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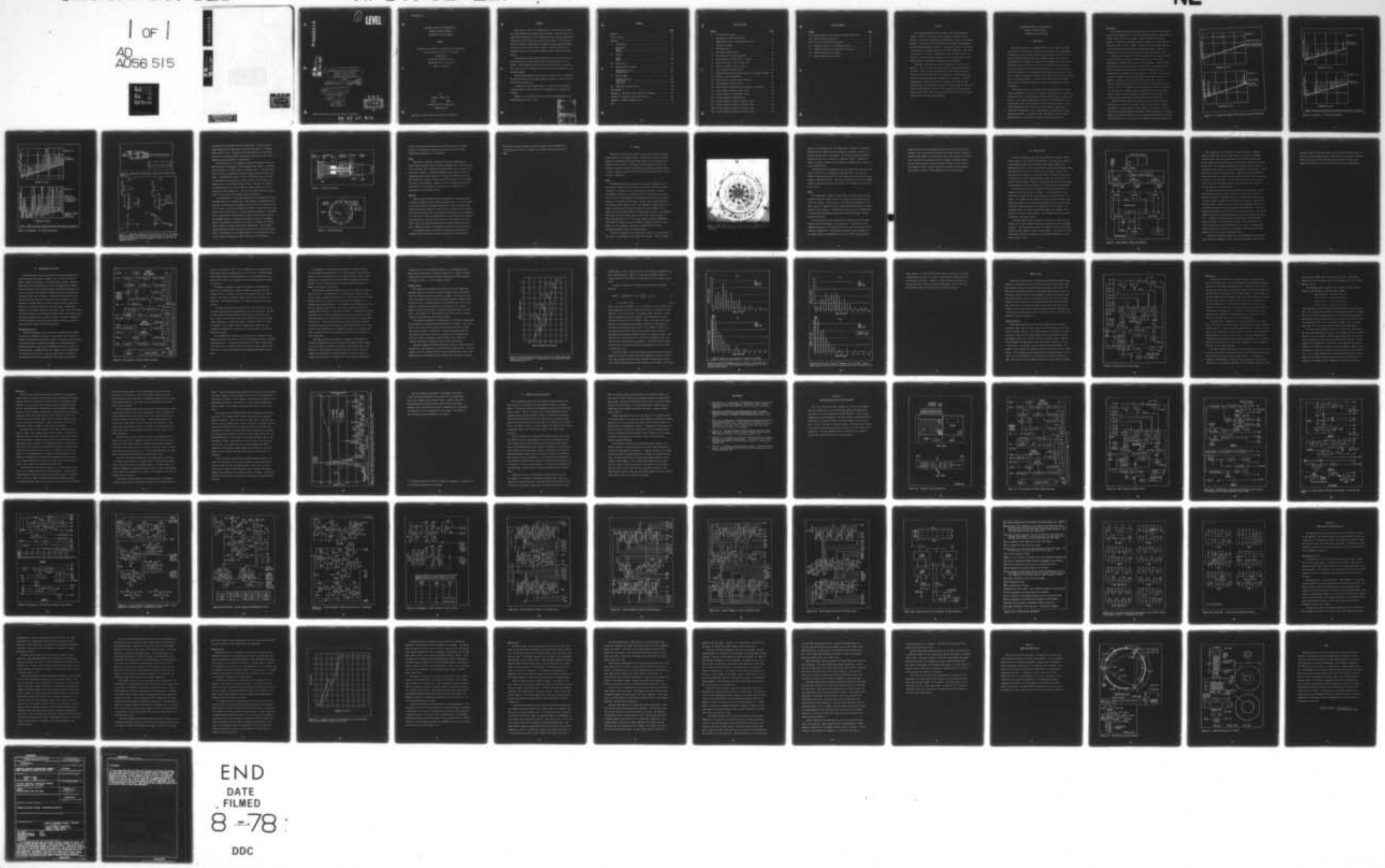

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ELECTRONIC ANALYSIS OF ELECTROSTATIC PULSES TO DETECT IMMINENT JET ENGINE GAS-PATH FAILURE.

THESIS

(14) AFIT/GE/EE/77-7

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(9) Master's thesis,

(11) Dec 77

(12) 84p.

78 07 07 019

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AFIT/GE/EE/77-7

ELECTRONIC ANALYSIS OF ELECTROSTATIC PULSES TO DETECT IMMINENT JET ENGINE GAS-PATH FAILURE

THESIS

Presented to the Faculty of the School of Engineering
of the Air Force Institute of Technology
Air University
in Partial Fulfillment of the
Requirements for the Degree of
Master of Science

by
Freddy L. Baker, B.S.
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Graduate Electrical Engineering
December 1977

Approved for public release; distribution unlimited.

Preface

This thesis is part of an ongoing effort to develop a system which can reliably predict jet engine gas-path failures. When the system becomes fully operational, the jet engine repair cost will be significantly reduced and in some cases may save an entire aircraft. This study was the first attempt to consolidate the complete analog signal processing into one unit and include a logic circuit to analyze the signals to determine excess wear of gas-path components which indicates a pending failure.

Tape recorded signals from probes installed in TF41 tailpipes were used to design the system called the jet engine gas-path wear rate monitor. The personnel of Detroit Diesel Allison Division, especially Mr. G. Hill and Mr. T. Larkin, were very helpful in providing these tape recorded signals.

The prototype models of the system were built by Mr. W. Lindsay and his staff at the Air Force Flight Dynamics Laboratory. I would like to thank them for their help.

I would also like to thank Major R. P. Couch of the Aeronautical System Division for his assistance and information on jet engine performance.

Finally, I would like to thank my wife for her understanding and patience during my tour at AFIT.

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Abstract

A jet engine gas-path wear rate monitor has been designed and tested. The monitor observes gas-path component rubbing, chaffing, burning, or erosion by measuring the electrostatic charge in the engine exhaust. This system continuously monitors the exhaust during engine operation and periodically checks the total metal content in the exhaust to determine the deterioration rate of gas-path components. The design of the monitor is based on 4000 hours of early (1972-1975) TF41 electrostatic count data and on 2000 hours of recent analog tape recorded data produced by TF41 engines undergoing severe distresses.

This thesis describes the theory and operation of the wear rate monitor. First the design and installation of the optimized probes is presented. Next the theory and operation of the analog and digital circuits in the wear rate monitor is discussed. Circuit diagrams are given for all of the electronic components of the monitor. Then the techniques for adapting the monitor to engines other than the TF41 turbofan engine are presented. Finally, test data is given in which the monitor showed excessive wear in a TF41 engine on which it was being tested at the AFAPL. This excessive wear condition occurred after more than 100 hours of stable wear operation.

ELECTRONIC ANALYSIS OF ELECTROSTATIC
PULSES TO DETECT IMMINENT
JET ENGINE GAS-PATH FAILURE

I. Introduction

The early detection of a pending failure of a jet engine can reduce the high cost of repairing jet engines. The typical cost of overhauling one engine varies between $80,000 and $200,000; however, much of the cost could be avoided by reducing secondary damage through early detection. The combination of reducing the repair cost for engines that fail and extending the routine overhaul cycles by early failure detection could reduce significantly the annual jet engine repair cost. The early failure prediction capability of electrostatic probes has been proven (Refs 3 and 5), but electronic analysis is needed to give the earliest possible warning and to increase reliability. The unit that combines the electrostatic probes and the electronic analysis is called a jet engine gas-path wear rate monitor.

This thesis discusses the design of the optimized probes, the basic theory of operation of the wear rate monitor, the analog signal processor and monitor logic in the electronics, and the application of the wear rate monitor. Only a brief discussion is presented of the background of the electrostatic probes and the source of the electrostatic charge. An in-depth explanation of the source of the electrostatic charges and of particular relationships used in processing the signals is given in the referenced material. In addition, there have been 23 other reports or papers written on electrostatic signals as listed in Reference 3.

Background

In 1970 Capt Vopalensky discovered a large increase in electrostatic charge in the exhaust prior to a second stage high pressure turbine blade fatigue failure in a J57 jet engine. Figure 1 shows the increasing number of electrostatic discharge pulses he measured on a probe placed in the exhaust (Ref 1:37-40). Figure 2 shows the early type probe that was used to measure these electrostatic charges, and Figure 3 shows the placement of the probe in the tailpipe of the jet engine (Ref 2:1-3).

Because of the importance of this discovery, the Air Force has spent over $1 million to determine the exact source of the electrostatic charges and to optimize the detection of these charges. Pratt & Whitney, Detroit Diesel Allison Division, General Electric, Aeronautical System Division, and the Air Force Wright Aeronautical Laboratories have collected about 10,000 hours of data containing the count rate of pulses on many jet engines using single and dual probes similar to the one in Figure 2. Eighteen of these engines failed during data collection. Twelve of these engine failures were preceded by an increase of at least a factor of ten in the pulse count rate indicating a prediction capability of 67 percent. However, there were three increases in count rate when no failure occurred indicating a reliability of 80 percent. The average warning time before the failures was four hours (Ref 3).

McDonnell Douglas Research Laboratories did an extensive study of the nature of electrostatic signals. They discovered that the signals are pockets of charge emerging from the engine. The pockets come from both metal errosion/burning and high speed rubbing, which give off charged metallic particles surrounded by an ion cloud that neutralizes the charge of the particles. As the particles flow through the engine, the particles

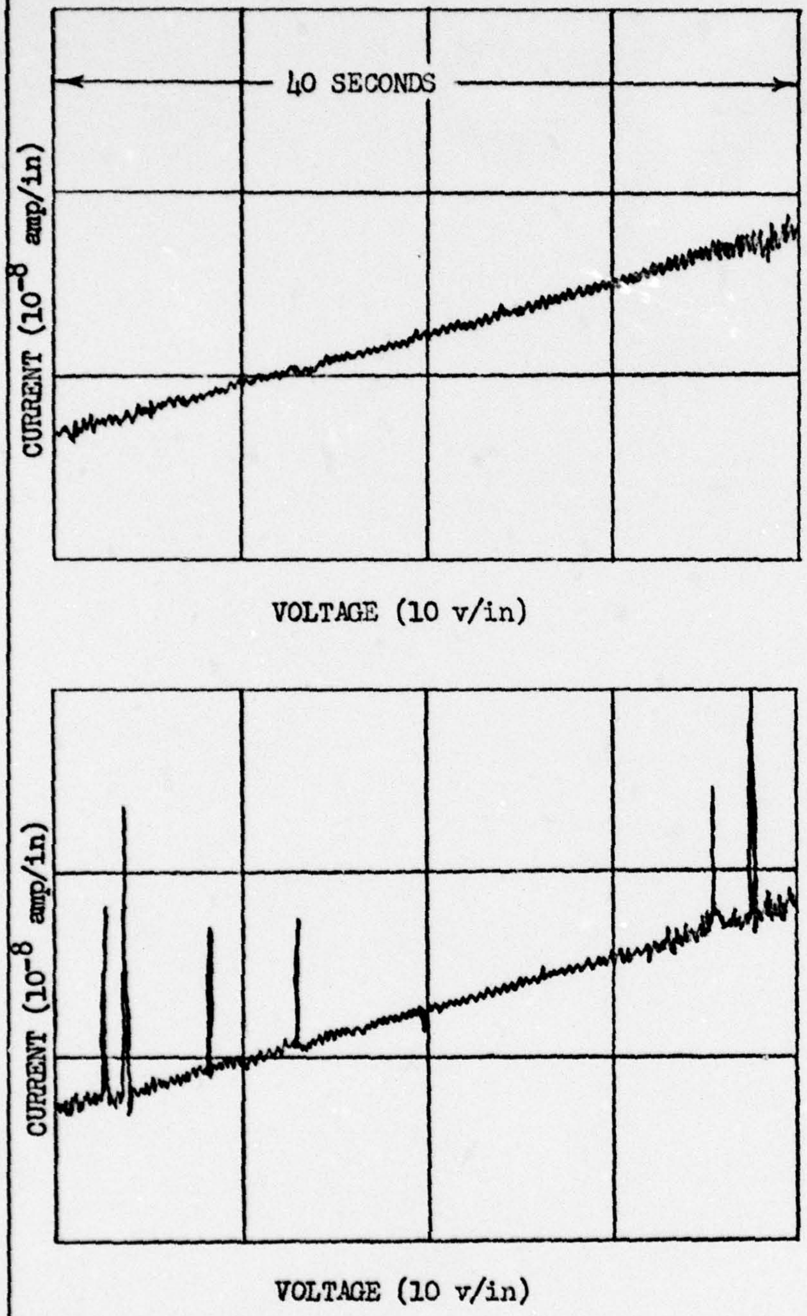


Figure 1 a.

NORMAL I-V TRACE

SLOPE EXPONENTIAL
WITH MIXTURE RATIO

Figure 1 b.

FIRST SPIKES

0900 HRS
17 NOV 1970

Figure 1. I-V Traces With Spikes (Ref 1:38-40). (Continued next page)

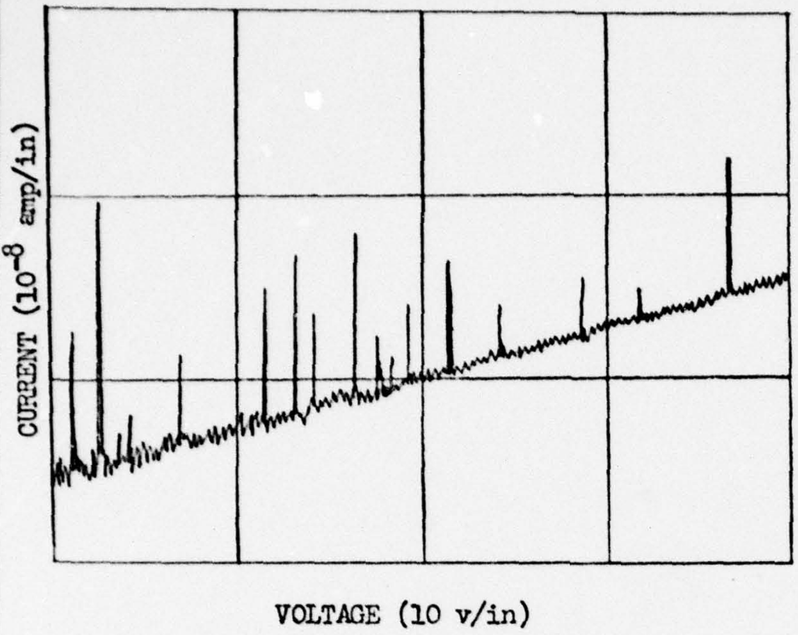


Figure 1 c.

0930 HRS
17 NOV 1970

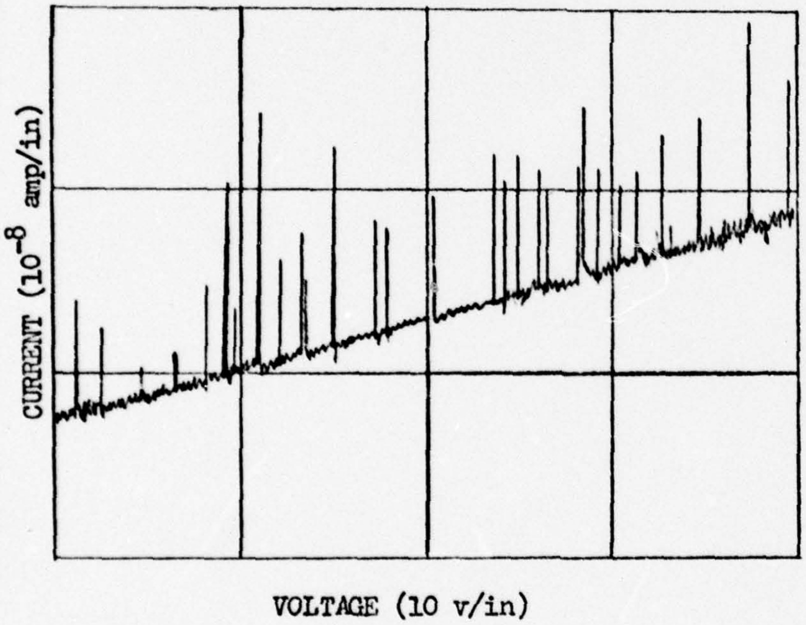


Figure 1 d.

1000 HRS
17 NOV 1970

(Note: Spiking sequence showing increasing spike size and number.)

Figure 1 (Continued). I-V Traces With Spikes.

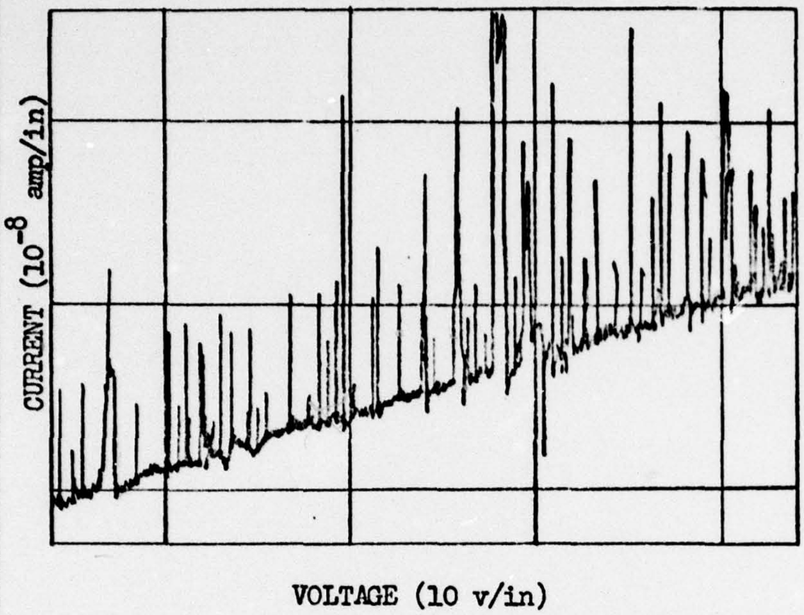


Figure 1 e.

1200 HRS
17 NOV 1970

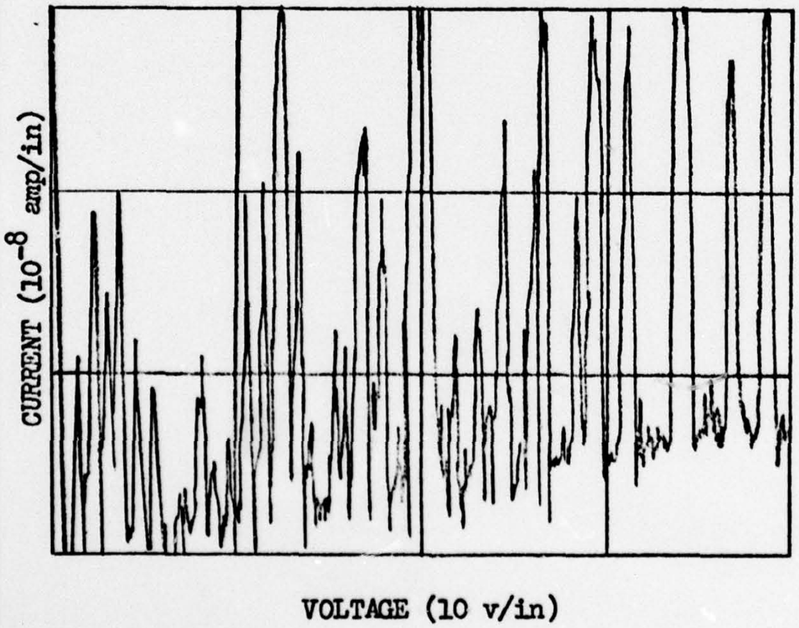


Figure 1 f.

1300 HRS
17 NOV 1970
(5 HOURS PRIOR
TO FAILURE)

(ENGINE FAILURE)
1000 HRS
18 NOV 1970

(Note: Spiking sequence showing increasing spike size and number.)

Figure 1 (Continued). I-V Traces With Spikes.

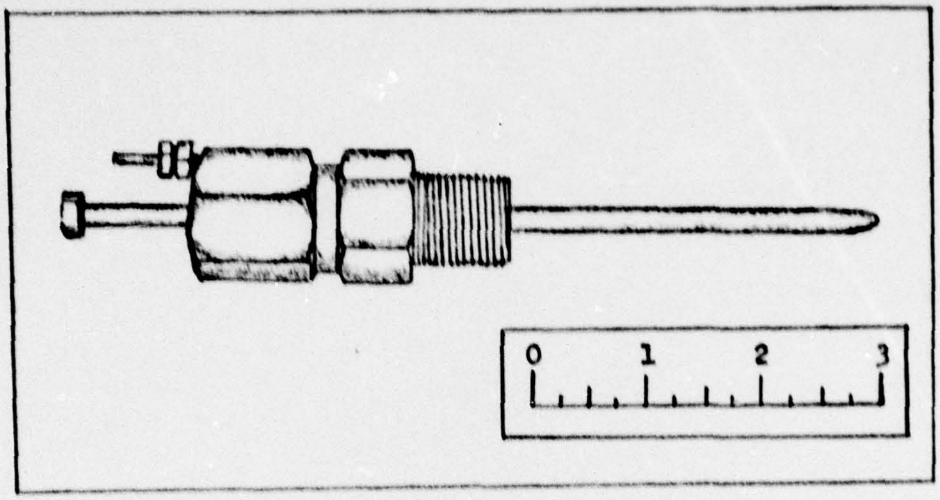


Figure 2. Electrostatic probe used by AFFDL in J57 engine tests (Ref 2:3).

