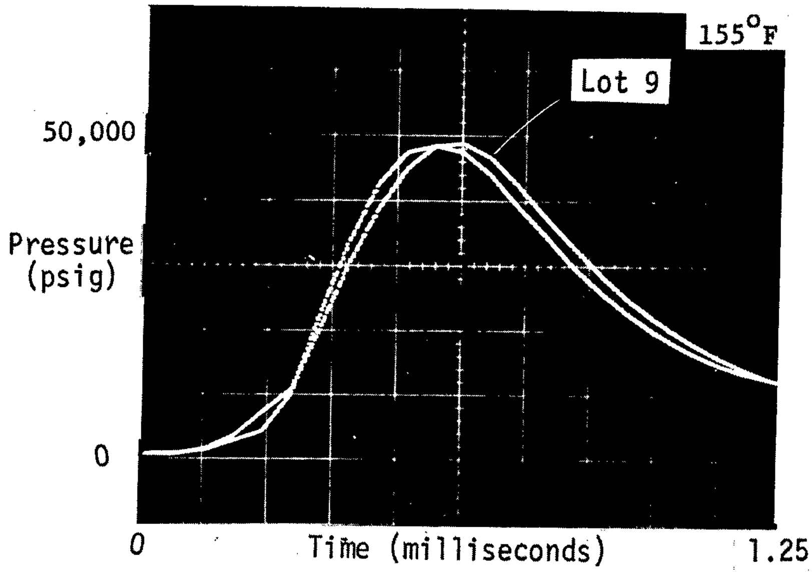
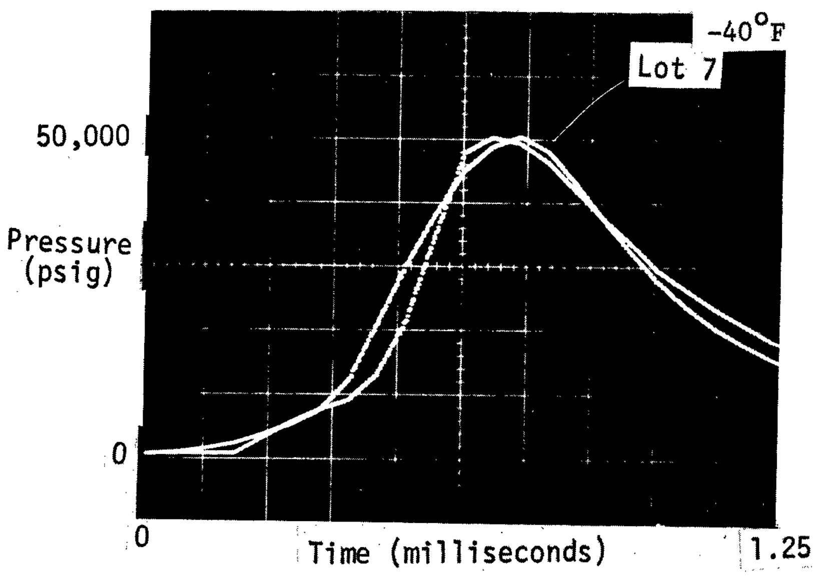


Figure 2b
Unknown Lot WCC-6101



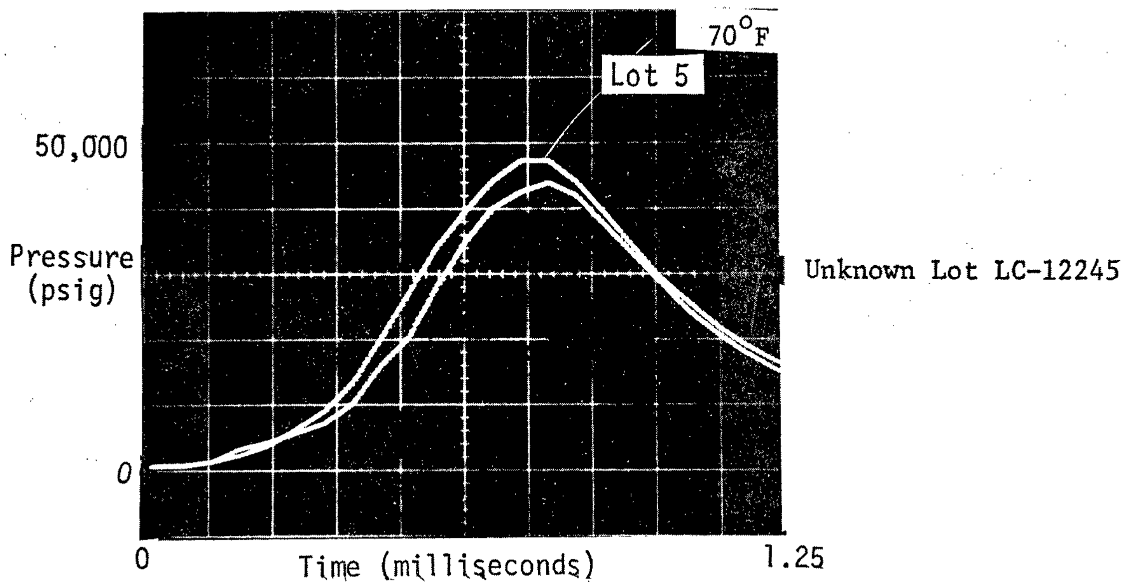
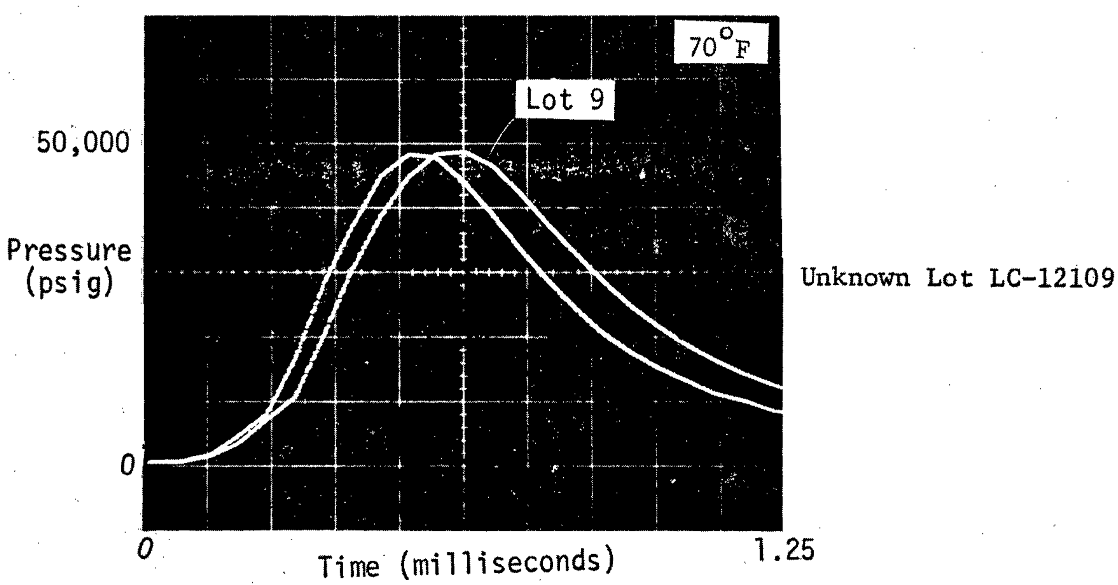

70°F
Lot 5
50,000
Pressure
(psig)
0
0
Time (milliseconds)
1.25
Unknown Lot LC-12245

Figure 2c


70°F
Lot 9
50,000
Pressure
(psig)
0
0
Time (milliseconds)
1.25
Unknown Lot LC-12109

The curves of Figure 2b show that at $-40^{o}F$ ambient temperature, the lot matches with Lot 7, but at $155^{o}F$, it matches with Lot 9. Lot 9, as already mentioned, is a IMR tracer lot, but Lot 7 is a ball propellant lot. The temperature effect of unknown WCC-6101 is so pronounced that the propellant type is disguised.

Figure 2c shows that unknown Lot LC-12245 matches with Lot 5 which is a ball propellant lot while unknown Lot LC-12109 matches with Lot 9, an IMR tracer lot. Both of these unknown were fired at $70^{o}F$ ambient temperature. All of the original lots were fired at $70^{o}F$ ambient temperature.

Now that the feasibility of this approach of fingerprinting the chamber pressure has been demonstrated by confirmation that the unknown lots were correctly identified, it would seem natural to extend the model to include the effect of temperature, and chamber pressure on the port pressure and then on to the bolt pressure. A total model would then show the direct effects of different ammunition on bolt action and the important parameters could be pinpointed.

DISCUSSION

Frankford Arsenal furnished 200 photographs of chamber pressure versus time. There were 20 photographs for each of ten lots of ammunition. The pressure-time curve was divided each into 25 equal segments corresponding to time steps of 0.05 milliseconds. The corresponding pressure for each point in time was taken from the photographs. This yielded a set of 5,000 data points which were punched on IBM cards. A typical pressure-time curve as furnished by Frankford Arsenal is shown in Figure 3. The chopped trace at the bottom is the time marker, each cycle being equal to 0.1 milliseconds.

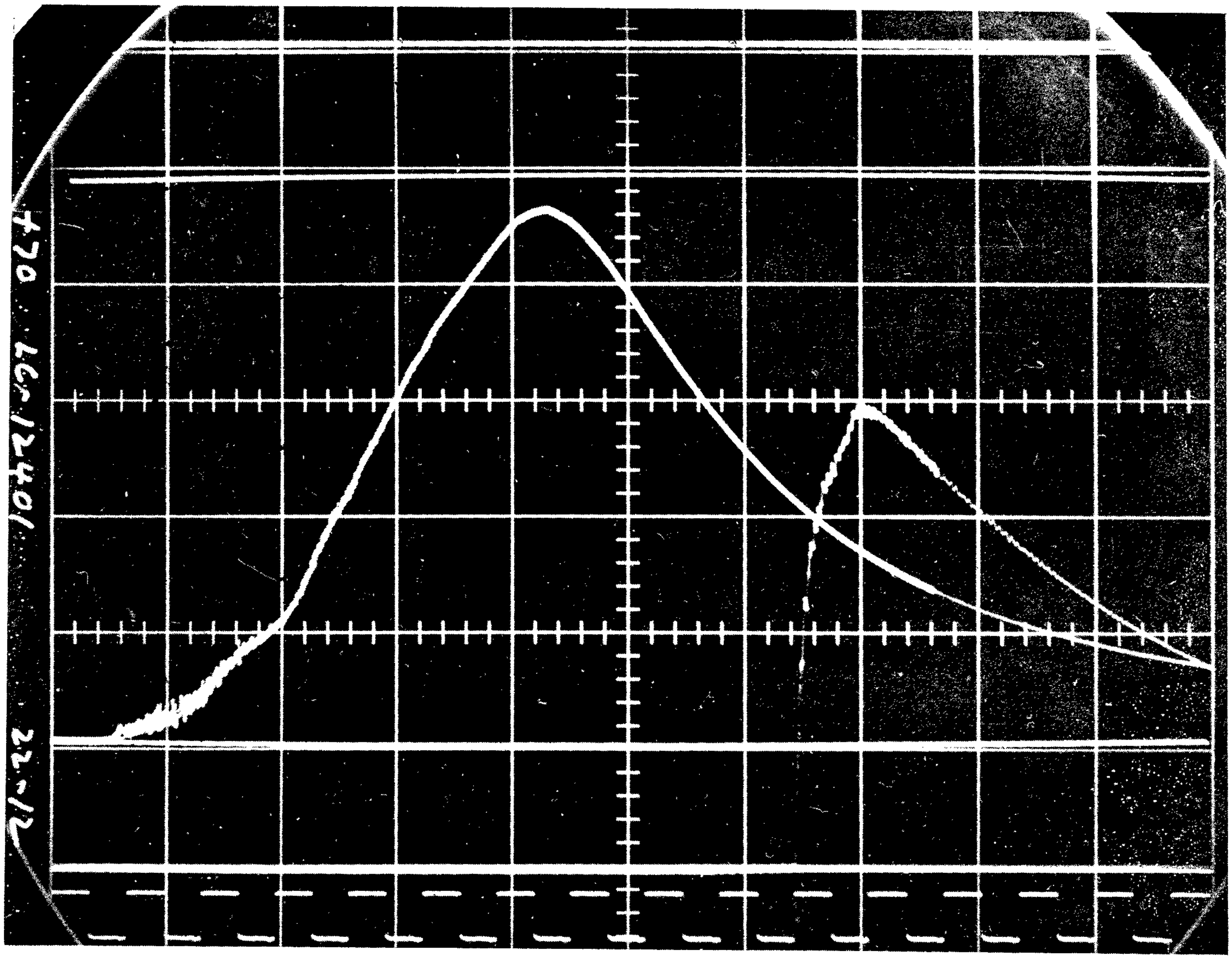


Figure 3

Typical Pressure-Time Curve

The heavy line at the top of the trace is the 60,000 psi calibration line for the chamber pressure curve while the lower heavy line is the 20,000 psi calibration line for the port pressure trace.

The chamber pressure curve is characterized by an initial burning of the propellant followed by a rapid increase of pressure due to pressure, temperature, burn-rate relationships. Part way up the pressure trace, the pressure is large enough to overcome the equivalant crimp pressure of the cartridge on the projectile and the projectile starts to move. This causes the arc of the curve to change from positive to negative since the volume is now starting to increase. The pressure is still rising however and will until the volume term becomes predominant. The initial acceleration of the projectile increases with pressure. So although the projectile is still accelerating as it leaves the muzzle, the acceleration is less as the pressure decreases.

A FORTRAN program was written which calculated the average pressure for each time interval as well as the largest and smallest pressure that went into the average calculation. The program punched IBM cards containing the biggest, smallest and average pressures. The FORTRAN program was run on a UNIVAC 1108 digital computer.

Figure A1 of the Appendix is the flow chart of the FORTRAN program (Figure A2). The IBM cards containing the 780 pressure data points are read into the computer and immediately printed out for checking purposes. The average for each point in time is computed by summing the pressure points and dividing by 20. As the average is being computed the maximum and minimum pressures that went into the computation are saved. The program then prints a list of the largest, smallest and average pressure for each point in time. Lastly, a set of IBM cards containing the largest, smallest and average pressure for each point is punched. The program then returns to the beginning and reads-in the next set of data. The programs continues through this loop until all of the lots have been inputed.

The FORTRAN program was written so that the PDP-7 (digital portion of the hybrid computer) would not have to store 5,200 data points in core memory. The core memory contains 8,192 cells. Instead, the data has been reduced to three sets of 26 points per lot or 780 core cells. This leaves a larger portion of memory available for data manipulation and model simulation.

For a complete description of BNW's Hybrid Computer I and our software (SIMPL-1) see Reference 2. That paper describes our approach to hybrid simulation.

The punched cards from the FORTRAN program were read into the hybrid computer and stored in data tables. By selecting switches on the digital computer console any one of the ten lots may be displayed along with the maximum and minimum values.

By simply using the averages as generated by the FORTRAN program, the following groupings can be made (see Figures 1a-1e).

Group	I	LOT#	5,8
Group	II	LOT#	6,10
Group	III	LOT#	3,4,9
Group	IV	LOT#	1
Group	V	LOT#	2
Group	VI	LOT#	7

The average of Lots 5 and 8, which make up Group I, are almost identical. The two curves displayed simultaneously on the oscilloscope almost gives the appearance of being one curve. There exists only very minute differences between the averages. Both of those lots are ball type propellant.

The averages of Lots 6 and 10 which make up Group II differ in the rate of increase in pressure and the peak pressure attained. They agree in that the peak pressure occurs at the same time and the pressure decay for both is practically identical. Lot 6 is a tracer with ball propellant and Lot 10 is a ball propellant.

The averages of Lots 3, 4, and 9 which compose Group III, are grouped together because they are very similar in rate of rise in pressure, peak pressure, time of peak pressure and pressure decay. Although these lots are very similar each one has a different rate of rise in pressure and a different peak pressure. They are however so similar in appearance that all three can be within the Large - Small limits of any one of them. Lots 3, 4 and 9 are tracers with IMR propellant.

The averages of Lots 1, 2 and 7 which compose Group IV, Group V, and Group VI respectively, are not directly similar to any other lot previously grouped or with any other lot mentioned here. Each one is a case of its own. Lot 1 could be grouped with Lots 5 and 8 since the curves are very nearly identical except that Lot 1 is delayed by .05 milliseconds. Lot 7 could be grouped with Lot 5 and 8 since they all have very similar pressure decay curves and initial pressure rise curves. Lot 7 however has a higher rate of increase in pressure and reaches a higher peak pressure because the time of peak pressure for Lot 5 and 8 and Lot 7 are identical. Lot 2 is truly an independent. This lot is not close to any other group. Its rate of increase in pressure is much slower, the peak pressure occurs much later, and the peak pressure is higher than any other lot. Lot 1, 2 and 7 are ball propellant lots.

Model Equations

The current model has been constructed from simple physical relationships and some generalized assumptions.

B is defined as the volume of propellant bed burned and has units of cubic inches. The rate of change of B is described by

$$\dot{B} = k_1' T + k_2 P \qquad (1)$$

where $\dot{B}$ is the derivative of B with respect to time or dB/dt. $\dot{B}$ increases as T and P increase. If the assumption is made that

$$T = k_1'' B \qquad (2)$$

then equation (1) can be written

$$\dot{B} = k_1 B + k_2 P \qquad (3)$$

where $$k_1 = k_1' k_1''$$

In reality the proportionality constant k_1 relates the amount of propellant burnt to the temperature which is then related to the burn-rate. In the model k_1 relates the amount of propellant burnt to the burn-rate and has the dimension sec^{-1}. The proportionality constant k_2 relates the pressure to the burn-rate and has dimensions of in^5/lb-sec. This is similar to the α used by Geene[(1)] in his burn-rate equation.

P is the chamber pressure in psig and is defined by

$$P = k_3' \frac{T}{V} + k_4 B + P_0$$

or

$$\dot{P} = k_3' \frac{1}{V} \dot{T} - k_3' \frac{T\dot{V}}{V^2} + k_4 \dot{B} \qquad (4)$$

In this model the pressure is derived from two sources. One source is the ideal gas law that relates the pressure of the existing gases to their temperature and volume. The other is due to the production of the gases in the combustion of the propellant. If the substitutions

$$T = k_1'' B$$

$$\dot{T} = k_1'' \dot{B}$$

$$k_3 = k_3' k_1''$$

$$\dot{V} = A\dot{x}$$

then equation (4) becomes

$$P = k_3 \frac{B}{V} + k_4 B + P_0 \tag{5}$$

or

$$\dot{P} = \frac{k_3}{V} (\dot{B} - \frac{B}{V} A\dot{x}) + k_4 \dot{B}$$

The term P_0 is an initial pressure due the primer. The proportionality constant k_3 is usually seen in the form of the ideal gas law nR where n is the number of moles of gas and R is the ideal gas law constant. In the model k_3 has the dimension lb/in^2. The proportionality constant k_4 relates the amount of propellant burnt to pressure. In fact, it might be considered similar to an efficiency term because it says that for so much burnt propellant the pressure should increase by so much. In the model it has the dimension of lb/in^5.

The equations describing the volume behind the projectile are:

$$V_T = V_0 + B + V_m \tag{6}$$

where V_T is the total volume behind the projectile, V_0 is the initial voids volume within the cartridge, B is the volume of propellant burned and V_m is the volume of the muzzle. The units of volume are cubic inches. The volume of the cartridge was given as 0.113 in^3 and the specific volume of the propellants as 65-70%. Using 70% as the specific volume of the propellant $V_0 = (.113)(.3) = 0.034\ in^3$ and therefore the maximum the B can be is 0.079 in^3.

The volume of the muzzle can be described by $V_m = 0.038\ x$ where 0.038 is the cross-sectional area of the muzzle in square inches, x is the length of the muzzle in inches. The maximum value for x is 18.1 inches; x is zero until the projectile starts to move. x which is a function of time can be obtained by the following equations

$$\ddot{x} = \frac{d^2x}{dt^2} = \begin{cases} 0 & P \leq P_{sw},\ t \leq 0.1 \\ k_a\ P & P > P_{sw} \end{cases} \tag{7}$$

where $\ddot{x}$ is the acceleration of the projectile in inches/sec^2 and k_a is a parameter converting the units of pressure to units of acceleration. k_a can also be used to obtain the measured muzzle velocity (approximately 38,400 in/sec) since

$$\dot{x} = \int_0^t \ddot{x}\ d\tau. \tag{8}$$

The units of k_a are in/lb-sec^2. P is the chamber pressure in psig and P_{sw} is the pressure at the time the projectile starts moving. P_{sw} is a parameter which can be varied in the model.

To obtain x, $\dot{x}$ is integrated

$$x = k_x \int_0^t \dot{x} \, d\tau . \qquad (9)$$

where k_x is a psuedo-friction term and is unitless. k_x can be used to adjust x to be 18.1 inches at the appropriate time. k_x and k_a are parameters which can be varied in the model.

The error is determined by

$$E = \int_0^t \frac{(AVRAGE - P)}{P + \Delta P}^2 \, d\tau \qquad (10)$$

where AVRAGE (digital computer mnemonic) is the average data curve for any of the ten lots. The ΔP term in the denominator is small but necessary. It is used to keep the division from blowing up at $\tau = 0$ when (AVRAGE - P)/P = 0/0. The model is matched to AVERAGE when E is minimized.

The analog computer diagram as well as the digital program, digital flow diagram and digital memory allocation is shown in the Appendix (Figures A3-A6). The circles are symbolic of analog potentiometers. Most of these are available on the analog computer console and they are used for rapid adjustment of the parameters. The triangles with a box on one of the edges are analog integrators. The hexagons are trunk lines which connect the analog signals (MX's) to the digital computer and the digital signals (DA's) to the analog computer.

An advantage of analog computers is that they integrate differential equations exactly and in parallel. One of the advantages of the digital computer is that it accurately performs arithmetic functions.

The fingerprinting model is set up to use these advantages. The digital computer is programmed to solve all of the differential equations, display the results and change parameter values rapidly.

Model Constants

As the model now stands these constants are only an indication of some real physical constant. In general, they give an indication of the magnitude of the effect that a parameter has upon the actual physical system. The actual number and its units have no real physical significance, for most of the constants, at this time.

The term P_0 is used by the model to get started. It is related to the pressure output of the primer. It however should not be considered as the actual pressure output of the primer, but rather the pressure due to the primer as seen by the sensing pressure gauge. This gauge is some distance away from the primer and much of the initial force of the primer would be absorbed by the propellant between the primer and the gauge. The pressure output of the primer as reported by Squire and Devine(3) was measured in a closed bomb at approximately 30,000 psig. The model begins with a pressure of approximately 350 psig.

The constant termed switching pressure P_{sw} or the pressure at which the motion of the projectile becomes a significant factor in the pressure-time relationship, appears to have much more physical significance. Squire and Devine(3) report that a valid estimate of this pressure is 18,000 psig. The model predicts pressures ranging from 13,000 to 25,000 psig for this pressure. Lot 2 showed a switching pressure of 31,000 psig. This is not out of order because Lot 2 has a much later and higher peak pressure than any other lot. Also, if one looks carefully at the photo for Lot 2 there is an inflection point in the data at 30,000 psig where the slope of the pressure curve decreases, which is what would happen as the volume began to increase as the projectile moves. If one looks at the switching pressure used by the model and then the data, there is this noticeable inflection point in almost all of the lots.

The proportionality constants k_x and k_a are primarily used to calibrate the model. They are to be adjusted such that the distance parameter x would be about 18 inches. The length of the barrel is the only available data for the calibration of these constants. Data concerning the acceleration or velocity of the projectile at any time while it is in the muzzle was not available. For this first model too many simplifications had been made and the lack of data meant that this calibration could not be accomplished. If the source of term x is written in this fashion, one can see the possibility of combining the constants k_x and k_a into one constant.

$$x = k_x \int_0^t \dot{x}\, d\tau = k_x \int_0^t \int_0^t k_a\, P\, d\alpha\, d\tau = k_x\, k_a \int_0^t \int_0^t P\, d\alpha\, d\tau$$

This is pointed out also by the fact that if the multiplication of k_x, k_a, and P are performed and integrated by the model, x has the following form

$$x = k\, P\, t^2 \qquad .14 < k < .16$$

For all practical purposes this proportionality constant k is constant.

The proportionality constant k_1 was held constant while the data for Table 1 was taken. This was done because the model was relatively insensitive to k_1. The response of the model to a large change in k_1 could be completely masked by a small change in k_2. What this says is that the burnrate is relatively insensitive to temperature once combustion has started.

The way that the model currently exists, the proportionality constants k_2, k_3, k_4 interact a great deal. This interaction makes it impossible to directly separate the physical significance of any one given constant. Currently the constants k_1, k_2, k_3, k_4 are not unique for any given lot number. If the coefficients k_1 and k_2 could be set according to some calibration which says that so much propellant will be burnt at some time, this would then remove some of the freedom of the constants and tend to produce unique values for k_1, k_2, k_3, k_4. These constants would then have more direct physical significance. Data wasn't available to accomplish this. The model was sensitive to the proportionality constant k_3. This is the constant that turns the pressure around and relates the volume to the pressure. Of the constants k_1, k_2, k_3, k_4, the constant k_3 is the most independent constant of the group. If k_3 is used to separate the 10 lots into groups the following grouping could be made

Group A	Lots	1, 2, 6, 7, 10
Group B	Lots	3, 4, 9
Group C	Lots	5,8

Group B is the same as Group III, and Group C is the same as Group I as previously defined by the photographs of the average data.

The constants k_2 and k_4 both control the upward swing of the pressure. Due to magnitudes in the model the positive slope portion of the pressure curve is almost completely controlled by the product of k_2 k_4 P. This means that if k_2 is increased then k_4 should reflect some equivalent decrease. This is evident by comparing the two very similar lots, Lots 6 and 10. For Lot 6, k_2 is 3.231×10^{-6} and k_4 is 1.386×10^{5} while for Lot 10, k_2 is 4.393×10^{-6} and k_4 is 1.178×10^{5}. This same type of thing is evident in Lots 3, 4, 9.

Model Modifications

The current simplified model only partially relates directly to the real physical system. With a few modifications one could still have a relatively simplified model yet which would relate more directly to the physical system.

One such modification would be to include temperature T in the model explicitly rather than implicitly. This equation would be a boundary value equation of the form

$$\begin{aligned} \dot{T} &= -kT \\ T(0) &= 0 \\ T(\infty) &= T_a \end{aligned} \qquad (11)$$

Here T_a is the adiabatic flame temperature of the propellant.