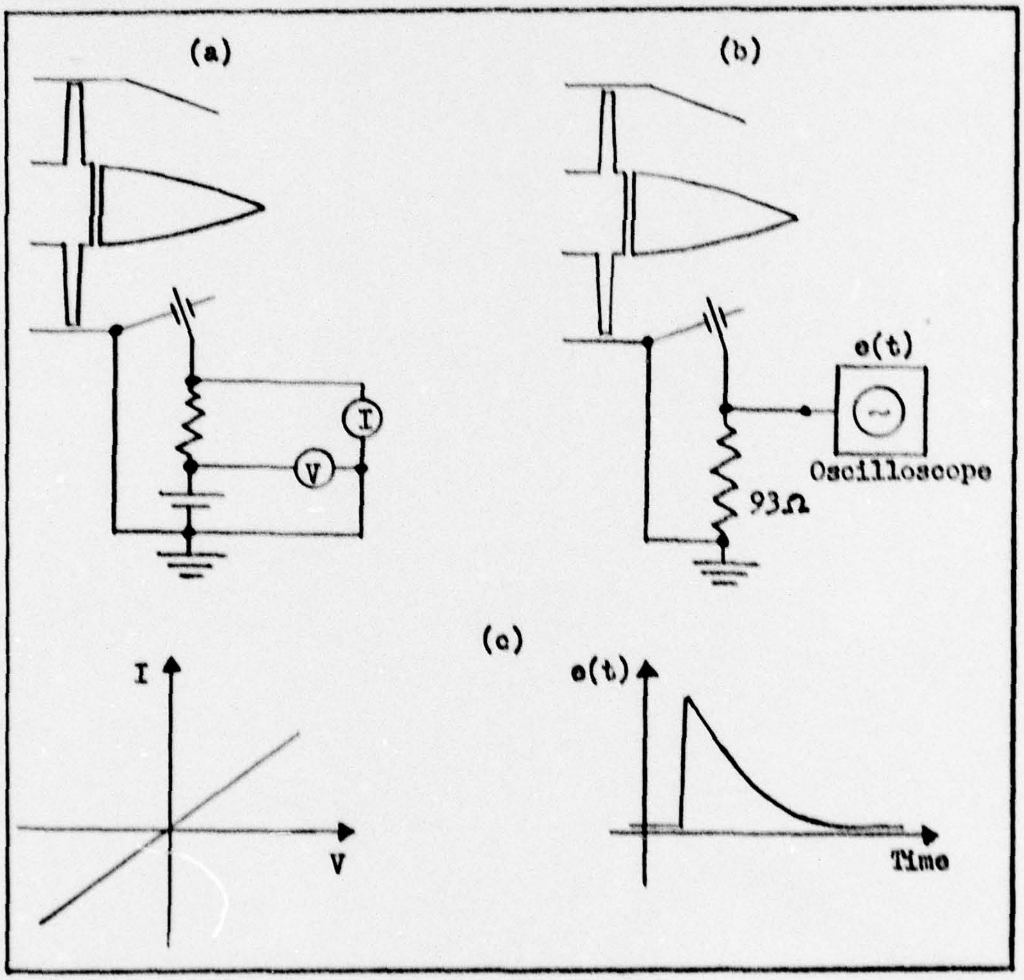


Figure 3. Simplified circuits for electrostatic probes: (a) circuit used to determine current-voltage characteristics, (b) circuit used to monitor pulse shapes, and (c) examples of types of test records obtained (Ref 2:3).

strike parts of the engine and loose their charge. The ion cloud is swept along with the exhaust gases and leaves the engine as a charged pocket (Ref 2:33-77). Subsequent laboratory studies at the Air Force Institute of Technology (AFIT) confirmed that both metal errosion and rubbing cause these pockets of charge (Ref 4).

After the source of the charges was known, two graduate students at AFIT optimized the detection of these charges (Refs 4 and 5). The final design consist of two probes shown in Figures 4 and 5. The first probe has been called the PRION probe for patch ring ion probe because of its shape. The PRION probe consist of three 4 inch wide pieces of circuit board material epoxied around the inside surface of the tailpipe just behind the core of the engine forming a ring. The probe is located in the tailpipe where the cool air joins the engine exhaust so it is not subjected to high temperatures. Since the ring probe encircles the exhaust, it can detect all the charge leaving the engine.

The second probe is called the TRION probe for triangular ion probe. The TRION probe is a triangle made of high temperature (HASTELLOY-X) wire with the vertices near the tailpipe walls and is placed 10 inches behind the ring probe. The 10 inch separation provides a time difference in the signals from the two probes to increase detection reliability. The TRION probe is placed down stream because it removes charge from the exhaust. The triangle design of the TRION probe places the wire in the exhaust path to provide direct coupling of the charge to the wire, thus giving larger "spikes" of current than from the PRION probe. These "spikes" give an increase in detection capability over the use of the PRION probe alone. The amplitude of the voltage signal to be used from both probes can be varied by changing the input resistance of the electronic

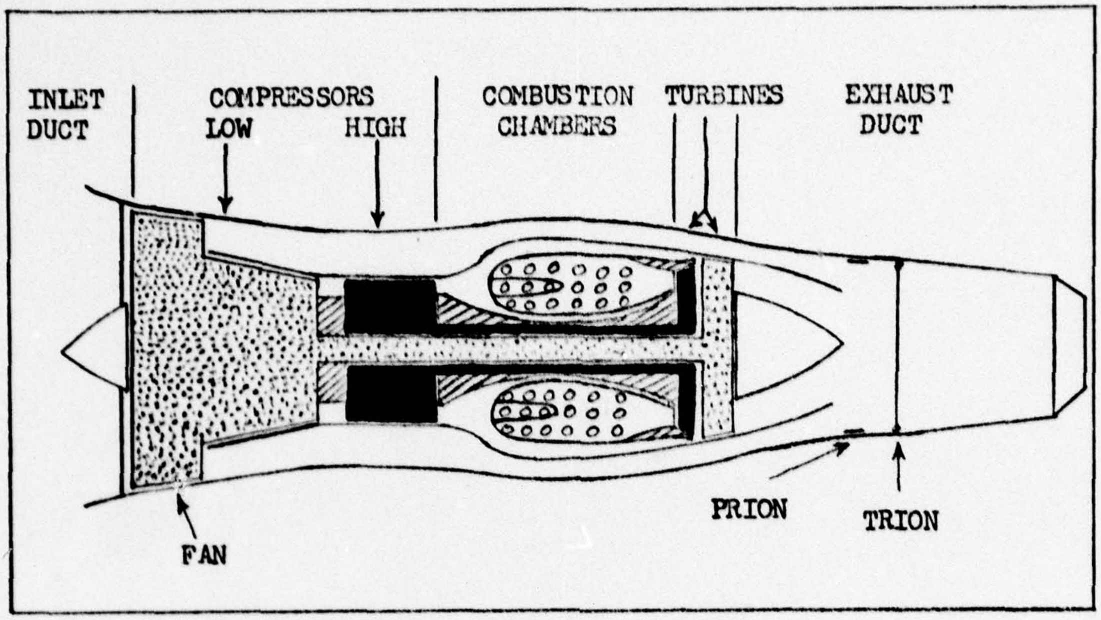


Figure 4. Turbofan Jet Engine.

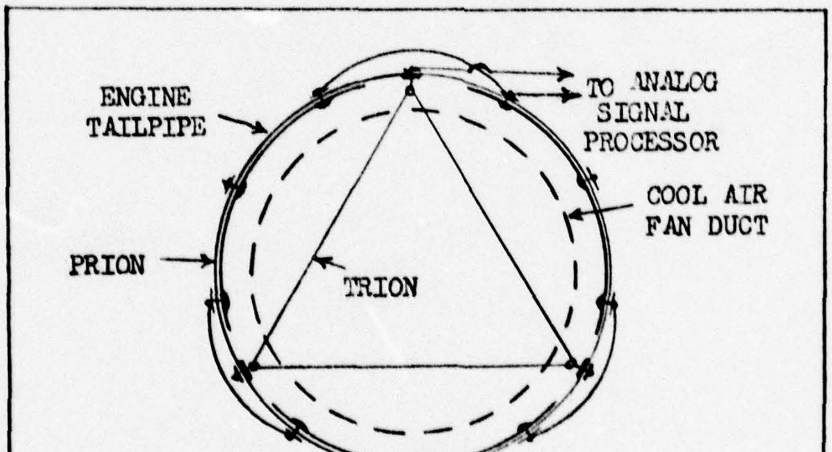


Figure 5. Optimized Probes.

circuits, since both probes have been verified to behave as current sources for terminating resistances less than 200 kΩ (Ref Private Communication with Major R. P. Couch/ASD).

Scope

This thesis is directed toward electronically normalizing and quantifying the signals from the TRION and PRION probes. This electronic process provides stable trending data during normal engine operation and an automated warning of impending component failure when an engine is undergoing severe gas-path distress. Probes were installed in several TF41 turbofan jet engines, and all design and testing of the electronics were done on these engines. Adaption of this jet engine gas-path wear rate monitor to other engines may be possible as explained in the Application and Conclusions section.

Approach

Detroit Diesel Allison Division of General Motors Corporation tape recorded the signals from the TRION and PRION probes on the TF41 turbofan jet engines they were testing at Indianapolis. These recordings were used to design the electronic circuit to give a uniform wear rate indication for a good engine under all operating conditions that were simulated on a test stand. After a prototype model was constructed and tested with recorded data, the model was then tested on a TF41 engine being run at the Air Force Aero Propulsion Laboratory at Wright-Patterson Air Force Base. Eight pre-production prototypes are currently being fabricated.

The original design of the wear rate monitor has flexibility in alignment and in observing the signal processing of the electronics.

After several types of engines have been analyzed and the alignment of the electronics finalized, a simplier and compact production unit can be made.

II. Probes

The probes in the wear rate monitor are used to detect the electrostatic charge in a jet engine exhaust. The two probes used in the TF41 engine are the TRION probe and the PRION probe. The two probes are described in this section. A photograph of the probes as seen from the tailpipe is given in Figure 6; the electrical connection to these probes is shown in Figure 5; and the physical dimensions and supporting hardware is given in Appendix C.

TRION

The TRION grid probe is designed to give direct coupling of the electrostatic charge to the electronic circuit and to give more uniform coverage of the exhaust cross section than the rod probe in Figure 2. The triangular design of the TRION probe with the vertices at the edge of the exhaust was mathematically determined to give the best average of distance to all points in the exhaust (using a three region model) without going to a more complex design. The additional coverage given by more complex designs did not justify the additional drag presented to the exhaust and the problems involved in constructing the probe. The maximum drag expected from the TRION probe at full thrust (14,000 pounds) is about 40 pounds (Ref 6:21). The probe is made of 3/32 inch HASTELLOY-X wire which is designed to have an "infinite" fatigue life with a safety factor of 3 when operated continuously at 1250°F and full thrust (called intermediate power) on the TF41 engine.

The direct coupling of the electrostatic charge to the TRION probe is due to the close proximity of the probe to the charge. Since the TRION

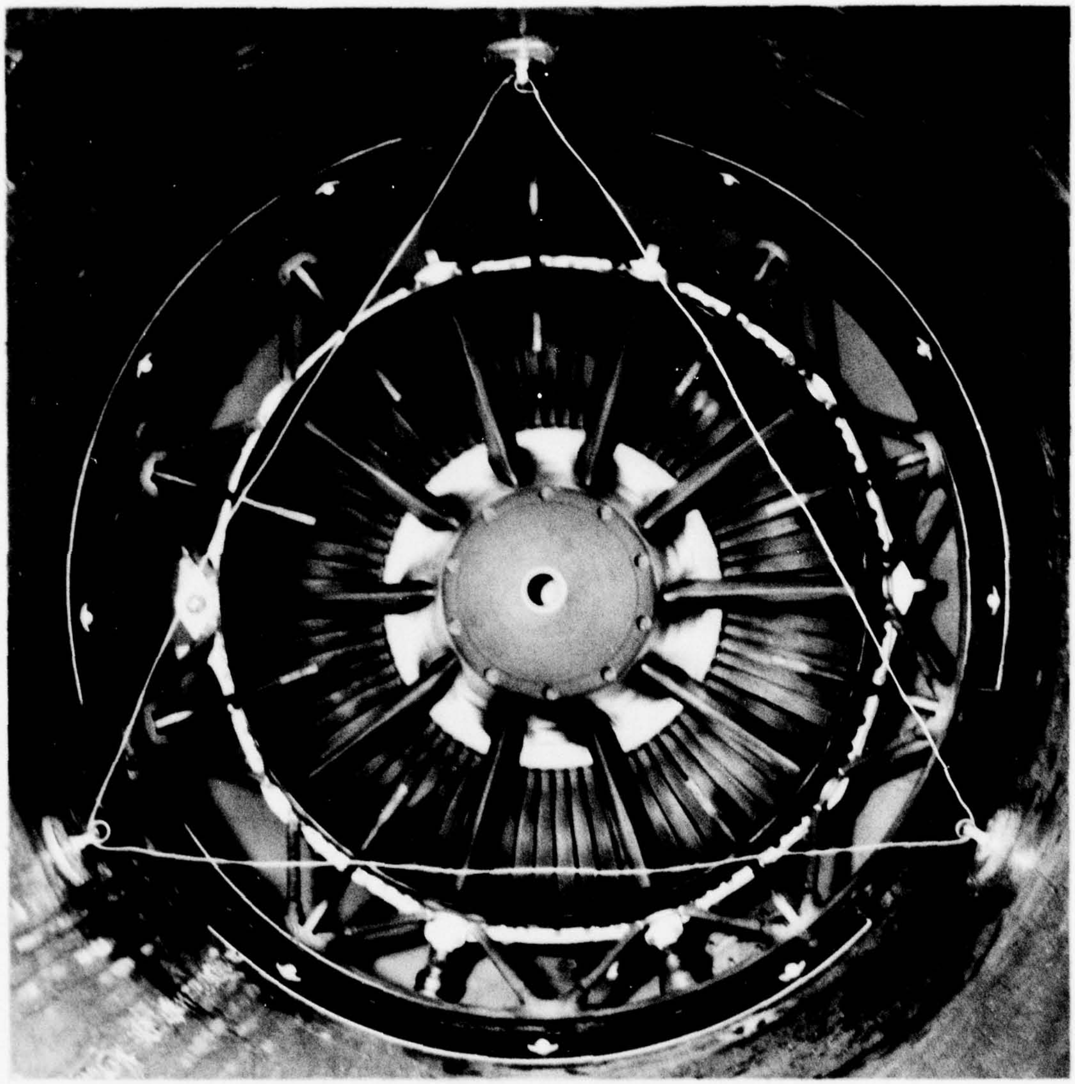


Figure 6. The TRION grid probe and PRION probe as viewed from the end of the tailpipe on a TF41 engine. Each side of the triangle probe is 2 ft long.

probe is in the exhaust path, the charge that is coupled to the probe is removed from the exhaust and goes through the termination resistor to ground (the main body of the engine). The voltage developed across the termination resistor is used by the electronic circuit. Because net charge is actually removed from the exhaust, the TRION probe is placed after the PRION probe.

The TRION probe is supported by 5/8 inch eyelet bolts mounted in the center of three 1-1/4 inch phenolic insulative bolts. The cool air from the turbofan stream cools the wire enough at the vertices to prevent damage to the phenolic bolts. Electrical connection is made to the TRION probe by connecting a wire on the outside of the tailpipe to one of the eyelet bolts.

PRION

The PRION probe is made of three patches of circuit board material placed so that they almost encircle the inside of the tailpipe near the core of the engine. As the charge in the exhaust goes through the tailpipe, there is an opposite polarity charge following along on the inside surface of the tailpipe. As this surface charge crosses the PRION probe, a current flows through the termination resistor developing a voltage across the resistor.

The three patches of the PRION probe are made of 1/16 inch single sided circuit board material. The patches are 4 inches wide to give adequate detection of the charge, and 2 feet long to enclose most of the tailpipe circumference. The patches are epoxied to the tailpipe near the engine where the temperature does not reach 500°F (the temperature limit of the circuit board material) because of the cool air from the turbofan. Three bolts are placed through each patch and the tailpipe to provide further support for the patches and to obtain electrical connection. The bolts are insulated from the tailpipe by phenolic washers. The end bolts on adjacent patches are wired together on the outside of the tailpipe to give a complete electrical enclosure of the tailpipe. The electronic circuit is then connected to one of these bolts.

III. Basic Theory

The basic function of the wear rate monitor is to measure electrostatic signals on the TRION and PRION probes, to process these signals to obtain digital signals, and to compare these signals against some predicted wear rate. If one of the measured electrostatic signals exceeds the predicted wear rate by a factor of ten, an alarm is given to the operator, and the engine on a test stand may be shut down automatically, if desired. The total charge leaving the engine can be related to the amount of metal leaving. However, this monitor uses only relative charge amounts because each type of metal has a different charge relationship.

The theory of the wear rate monitor can be better understood by looking at the block diagram in Figure 7. The measurement circuits determine the charge in the exhaust relating to the actual wear of the engine. The timing circuit analyzes the engine operating condition and varies the sample time to achieve normalization of data for each sample. The monitor logic determines if any measured data has exceeded a set threshold within the sample interval and sends a print command to the printer at the end of each interval. If a threshold has been exceeded, the monitor logic sets an alarm.

The grid signal from the TRION probe and the ring signal from the PRION probe in the jet engine tailpipe are processed by the measurement circuits. This processing determines the number of large charge pulses and the relative amount of charge in these pulses. The outputs of these measurement circuits are digital and are stored accumulatively in the monitor logic circuit.

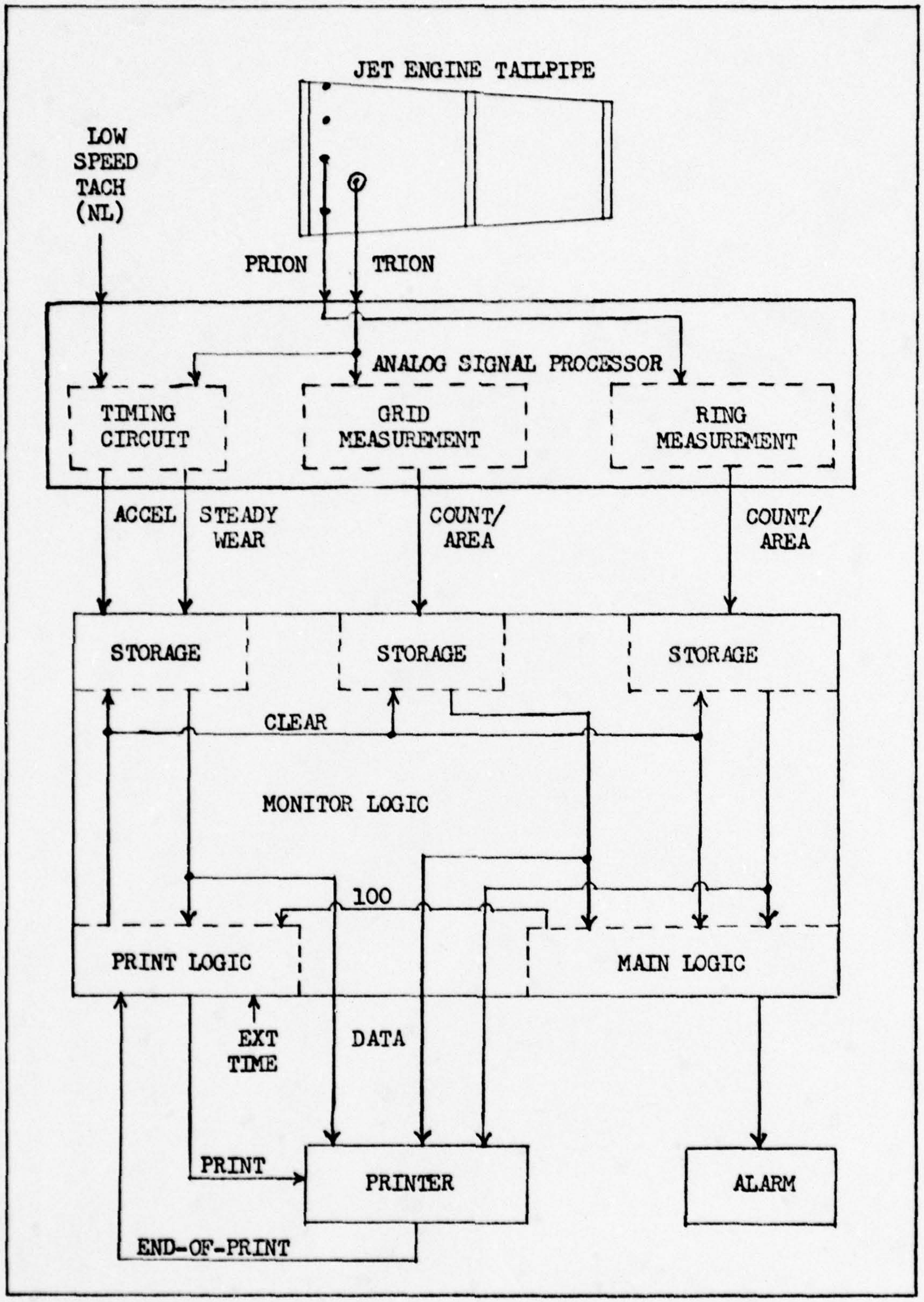


Figure 7. Block Diagram of Wear Rate Monitor.

The tachometer on the low pressure turbine provides a frequency modulated signal (NL) for the timing circuit. NL is used to generate the predicted acceleration digital pulses (AC), and is combined with the dc component of the grid signal to generate the predicted steady wear pulses (SW). If the engine is operated so that more wear is expected, the timing circuit generates the AC and SW pulses at a faster rate. These pulses are stored in the monitor logic. When the sum of the AC and SW pulses equals 100, the print logic in the monitor logic causes the printer to print all the stored data. At the end of the print cycle, the print logic clears all the storage registers and sends the "clear" signal to the main logic in the monitor logic.

The main logic monitors the grid and ring storage registers in the monitor logic to detect either of two types of alarms and to detect a 100 print condition. The main logic gives an immediate type alarm when a storage register reaches 900. The other type of alarm is based on any storage register exceeding a preset value (70 for example) and giving a threshold alarm pulse on three consecutive sample intervals. The first threshold alarm pulse is stored in a four bit shift register. The "clear" signal from the print logic mentioned above shifts this pulse one register. If another threshold pulse is received before the next "clear" signal, the pulse is stored and then shifted. After three shifts, an alarm is given which is called the three count alarm. If a threshold pulse is missing, the registers are cleared by the print logic "clear" signal and the shift count starts back at one.

A 100 print condition is when one of the measurement storage registers reaches an increment of 100. This condition causes the main logic to send a signal to the print logic to print the stored data, but not to clear any of the storage registers. This 100 print condition is required becuase the printer used in this prototype version of the wear rate monitor has columns to print only two digits for each storage register.

IV. Analog Signal Processor

The analog signal processor converts the analog signals from the probes and engine tachometer to digital form for use by the monitor logic in engine wear analysis. The analog signal processor takes the grid signal from the TRION probe and the ring signal from the PRION probe and converts them to digital signals representing the number and size of the positive and negative electrostatic pulses, which indicate the actual wear of the jet engine. The analog signal processor also takes the FM signal from the low pressure turbine tachometer and the dc level of the grid signal and converts them to digital signals that represent the operating condition of the jet engine. These digital signals vary the sample interval of the monitor logic. This section gives the basic operation of the measurement circuits and of the timing circuit. The detailed operation of the wear rate monitor is given in Appendix B. The block diagram of the analog signal processor is shown in Figure 8, and the circuit diagrams are given in Appendix A.