An additional modification can be made in equation (3) for the pressure. In equation (3) the ideal gas law written as $k_3' \frac{T}{V}$. The constant k_3' is usually seen as nR where n is the number of moles of gas and R is the ideal gas constant. Since the number of moles of gas changes as the propellant is burnt, terms in the model need to reflect this increase.

When the temperature T and moles of gas n are included in the model, the model would then become

$$\begin{aligned} \dot{B} &= k_1 \, T + k_2 \, P \\ \dot{P} &= \frac{k_3}{V} (n\dot{T} + T\dot{n} - \frac{nT}{V}\dot{V}) + k_4 \, \dot{B} \\ \dot{T} &= - k_5 \, T \end{aligned} \qquad (12)$$

Some more major type of modifications would include dividing the propellant bed into sections of different characteristics. These sections are described by Squire and Devine[3]. Such a model would include the differences in propellant burning throughout the propellant bed, the effect of compaction on the burn-rate, the geometry of the burning face of the propellant, the effect of pressure differentials on the burning rate, and the effect of volume change on temperature, and burn-rate. Another parameter that needs to be considered is the muzzle temperature. Such a model would indeed be much more complex and require more time to implement.

Since the model up to this point has started with conditions after the primer has done its job, perhaps some modeling should be done from the time the firing pin strikes the primer to the point where the existing model begins. This type of model would predict the condition of the propellant bed, temperature, pressure and other parameters due to the primer. By combining this model with the previous one, the model should be such that it could relate to the actual physical system from the time the firing pin strikes the primer to the time the projectile leaves the muzzle.

REFERENCES

1. Geene, Robert W., "Computer Simulation of 5.6mm Propellants," Ballistic Research Laboratory Research Memorandum No. 1937, September 1968.

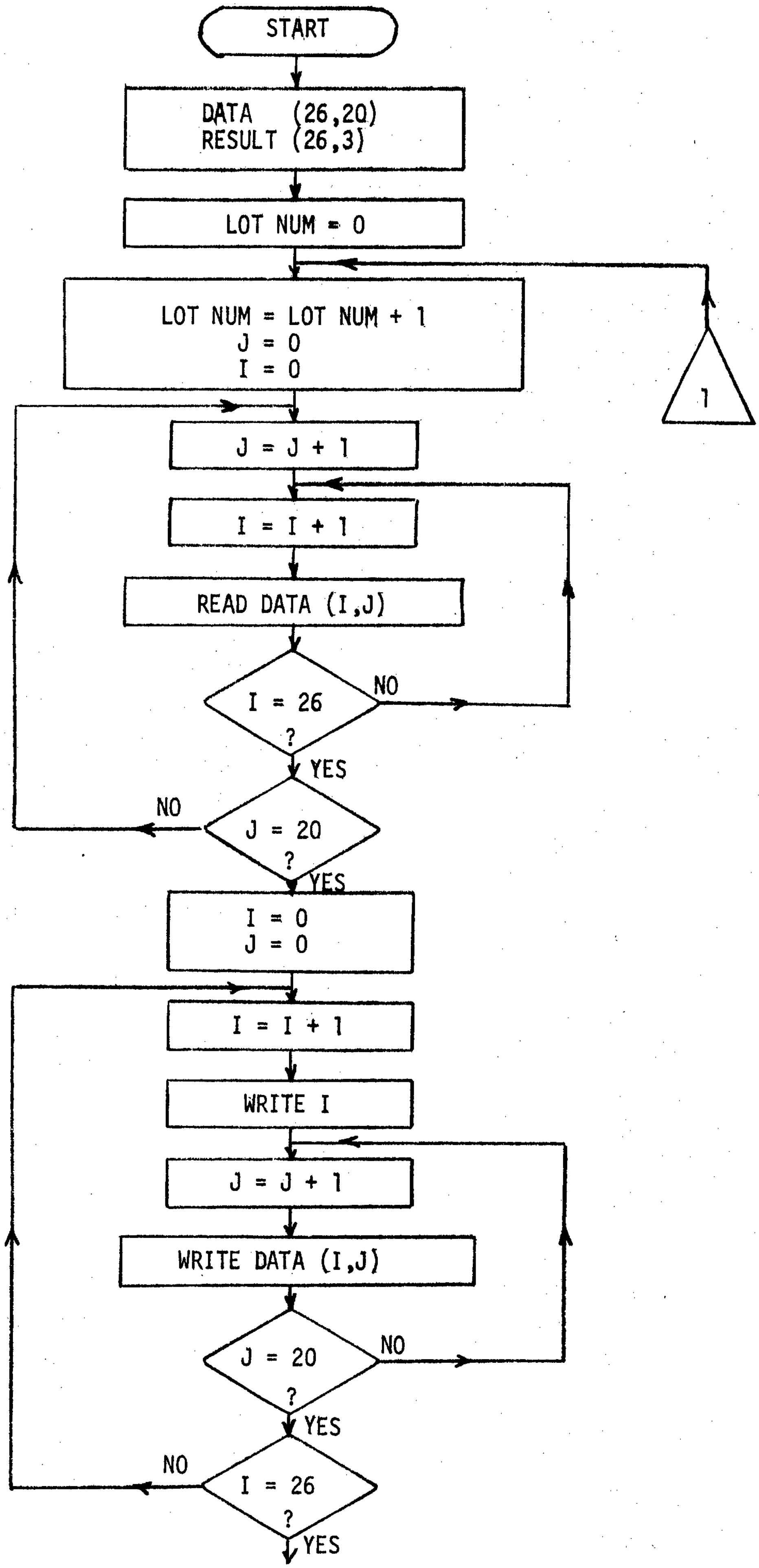
2. Benham, R.D., et.al., "SIMPL-1...A Simple Approach to Simulation," SIMULATION, Volume 13, No. 3, September 1969.

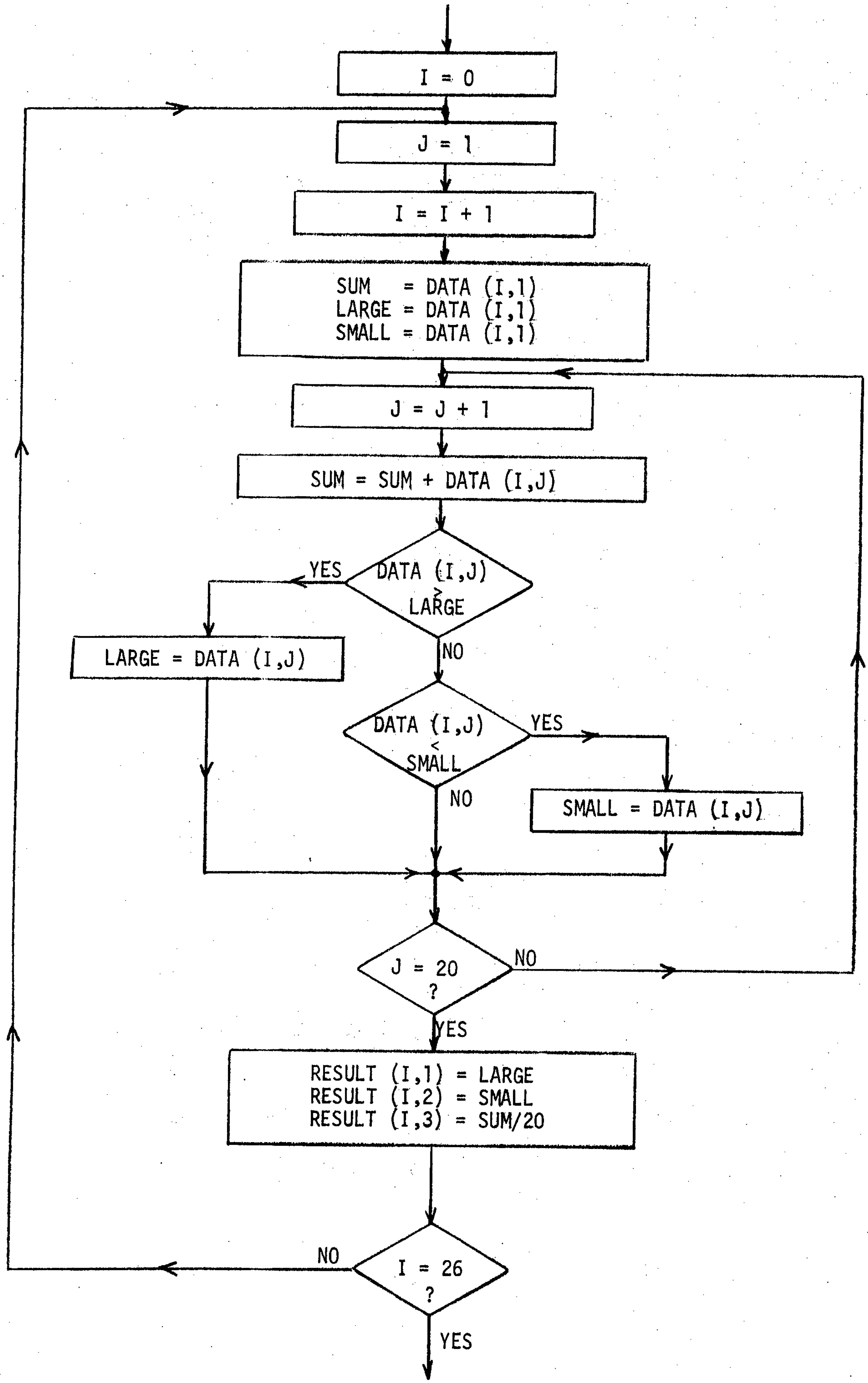
3. Squire, Walter H. and Michael P. Devine, "The Interface Between Primer and Propellant," Parts I and II, June 9, 1969.

APPENDIX

Figure A1

FORTRAN Program
Flow Diagram


START
DATA (26,20)
RESULT (26,3)
LOT NUM = 0
LOT NUM = LOT NUM + 1
J = 0
I = 0
1
J = J + 1
I = I + 1
READ DATA (I,J)
I = 26
?
NO
YES
J = 20
?
NO
YES
I = 0
J = 0
I = I + 1
WRITE I
J = J + 1
WRITE DATA (I,J)
J = 20
?
NO
YES
I = 26
?
NO
YES


I = 0
J = 1
I = I + 1
SUM = DATA (I,1)
LARGE = DATA (I,1)
SMALL = DATA (I,1)
J = J + 1
SUM = SUM + DATA (I,J)
DATA (I,J) ≥ LARGE
YES
LARGE = DATA (I,J)
NO
DATA (I,J) < SMALL
YES
SMALL = DATA (I,J)
NO
J = 20 ?
NO
YES
RESULT (I,1) = LARGE
RESULT (I,2) = SMALL
RESULT (I,3) = SUM/20
I = 26 ?
NO
YES

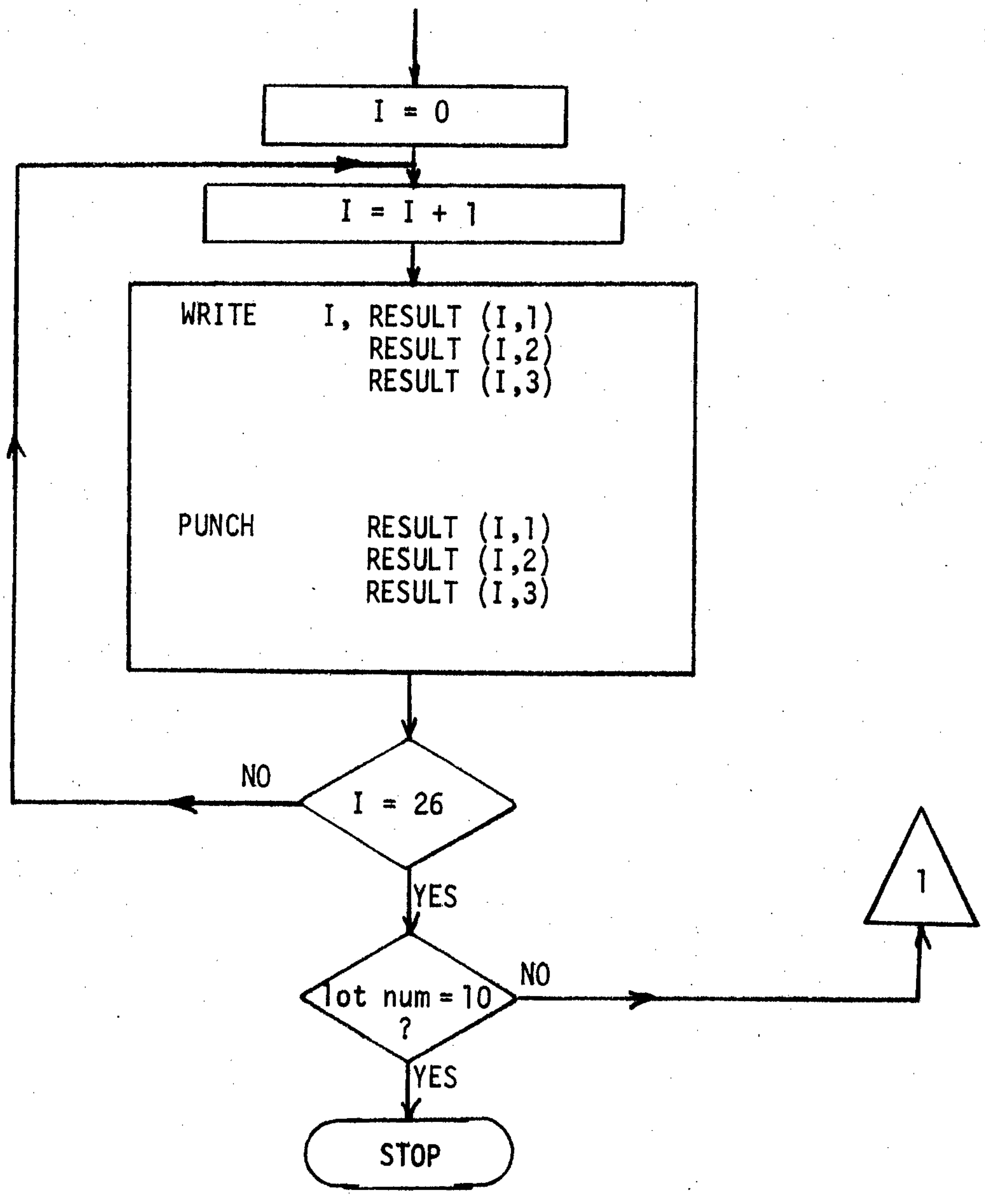

I = 0
I = I + 1
WRITE I, RESULT (I,1)
RESULT (I,2)
RESULT (I,3)
PUNCH RESULT (I,1)
RESULT (I,2)
RESULT (I,3)
NO
I = 26
YES
lot num = 10
?
NO
1
YES
STOP