Measurement Circuits

The grid measurement circuit processes the signal from the TRION grid probe to determine the number of charge pulses and the amount of charge in both positive and negative pulses. The polarity of the pulses in the pulse counter circuitry is determined by two multivibrators. A positive pulse will trigger one multivibrator and block the other for 35 milliseconds. A negative pulse will trigger the second multivibrator and block the first one. Thus, the first polarity to arrive at the multivibrators will be transmitted to the output as one digital

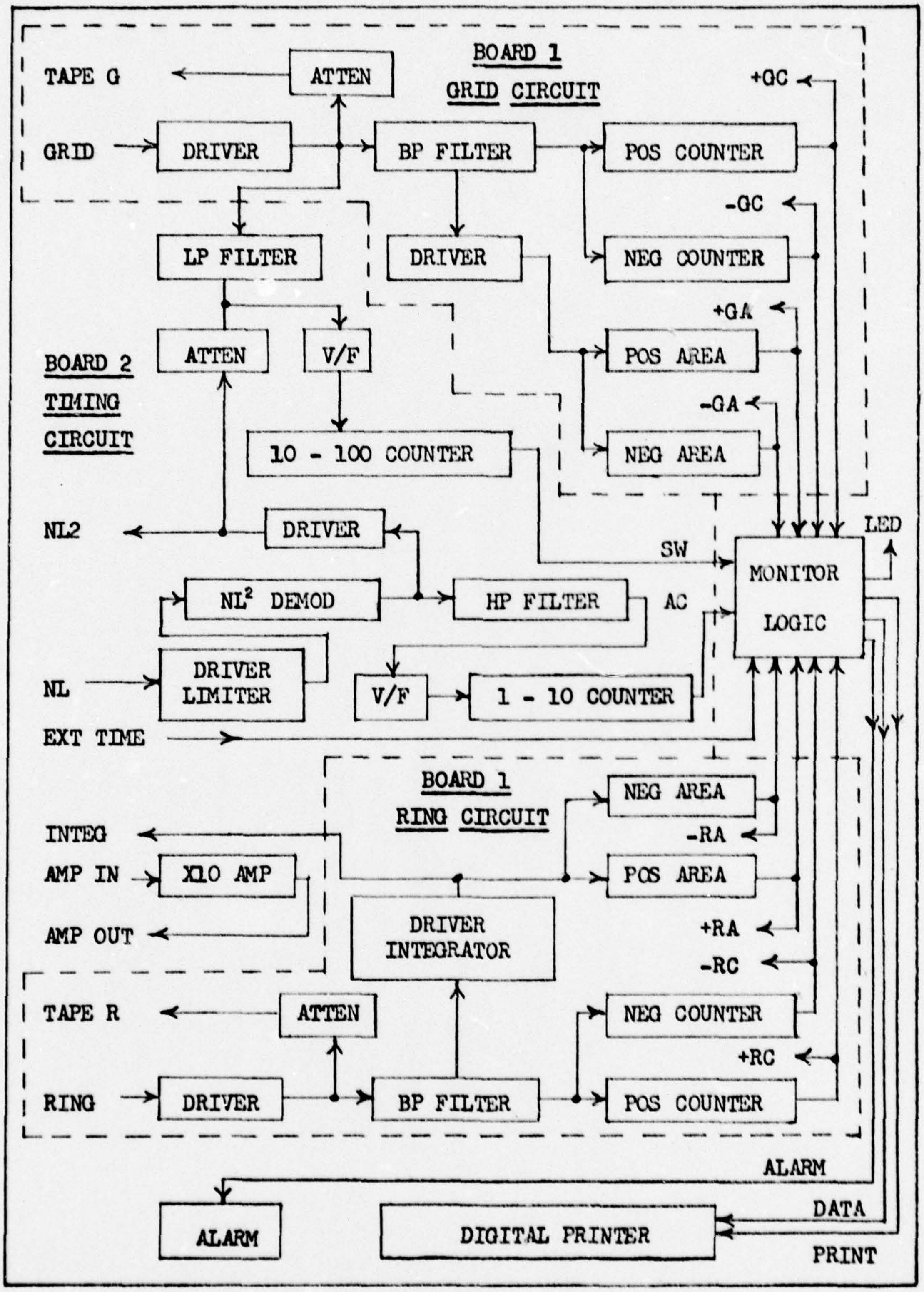


Figure 8. Block Diagram of Analog Signal Processor.

count of this polarity (+GC or -GC). Blocking the other input prevents fast bipolar pulses from being counted as two pulses. For pulses longer than 35 milliseconds, the multivibrators will not retrigger until the signal level crosses a set threshold, thus preventing multiple counting of one pulse.

The amount of charge in a pulse is determined by the pulse area above a set level driving a voltage-to-frequency converter (V/F) for positive pulses, and below a set level driving another V/F for negative pulses. The outputs are digital signals (+GA or -GA) relating to the pulse area. These digital signals are relative measures of the charge content.

The ring measurement circuit differs from the grid circuit only by the first stage gain and the integrator in the area processing. The size of large pulses from the TRION when terminated in 50 kΩ is ten volts (i.e. 200 μa), which requires unity gain by the first stage for optimum signal processing. A large ring signal is only two volts (i.e. 40 μa), so a gain of five is used to obtain optimum signal processing. The optimum processing level is limited to ten volts because of the twelve volts power supply.

The termination resistance of the ring circuit is limited to 50 kΩ because of the RC time constant of the ring termination resistor and PRION probe capacitance. A larger resistor would give a larger voltage since the probe acts as a current source, but the circuit time constant would filter the signal too much and some high frequency information would be lost.

An integrator is used in the ring measurement circuit, because the ring signal was determined to be the time derivative of the charge flow rate. The grid signal has only a slight derivative effect. After integration of the ring signal, the grid and ring signals are similar. However, there is enough difference to justify using both probes to monitor the charge in the exhaust.

The grid and ring signals differ in the way the charge is coupled onto the probes. The TRION probe is in the exhaust flow path so that the net charge is coupled directly onto it. On the other hand, the PRION probe encircles the tailpipe and all the charge is coupled onto it through electrostatic induction. The coupling to the PRION probe is done from the opposite polarity skin effect charge, which flows along the tailpipe wall following the charge in the exhaust. The different coupling techniques tend to cause the TRION probe to be more responsive to charge pulse amplitude and the PRION probe to be more responsive to total charge or pulse area. This fact may mean that the flight version of the wear rate monitor could use four signature elements (± grid counts and ± ring area) to obtain adequate pulse recognition; however, at the present time eight elements are being used (± grid area, ± grid count, ± ring area, and ± ring count).

The normal charge in the exhaust is eliminated from analysis by threshold adjustments to both the positive and negative voltage signals in the count and area processing circuitry. This normal charge in the exhaust is caused primarily by excess ions created in the combustion chamber when high mobility electrons migrate to the walls leaving an excess positive charge in the exhaust gas. This normal charge appears as white noise to the measurement circuits, so the thresholds in the measurement circuits are set above this noise level. Thus, the charge pulses analyzed are primarily caused by rubbing, metal burn, errosion, or component chaffing in the jet engine gas-path.

Timing Circuit

The timing circuit monitors the operation of the jet engine and generates digital pulses which vary the processing time of the monitor logic in accordance with the expected wear (EXPW). The engine's operation is monitored by observing the low pressure turbine tachometer (NL) and the dc level of the grid signal from the TRION probe. The dc level relates to turbine inlet temperature and mass flow rate as shown in Figure 9, which in turn relates to engine thrust above 8500 pounds (Ref 5:21). The frequency of NL (0 to 440 Hz on the TF41 tested) is proportional to the speed of the low pressure turbine.

The component of EXPW due to acceleration is obtained by demodulating NL to produce a dc voltage (NL2) proportional to NL squared. The derivative of NL2 is then the acceleration and deceleration factor of EXPW. The derivative signal is applied to a voltage-to-frequency converter (V/F) whose output (AC) is sent to the monitor logic in digital form. Since only large accelerations cause significant wear, there is a threshold adjustment to eliminate small or slow accelerations.

The other component of EXPW is "thrust" (T) which is derived from the average value (dc component) of the grid signal and part of NL2. The grid signal is low pass filtered to obtain the dc component (DC). NL2 is then added to DC in such a manner that, at full speed of the engine and with

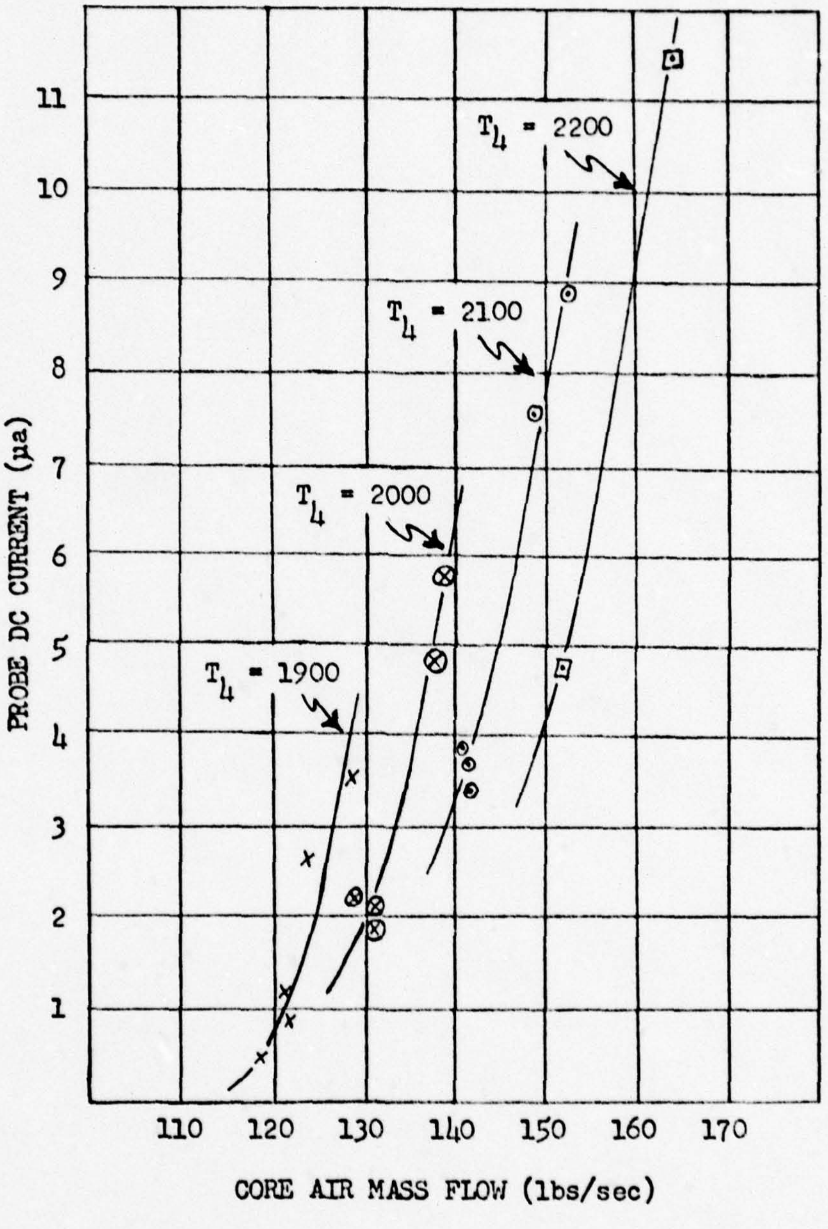


Figure 9. Probe DC Current vs Core Air Mass Flow on TF41 engine with the Grid Probe terminated with a 240kΩ resistor for different Turbine Inlet Temperatures (°F).

14,000 pounds of thrust, the NL2 factor is one fifth the amplitude of DC. This combined signal is applied to a V/F, and the digital output is called steady wear (SW) which may be thought of as a "hot section factor count".

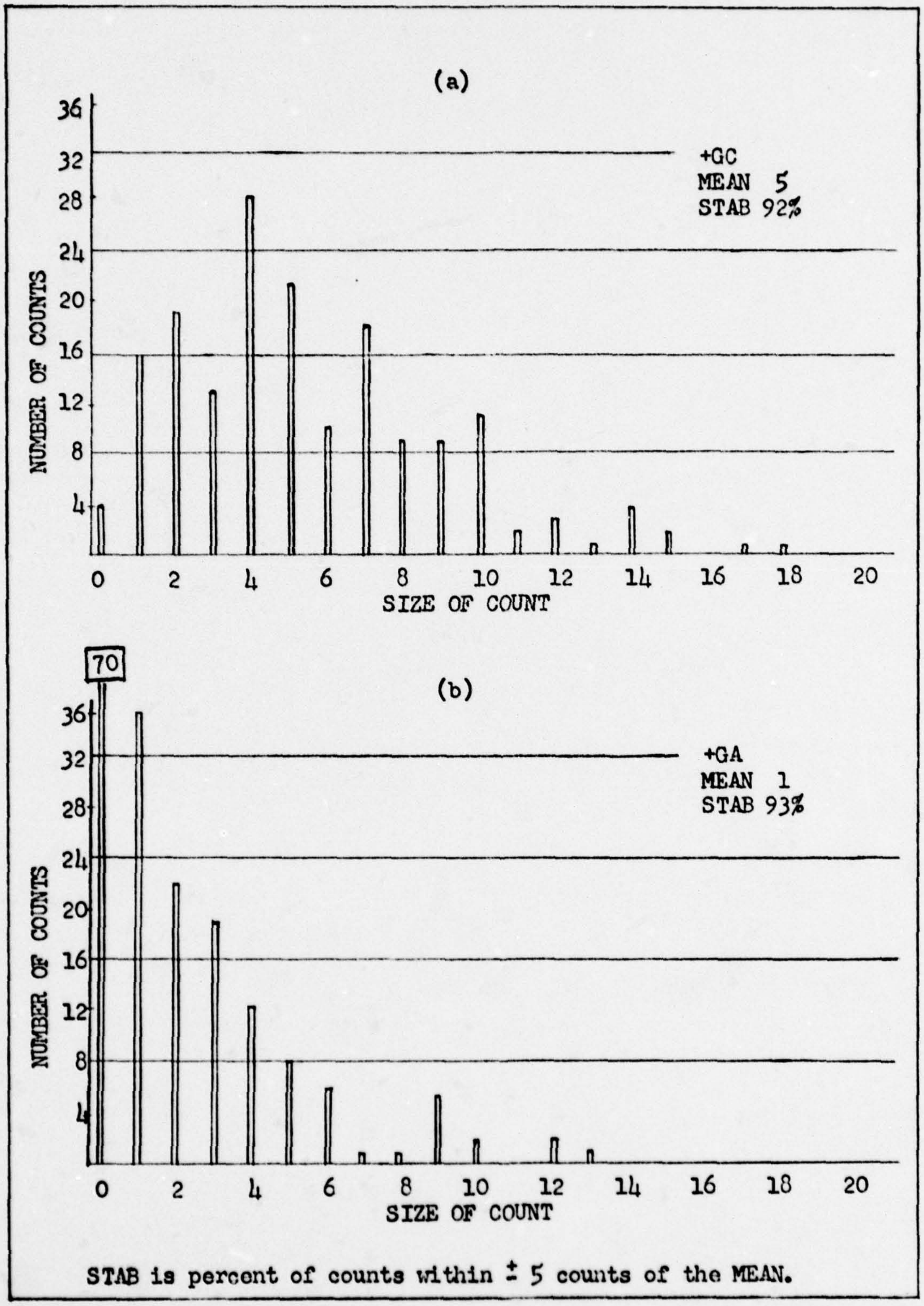
The above relationship for EXPW can be shown by the following equations:

$$\text{EXPW}\Big|_{o}^{t} = \alpha\int_{o}^{t}(dNL2/dt - \beta)dt + \alpha\delta\int_{o}^{t}(T - T_{o})\,dt \qquad (1)$$

$$T = DC + NL2 * 1/25 \qquad (2)$$

where β and T_o are thresholds. The α in equation (1) is a relative term and is unimportant since each sample interval data is compared to other intervals. On the other hand, δ is adjusted under a variety of engine running conditions to obtain a constant count independent of engine thrust and acceleration for a "healthy" engine. The time between logic analysis is shortened when the engine is operated at high thrust or accelerated and decelerated many times. If the engine is operated so the expected wear would be less, the time between logic analysis is lengthened to allow the measurement circuits to accumulate counts. The intent of this time variation is to remove the variations in the count with different engine operating conditions. This time variation simplifies both the trending process and the determination of when an engine is beginning to fail.

A six day trend of the positive signals (grid and ring) is shown in Figure 10 for the TF41 tested. The inlet temperature varied from 40° to 73°F, and the engine was run through a mixture of three different test cycles which produced different stress factors on the engine. The overall



STAB is percent of counts within ± 5 counts of the MEAN.

Figure 10. Counts of Signals vs Size of Count on a TF41 engine for a six day sample with the inlet temperature varying from 40° to 73°F. (Continued next page)

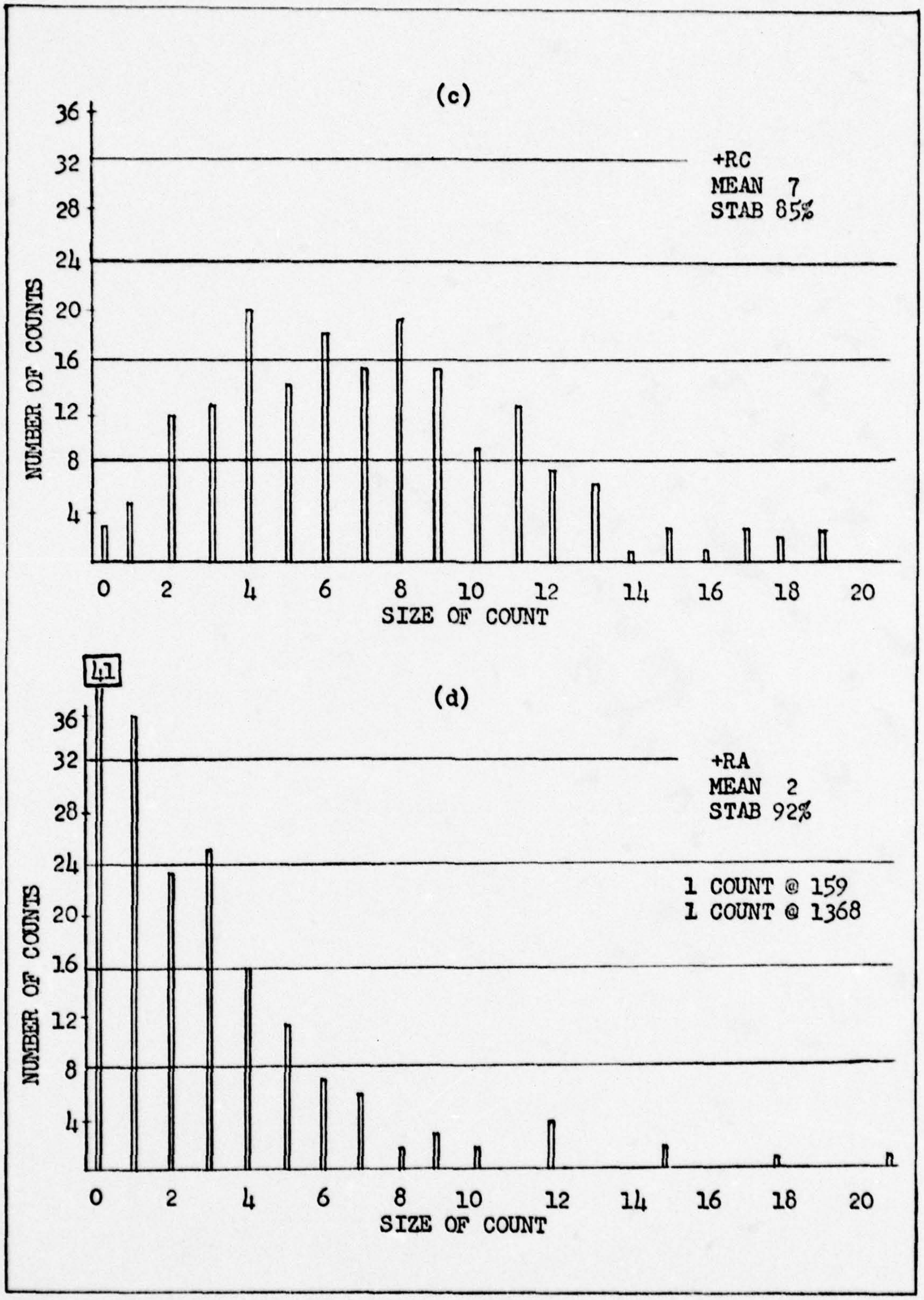


Figure 10 (Continued). Counts of Signals vs Size of Count. The two large counts on +RA were caused by washing the screen on the TF41 inlet.

count stability for this period was 91%, based on the size of the count staying within ±5 counts of the mean. The stability indicates the data is reasonably normalized. However, a flight version of the wear rate monitor may require further normalizing parameters, such as "g" force. The individual means and stabilities are shown on each plot.

V. Monitor Logic

The monitor logic uses the ten digital signals from the analog signal processor to produce printouts for manual engine wear analysis and to perform internal analysis with an alarm given to indicate excess wear. The main parts of the monitor logic are the storage registers which store the ten digital signals until they are analyzed, the print logic which causes the digital printer to print the stored data and then clears the storage registers, and the main logic which primarily analyzes the data to determine excess wear. The basic operation of these three main parts is discussed in this section, and the detailed operation is given in Appendix B. A block diagram of the monitor logic is shown in Figure 11, and the circuit diagrams are given in Appendix A.

Storage Registers

The storage registers store the digital signals from the analog signal processor, until the print logic clears the registers, so the main logic can analyze the data. The storage registers are ten sets of decade counters to store the ten digital signals from the measurement circuits and timing circuit (+GC, -GC, +GA, -GA, +RC, -RC, +RA, -RA, AC, and SW). The measurement storage registers have three decade counters to store up to 999 count or area pulses, and an optional divide-by-ten input. The optional input increases the storage capability by a factor of ten to 9999 pulses. The two timing storage registers have two decade counters each to store up to 99 timing pulses of both acceleration (AC) and steady wear (SW). The outputs of these storage registers are binary coded data (BCD).

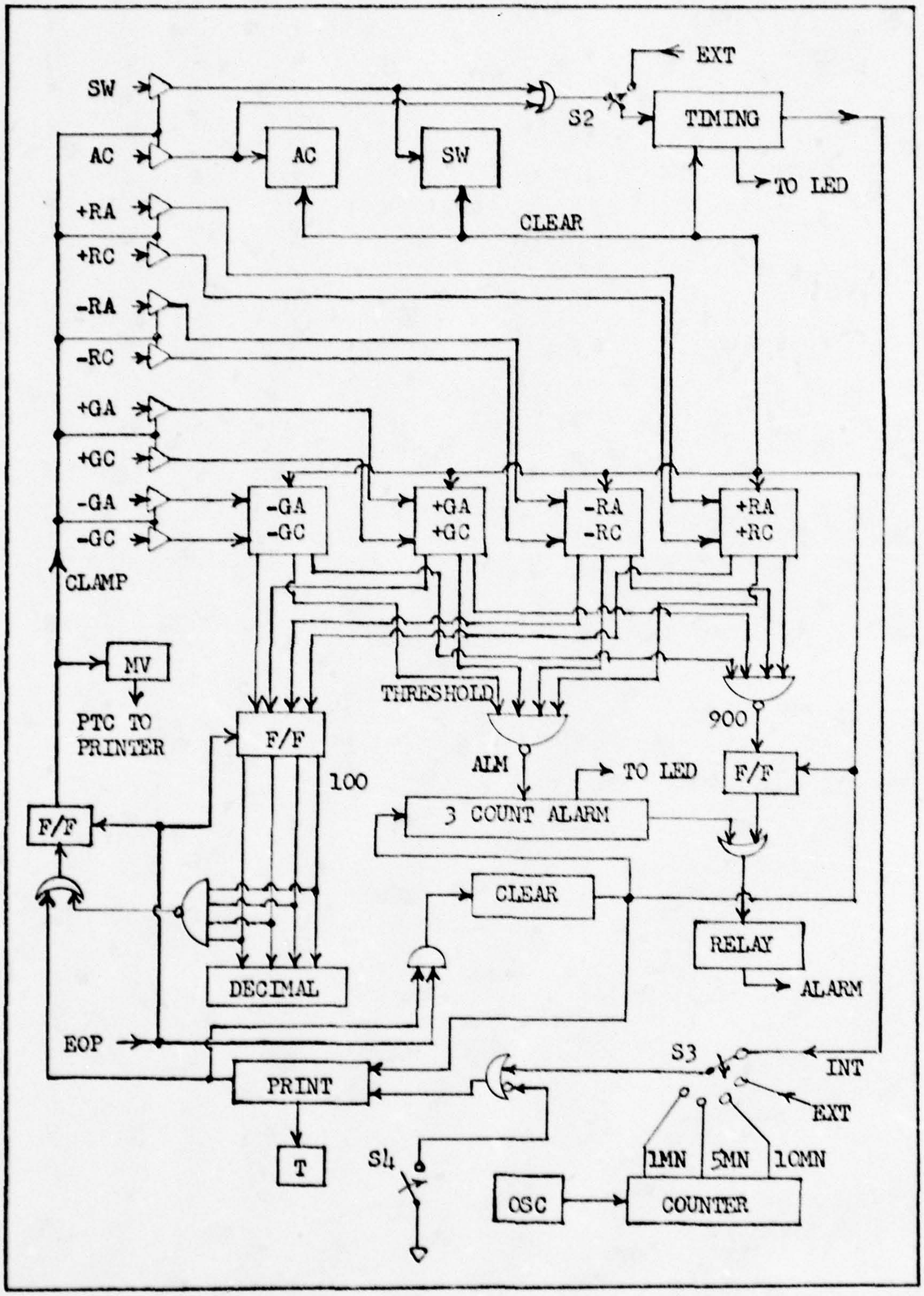


Figure 11. Block Diagram of Monitor Logic.

Print Logic

The print logic instructs the digital printer to print, and also clears the storage units. The print command is derived from four sources. One source is the timing storage registers. When the sum of AC and SW timing pulses equals 100, the print logic sends out the print command and sets one side of an AND gate for the "clear" signal. A second source is external timing, where the external input can be used directly to trigger the print logic or can be counted down by 100 in the same manner as the internal timing pulses. The third source that can be selected is an internal clock that will cause a print and also set the "clear" AND gate every minute, five minutes, or ten minutes. Only one of these three sources can be chosen by the selector switch S3 at a particular time. The source normally used is the AC and SW timing pulses.

The fourth print command source is always connected to the print logic. This source is the main logic which monitors the eight measurement storage registers. When one of these storage registers reaches an increment of 100, the main logic sends a pulse to the print logic and inserts a decimal between the zeroes on the printer of the data that reached 100. The decimal marks the double zeroes as being 100 instead of 0. The print logic uses the pulse from the main logic to generate a print command, but does not set the "clear" AND gate.

The print command simultaneously causes the printer to print the data stored in the two most significant digits of all the storage units except SW, and blocks the inputs to the storage registers. The inputs are clamped to ground during printing to prevent erroneous print-outs due to transitions at the instant of printing. After printing, the printer sends an end-of-print (EOP) signal back to the print logic. This signal unclamps the inputs and will clear all the storage units if the "clear" AND gate is set.

The following sample of three lines of print is given to better explain the printed data and the 100 print command.

```
+RA -RA +RC -RC   +GA -GA +GC -GC  AC

1 0 3 3 0 4 1 6   7 0 1 2 3 5 0 6 4 4   T

0.0 3 0 0.0 1 4   6 1 1 0 3 2 0 4 4 2   A

0.0 1 8 3 1 0 7   4 2 0 4 2 3 0 0 2 0   A
```

The bottom line is the first print which was caused by a 100 print command. The second line was caused by two simultaneous 100 print commands, while the top line was caused by one of the other three print commands. The 100 print lines are characterized by a decimal in the column that had 100 counts and an "A" in the last column to indicate add. The final print has a "T" in the last column to indicate total measurement.

The total count of pulses is the value in the total line (T) plus 100 for each decimal under that value. For instance, +RA has 10 plus two decimals or 210, -RA has 33, +RC has 104, and -RC has 16. The total SW count is obtained by subtracting the total AC count from 100. In this example, SW is 100 minus 44 or 56 counts. The reason for this type of display is to eliminate the complex circuitry needed to display all the information on two lines of print with three digits for each channel of data. The two digit display causes little problem since the storage registers do not exceed 100 counts except when there is excess wear, in which case the display helps to identify the excess wear condition.

Main Logic

The main logic in the wear rate monitor observes the measurement storage registers to detect alarm conditions and to detect the 100 print condition which was discussed in the print logic. The simpliest alarm condition to detect and yet most damaging type is the 900 count alarm. The main logic monitors the 900 digit on all the measurement storage registers. When a register reaches 900, a flip-flop is set in the main logic which turns on the alarm relay. This alarm stays on until the "clear" pulse from the print logic clears the storage registers and at the same time resets the flip-flop. When a 900 count alarm occurs, a considerable amount of damage is being done to the engine.

The other type of alarm condition is the three count alarm, which does not require severe damage before giving an alarm. The three count alarm is based on getting a threshold alarm pulse between three consecutive "clear" pulses. The main logic monitors a certain digit on each measurement storage register. This digit determines the threshold for that register. When one of the thresholds is reached, a threshold pulse is sent to the three count alarm circuit. The digit on each storage register can be independently set from 10 to 90 in increments of ten. Analysis of measured data showed smaller increments are not necessary. For a larger threshold, the divide-by-ten input in the storage register would be used, making the thresholds from 100 to 900.

The three count alarm circuit consist of four flip-flops and logic gates. The threshold pulse sets the first flip-flop. Any additional threshold pulses during the sample interval have no effect on the flip-flop. The "clear" pulse, which clears the storage registers, clocks the flip-flops which causes them to shift the set to the second flip-flop.

If the two variable inputs to the alarm AND gate in the three count alarm circuit are wired to 5 volts, this condition would give a one count alarm, since the third input is permanently connected to the output of the second flip-flop. The output of the alarm AND gate would then turn on the alarm relay.

The next threshold pulse would set the first flip-flop again, and the "clear" pulse would shift both sets one position. If the two inputs to the alarm AND gate are wired to the output of the third flip-flop, this condition would give a two count alarm. A third threshold pulse and "clear" pulse would shift the sets to the last three flip-flops. Thus, a three count alarm would be given if one input of the alarm AND gate is wired to the output of the third flip-flop and the other input to the fourth flip-flop.

The three count alarm is based on at least one threshold pulse between each "clear" pulse. When two consecutive "clear" pulses reach the three count alarm circuit without a threshold pulse between the pulses, the second "clear" pulse will clear all four flip-flops. Thus, the three count alarm circuit is reset to zero, and the count would have to accumulate to the value set above before an alarm would be given.

The three count alarm configuration is normally wired in the three count alarm circuit because of spurious signals. These spurious signals can be caused by lightning, loose metal objects, or similar items. For example, lightning has charged air associated with it that could give one high count and do no damage to the engine. If no damage is done, then an alarm should not be given.

The spurious signal caused by a loose metal object is the signal resulting from an object causing metal rubbing as it is expeled from the engine. There may be minor damage caused by the object as it goes through the engine; however, after the object is out there is no further deterioration of the engine. If the damage to the engine is not minor, the 900 alarm would activate the alarm relay. If there is more deterioration, then the signal is not spurious and will be detected as a three count alarm.

On 11 October 1977 following the six day trending period discussed previously in the timing circuit section, the engine had an apparent distress condition. Figure 12 shows the + grid count, + ring area, and turbine vibration signals before, during, and after the rubbing condition. The turbine vibration before 11 October had a mean of 1.5 mills, and afterwards had a mean of 1.9 mills until engine shut-down on 20 October. The compression and combustor vibrations did not change during this time period indicating the distress was in the turbine section. Most of the measurement circuit signals prior to this condition were less than 20 in count size. The -grid count and -ring area signals were almost identical to the positive signals shown, and the other four wear rate monitor signals followed the same trend but were less than half the amplitude.

After the large count which was an alarm condition based on a 70 count size threshold, all the wear rate monitor signals increased by a factor of about ten over the previous means. This factor is on the border line of being an alarm condition, which indicates the distress condition was slight after the severe period on 11 October. The turbine vibration did not reach the alarm limit of 3.5 mills at any time during the test.

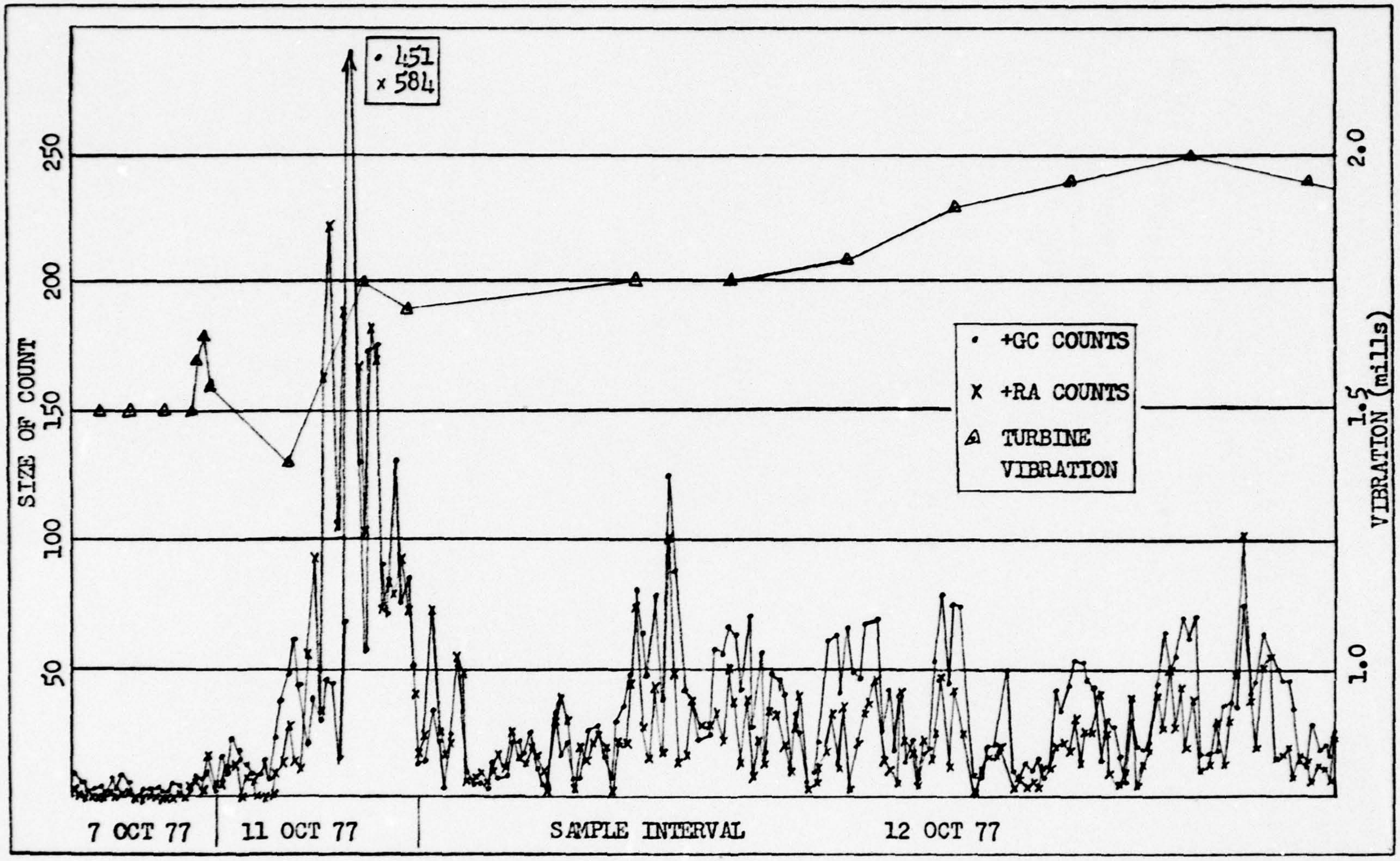


Figure 12. Turbine Vibration and +GC/+RA Counts vs Sample Interval during an Apparent Rubbing Condition on a TF41 engine. The sample intervals averaged about six minutes during this period.

The exact damage to the engine is not known at this time. A quick borescope examination on 14 October 1977 concluded there was no major damage to the turbine section. However, there were several parts of the turbine section that could not be viewed. A complete engine tear-down will be done in December 1977 to determine the condition of all the components in the engine. The results of this tear-down are not available at this time.*

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* Tear-down results will either be added as a supplement to this thesis or published separately when available.

VI. Application and Conclusions

The jet engine gas-path wear rate monitor has been proven to give early warning of a jet engine gas-path component failure on the TF41 engine. The wear rate monitor was designed and tested on the TF41 turbofan jet engine. However, the monitor can be easily adapted to other turbofan engines, straight turbojet engines, or other turbine engines. This section will discuss how the wear rate monitor is presently being applied and what modifications in the probes are needed for other applications. For engines without a 440 Hz NL signal, the timing circuit section of Appendix B gives the modifications needed in the analog signal processor.

The wear rate monitor is designed for turbofan engines such as the TF41, TF30, and F100. These engines have cool air surrounding the hot core exhaust which cools the TRION grid probe supports and the PRION probe. The thrust on these three engines is different, so the termination resistors of the measurement circuits would have to be changed to yield an equivalent signal level of processing as given in the measurement circuits section of Appendix B. The afterburner on the F100 and some models of the TF30 engines presents no problem since the probes can be installed in front of the afterburner. This type of installation on the F100 engine is being tested at NASA Lewis Laboratories, Cleveland, Ohio.

Adaption of the wear rate monitor to other turbofan and turbojet engines is controlled by temperature considerations. After the temperature limit is reached for the probes used in the present version of the wear rate monitor, other types of probes would have to be used.

Since the present configuration of probes is an optimized design, the other types of probes would be less reliable and give a shorter failure warning time. One type of probe that might be used is the early version rod probe shown in Figure 2. This rod probe reacts somewhat like the TRION probe, and provides some warning time before a complete engine failure (Ref 4).

Current application of the wear rate monitor is on endurance tests of the TF41 engines at the Air Force Aero Propulsion Laboratory at Wright-Patterson Air Force Base, Ohio, and Detroit Diesel Allison Division of General Motors at Indianapolis, Indiana. Preparations are being made for data collection on these wear rate monitors at the jet engine overhaul facility at Oklahoma City Air Logistic Center, Oklahoma, and for flight testing of the system on an A-7 Corsair aircraft by the Navy Test Group at Patuxent, Maryland.

After proper documentation and evaluation, many features on the present version of the wear rate monitor used for internal analysis of the monitor system will be eliminated. A simplier version of the system will be available for ground maintenance, testing, and overhaul facilities. The final application of the wear rate monitor would be in the aircraft during flight. A very simplified and small version of the wear rate monitor would be connected to each engine in the aircraft to give the pilot a yellow light when he had an alarm condition. With average warning times of over four hours before engine failure, the pilot could safely return the aircraft to the ground.

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Appendix A

Wear Rate Monitor and Circuit Diagrams

All of the wear rate monitor diagrams are given in this Appendix. The first drawing shows the front and back panels to illustrate the location of the circuit boards and the BNC connectors. The next two drawings give a block diagram of the entire system to explain the interconnection of the circuit boards. The block diagram of each circuit board is next, and then the circuit diagrams. Following these diagrams is a listing of the wiring connections between the circuit boards and to the printer. The last drawing in this section gives the integrated circuit chips (IC's) used with all the pins labeled.

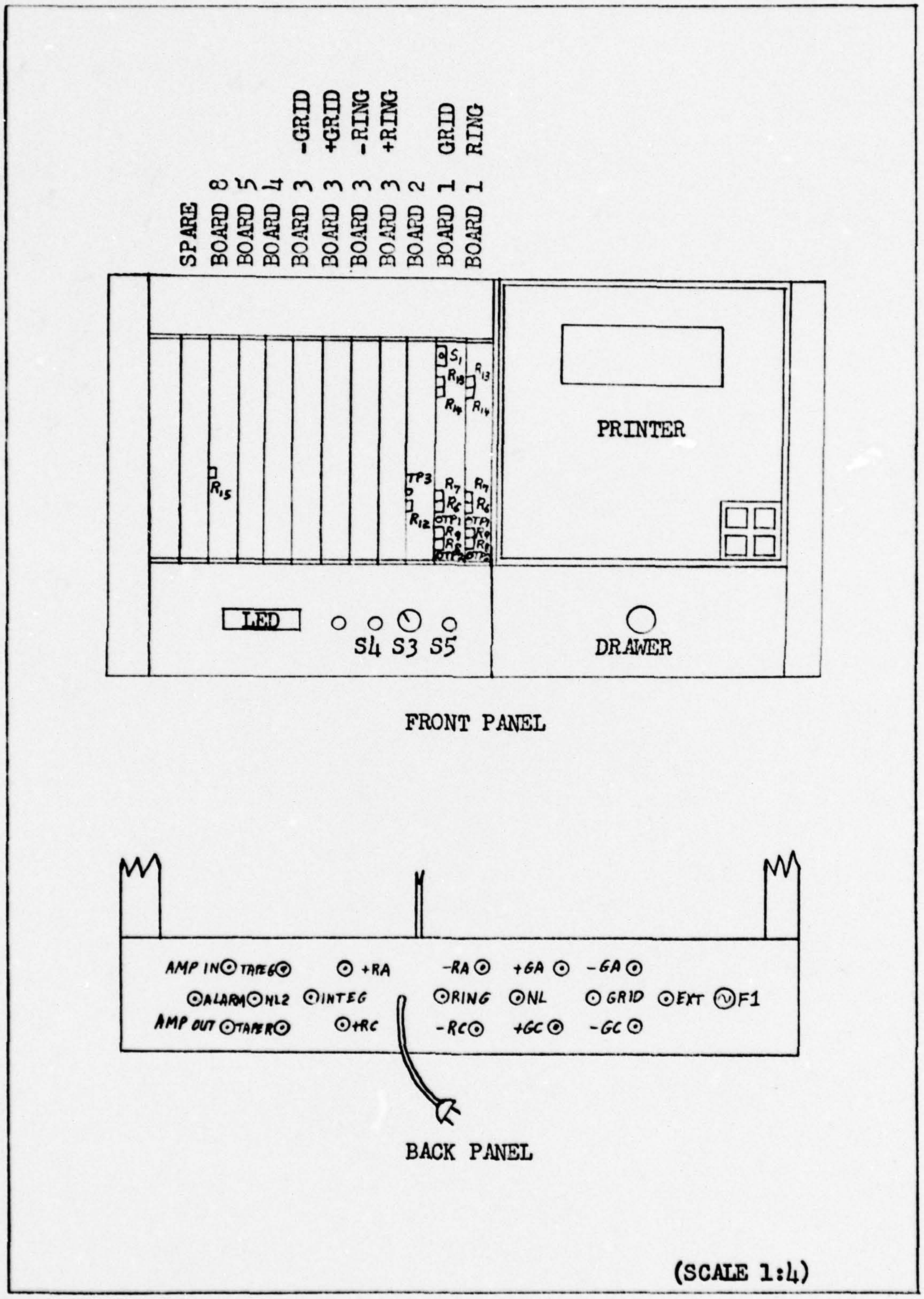


Figure A-1. Drawing of Wear Rate Monitor.