Figure A2

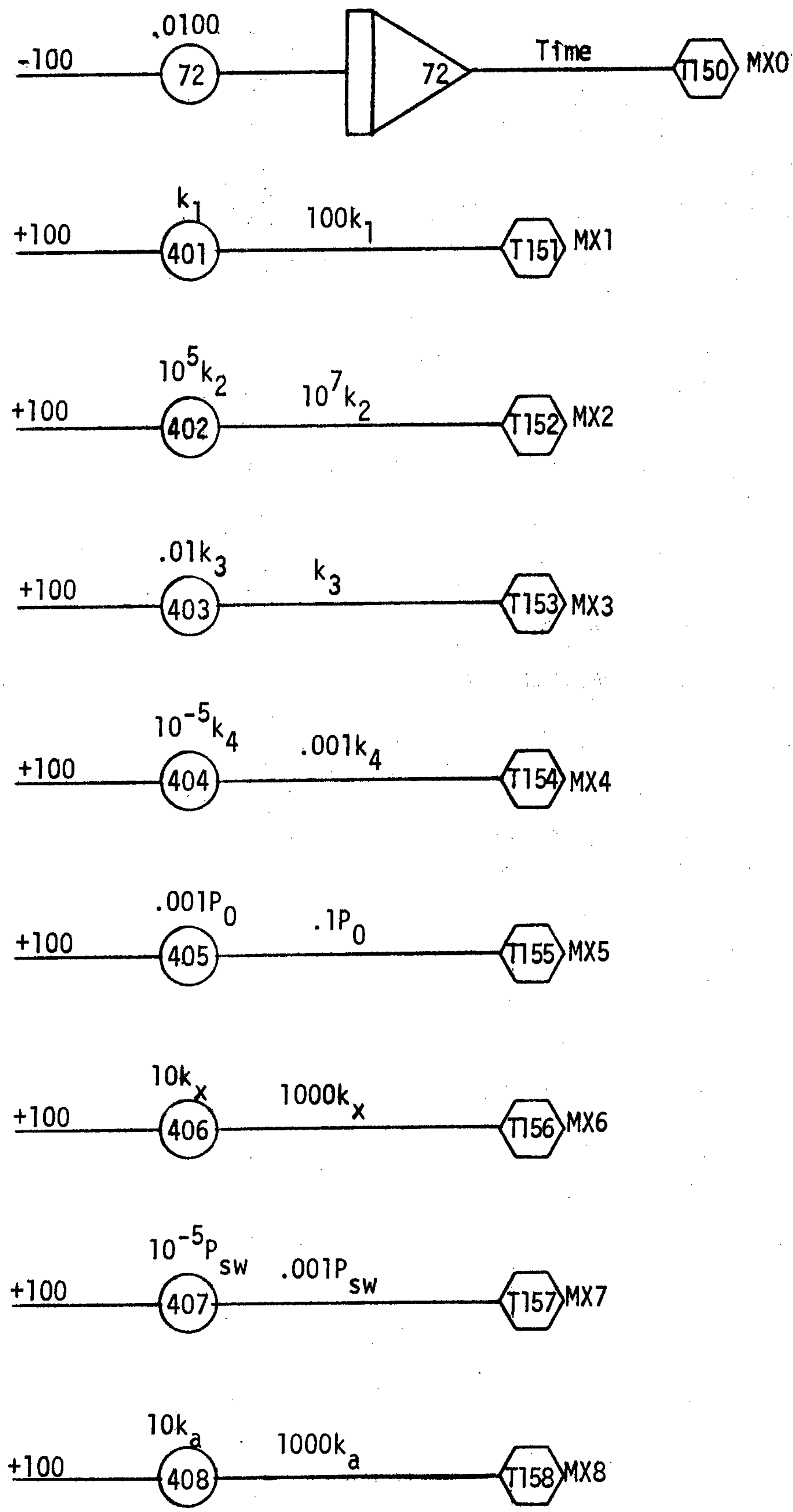
FORTRAN Program

```
      DIMENSION DATA (26,20), RESULT(26,3)
1     FORMAT (1H1)
2     FORMAT (/)
10    FORMAT ( 6F12.2 )
12    FORMAT ( 1H , 6(F5.2,7X) )
13    FORMAT ( 6(F5.2,7X) )
14    FORMAT ( 1H , F5.2, 7X, F5.2 )
15    FORMAT ( F5.2, 7X, F5.2 )
20    FORMAT ( 2F12.2 )
25    FORMAT ( 1H1, 10X, 12H LOT NUMBER , I2, // )
30    FORMAT ( 1H , 3X, 5H TIME, 15X, 9H PRESSURE )
40    FORMAT ( 1H , 5X,10(7X,I2),/ )
50    FORMAT ( 1H ,4X, I2,10(5X,F4.1) )
60    FORMAT ( 1H1,35H TIME  LARGEST  SMALLEST    AVERAGE, / )
70    FORMAT(1H , 3X, I2, 5X, F4.1, 6X,  F4.1, 6X, F5.2 )
80    FORMAT ( I2 )
      READ(5,80) KK
      DO 2000 II = 1,KK
      DO 200 I = 1,20
      DO 100 J = 1,19,6
      K=J+5
      READ (5,10) ( DATA (L,I), L=J,K )
100   CONTINUE
      READ (5,20) DATA (25,I), DATA(26,I)
200   CONTINUE
      DO 400 I=1,11,10
      WRITE(6,25) II
      WRITE (6,30)
      K2 = I+9
      WRITE (6,40) (L,L=I,K2)
      DO 300 J=1,26
      K1 = J-1
      WRITE(6,50) K1, ( DATA(J,L),L=I,K2 )
300   CONTINUE
400   CONTINUE
```

```
      DO 700 J=1,26
      BIG = DATA(J,1)
      SMALL = BIG
      SUM = BIG
      DO 600 I =2,20
      SUM = SUM + DATA(J,I)
      IF ( DATA(J,I)-BIG ) 500,500,450
  450 BIG = DATA(J,I)
  500 IF ( DATA(J,I)-SMALL ) 550,600,600
  550 SMALL = DATA(J,I)
  600 CONTINUE
      AVRAGE = SUM/20.
      RESULT(J,1) = BIG
      RESULT(J,2) = SMALL
      RESULT(J,3) = AVRAGE
  700 CONTINUE
      WRITE (6,60 )
      DO 800 J=1,26
      K1 = J-1
      WRITE(6,70) K1, ( RESULT(J,L), L=1,3 )
  800 CONTINUE
      WRITE(6,1)
      DO 1000 I= 1,3
      WRITE(6,2)
      DO 900 J=1,19,6
      K = J + 5
      WRITE(6,12) ( RESULT(L,I) , L=J,K )
      PUNCH 13, ( RESULT(L,I), L=J,K )
  900 CONTINUE
      WRITE(6,14) RESULT(25,I), RESULT(26,I)
      PUNCH 15, RESULT(25,I), RESULT(26,I)
 1000 CONTINUE
 2000 CONTINUE
      STOP
      END
```

Figure A3

Analog Computer Diagram



-100
.0100
72
72
Time
T150
MX0
+100
k1
401
100k1
T151
MX1
+100
10^5k2
402
10^7k2
T152
MX2
+100
.01k3
403
k3
T153
MX3
+100
10^-5k4
404
.001k4
T154
MX4
+100
.001P0
405
.1P0
T155
MX5
+100
10kx
406
1000kx
T156
MX6
+100
10^-5Psw
407
.001Psw
T157
MX7
+100
10ka
408
1000ka
T158
MX8

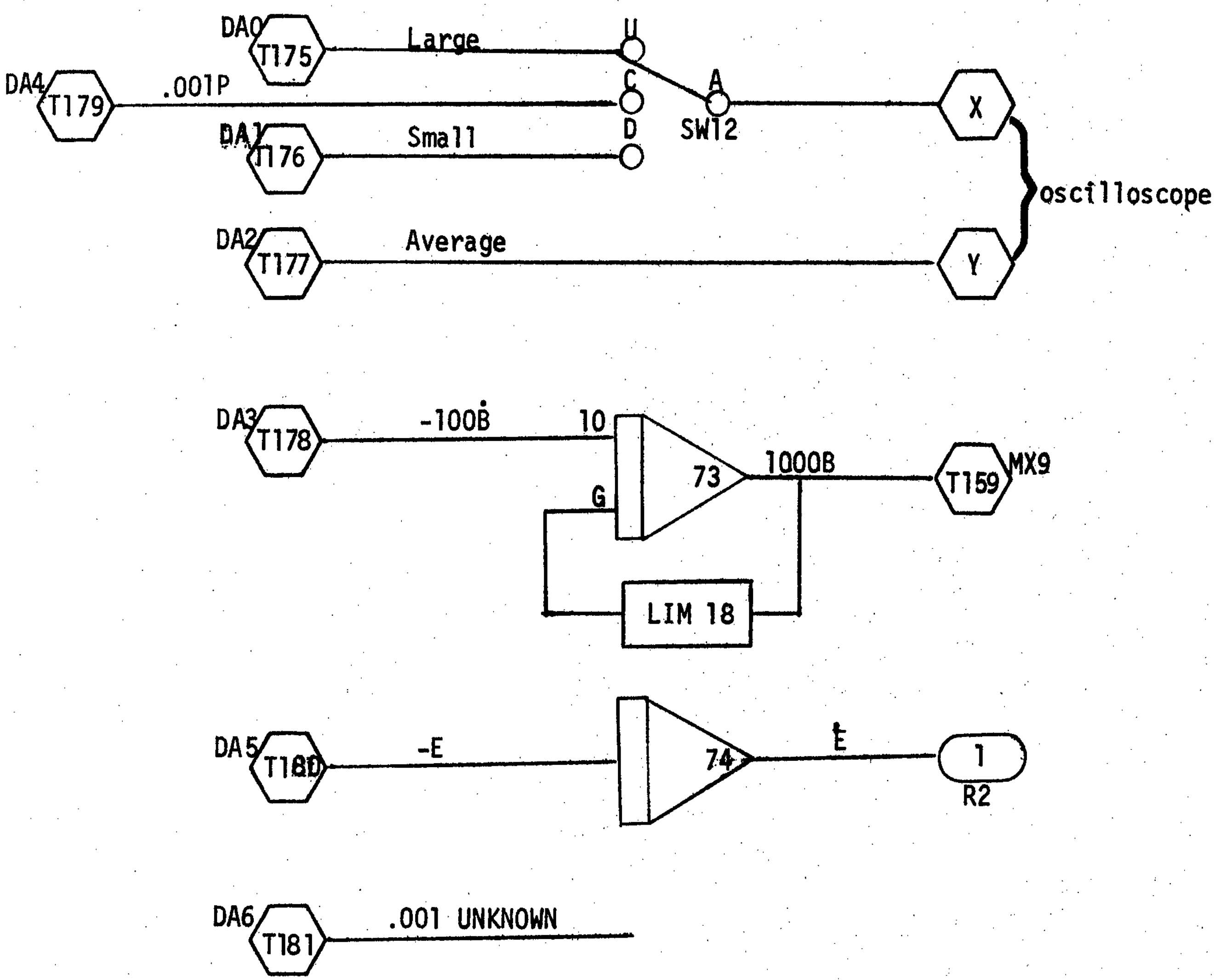

DA0
T175
Large
U
DA4
T179
.001P
C
A
SW12
X
DA1
T176
Small
D
oscilloscope
DA2
T177
Average
Y
DA3
T178
-100Ḃ
10
73
G
1000B
T159
MX9
LIM 18
DA5
T180
-E
74
Ė
1
R2
DA6
T181
.001 UNKNOWN

Figure A4

Digital Computer Program
(Hybrid)