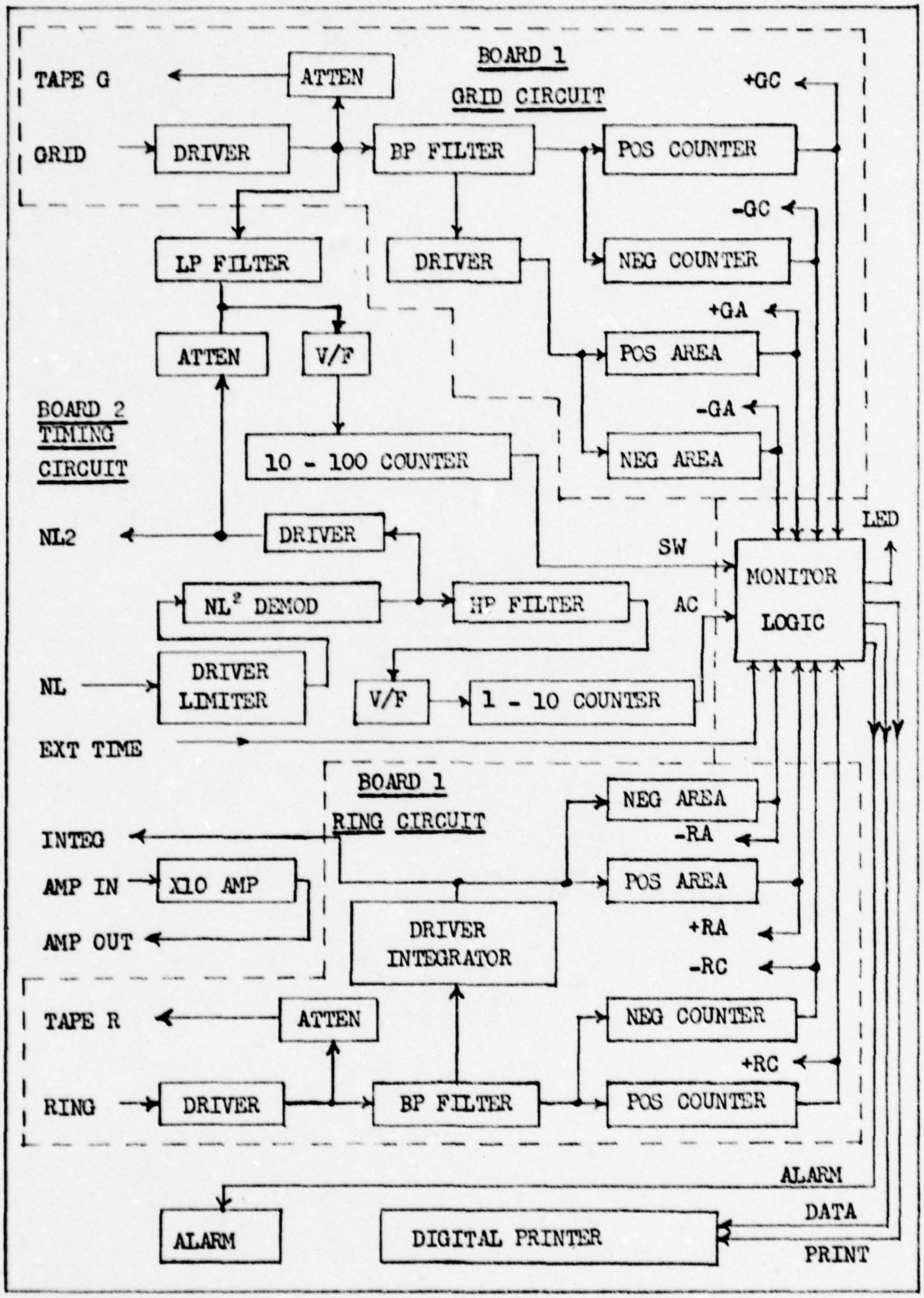


Figure A-2. Block Diagram of Analog Signal Processor.

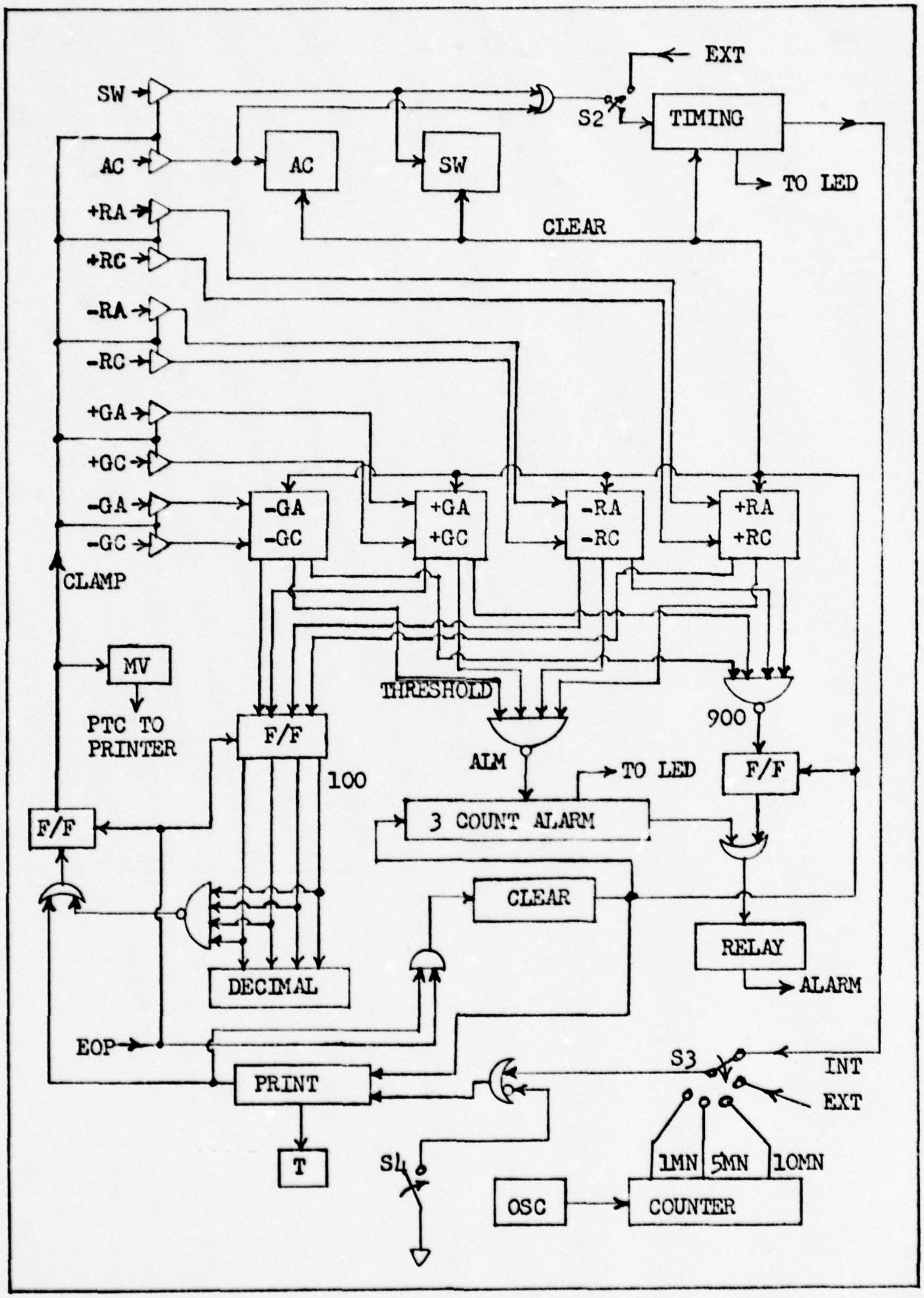


Figure A-3. Block Diagram of Monitor Logic.

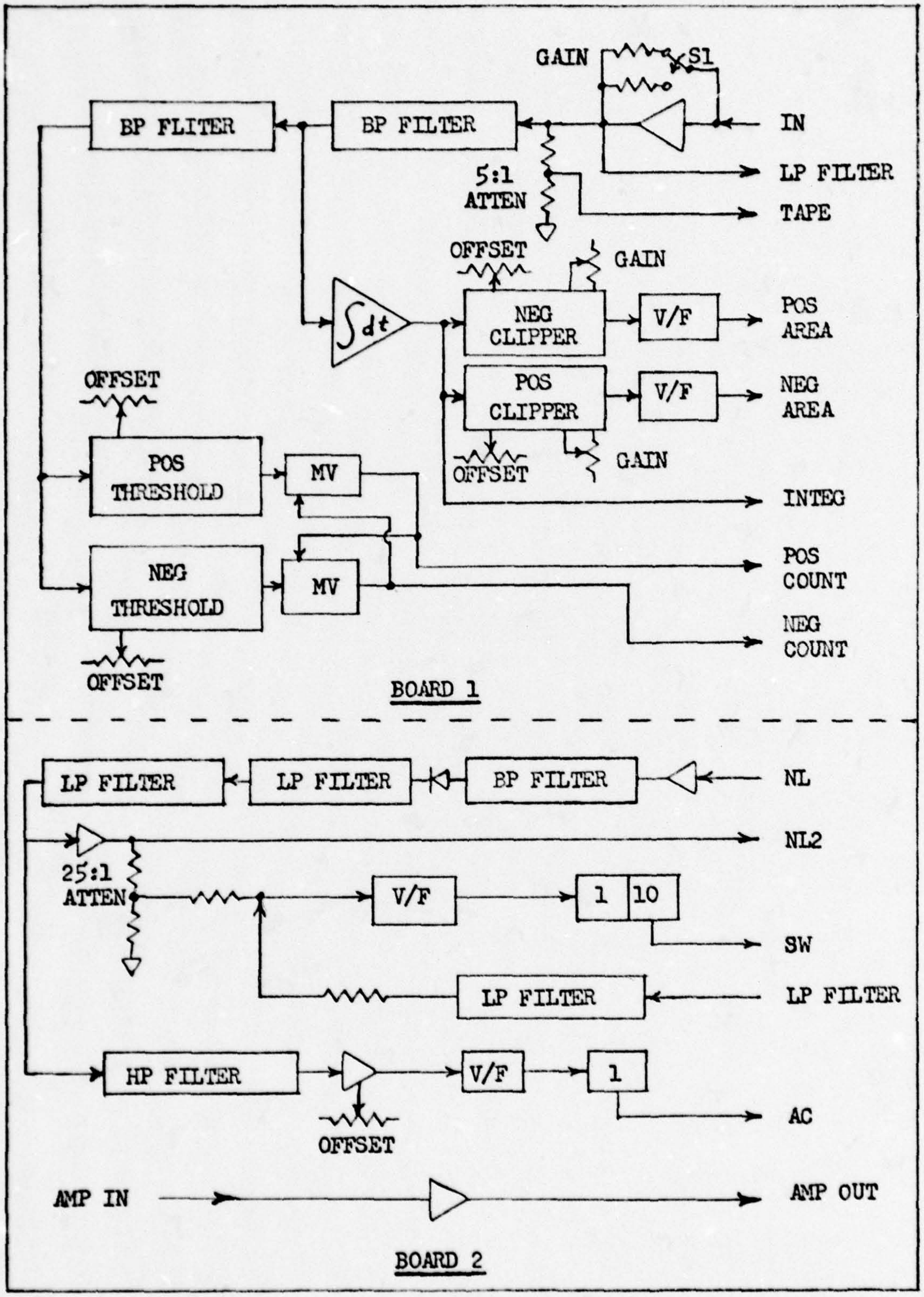


Figure A-4. Block Diagram of Measurement and Timing Circuit Boards. S1 is missing on the Ring Measurement Circuit Board.

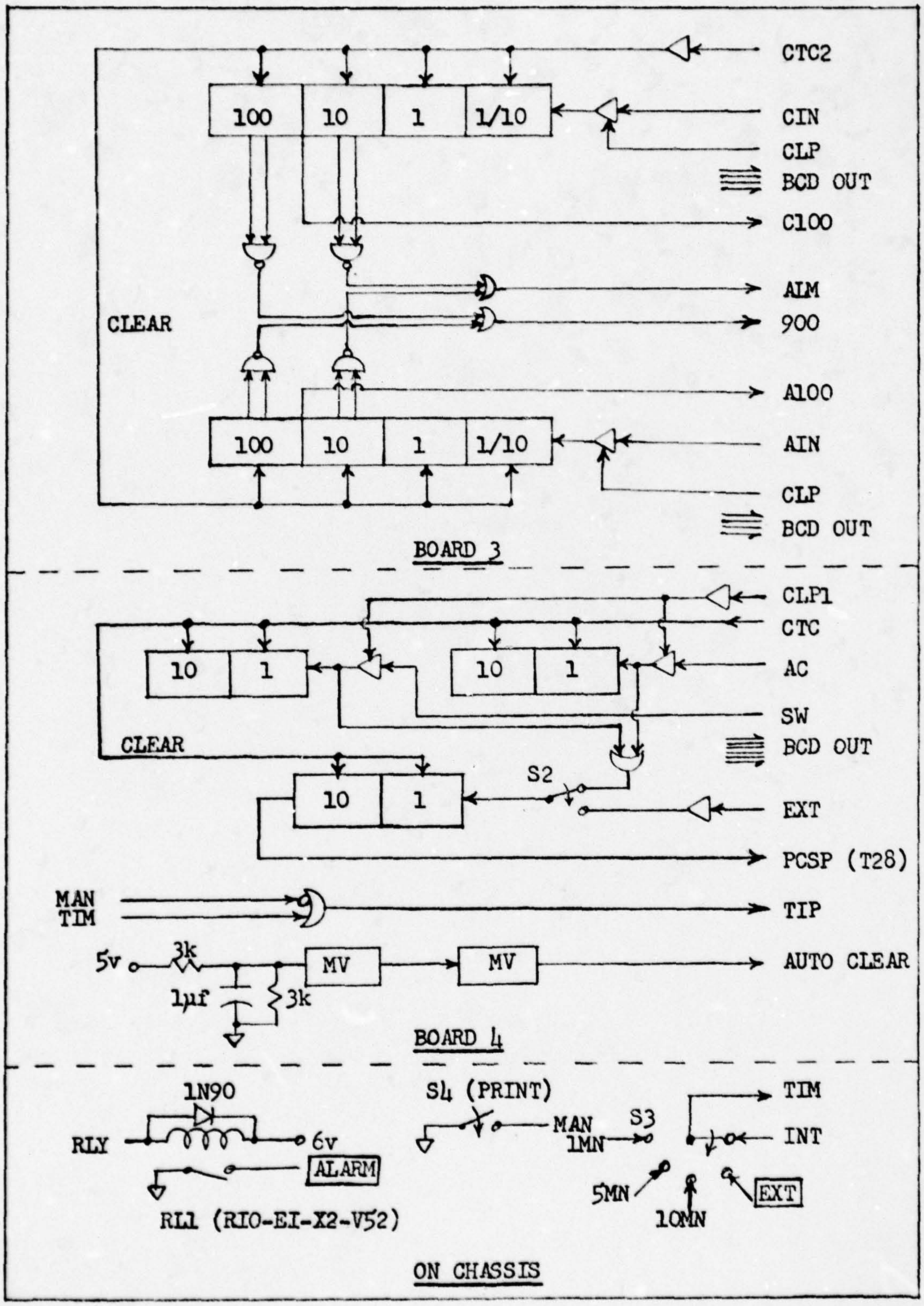


Figure A-5. Block Diagram of Monitor Logic Boards. (Continued next page)

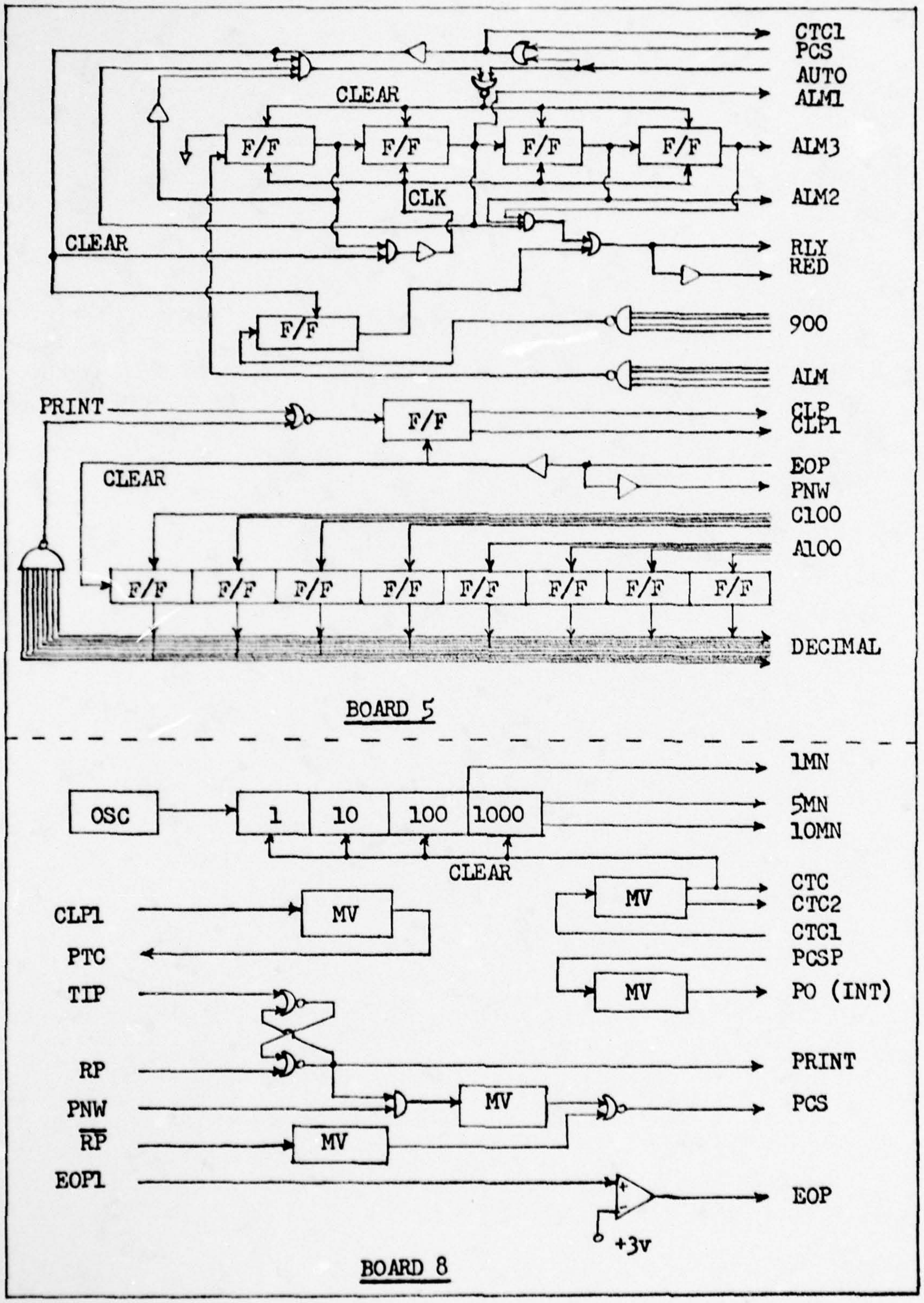


Figure A-5 (Continued). Block Diagram of Monitor Logic Boards.

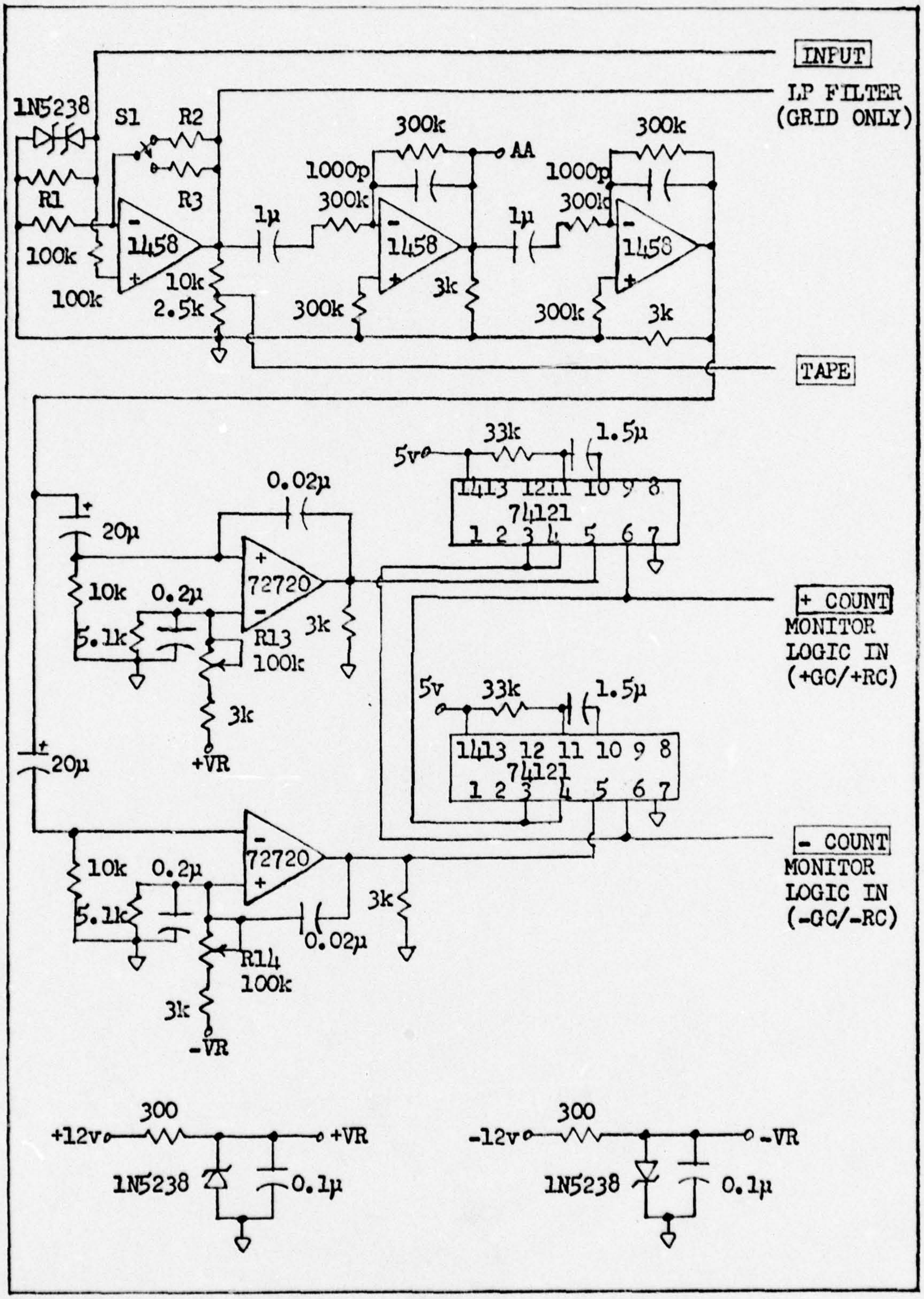
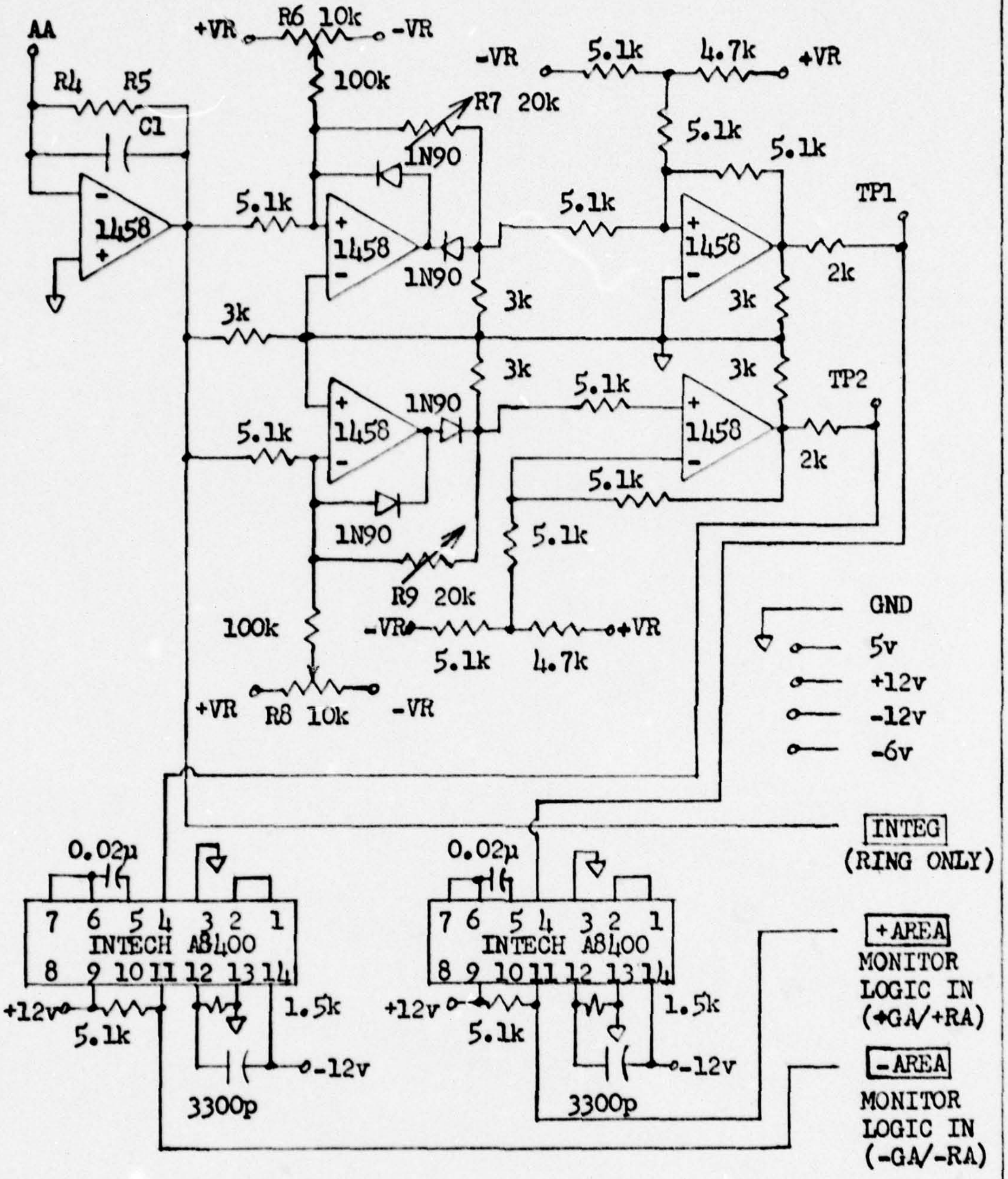


Figure A-6. Circuit Diagram of Measurement Circuit, Board 1. S1 is missing on the Ring Circuit. (Continued next page)



	R1	R2	R3	R4	R5	C1
GRID	48k	100k	510k	20k	20k	3300p
RING	48k	-	510k	100k	1M	0.08μ

Figure A-6 (Continued). Circuit Diagram of Measurement Circuit.

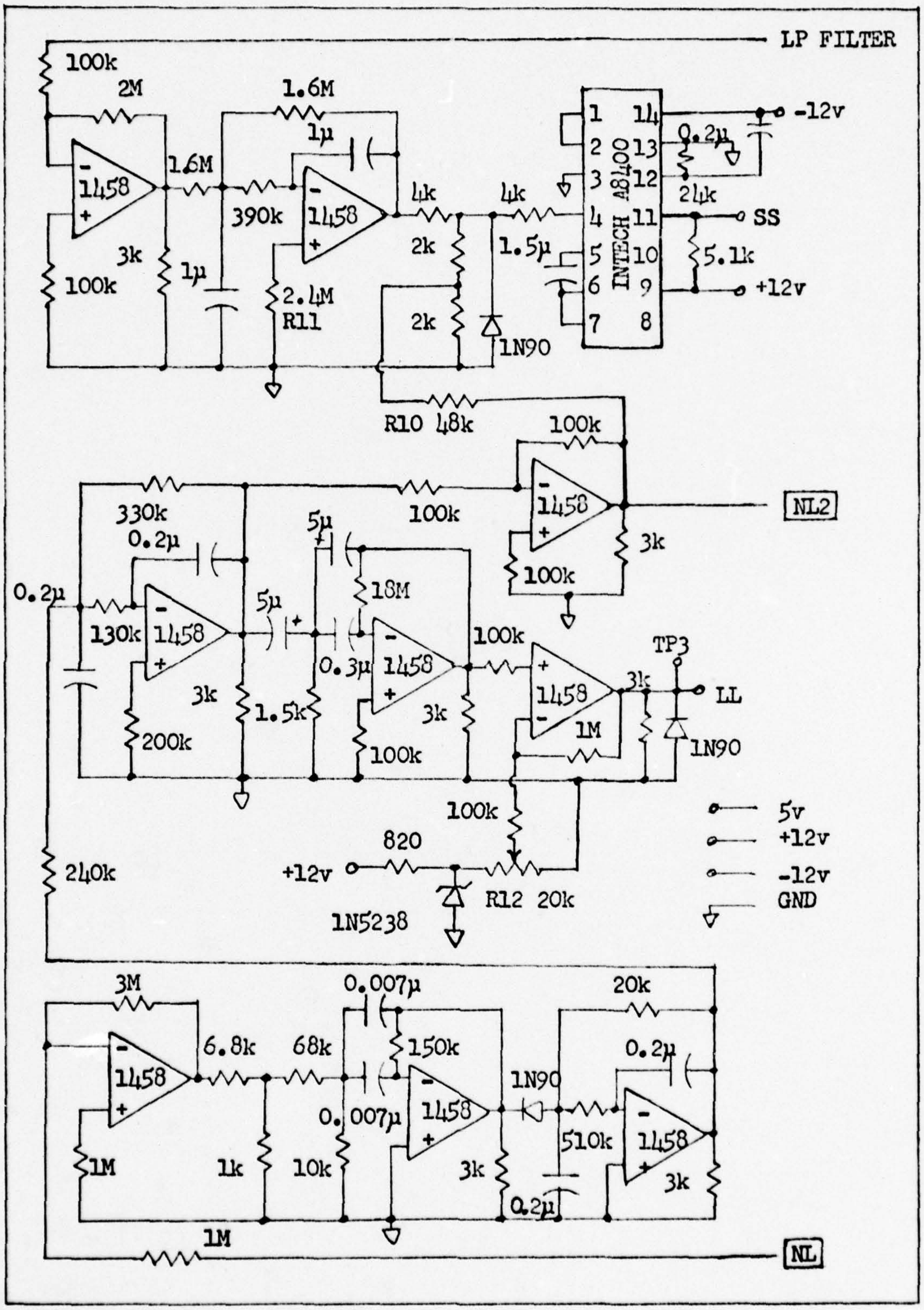
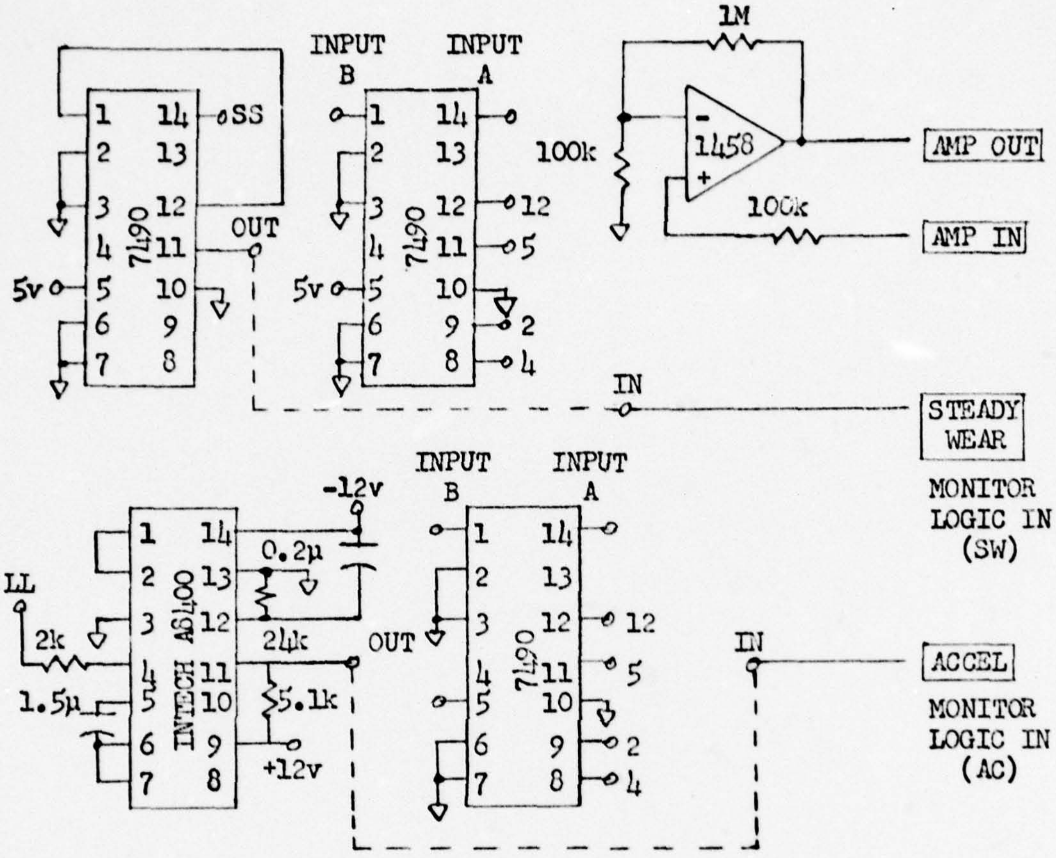


Figure A-7. Circuit Diagram of Timing Circuit, Board 2. (Continued next page)



FOR MORE COUNT DOWN OF STEADY WEAR OR ACCEL THAN GIVEN BY THE DASHED LINES, CONNECT OUT TO THE INDICATED INPUT ON THE 7490 AND PIN OUT TO IN.

COUNT DOWN	PIN INPUT	PIN OUT
2	1	9
4	1	8
5	1	11
8	14	8 (12 to 1)
10	14	11 (12 to 1)

Figure A-7 (Continued). Circuit Diagram of Timing Circuit.

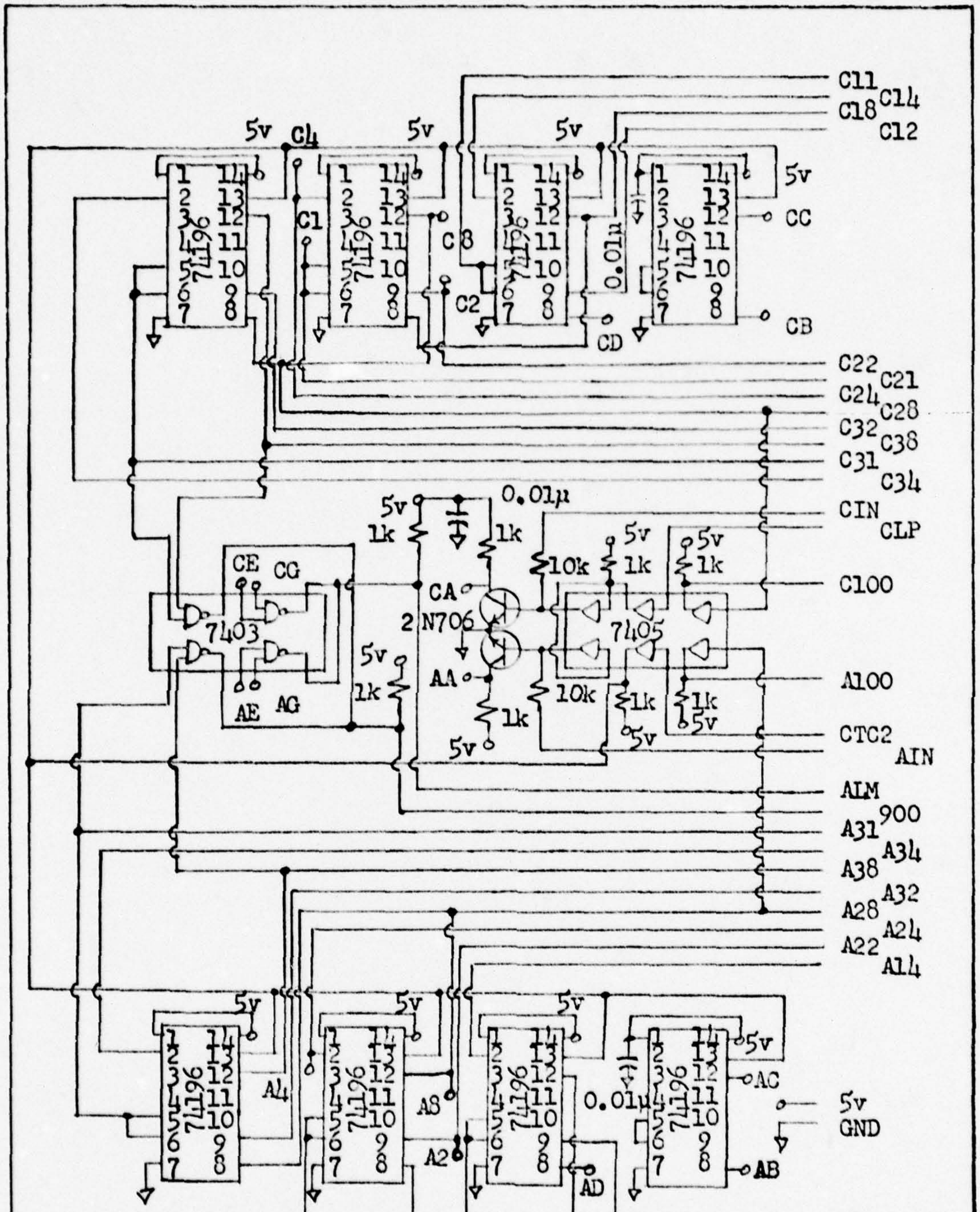


Figure A-8. Circuit Diagram of Board 3 in Monitor Logic.

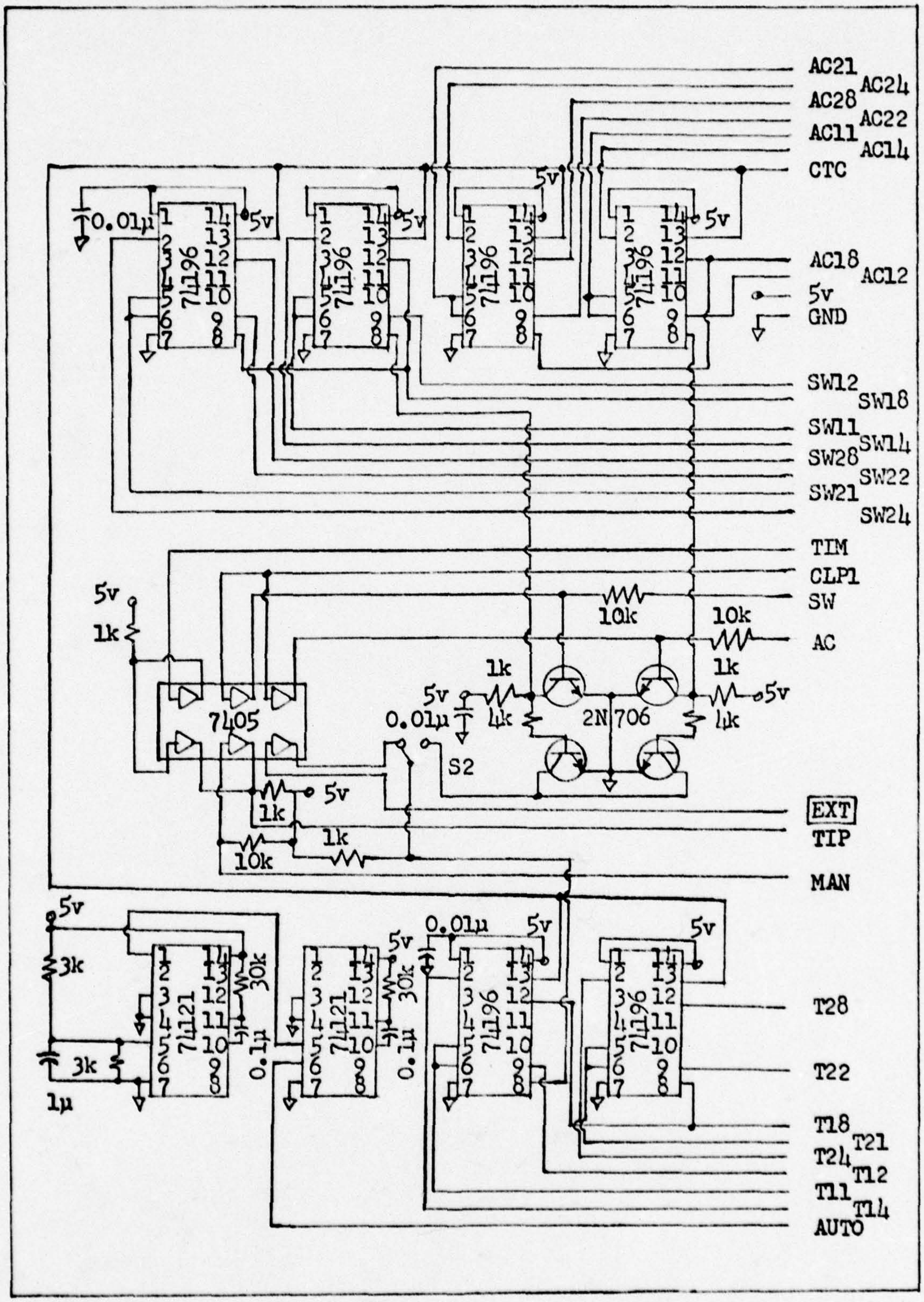


Figure A-9. Circuit Diagram of Board 4 in Monitor Logic.

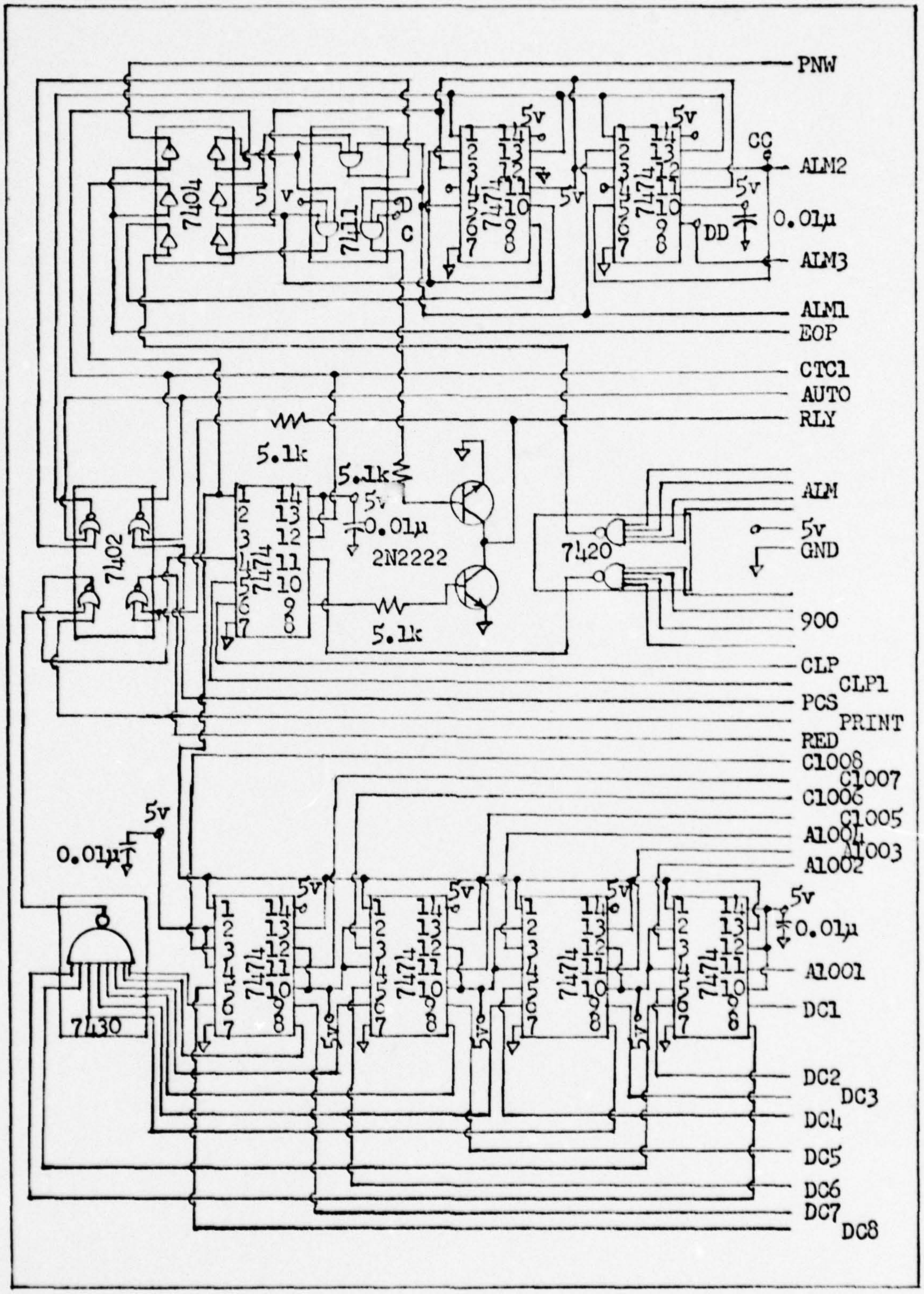


Figure A-10. Circuit Diagram of Board 5 in Monitor Logic.