PROGRAM NAME : FINGER
PAGE 1 OF LISTING

```
FINGER

/ LEA  1-12-7Ø

/  MAIN PROGRAM LOOP

BGN,         JMS INIT     / INITIALIZATION PROGRAM
             JMS CLEAR    / CLEARS ALL D TO A LINES
LOOP,        LAW DKMTBL   / DKM$ INSTRUCTION TABLE
             JMS DKM.     / DKM$
             JMS CHECK    / EXAMINES AC SWITCHES
             JMS GETMOD   / GET OPERATION MODE
             SNA          / POTSET?
             JMP LOOP-1   / YES

A1,          JMS DISPLA
             JMS MODEL
             LAW INT1
             JMS RINT1.
             Ø
             ISZ 4777
             JMP LOOP
             JMP LOOP

RELOC=5ØØØ  / RELOCATION CONSTANT

INT1,        SX           Ø
```

```
/ TABLE OF CHARACTERS AND LOCATIONS FOR DKM$ CONTROL

DKMTBL,     220             / CONTROL P
            RESTRT          / RE-INITIALIZE MAIN PROGRAM
            224             / CONTROL T
            LOADDT          / LOAD DDT
            HLT

/ PROGRAM TO LOAD DDT

LOADDT,     DPI             / DISABLE PRIORITY INTERRUPT
            MICL            / CLEAR MODIFIED INSTRUCTIONS
            LAC (10000      / UNIT 1
            MMSE            / SELECT TRANSPORT
            LAC (-'10000
            IAC!SZA
            JMP .-1         / 35 MS DELAY
            LAC (76         / BLOCK NUMBER
            DAC 17701
            JMS 17620       / READ FILE
            MMLC 10         / STOP TAPE
            LAC BTMSYM      / BOTTOM OF SYMBOL TABLE
            DAC 15216
            LAC POISV       / POINTER LOCATION
            DAC 15204       / RESET POINTER
            JMP 16000       / START DDT
```

```
/ PROGRAM FOR CLEARING ALL D TO A LINES

CLEAR,      Ø
            CLA           / CLEAR AC
            DAØ           DA1           DA2           DA3           DA4
            DA5           DA6           DA7           DA8           DA9
            DA1Ø          DA11          DA12          DA13          DA14
            DA15          DA16          DA17          DA18          DA19
            DA2Ø          DA21          DA22          DA23
            JMP I CLEAR

/INITIALIZATION ROUTINE

INIT,       Ø
            LAC (-'1ØØØØ
            IAC!SZA
            JMP .-1       / DELAY BEFORE CAF
            CAF           / CLEAR ALL FLAGS

            LAC 15216     / ADDRESS OF BOTTOM OF DDT'S SYMBOL TABLE
            DAC BTMSY#M   / SAVE
            LAC 152Ø4     / DDT POINTER LOCATION
            DAC POISV#    / SAVE DDT POINTER LOCATION

            LAC (2ØØØØ    / UNIT 2
            MMSE          / SELECT TRANSPORT
            LAC (-'1ØØØØ
            IAC!SZA
            JMP .-1       / 35 MS DELAY
            LAC (2        / PROGRAM DDTFIL  (ALL SUBROUTINES)
            DAC 177Ø1
            LAC (RELOC    / RELOCATION CONSTANT
            DAC 177Ø2
            JMS 1762Ø     / READ FILE
            MMLC 1Ø       / STOP TAPE

            LAC BTMSYM
            DAC SYMBL.    / SYMBL$
            LAC POISV
            DAC POINT.    / POINT$
```

```
RESTRT,     CAF
            CAC
            MIST            / MODIFIED INSTRUCTIONS
            JMS GETMOD      / GET OPERATION MODE
            XOR (4
            SZA             / IS IT COMPUTE?
            LAC (3          / YES SET TO IC
            JMS SETMOD      / SET OPERATION MODE

            LAM             / SET COUNTER TO CHECK AC SWITCHES
            DAC #SWMNTR
            DAC #MXCNTR
            LAW DATA        / ADDRESS OF TABLES
            DAC DATADR#
            LAW KONTBL      / THIS IS THE TABLE WHERE THE MODEL CONSTANTS
            DAC #CONTBL
            DZM TT#
```

PROGRAM NAME : FINGER
PAGE 5 OF LISTING

```
                MXRN            / RANDOM MULTIPLEXING

                JMS ICL.        / ICL$
TS,             1               / TIME SCALE
FC,             5000'           / CLOCK FREQUENCY
NIC,            50'             / # OF ITERATIONS IN COMPUTE
NIIC,           50'             / # OF ITERATIONS IN IC
                CLSCMP          / CLOCK SERVICE  COMPUTE
                CLSIC           / CLOCK SERVICE  IC
                0               / HOLD (NO ROUTINE)
TIM,            0               / TIME SINCE ENTERING COMPUTE

                LAC (4000       / ADOV
                ASC             / ENABLE A TO D OVERLOAD
                EPI             / ENABLE PRIORITY INTERRUPT

                LAW TBUF        / TELETYPE BUFFER TABLE ADDRESS
                LMQ
                LAW TBUFE       / END OF TELETYPE BUFFER
                JMS IATYP.      / INITIALIZE PRIORITY TYPING (IATYP$)

                JMP I INIT

TBUF=RELOC 3542
TBUFE=RELOC 3717

/ PROGRAM FOR SETTING OPERATION MODE

SETMOD,         0
                DAC MODE.       / SAVE MODE ($MODE)
                LAC MODFLG
                XOR (ANAL
                SZA             / IS MODE ANALOG OR DIGITAL?
                JMP I SETMOD                / DIGITAL
                LAC MODE.       / GET MODE  ($MODE)
                JMS SMODE.      / SET ANALOG MODE  (SMODE$)
                JMP I SETMOD

/ PROGRAM FOR DETERMINING OPERATION MODE

GETMOD,         0
                LAC MODFLG
                XOR (ANAL
                SNA             / IS MODE ANALOG OR DIGITAL?
                JMS AMODE.      / ANALOG (AMODE$)
                LAC MODE.       / DIGITAL  (GET $MODE)
                JMP I GETMOD

MODFLG,         ANAL            / DIGT OR ANAL
DIGT=12345
ANAL=01234
```

```
/ VARIABLES USED IN VARIABLE STORING ROUTINES

VARX,       1              / NUMBER OF VARIABLES TO BE STORED
VAR1,       TIME
VAR2,       TIM
VAR3,       TIME
VAR4,       TIME
VAR5,       TIME
VAR6,       TIME

/ CLOCK SERVICE ROUTINES

CLSCMP,
21/         HLT            / FOR ILLEGAL CAL
44/         NOP            / A TO D OVERLOAD

CLSCMP/     LAS
            AND (4000      / LOOK AT SWITCH 6
            XOR #LSTSW
            SNA            / TIME TO STORE VARIABLES?
            JMP CLSIC 3'              / NO   USE IC ROUTINE
            LAC ENT1#
            SMA            / TIME = ZERO?
            JMP .+4        / NO
            LAC TIM        / YES
            DAC TREF       / STORE REFERENCE TIME
            DZM ENT1       / SET FLAG
            LAC TIM
            SUB TREF#      / SUBTRACT REFERENCE
            DAC TIME       / GIVES VALUE OF TIME
            STL            / SET LINK FOR STORE$
            JMS STORE.     / STORE$
            TAU1           / LOCATION OF TABLE OF TIME INTERVALS
            STRTBL         / STORAGE TABLE ADDRESS
NSTOR,      300'           / # OF LOCATIONS IN TABLE
            LAC NIC        / # OF ITERATIONS PER SECOND  (COMPUTE MODE)
            JMP RCL.

CLSIC,      LAS
            AND (4000
            DAC LSTSW
            LAM
            DAC ENT1
            DZM TIME#
            CLL
            JMP NSTOR-3
```

```
/ TIME INCREMENT TABLE FOR STORAGE PROGRAM STORE$

TAU1,       '10          / INTERVAL FOR STORAGE UNTIL TIME1
TIME1,      10'00
TAU2,       1'00
TIME2,      50'00
TAU3,       5'00
TIME3,      1000'00
TAU4,       '01
TIME4,      1100'00
TAU5,       0
TIME5,      0
TAU6,       0
TIME6,      0
TAU7,       0
TIME7,      0
. 10'/

/ STORAGE TABLE FOR STORE$

STRTBL,     0
. 300'/
```

```
/ AC SWITCH CHECKING PROGRAM

CHECK,          Ø
                LAS
                AND (6ØØØØ
                SNA             / TIME TO SET MODE?  (SWITCHES 3 AND 4)
                JMP VRCHK       / NO
                CAS (4ØØØØ      / YES
                JMP .+6         / HOLD
                JMP .+3         / IC
                LAC (4          / COMPUTE
                JMP .+4
                LAC (3
                SKP
                LAC (1
                JMS SETMOD      / SET OPERATION MODE
VRCHK,          LAS
                CLL
                AND (1ØØØ       / LOOK AT SWITCH 8
                SZA             / TIME TO LIST TABLE?
                STL             / YES
                LAW STRTBL      / NO
                JMS VRTYP.      / VRTYP$
NTYP,           3ØØ'
                CLL
                LAS
                AND (2ØØØ       / LOOK AT SWITCH 7
                SZA             / TIME TO PRINT VARIABLES CONTINUOUSLY?
                STL             / YES
                JMS VMNTR.      / VMNTR$
```

```
            ISZ CNT123   / COUNTER FOR SETTING VARIABLE LOCATIONS
            JMP I CHECK
            LAC VARX
            DAC VARX.    / VARX$
            LAC VAR1
            DAC VAR1.    / VAR1$
            LAC VAR2
            DAC VAR2.    / VAR2$
            LAC VAR3
            DAC VAR3.    / VAR3$
            LAC VAR4
            DAC VAR4.    / VAR4$
            LAC VAR5
            DAC VAR5.    / VAR5$
            LAC VAR6
            DAC VAR6.    / VAR6$
            LAM-700'
            DAC CNT123
            JMP I CHECK

CNT123,     LAM-20'
```

PROGRAM NAME : FINGER
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```
ICL.=RELOC 2601
DKM.=RELOC 562 1
VRTYP.=RELOC 172 1
STORE.=RELOC 21 1
VMNTR.=RELOC 432 1
TRIP1.=RELOC 2146 1
FG2.=RELOC 2457
SMODE.=RELOC 2545
AMODE.=RELOC 2523
HMPY1.=RELOC 2266
HMPY2.=RELOC 2316
HDIV.=RELOC 2400
X.1.=RELOC 2444
TFRM.=RELOC 3360
TMSG.=RELOC 3235
HMPY3.=RELOC 2347
RINT1.=RELOC 1777 1
VAR1.=RELOC 553 1
VARX.=VAR1.-1
VAR2.=VAR1.+1
VAR3.=VAR2.+1
VAR4.=VAR3.+1
VAR5.=VAR4.+1
VAR6.=VAR5.+1
TTAB.=RELOC 3367
TCR.=RELOC 3347
TVOLT.=RELOC 3156
HEADR.=RELOC 502 1
TTYP.=RELOC 3535
TFLG.=RELOC 3520
TOCT.=RELOC 3053
TTAG.=RELOC 1677 1
ATYP.=RELOC 3424
TDEC.=RELOC 3101
POINT.=RELOC 1676 1
SYMBL.=RELOC 1675 1
TSP.=RELOC 3340
CL2.=RELOC 3051
X10.=RELOC 2424
```

```
END.=RELOC 2127 1
FC.=RELOC 3Ø46
TS.=RELOC 3Ø47
MODE.=RELOC 3Ø52
CLI.=RELOC 3Ø5Ø
RCL.=RELOC 3Ø21
IATYP.=RELOC 3376

NOP=NOP
SNA=SNA
HLT=HLT
CMA=CMA
SMA=SMA
SPA=SPA
SZA=SZA
SKP=SKP
CLL=CLL
STL=STL
CLA=CLA
LAS=LAS
LMQ=LMQ
LACQ=LACQ
LRSS=LRSS
LLSS=LLSS
```

```
/ THIS IS THE WORKING PORTION OF FINGER
/ THIS IS THE DISPLAY AND THE MODEL


/ DISPLA IS A FUNCTION GENERATOR PROGRAM THAT DISPALYS THE FOLLOWING
/ DATA BY CONTROL OF THE AC SWITCHES
/ LARGEST, SMALLEST, AVERAGE, FOR ANY GIVEN LOT OF DATA
/ THE AC SWITCHES SELECT THE LOT BEING VIEWED
/ AC SWITCHES 14 TO 17 FOR LOTS 1 TO 10 DECIMAL OR 1 TO 12 OCTAL


DISPLA,     0
            LAC TT
            CAS (1.0
            JMP DOFUNC   / > SO IN THE MIDDLE OF A CALCULATION
            NOP          / =
            ISZ FLAG#    / < SO SET FLAG AND LOOK
            ISZ SWMNTR   / THIS DECIDES TO SEE IF WANT DIFFERENT LOT
            JMP DOFUNC   / DON'T CHECHK NOW JUST DO
            LAM -20'     / RESET COUNTER
            DAC SWMNTR
            LAC LOTNUM   / NEED TO SEE IF ANYONE IS IN THERE
            SNA          / IF 0 THEN FIRST TIME THROUGH
            JMP .+5
            LAS          /  CHECK TO SEE IF YOU WANT TO CHANGE LOTS
            AND (20      / BIT 13 IS THE ONE 1 YES, 0 NO
            SNA
            JMP DOFUNC
            LAS
            AND (17
            SNA
            ADD (1       /IF YOU FORGET YOU GET LOT 1
            CAS LOTNUM   / DO YOU ALREDY HAVE THIS ONE LOADED
            SKP
            JMP DOFUNC   / YEP NO NEED TO RELOAD A NEW LOT
            DAC LOTNUM   / THIS IS TO CHECK NEXT TIME
            CLL
            MUL
            116
            LACQ
            ADD (-116
            ADD DATADR   / THIS IS THE LOCATION OF THE START OF DATA
            DAC #ADRESD  / THIS IS THE POINTER USED IN LOADING
            LAC (-114
            DAC COUNT#   / THIS KEEPS TRACK OF WHEN TO STOP LOADING
            LAW TABLAD
            DAC #ADREST  / THIS IS TH POINTER OF WHERE TO LOAD
            LAC I ADRESD
            DAC I ADREST
            ISZ ADRESD
            ISZ ADREST
            ISZ COUNT    / DONE
            JMP .-5      / NOPE
```