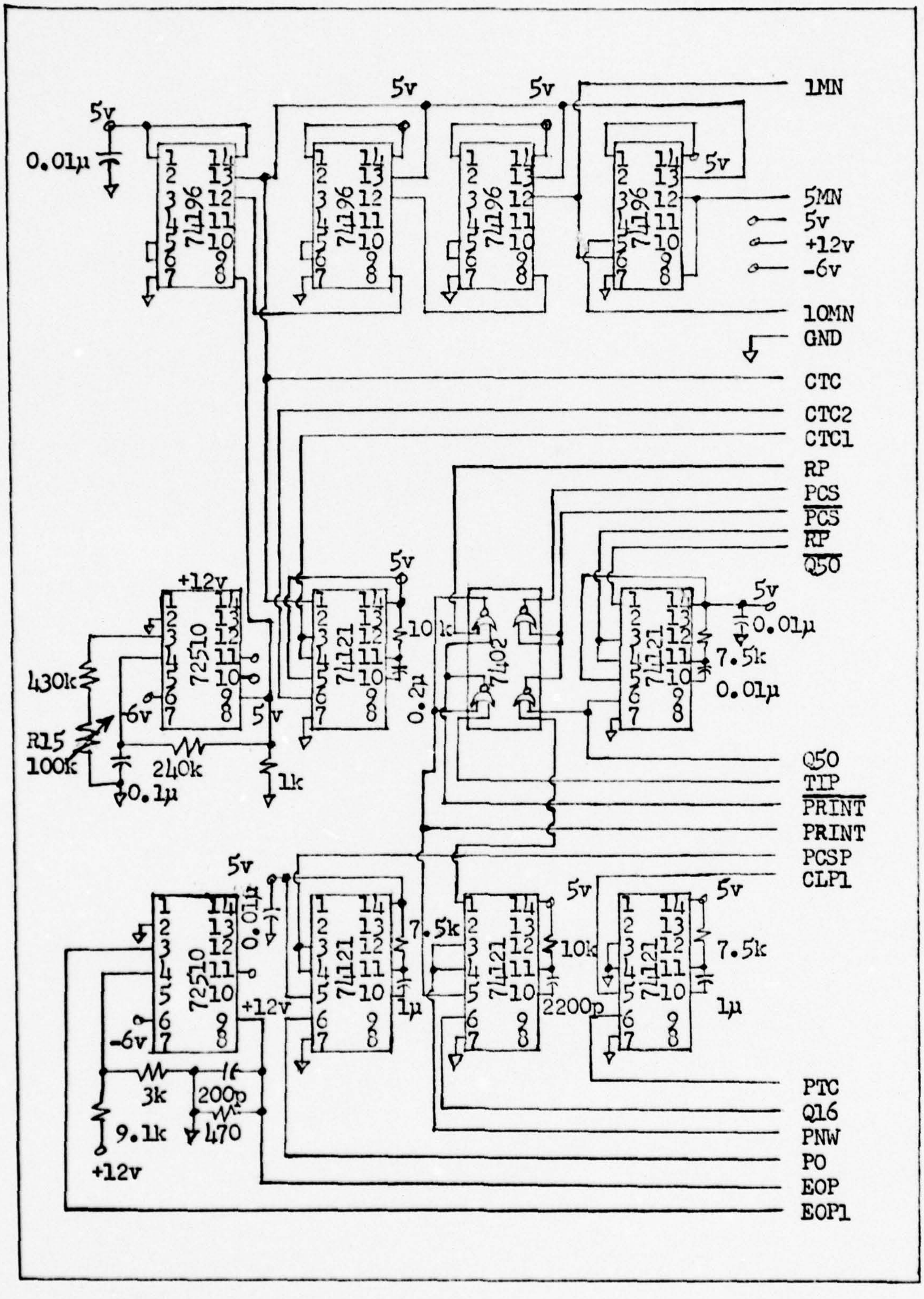


Figure A-11. Circuit Diagram of Board 8 in Monitor Logic.

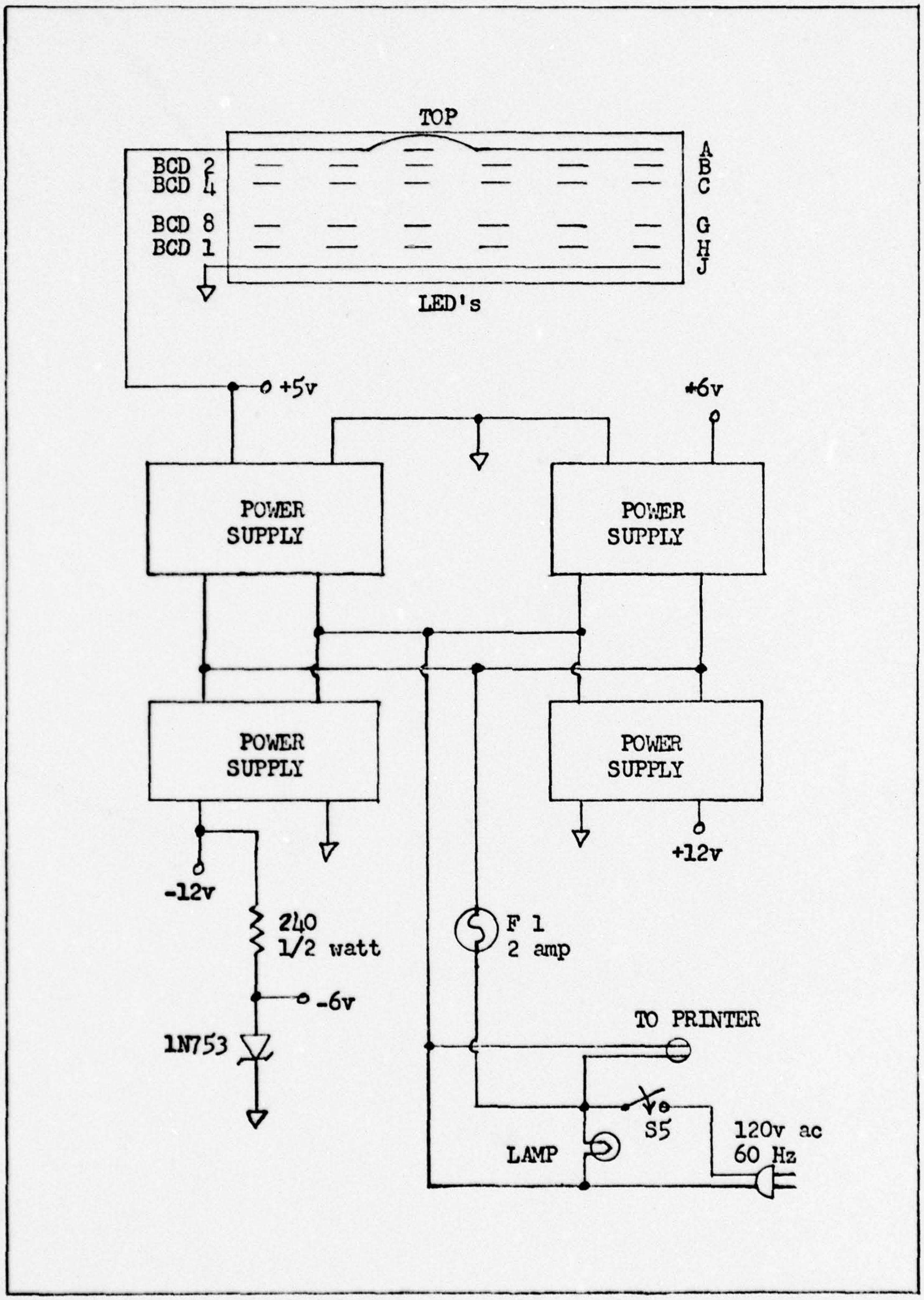


Figure A-12. Block Diagram of Power Supplies and LED Connections.

All boxed connections go to BNC plugs on the back panel, i.e. INPUT .

Monitor Logic In is connected to the respective AIN, CIN, SW, or AC. The order from right to left of the circuit boards is +R, -R, +G, -G, and Timing; and left to right of the printer columns is +RA, -RA, +RC, -RC, +GA, -GA, +GC, -GC, and AC.

CXY, AXY, and ACXY connections on Board 3 and 4 go to the respective printer column inputs. X is the digit and Y is the binary code for that digit, only two digits are printed for each input.

TIM is connected to the wiper of S3 on the front panel.

MAN is connected to S4 on the front panel.

TXY on Board 4 go to the first and second LED on the front panel. X is the digit and Y is the binary code for that digit.

T28 is also connected to PCSP.

ALM1, 2, 3 go to binary 1 on sixth, fifth, and fourth LED respectively.

RLY goes to relay R10-E1-X2-V52 (Potter & Brumfield) on the chassis.

ALM and 900 connections on Board 5 go to the four Board 3's.

RED is connected to red print input on the printer.

DCX is connected to the printer decimal input corresponding to YA1 or YC1 column for which A100 or C100 is connected to A100X or C100X, i.e. A1002 goes to +RA A100, thus DC2 goes to column 2 (+RA1).

1MN, 5MN, and 10MN go to S3 on the front panel.

RP is connected to PCS.

$\overline{\text{RP}}$ is connected to +5 volts.

PRINT goes to binary codes 2 and 8 inputs of column 21 on the printer.

PTC is connected to the print input of the printer.

PO is connected to the internal position of S3 on the front panel.

EOP1 is connected to the End-Of-Print signal from the printer.

EXT from the back panel is connected to Board 4 and to S3.

All other connections of the same name are connected together.

Figure A-13. Primary Wiring Connections.

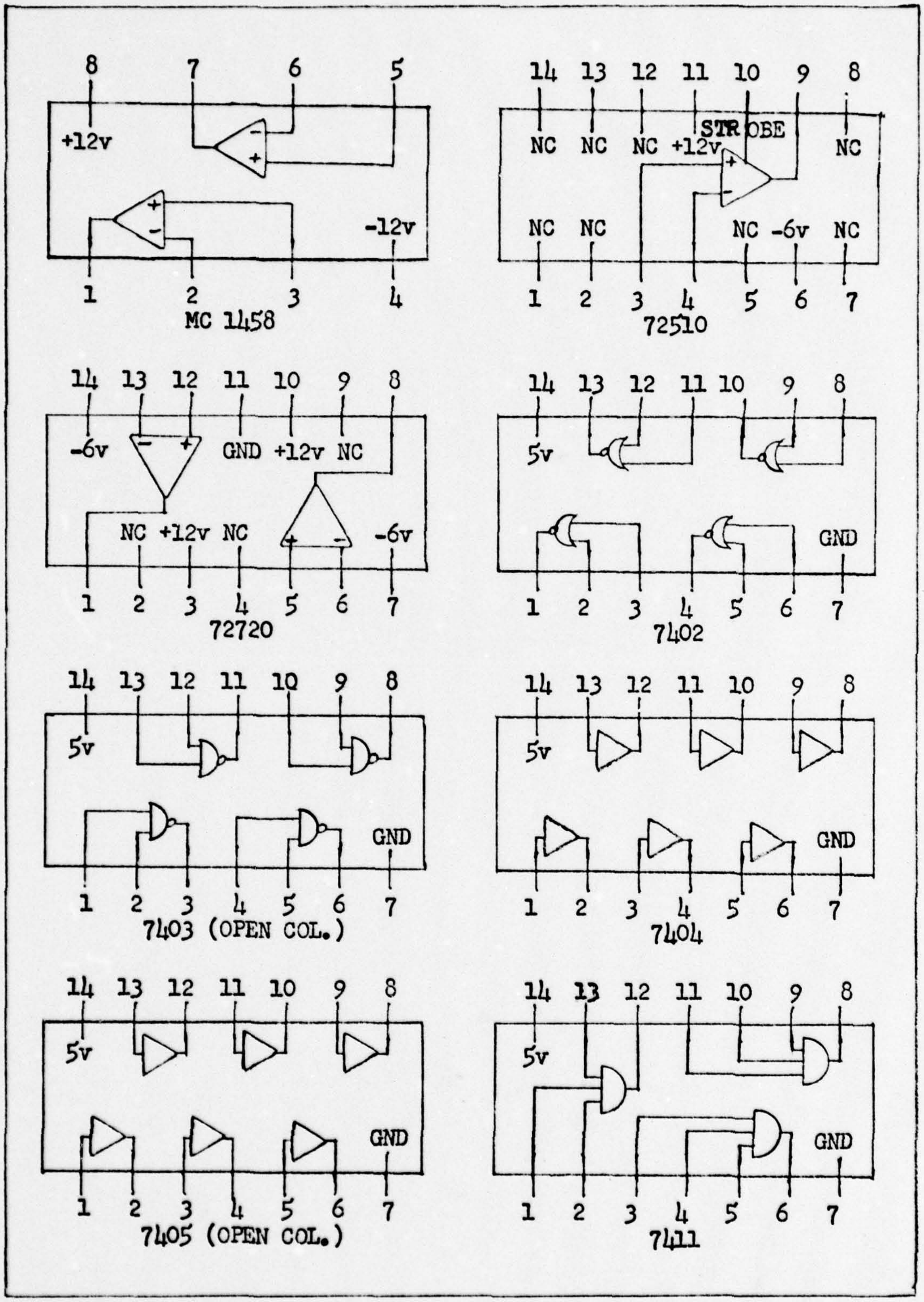
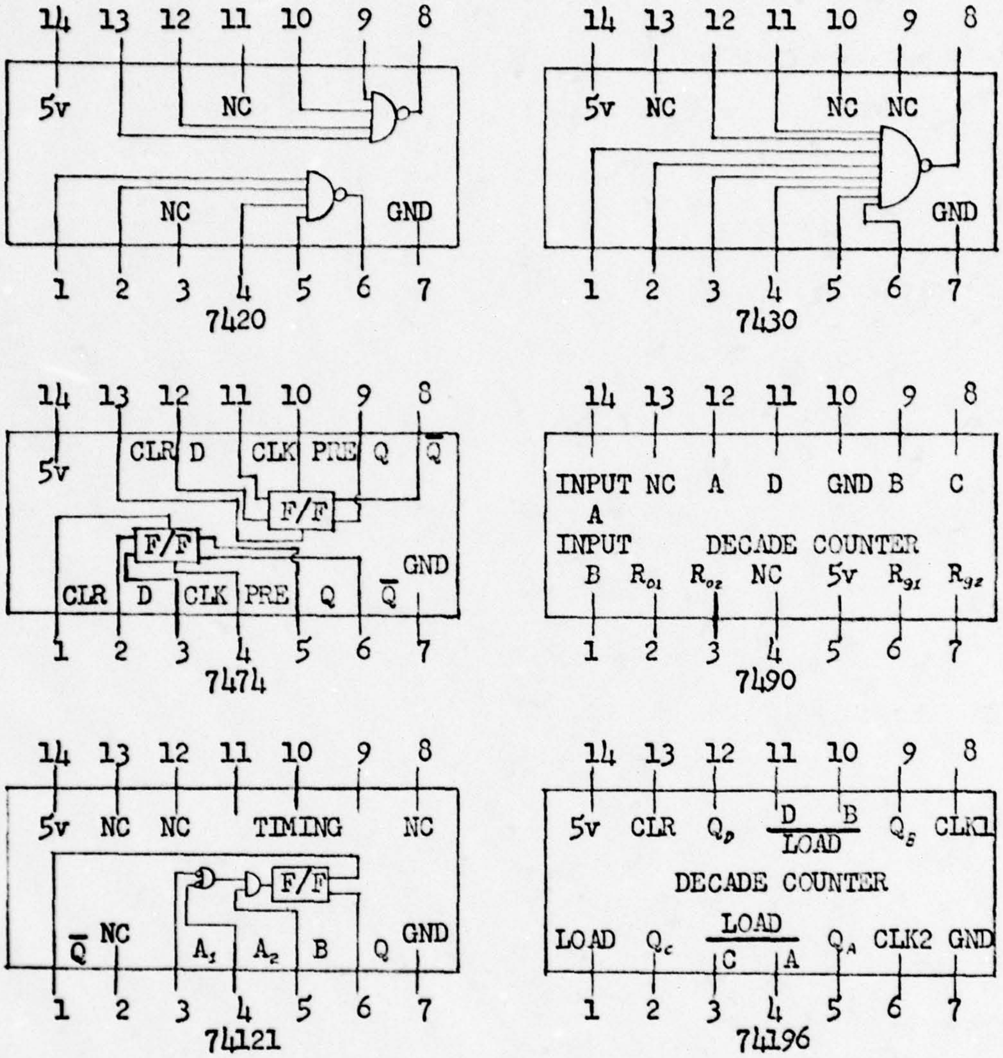


Figure A-14. IC's used in the Wear Rate Monitor, except A-8400 voltage-to-frequency converter. (Continued next page)



NC - Not Connected

Figure A-14 (Continued). IC's used in the Wear Rate Monitor.

Appendix B

Operation of Wear Rate Monitor

The implementation of the theory of the wear rate monitor is given in this Appendix. The units discussed are the measurement circuits, the timing circuit, and the monitor logic. The reasons for particular signal processing is given in the main body of the thesis. The signal flow and components mentioned in this section are shown in the block diagrams and circuit diagrams in Appendix A.

Measurement Circuits

The measurement circuits process the electrostatic charge signals from the jet engine exhaust to produce digital signals. There are two completely independent circuits used, one for the grid signal and one for the ring signal. The main parts of the measurement circuits are the input termination resistor and amplifier, the count circuitry, and the area circuitry.

The actual input to both amplifiers is high impedance, so the input resistors determine the input termination resistance for the probes. The input resistors terminate the probes so that the large charge pulses develop ten volts on the output of the first stage of amplification. This output is attenuated by a factor of five and sent out as the tape recorder output on the back panel of the wear rate monitor. The nonattenuated output in each circuit is sent to a two stage band pass filter with a frequency response of 2 to 500 Hz.

The grid tape output, after proper adjustment for the large pulses, has a nominal noise level of 0.02 volts from a TF41 engine operating at

14,000 pounds of thrust and many pulses up to 0.10 volts. The ring tape output has a nominal noise level of 0.05 volts and pulses up to 0.25 volts. These measurements are needed to determine the termination resistance to use when the wear rate monitor is connected to engines other than the TF41.

The tape recorded signal can be played back through the input amplifiers. The ring input amplifier has a gain of five, and the tape output is attenuated by a factor of five; therefore, the amplifier can be used directly. However, the grid input amplifier has unity gain. Thus on tape playback, the amplifier feedback is switched to a larger resistor to provide a gain of five.

The count processing circuitry determines the number of pulses greater than a certain threshold for both positive and negative polarity. The count processing circuitry is driven by the second stage of the bandpass filter. The filtered signal is sent to two comparators. One comparator compares the signal against some positive voltage, while the other comparator compares the signal against some negative voltage. This comparison sets the positive and negative count thresholds respectively. For the TF41 engine, the count threshold using a 100 Hz signal is set at ±0.4 volts at the grid input and ±0.2 volts at the ring input. The two outputs from the comparators go to two positive edge triggered multivibrators, which have their outputs tied to the opposite multivibrator input logic. Thus, the 35 millisecond output of either multivibrator will block the other multivibrator input. The outputs are sent to the monitor logic as either positive or negative count pulses depending on the comparator used.

The area circuitry generates digital pulses that are related to the electrostatic pulse area greater than a certain level for both positive and negative pulses. The input to the area circuitry is an integrator amplifier driven by the first stage of the band pass filter. This input amplifier is a buffer in the grid circuit. In the ring circuit the integration time constant is 80 milliseconds. This integration factor counteracts the derivative effect of the PRION probe so that the pulses in the grid and ring circuits appear similar in the respective area processors. The integrator output on the back panel of the wear rate monitor is connected to the ring integrator amplifier, since the grid signal is not altered by the integrator amplifier. The grid and ring integrator outputs are each sent to two clipper amplifiers.

One clipper amplifier only passes signals above a certain level set by the input offset adjustment, and the other clipper passes signals below a set level. The outputs of the clipper amplifiers are sent to fixed offset amplifiers, which are biased about 0.3 volts negative. The negative signal from the second clipper is inverted so that both signals have positive variations. The fixed negative offset voltage and the clipper amplifier offset determine the reference voltage level. The gain adjustment on the clipper amplifiers determine the threshold level of the signal into the system that will cause the output of the fixed offset amplifiers to go positive. These area thresholds are set at the same level as the count thresholds above.

After the threshold is passed and a positive signal is applied to the voltage-to-frequency converter, the converter will start generating pulses. The larger the signal and the longer the signal is positive, the larger will be the number of pulses generated. Thus, the circuit provides pulses relative to the area of the signals above the thresholds.

Timing Circuit

The timing circuit is composed of the steady wear circuit and the acceleration circuit. The steady wear circuit gets its main input from the input amplifier of the grid measurement circuit and generates digital pulses related to the thrust of the engine. The input signal is applied to an amplifier with a gain of 20. This amplifier acts as a buffer to the measurement circuit and a clipper to most of the large pulses. The output signal is then applied to a low pass filter, which has a gain of a half, to obtain the dc component of the grid signal.

A small correction factor is added to this dc signal before it is applied to the voltage-to-frequency converter. The resistive network after the low pass filter adds the NL2 signal of the acceleration circuit to the dc signal. At the output of this network, the dc signal is five times larger than NL2 when the engine is running with 14,000 pounds of thrust on a sea level static test stand.

The other part of the timing circuit is the acceleration circuit, which uses the low pressure turbine tachometer signal (NL) to generate digital pulses related to the acceleration and deceleration of the engine. NL is applied to a buffer amplifier, which serves as a clipper amplifier to remove amplitude variations from NL. NL is then sent to a band pass filter which has a center frequency of 600 Hz for the TF41 tested. NL varies from 100 Hz to 440 Hz when the engine is run from idle to full speed. This frequency range on the band pass filter has a square law response (double the frequency and the voltage out is four times as large) as seen in Figure B-1.

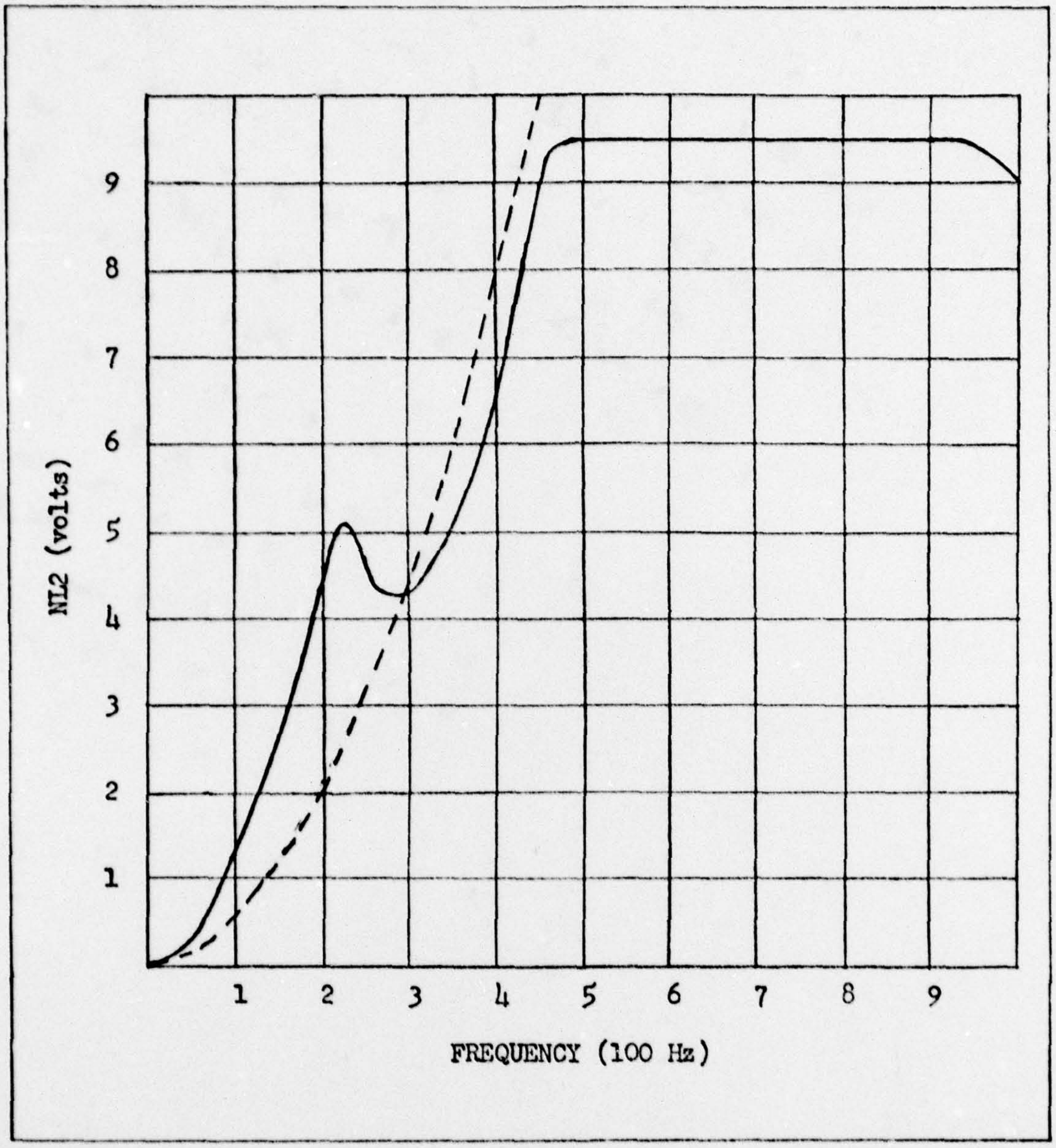


Figure B-1. Frequency Response of NL Band pass Filter, with Dashed Line showing Frequency Squared Curve ($F^2/2$).

On engines where the maximum frequency of NL is not 440 Hz, the capacitors in the band pass filter would have to be changed. For engines where NL only goes to 70 Hz, the two 0.007 μf capacitors in the band pass filter would be changed to 0.05 μf capacitors. For engines like the F100 which goes to 2253 Hz, the capacitors installed would be 1500 pf. After the capacitors are changed, the maximum frequency should be applied and the 20KΩ feedback resistor (R) in the next stage changed to give approximately 8 volts out at NL2 on the back panel ($R = \propto NL2$). NL is preferred, but if it is not available, then the high pressure turbine tachometer signal can be used.

The output of the band pass filter is sent through a diode and two stages of low pass filtering. The signal at this point is a dc voltage (NL2) related to the square of NL. NL2 is applied to a driver amplifier and to a derivative circuit. The driver amplifier sends the NL2 signal to an output connection on the back panel of the wear rate monitor and to the additive network in the steady wear circuit discussed above. The derivative circuit is a high pass filter that yields the derivative, or acceleration/deceleration, of NL2.

The derivative of NL2 is then applied to an offset amplifier. This amplifier has a gain of ten and offsets the reference voltage to determine the threshold of the size of acceleration that will go to the voltage-to-frequency converter. The size of the acceleration above the threshold determines how many acceleration pulses will be generated by the converter. The size of the acceleration signal is determined by the amount of change in NL2 and how fast this change occurs.

Monitor Logic

The monitor logic stores the data from the previous circuits, controls the digital printer, and analyzes the stored data to detect excess wear. The monitor logic has the storage registers, the print logic, and the main logic. The storage registers store the pulses from the measurement circuits and the timing circuit. These storage registers are decade counters which store up to ten pulses. At the tenth pulse, the counter resets to zero and gives an overflow pulse. Two counters connected in series can store up to 100 pulses. The inputs to the counters are amplifiers that can be clamped to ground to prevent pulses from going to the counters during the print process, and thus prevent garbled prints.

The print logic controls the digital printer. The inputs to the print logic are the acceleration (AC) and steady wear (SW) pulses and the 100 print signal from the main logic. The AC and SW pulses are added in an OR gate and counted down by two decade counters. Thus for every 100 pulses, there is one internal timing pulse. These two counters can also be used to count down external pulses by 100 to generate an internal timing pulse.

A front panel switch (S3) selects either this internal timing pulse, an external timing pulse which is not counted down, or an internal clock pulse to be the system timing pulse. This timing pulse sets a flip-flop to clamp the storage unit inputs as explained above, sets an AND gate for the "clear" signal, and sends a signal to the printer to put a "T" in the last column of the print to indicate a total measurement print. The clamp signal triggers a multivibrator that sends a pulse to the printer causing it to print. The 100 print signal from the main logic goes only to the flip-flop to clamp the input signals and trigger the printer.

The clock pulses used as timing pulses come from the print logic. An internal oscillator and count down decade counters are set to provide a pulse every minute. This pulse is then counted down by five to give a pulse every five minutes, and counted down by two more to give a pulse every ten minutes. These three clock pulses are selectable by the front panel timing switch (S3).

Another print command source is a front panel push button (S4). This push button provides a manual clear and reset for the entire wear rate monitor. The push button shorts out an inverted input to the timing pulse path, thus causing a timing pulse which effects the print logic as explained above for the system timing pulse. There is also a manual print button on the digital printer. However, this button only causes the printer to print the stored data and does not effect the monitor logic.

At the end of the printing process, the printer sends an end-of-print (EOP) signal to the print logic. This signal resets the flip-flop which unclamps the inputs, and also goes to the "clear" AND gate. If the gate is set, the EOP signal will go through the gate and clear all the storage registers, and then reset the AND gate.

The main logic monitors the measurement storage registers to determine the 100 print condition and alarm conditions. The 100 print condition occurs when one of the storage registers reaches a 100 increment. The 100 pulse from the storage register sets a flip-flop which provides a decimal signal to the printer for the column that reached 100. This decimal signal is also sent through a NAND gate to trigger the clamp flip-flop, and thus produce the print command. The "clear" AND gate is not set by the 100 print signal, so the storage registers will not be cleared by the EOP signal. However, the flip-flops are cleared by the EOP signal to release the decimal signal and the clamp signal.

There are two alarm conditions in the wear note monitor. The 900 alarm condition is determined by the 900 digit of the measurement storage registers. When one of the registers produce a 900 signal, the signal is sent through a NAND gate to set a flip-flop. The output of this flip-flop is sent to an OR gate. This OR gate then turns on the alarm relay whose contact leads are connected to the back panel of the wear rate monitor as ALARM output. The contacts to this relay are normally open, but can easily be rewired to be normally closed. The OR gate also drives an inverter amplifier that causes the printer to print in red during an alarm condition. The flip-flop, and thus the 900 alarm, is cleared by the "clear" pulse from the print logic.

The other alarm condition is the three count alarm, which has a threshold pulse between three consecutive "clear" pulses. The threshold is set in each measurement storage register. This setting can be varied from 10 to 90 in increments of 10 by connecting the input leads of an AND gate to one of the tens digit in the storage register. If a larger number is desired, the optional divide-by-ten input is wired in, so the tens digits are actually hundreds digits, and the threshold is set from 100 to 900 in increments of 100.

The threshold pulses from the storage registers is sent through a NAND gate to set the first of four flip-flops in the three count alarm circuit. Once the flip-flop is set, the three count alarm circuit is uneffected by more threshold pulses. The first flip-flop sets an AND gate so that the "clear" pulse from the print logic can pass through and clock (shift) the four flip-flops. When this happens, the first flip-flop is reset and the second one is set. If another threshold pulse is received, the first flip-flop is set again, and the next "clear" pulse shifts both sets. At this point, the second and third flip-flops are set. This setting and shifting will continue as long as a threshold pulse is received before the "clear" pulse.

When a threshold signal is missing, the "clear" pulse will clear all four flip-flops. This clear decision is made by an AND gate. The inputs to the AND gate are the "clear" pulse, the output of the second flip-flop and the inverted output of the first flip-flop. Thus the three count alarm circuit is cleared when the first flip-flop is reset, the second is set, and the "clear" pulse is generated in the print logic.

The three count alarm is given by an AND gate driving the other input to the OR gate explained in the 900 alarm condition above and activating the alarm relay. The inputs to the AND gate are two variable leads and the fixed connection to the second flip-flop output. These leads can be connected to five volts, which would give a one count alarm when the second flip-flop is set. Both the leads could be connected to the third flip-flop, which would give a two count alarm when the second and third flip-flops are set. However, the most common connection is to have one lead connected to the third flip-flop and the other to the fourth flip-flop. This gives a three count alarm when three consecutive sets have been made and shifted.

A minor function of the main logic is to clear the entire system when it is turned on. This automatic clear is accomplished by a large capacitor charging up to the supply voltage through a resistor. At half voltage, a multivibrator is triggered. At the end of this pulse, a second multivibrator is triggered. The end of the second pulse then clears the entire monitor logic.

The LED (light emitting diode) outputs on the wear rate monitor give a continuous display of the timing pulse count and the number of threshold alarm counts. The right two LED's on the front panel display the timing pulses accumulated in the timing pulse decade counters from 00 to 99. The input to these LED's is the binary coded output of the 100 count down decade counters. This display indicates at what portion of the timing cycle the wear rate monitor is operating.

The left LED on the front panel will display "1" when the second flip-flop in the three count alarm circuit is set indicating one alarm. The second LED will display "1" to indicate a two count alarm, and the third LED indicates a three count alarm. The binary code "1" inputs to these three LED's are connected to the respective flip-flop outputs in the three count alarm circuit.

Appendix C

TRION and PRION Probes

The physical size and installation information of the probes and their supporting hardware is given in this Appendix. The first drawing gives the basic installation information, and the other two drawings show the physical construction of the supporting bolt assemblies. All materials not labeled are noncorrosive materials such as aluminum or cadmium plated steel. The TRION grid probe is made of 3/32 inch HASTELLOY-X wire, and the PRION probe is made of 4 inches wide single sided 1/16 inch circuit board material. The TRION supporting bolt assemblies are prevented from unscrewing by RTV rubber glue applied during installation. The PRION probe is epoxied in the tailpipe with EPY 500 epoxy and then secured with the PRION supporting bolt assemblies.

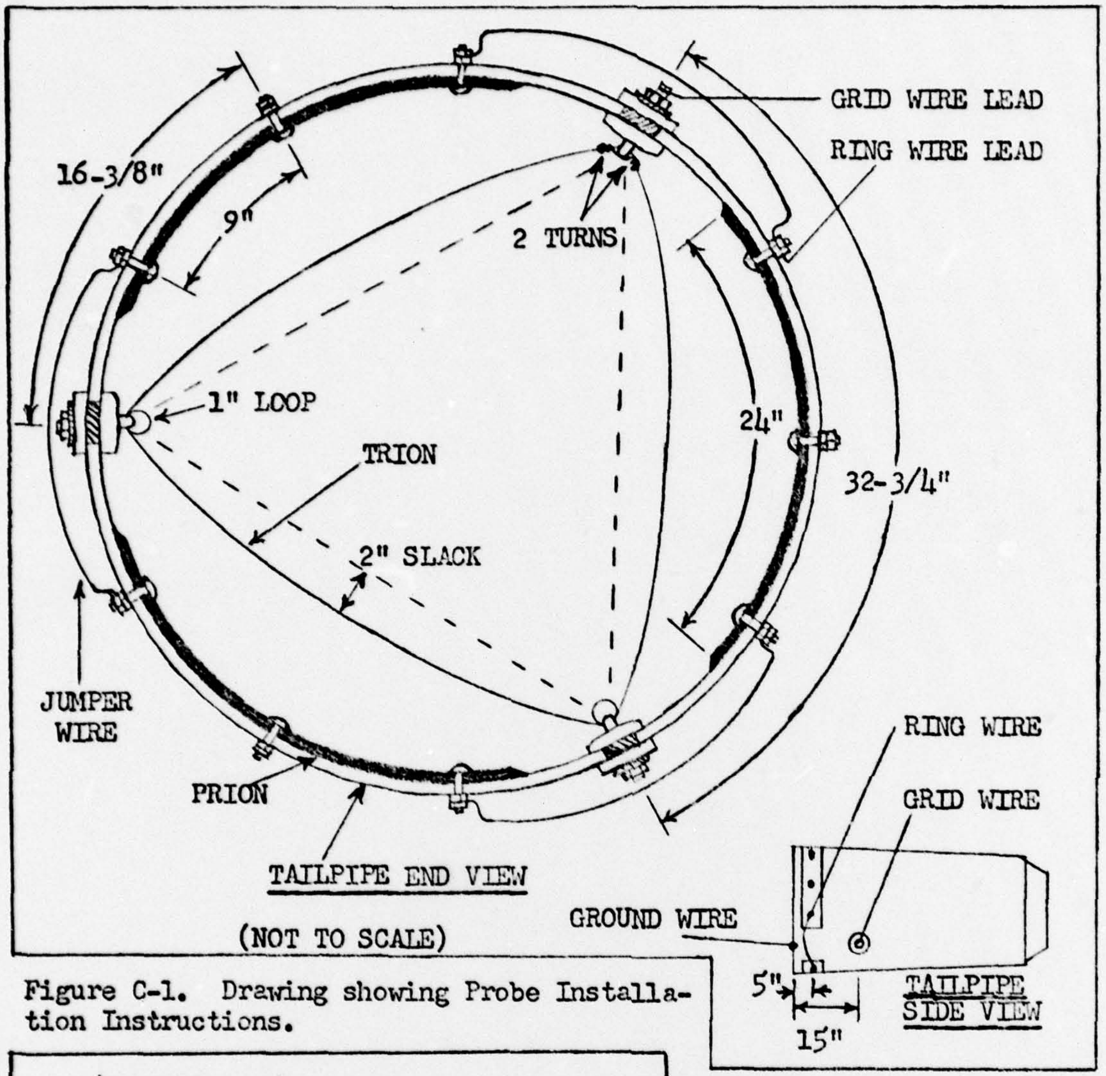


Figure C-1. Drawing showing Probe Installation Instructions.

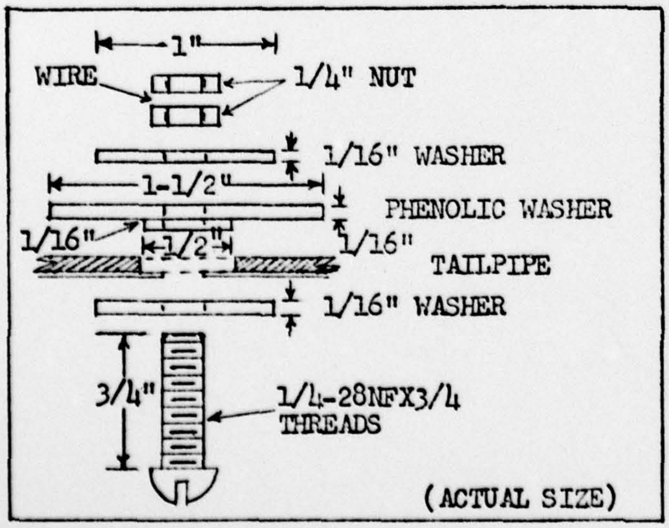


Figure C-2. PRION Supporting Bolt Assembly.

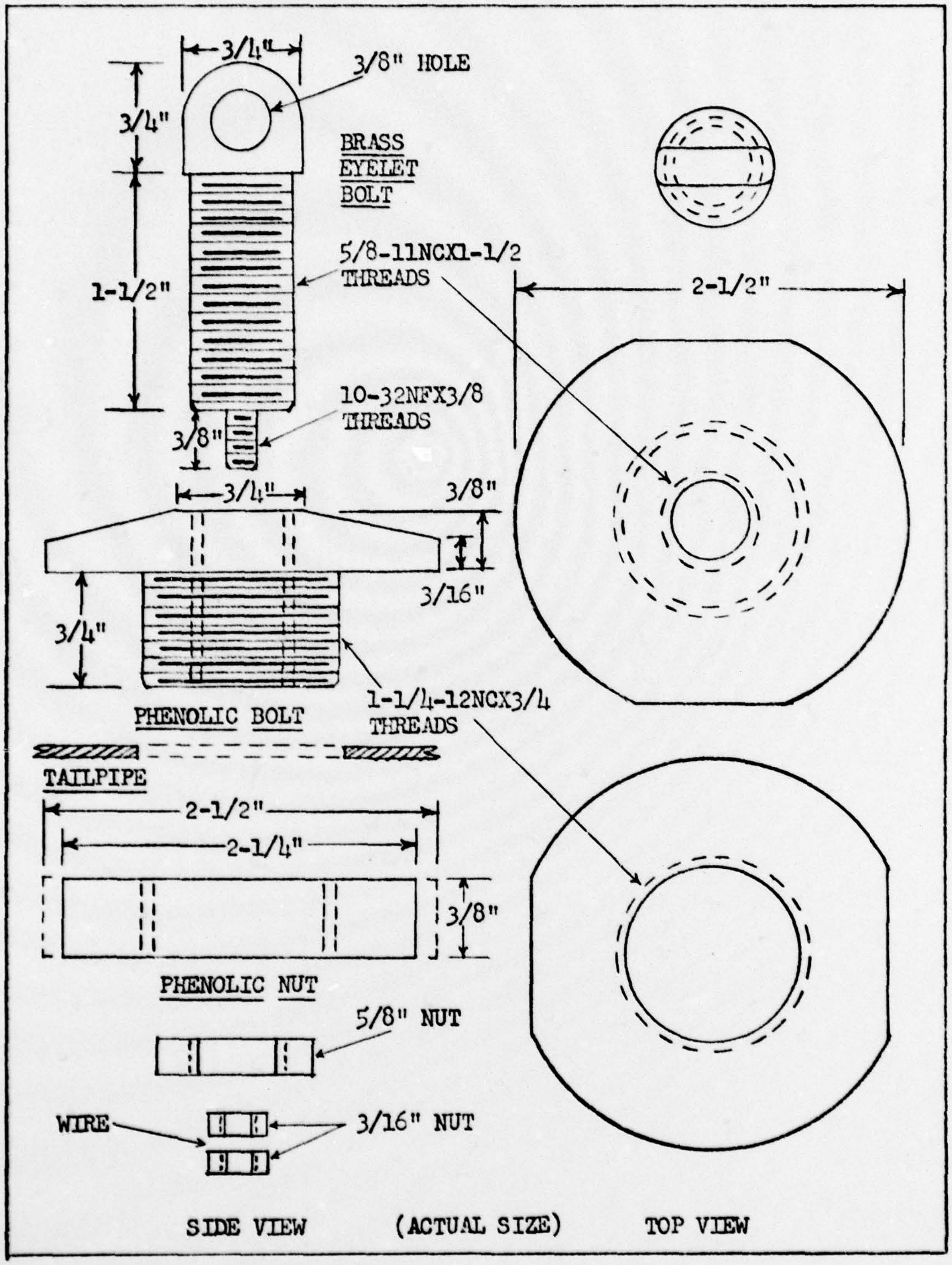


Figure C-3. TRION Supporting Bolt Assembly.

Vita

Freddy Leon Baker was born on 12 March 1946 in Nash County, North Carolina. He graduated from Coopers High School, Nash County, North Carolina in 1964 and attended North Carolina State University for three years majoring in Electrical Engineering. In July 1967 he enlisted in the USAF and received training as a ground control approach radar repairman. In September 1968 he attended Texas Tech University under the Airman Education and Commissioning Program, and received a Bachelor of Science degree in Electrical Engineering in June 1970. After attending Officers Training School, he received a commission in the USAF in October 1970. After receiving communications officer training, he worked for the 1973rd Communications Squadron and then the 1974th Communications Group, Udorn Royal Thai AFB, Thailand. He then served as long haul communications system evaluator for Headquarters European Communications Area, Wiesbaden, Germany until entering the School of Engineering, Air Force Institute of Technology, in June 1976.

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REPORT DOCUMENTATION PAGE		READ INSTRUCTIONS BEFORE COMPLETING FORM
1. REPORT NUMBER AFIT/GE/EE/77-7	2. GOVT ACCESSION NO.	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) ELECTRONIC ANALYSIS OF ELECTROSTATIC PULSES TO DETECT IMMINENT JET ENGINE GAS-PATH FAILURE		5. TYPE OF REPORT & PERIOD COVERED MS Thesis
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) Freddy L. Baker Capt USAF		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS Air Force Institute of Technology (AFIT-EN) Wright-Patterson AFB, Ohio 45433		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
11. CONTROLLING OFFICE NAME AND ADDRESS ASD/YZN Wright-Patterson AFB, Ohio 45433		12. REPORT DATE December 1977
		13. NUMBER OF PAGES 81
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 Approved for public release; IAW 190-17 Jerral F. Guess JERRAL F. GUESS, Captain, USAF Director of Information		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Jet Engines Electronic Equipment Electrostatic Fields Predictions Processing Ions Probes Failure		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A jet engine gas-path wear rate monitor has been designed and tested. The monitor observes gas-path component rubbing, chaffing, burning, or erosion by measuring the electrostatic charge in the engine exhaust. This system continuously monitors the exhaust during engine operation, and periodically checks the total metal content in the exhaust to determine the deterioration rate of gas-path components. The design of the monitor is based on 4000 hours of early [illegible] TF41 electrostatic count data and on 2000 hours of recent analog tape recorded data produced by TF41 engines undergoing severe distresses.		

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20 Continued

This thesis describes the theory and operation of the wear rate monitor. First the design and installation of the optimized probes is presented. Next the theory and opeation of the analog and digital circuits in the wear rate moniter is discussed. Circuit diagrams are given for all of the electronic components of the monitor. Then the techniques for adapting the monitor to engines other than the TF41 turbofan engine are presented. Finally, test data is given in which the monitor showed excessive wear in a TF41 engine on which it was being tested at the AFAPL. This excessive wear condition occurred after more than 100 hours of stable wear operation.