```
DOFUNC,     MXØ             / GETT THE TIME
            JMS ADFLG
            DAC TT
            LAM -4+1
            JMS FGMOD$
            LAW TABLE
            LAC TT
            DAØ             / SEND OVER THE LARGEST
            DA1             / SEND OVER THE SMALLEST
            DAC #AVRAGE /STORE THE AVERAGE FOR THE FUTURE
            DAC #UNKWN      / THIS IS THE UNKNOWN
            DA6
            LAC AVRAGE
            DA2             / SEND OVER THE AVERAGE

            JMP I DISPLA


TABLE,      Ø
            25ØØ.
            LRS 6
            25'
TABLAD,     Ø
TABLAD 78'/
UNKADD,     Ø
UNKADD 28'/


ADFLG,      Ø               / THIS IS MX LINE CHECK
            ADSF
            JMP .-1
            ADRB
            JMP I ADFLG

OVERLD,     Ø               / THIS STORES ADDRES WHERE DIGITAL OVERLOAD
            722102
            LAC OVERLD
            DAC OVERAD
            JMP I OVERLD
OVERAD,     Ø
```

```
MODEL,      Ø              / THIS IS THE MODEL PORTION OF THE PROGRAM

            LAC FLAG       / FLAG=1 IF START OF NEW CALCULATION
            SNA            / FLAG=Ø IN THE PROCESS OF CALLCULATING
            JMP DOMODL
            DZM FLAG

            ISZ MXCNTR     / ONLY SEE IF CONSTANTS ARE HOW ONCE IN A
            JMP DOMODL     / WHILE NOT EVERY TIME
            LAM-5'         / THIS TIME CHECK
            DAC MXCNTR

            LAS            / BIT 1Ø=1 THEN GET THE ONES IN MEMORY
            AND (2ØØ
            SNA
            JMP WRTCON
            LAC LOTNUM     / THIS IS THE LOT NUMBER OF DATA WANTED
            SUB (1
            CLL
            MUL
            1Ø
            LACQ
            ADD CONTBL
            DAC ADRESD
            LAW MODCON+1
            DAC ADREST
            LAC (-7
            DAC COUNT
            LAC I ADRESD
            DAC I ADREST
            ISZ ADREST
            ISZ ADRESD
            ISZ COUNT
            JMP .-5
            JMP DOMODL
```

```
WRTCON,     LAS              / THIS IS TO SEE IF YOU WANT TO WRITE
            AND (100         / BIT 11=1 THEN STORE THESE AWAY FOR THIS LOT
            SNA
            JMP GETCON
            LAC LOTNUM
            HLT              / TO MAKE SURE YOU ARE WRITTING AND KNOW IT
            LAS              / IF WANT TO WRITE MUST HAVE LOTNUM ON AC SW
            AND (17
            CMA
            AND LOTNUM
            SZA
            JMP DNTWRT       / NOT THE SAME SO DO NOT WRITE
            LAC LOTNUM
            SUB (1
            CLL
            MUL
            10
            LACQ
            ADD CONTBL
            DAC ADREST
            LAW MODCON+1
            DAC ADRESD
            LAC (-7
            DAC COUNT
            LAC I ADRESD
            DAC I ADREST
            ISZ ADREST
            ISZ ADRESD
            ISZ COUNT
            JMP .-5
            JMP DOMODL

DNTWRT,     LAC LOTNUM       / THIS IS FOR NOT WRITING
            CMA
            HLT              / TO LET YOU KNOW THAT NO WRITE
            JMP DOMODL
```

```
GETCON,     LAS
            AND (40         / BIT 12=1 THEN MX
            SNA
            JMP DOMODL      / NO READ,WRITE,MX SO USE WHAT IS THERE

KK1,        MX1             / RELATES BDOT,B
            JMS ADFLG
            DAC K1

KK2,        MX2             / RELATES BDOT,P
            JMS ADFLG
            DAC K2

KK3,        MX3             /RELATES T,P,B
            JMS ADFLG
            DAC K3

KK4,        MX4             / RELATES BDOT,PDOT
            JMS ADFLG
            DAC K4

KP0,        MX5             / THE INITIAL PRESSURE
            JMS ADFLG
            DAC P0

KKX,        MX6
            JMS ADFLG
            DAC KX          / PSEUDO FRICTION CONSTANT

KPSW,       MX7
            JMS ADFLG
            DAC PSW         / THE SWITCHING PRESSURE

KKA,        MX8
            JMS ADFLG
            DAC KA          / THE ACCERERATION CONSTANT

            JMP DOMODL      / THIS IS TO GET OVER THE CONSTANT TABLE
```

```
MODCON,     0               / THIS IS DUMMY SO TABLE WILL HAVE TAG
K1,         0               / 10↑4 SF
K2,         0               / 10↑7 SF
K3,         0               / .5 SF
K4,         0               / .0005 SF
P0,         0               / .1 SF
KX,         0               / 10↑5 SF
PSW,        0               / PSW .001 SF
KA,         0               / 1/SEC  10↑4 SF

/ LIST OF OTHER SCALE FACTORS
/                           DIGITAL      ANALOG
/ B         IN↑3            2000 SF      1000 SF
/ BDOT      IN↑3/SEC        1000 SF      1000 SF
/ P         LB/IN↑2         .001 SF
/ PDOT      LB/IN↑2/SEC     .001 SF
/ V         IN↑3            2000 SF
/ A         IN↑2            10↑4 SF
/ X2DOT     IN/SEC↑2        .04 SF
/ XDOT      IN/SEC          .04 SF
/ X         IN              5 SF

/ NOW WITH CONSTANTS LETS DO SOME WORK

DOMODL,     MX9             / GET B THE AMOUNT OF MATERIAL BURNT
            JMS ADFLG       / 1000 B
            ALSS+1
            DAC B#          / 2000B
```

```
CBDOT,      LAC P           / .ØØ1 P
            JMS X1Ø.        / .Ø1P
            SZL
            JMS OVERLD
            JMS HMPY2.
            LAC K2          / 10↑7 K2
            SZL
            JMS OVERLD
            DAC SPOT1#      / 1ØØØ(K2*P)
            LAC B           / 2ØØØ B
            JMS HMPY2.
            LAC K1          / 1Ø↑4 K1
            SZL
            JMS OVERLD
            JMS HMPY1.      / 2*1Ø↑5 K1*B
            Ø.5             / 1ØØØ K1*B
            ADD SPOT1       / 1ØØØ(K1*B+K2*P)
            DAC BDOT#       / 1ØØØ * BDOT
            JMS X.1.        / 1ØØ BDOT
            CMA             / -1ØØ BDOT
            DAC #DABDOT

CX2DOT,     LAC P           / .ØØ1 P
            JMS HMPY2.
            LAC KA          / 1Ø↑4 KA
            SZL             / .1 KA*P
            JMS OVERLD
            JMS HMPY1.
            4Ø.
            DAC X2DOT       / .Ø4 X2DOT
```

```
CPSW,       LAC TT       / THIS IS SUCH ONLY SWITCH XDOT ON, NOT OFF
            CAS (Ø.1     / WHEN IN COMPUTE
            NOP          / > Ø.1
            JMP .+6      / = Ø.1
            DZM #SWITCH  / < Ø.1
            DZM XDOT
            DZM X
            DZM P
            JMP .+1Ø'

            LAC SWITCH
            CAS (Ø
            SKP          / >Ø
            SKP          / =Ø
            JMP .+8'     / <Ø

            LAC P
            CAS PSW
            JMP .+4      / > PSW
            NOP          / = PSW
            DZM X2DOT    / < PSW
            SKP
            ISZ SWITCH

CV,         LAC XDOT     / .Ø4 XDOT
            JMS HMPY2.
            LAC KX       / 1Ø↑5 SF
            SZL
            JMS OVERLD   / -4Ø*XDOT*KX
            JMS HMPY1.
            12.5
            SZL
            JMS OVERLD
            DAC KXXDOT   / 5 XDOT*KX

            LAC X        / 5X
            ALSS+2       / 2Ø X
            JMS HMPY1.
            38Ø.         / MUZZLE AREA ( IN↑2 ) -1Ø↑4 SF
            SZL
            JMS OVERLD
            ADD (68.     / INITIAL CHAMBER VOLUME 2*1Ø↑3 SF
            ADD B        / BURNT MATERIAL ( IN↑3 2*1Ø↑3 SF
            DAC V#       / 2ØØØ V
```

```
CPDOT,     LAC XDOT      / .04 XDOT
           JMS HMPY1.
           380.          / 10↑4 A
           SZL
           JMS OVERLD    / 4*A*XDOT
           JMS HMPY3.
           LAC B         / 2000 B
           LAC V         / 2000 V
           SZL
           JMS OVERLD
           DAC SPOT2#    / 4*B*A*XDOT/V
           LAC BDOT      / 1000 BDOT
           ALSS+2        / 4000 BDOT
           JMS X.1.      / 400 BDOT
           JMS X.1.      / 40 BDOT
           JMS X.1.      / 4*BDOT
           SUB SPOT2
           JMS HMPY3.    / 4*(BDOT-B*A*XDOT/V)
           LAC K3        /  K3/2
           LAC V         / 2000V
           SZL
           JMS OVERLD
           DAC SPOT2     / .001 K3(BDOT-B*A*XDOT/V)/V
           LAC BDOT      / 1000 BDOT
           JMS HMPY3.
           LAC K4        / .0005 K4
           LAC (500.
           SZL           / .001 K4*BDOT
           JMS OVERLD
           ADD SPOT2
           DAC SPOT2     / .001K3(BDOT-B*A*XDOT/V)/V+.001K4*BDOT
           LAC P0        / .1 P0
           JMS X.1.      / .01 P0
           JMS X.1.      / .001 P0
           ADD SPOT2
           DAC PDOT      / .001 PDOT
           LAC P
           NOP
           DA4

           LAC DABDOT    / -100 BDOT
           DA3
```

```
CERR,       LAC AVRAGE  / THIS IS TO GET RID OF THE Ø IN THE DENOM
            JMS ERR
            DA5
            JMP I MODEL

ERR,        Ø
            DAC N#UMRAP
            ADD DELP
            DAC #DENOMP

            LAC NUMRAP  / START GETTING THE ERROR.
            SUB UNKWN
            JMS HDIV.
            LAC DENOMP
            SZL
            JMS OVERLD
            JMS HSQ$
            SZL
            JMS OVERLD
            JMS X.1.
            JMS X.1.
            CMA
            JMP I ERR

            JMP I MODEL

SX,         Ø.          / IC FOR X2DOT
X2DOT,      Ø.
            LRSS+Ø
            ADD XDOT#
            Ø
            DAC XDOT

            Ø.          / IC FOR XDOT
KXXDOT,     Ø.
            LRSS+Ø
            ADD X#
            Ø
            DAC X

            Ø.          / IC FOR P
PDOT,       Ø.
            LRSS+Ø
            ADD P#
            Ø
            JMP .+1
            DAC P
            JMP END.
```

PROGRAM NAME : FINGER
PAGE 22 OF LISTING

```
DATA,
0.00     0.50     2.00     3.50     5.00     5.50
 7.00    10.00    15.00    23.00    32.00    40.50
47.00    51.00    52.00    51.00    49.00    45.00
39.50    35.50    31.00    27.00    23.50    20.00
18.00    16.00
0.00     0.00     0.00     0.00     0.00     0.00
 1.00     2.00     5.50    11.00    19.50    23.00
30.50    36.00    40.00    44.00    42.00    36.50
31.00    26.00    22.00    19.00    17.00    14.50
12.50    11.50
0.00     0.05     1.05     1.72     2.70     4.03
 5.52     7.55    11.57    17.95    25.52    32.67
39.45    44.30    48.20    48.47    45.52    40.92
35.35    30.55    26.12    22.70    19.55    17.23
15.15    13.47
0.00     0.00     2.00     3.50     5.50     6.50
 8.00    10.50    16.00    21.50    27.00    32.50
39.50    48.00    56.00    62.00    62.50    61.00
56.00    48.00    41.00    35.50    31.00    27.00
24.00    21.00
0.00     0.00     0.00     1.00     2.50     4.50
 5.50     6.50     7.50    10.00    13.50    18.50
23.50    28.50    33.50    38.00    43.00    46.00
42.00    35.50    30.50    26.00    22.50    19.50
17.50    15.00
0.00     0.00     0.72     2.00     3.72     5.67
 6.60     8.32    10.55    15.00    20.85    27.03
33.15    40.00    46.37    51.45    53.92    51.72
47.42    40.87    35.15    30.30    25.95    22.42
19.65    17.27
0.00     0.50     2.00     3.00     8.00    12.50
22.50    32.50    42.00    49.50    53.00    54.00
53.00    48.00    42.00    36.00    31.50    27.00
23.00    20.00    18.00    15.50    14.00    12.50
11.50    10.50
0.00     0.00     0.00     0.50     1.50     3.00
10.00    19.50    31.50    38.50    45.50    47.50
44.00    40.00    34.50    30.00    25.50    22.00
18.00    16.00    14.00    12.00    10.50     9.50
 8.50     8.00
0.00     0.30     0.95     2.03     4.32     7.77
15.90    27.35    37.27    44.15    49.10    50.52
48.08    43.65    37.92    32.55    28.00    24.05
20.45    17.80    15.52    13.55    11.97    10.65
 9.52     8.60
0.00     0.50     1.50     4.00     9.50    12.50
22.50    33.00    41.50    48.00    52.00    52.50
49.50    46.50    43.50    39.50    35.00    30.00
26.50    23.00    20.00    17.00    15.00    13.50
12.00    10.50
```

0.00	0.00	0.00	1.00	2.50	6.00
10.00	18.00	25.00	31.50	39.00	43.00
44.00	37.00	32.00	28.00	24.00	20.50
17.50	15.00	13.50	12.00	10.50	9.50
8.50	8.00				
0.00	0.03	0.60	2.10	5.60	9.65
15.52	25.35	33.50	40.12	45.85	48.47
47.77	44.37	39.67	34.57	30.05	25.70
22.15	19.07	16.55	14.47	12.70	11.32
10.27	9.12				
0.00	0.00	1.50	3.00	6.00	9.50
12.50	21.50	30.00	37.50	43.00	48.00
52.00	52.00	52.00	51.00	48.00	42.50
36.50	31.50	26.50	22.50	19.50	17.50
15.50	14.00				
0.00	0.00	0.00	0.50	1.00	3.00
5.50	7.00	10.00	16.00	24.00	30.50
37.50	44.50	45.00	40.00	34.50	30.00
26.00	22.00	19.50	17.00	14.50	13.50
12.00	10.50				
0.00	0.00	0.62	1.67	3.13	5.78
8.55	12.97	19.95	27.22	34.50	40.00
44.95	48.05	48.05	44.75	39.95	34.85
29.77	26.03	22.30	19.35	16.97	15.07
13.40	12.02				
0.00	0.00	1.00	2.50	7.50	12.00
22.00	33.50	41.50	49.00	54.00	58.00
59.50	56.00	54.00	47.50	42.00	35.50
30.00	26.00	22.50	19.50	17.00	15.00
13.50	12.00				
0.00	0.00	0.00	0.50	1.50	2.50
5.50	9.50	16.50	26.00	34.50	42.00
46.00	46.00	38.50	32.00	28.00	23.50
20.00	17.50	15.50	13.50	12.00	10.50
9.50	8.50				
0.00	0.00	0.30	1.35	3.05	6.07
10.82	19.30	29.02	38.02	45.35	50.72
52.80	50.92	46.02	39.62	34.08	28.80
24.72	21.23	18.50	16.27	14.27	12.67
11.32	10.22				
0.00	1.00	1.50	3.50	5.00	7.50
11.50	21.00	31.50	41.00	48.50	53.00
55.50	54.00	52.00	48.00	42.00	36.50
31.00	26.50	23.00	20.00	18.00	16.00
14.00	13.00				
0.00	0.00	0.00	0.50	1.50	2.00
3.00	7.00	13.50	24.00	32.50	40.00
44.50	47.50	45.00	39.00	34.00	28.50
24.50	20.50	18.00	16.00	14.00	12.00
11.00	10.00				

0.00	0.30	0.92	1.72	3.15	4.80
7.07	11.72	20.85	30.45	38.62	45.67
49.55	51.22	48.80	43.80	37.95	32.70
27.83	23.85	20.53	18.00	15.80	14.02
12.55	11.25				
1.00	2.00	3.00	5.00	6.50	9.00
13.50	22.50	30.00	38.50	44.50	49.00
51.00	51.50	50.00	47.00	42.50	37.50
32.00	27.50	24.00	21.00	20.00	16.00
14.50	13.00				
-1.00	-1.00	0.00	0.50	1.50	2.50
4.50	8.50	14.50	22.50	29.00	35.50
40.00	44.00	44.50	38.50	33.50	28.50
24.50	21.50	19.00	16.50	15.00	13.50
12.00	11.00				
0.07	0.40	1.35	2.25	3.80	5.50
7.72	11.82	18.87	26.52	33.95	40.45
45.15	47.70	47.55	44.02	39.45	34.00
29.20	25.20	21.80	18.70	16.87	14.80
13.17	11.80				
0.00	0.00	1.50	4.50	8.00	14.00
24.50	35.50	43.00	48.50	51.50	51.00
49.00	45.00	41.00	36.50	32.00	28.00
24.50	21.50	19.00	16.50	14.50	13.00
11.50	10.50				
0.00	0.00	0.50	2.00	5.00	8.00
12.00	23.00	32.00	39.00	44.00	47.00
45.50	40.00	35.00	31.00	26.50	23.00
20.00	17.00	15.00	13.00	11.50	10.50
9.50	8.00				
0.00	0.00	0.90	2.95	6.72	10.35
20.20	30.70	39.12	45.55	49.12	49.52
47.30	42.95	37.97	33.35	28.88	24.92
21.65	18.77	16.38	14.35	12.72	11.40
10.17	9.12				
0.00	2.00	4.00	7.00	11.50	19.00
27.50	34.50	42.50	49.00	54.00	55.00
53.50	53.00	51.00	47.50	42.50	36.50
31.00	27.00	23.00	20.00	17.50	15.50
14.00	12.50				
0.00	0.00	0.00	0.50	1.00	2.00
5.00	10.00	17.00	23.50	31.00	38.50
44.50	44.00	38.00	32.00	28.00	24.00
21.00	18.00	15.50	13.50	12.00	10.50
9.50	8.00				
0.00	0.65	1.67	3.07	5.32	8.42
13.87	20.92	28.90	37.00	43.27	48.47
50.87	49.25	44.90	38.90	33.80	28.82
24.72	21.42	18.60	16.35	14.60	12.87
11.62	10.47				

```
/ KONTBL IS THE TABLE OF CONSTANTS FOT THE MODEL

KONTBL,      Ø
KONTBL 8Ø'/

LOTNUM,      Ø
DELP,        Ø.5

PAUSE
```

ADFLG	1315*	GETMOD	205*	PØ	1475*
ADRESD	3473*	HDIV.	7400	RCL.	10021
ADREST	3474*	HEADR.	5503	RELOC	5000
AMODE.	7523	HMPY1.	7266	RESTRT	132*
ANAL	1234	HMPY2.	7316	RINT1.	7000
ATYP.	10424	HMPY3.	7347	SETMOD	174*
AVRAGE	3475*	HSQ$		SMODE.	7545
A1	10*	IATYP.	10376	SPOT1	3515*
B	3476*	ICL.	7601	SPOT2	3516*
BDOT	3477*	INIT	102*	STORE.	5022
BGN	0*	INT1	20*	STRTBL	311*
BTMSYM	3500*	KA	1500*	SWITCH	3517*
CBDOT	1505*	KKA	1464*	SWMNTR	3520*
CERR	1663*	KKX	1456*	SX	1711*
CHECK	766*	KK1	1437*	SYMBL.	6676
CLEAR	47*	KK2	1442*	TABLAD	1143*
CLSCMP	224*	KK3	1445*	TABLE	1137*
CLSIC	251*	KK4	1450*	TAU1	261*
CL1.	10050	KONTBL	3351*	TAU2	263*
CL2.	10051	KPSW	1461*	TAU3	265*
CNT123	1045*	KPØ	1453*	TAU4	267*
CONTBL	3501*	KX	1476*	TAU5	271*
COUNT	3502*	KXXDOT	1720*	TAU6	273*
CPDOT	1612*	K1	1471*	TAU7	275*
CPSW	1542*	K2	1472*	TBUF	10542
CV	1567*	K3	1473*	TBUFE	10717
CX2DOT	1532*	K4	1474*	TCR.	10347
DABDOT	3503*	LOADDT	27*	TDEC.	10101
DATA	1735*	LOOP	2*	TFLG.	10520
DATADR	3504*	LOTNUM	3471*	TFRM.	10360
DELP	3472*	LSTSW	3510*	TIM	163*
DENOMP	3505*	MODCON	1470*	TIME	3521*
DIGT	12345	MODEL	1330*	TIME1	262*
DISPLA	1046*	MODE.	10052	TIME2	264*
DKMTBL	22*	MODFLG	214*	TIME3	266*
DKM.	5563	MXCNTR	3511*	TIME4	270*
DNTWRT	1427*	NIC	156*	TIME5	272*
DOFUNC	1120*	NIIC	157*	TIME6	274*
DOMODL	1501*	NSTOR	246*	TIME7	276*
END.	7130	NTYP	1013*	TMSG.	10235
ENT1	3506*	NUMRAP	3512*	TOCT.	10053
ERR	1667*	OVERAD	1327*	TREF	3522*
FC	155*	OVERLD	1322*	TRIP1.	7147
FC.	10046	P	3513*	TS	154*
FGMOD$		PDOT	1726*	TSP.	10340
FG2.	7457	POINT.	6677	TS.	10047
FLAG	3507*	POISV	3514*	TT	3523*
GETCON	1433*	PSW	1477*	TTAB.	10367

FI-NGER

TTAG.	67Ø0
TTYP.	1Ø535
TVOLT.	1Ø156
UNKADD	1261*
UNKWN	3524*
V	3525*
VARX	215*
VARX.	5553
VAR1	216*
VAR1.	5554
VAR2	217*
VAR2.	5555
VAR3	22Ø*
VAR3.	5556
VAR4	221*
VAR4.	5557
VAR5	222*
VAR5.	556Ø
VAR6	223*
VAR6.	5561
VMNTR.	5433
VRCHK	1ØØ4*
VRTYP.	5173
WRTCON	137Ø*
X	3526*
XDOT	3527*
X.1.	7444
X1Ø.	7424
X2DOT	1712*

FINGER

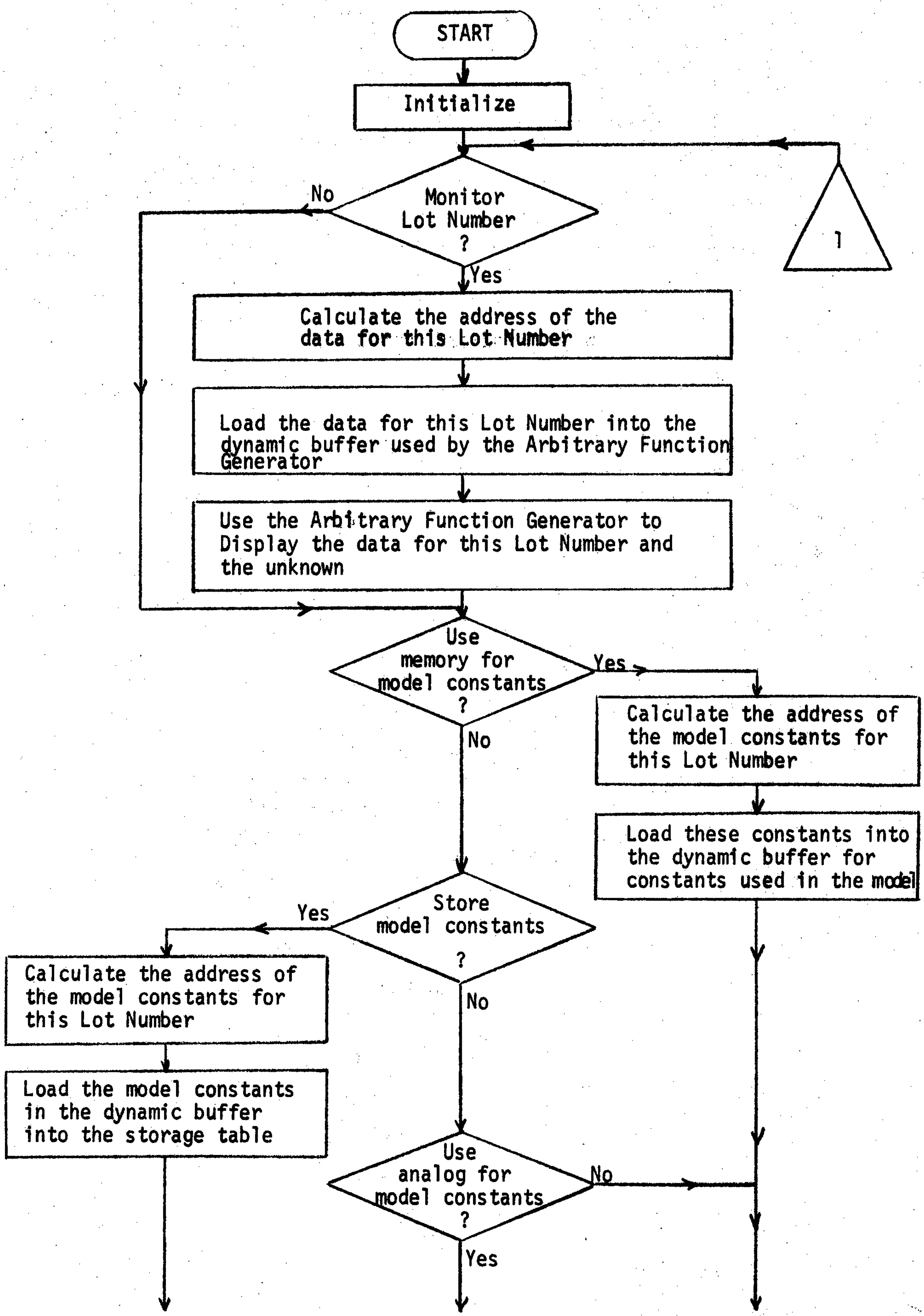
ANAL	1234	TBUF	10542	CNT123	1045*
RELOC	5000	TBUFE	10717	DISPLA	1046*
STORE.	5022	DIGT	12345	DOFUNC	1120*
VRTYP.	5173	BGN	0*	TABLE	1137*
VMNTR.	5433	LOOP	2*	TABLAD	1143*
HEADR.	5503	AI	10*	UNKADD	1261*
VARX.	5553	INTI	20*	ADFLG	1315*
VAR1.	5554	DKMTBL	22*	OVERLD	1322*
VAR2.	5555	LOADDT	27*	OVERAD	1327*
VAR3.	5556	CLEAR	47*	MODEL	1330*
VAR4.	5557	INIT	102*	WRTCON	1370*
VAR5.	5560	RESTRT	132*	DNTWRT	1427*
VAR6.	5561	TS	154*	GETCON	1433*
DKM.	5563	FC	155*	KK1	1437*
SYMBL.	6676	NIC	156*	KK2	1442*
POINT.	6677	NIIC	157*	KK3	1445*
TTAG.	6700	TIM	163*	KK4	1450*
RINTI.	7000	SETMOD	174*	KP0	1453*
END.	7130	GETMOD	205*	KKX	1456*
TRIP1.	7147	MODFLG	214*	KPSW	1461*
HMPY1.	7266	VARX	215*	KKA	1464*
HMPY2.	7316	VAR1	216*	MODCON	1470*
HMPY3.	7347	VAR2	217*	K1	1471*
HDIV.	7400	VAR3	220*	K2	1472*
X10.	7424	VAR4	221*	K3	1473*
X.1.	7444	VAR5	222*	K4	1474*
FG2.	7457	VAR6	223*	P0	1475*
AMODE.	7523	CLSCMP	224*	KX	1476*
SMODE.	7545	NSTOR	246*	PSW	1477*
ICL.	7601	CLSIC	251*	KA	1500*
RCL.	10021	TAU1	261*	DOMODL	1501*
FC.	10046	TIME1	262*	CBDOT	1505*
TS.	10047	TAU2	263*	CX2DOT	1532*
CL1.	10050	TIME2	264*	CPSW	1542*
CL2.	10051	TAU3	265*	CV	1567*
MODE.	10052	TIME3	266*	CPDOT	1612*
TOCT.	10053	TAU4	267*	CERR	1663*
TDEC.	10101	TIME4	270*	ERR	1667*
TVOLT.	10156	TAU5	271*	SX	1711*
TMSG.	10235	TIME5	272*	X2DOT	1712*
TSP.	10340	TAU6	273*	KXXDOT	1720*
TCR.	10347	TIME6	274*	PDOT	1726*
TFRM.	10360	TAU7	275*	DATA	1735*
TTAB.	10367	TIME7	276*	KONTBL	3351*
IATYP.	10376	STRTBL	311*	LOTNUM	3471*
ATYP.	10424	CHECK	766*	DELP	3472*
TFLG.	10520	VRCHK	1004*	ADRESD	3473*
TTYP.	10535	NTYP	1013*	ADREST	3474*

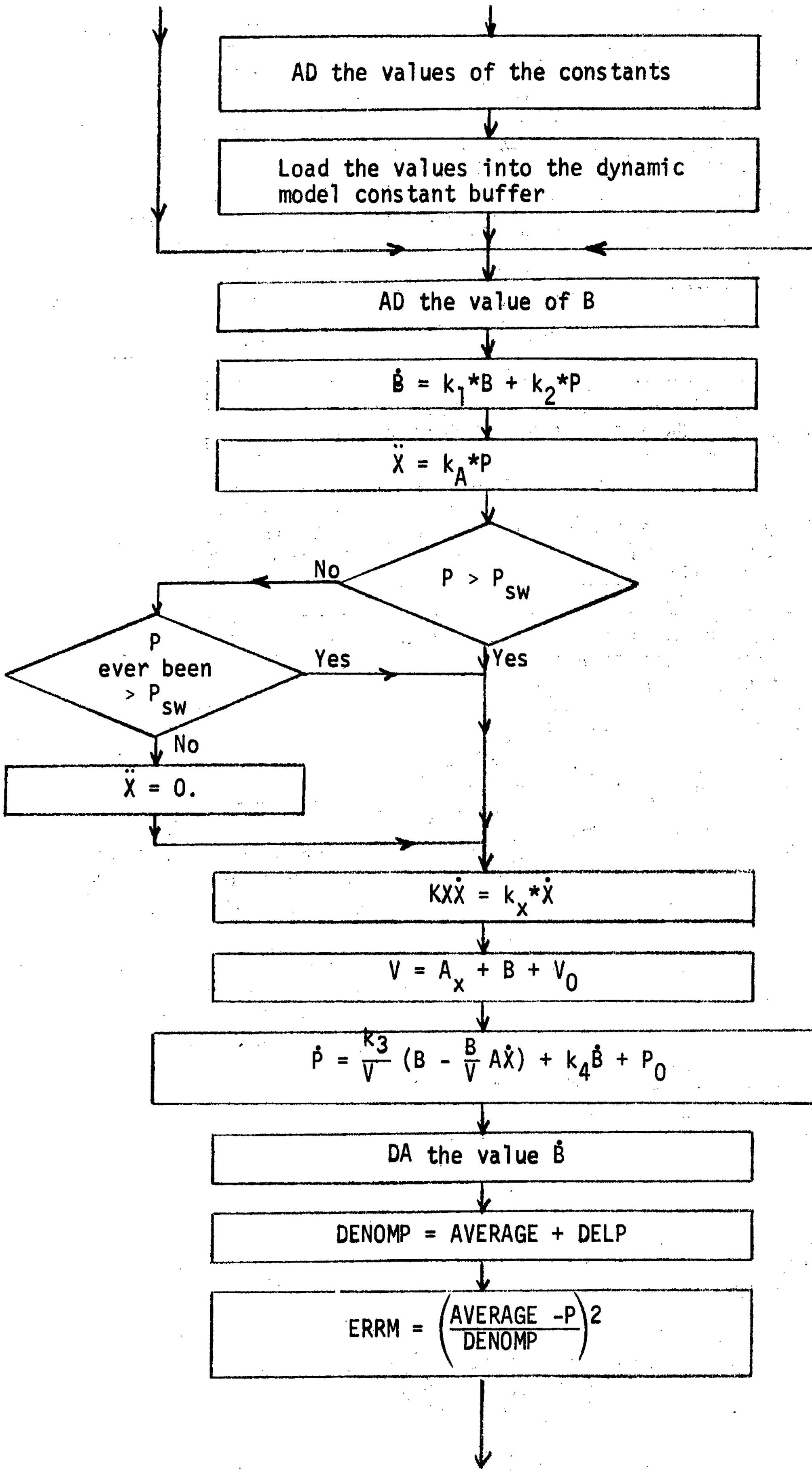
FINGER

AVRAGE	3475*
B	3476*
BDOT	3477*
BTMSYM	3500*
CONTBL	3501*
COUNT	3502*
DABDOT	3503*
DATADR	3504*
DENOMP	3505*
ENT1	3506*
FLAG	3507*
LSTSW	3510*
MXCNTR	3511*
NUMRAP	3512*
P	3513*
POISV	3514*
SPOT1	3515*
SPOT2	3516*
SWITCH	3517*
SWMNTR	3520*
TIME	3521*
TREF	3522*
TT	3523*
UNKWN	3524*
V	3525*
X	3526*
XDOT	3527*
HSQ$	
FGMOD$	

Figure A5

Digital Computer
Flow Diagram
(Hybrid)


START
Initialize
Monitor Lot Number ?
No
Yes
1
Calculate the address of the data for this Lot Number
Load the data for this Lot Number into the dynamic buffer used by the Arbitrary Function Generator
Use the Arbitrary Function Generator to Display the data for this Lot Number and the unknown
Use memory for model constants ?
Yes
No
Calculate the address of the model constants for this Lot Number
Load these constants into the dynamic buffer for constants used in the model
Store model constants ?
Yes
No
Calculate the address of the model constants for this Lot Number
Load the model constants in the dynamic buffer into the storage table
Use analog for model constants ?
No
Yes


AD the values of the constants
Load the values into the dynamic model constant buffer
AD the value of B
$\dot{B} = k_1 * B + k_2 * P$
$\ddot{X} = k_A * P$
$P > P_{sw}$
No
Yes
P ever been $> P_{sw}$
Yes
No
$\ddot{X} = 0.$
$KX\dot{X} = k_x * \dot{X}$
$V = A_x + B + V_0$
$\dot{P} = \frac{k_3}{V} (B - \frac{B}{V} A\dot{X}) + k_4 \dot{B} + P_0$
DA the value $\dot{B}$
DENOMP = AVERAGE + DELP
$ERRM = \left(\frac{AVERAGE - P}{DENOMP}\right)^2$

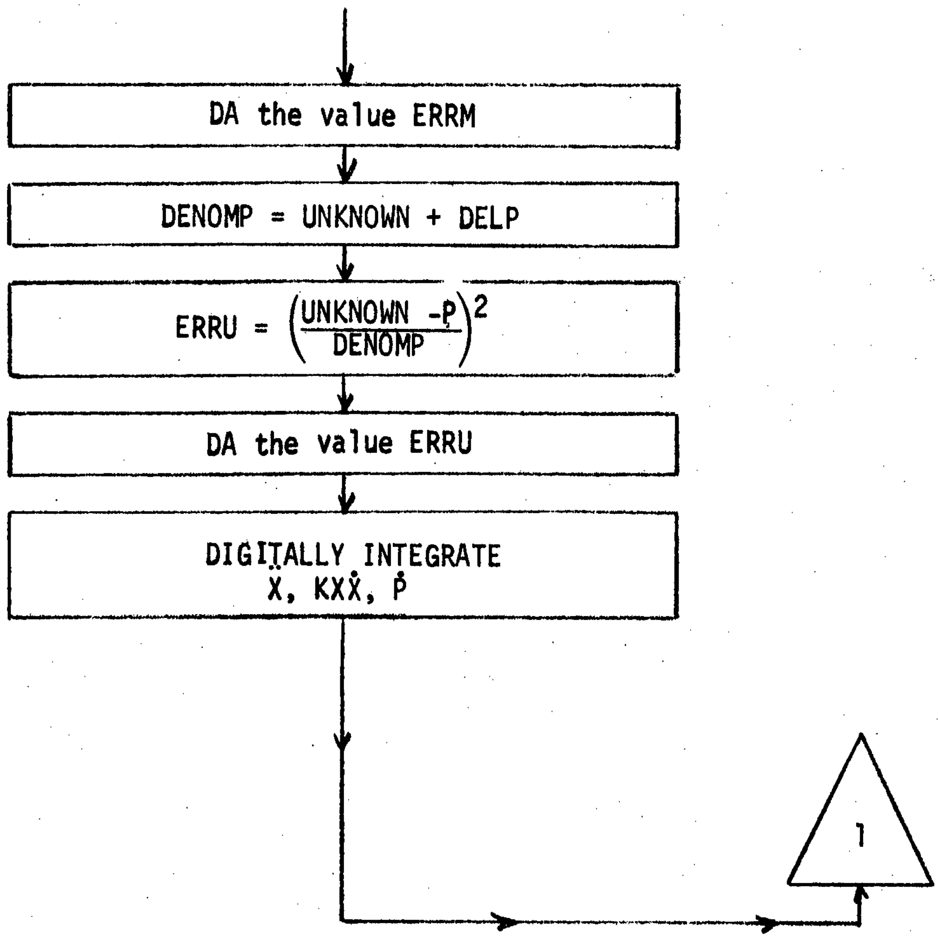

DA the value ERRM
DENOMP = UNKNOWN + DELP
ERRU = ((UNKNOWN - P) / DENOMP)^2
DA the value ERRU
DIGITALLY INTEGRATE
X, KXX, P
1

Figure A6

Digital Computer
Memory Map
(Hybrid)

Digital Computer Memory Map

Absolute Memory Addresses

12000_8	
	Open Memory
3600_8	
	Table of Model Constants (for all 10 Lots)
3500_8	
	Table of Data for Display (Large, Small, Average for all 10 Lots)
1850_8	
	Model
1610_8	
	Dynamic Buffer for Model Constants
1600_8	
	Control Portion of Model (selects source of model constants)
1325_8	
	Data from Unknown
1300_8	
	Dynamic Data Buffer for Arbitrary Function Generator
1225_8	
	Arbitrary Function Generator
1200_8	
	Control and Loading Program for Display (selects and loads desired Lot Number)
1100_8	
	Main (bookkeeping portion of the program)
100_8	

Digital Computer Data Storage Map

Absolute Memory Addresses

3600_8 →	Model Constants	Lot # 10
	Model Constants	Lot # 9
	Model Constants	Lot # 8
	Model Constants	Lot # 7
	Model Constants	Lot # 6
	Model Constants	Lot # 5
	Model Constants	Lot # 4
	Model Constants	Lot # 3
	Model Constants	Lot # 2
	Model Constants	Lot # 1
3500_8 →	Average Small Large	Lot # 10
	Average Small Large	Lot # 9
	Average Small Large	Lot # 8
	Average Small Large	Lot # 7
	Average Small Large	Lot # 6
	Average Small Large	Lot # 5
	Average Small Large	Lot # 4
	Average Small Large	Lot # 3
	Average Small Large	Lot # 2
	Average Small Large	Lot # 1
1850_8 →		