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It is the intention of this article to describe the construction and operation of the hardware and the software that constitutes a 4,096 channel bi-stabilized pulse height analyzer, data processing, and control system. The system was designed for studying mesic γ-ray spectrums at the 184" Cyclotron.

HARDWARE

Figure 1 shows a simplified block diagram of the system. In operation, a γ-ray of a given energy is stopped in the Ge or Si solid state detector and converted into a given number of hole-electron pairs. These carriers are then collected by the high field due to reverse bias voltage of 300-1500 volts and appear as a charge pulse, Q, and a small voltage signal is applied to the preamplifier of $V=Q/C$ where C is the capacitance of the detector and any stray capacitance. Two types of preamplifiers have been used: The charge sensitive type has a strong feedback which integrates the input and produces a signal proportional to Q and independent of changes in C; this is useful if C has a tendency to change due to changing bias voltage or perhaps to deterioration from beam particles; the voltage sensitive type which produces a signal proportional to Q/C.

The signal now passes through a variable gain amplifier, a linear amplifier, and a linear gate, and then into the ADC. Here it is converted into 12-bit words and transferred in parallel into the PDP-5 computer for data storage, data display, and feedback control. As the computer data memory periodically fills up, the computer suspends its normal data-taking function while it transfers the data memory contents onto magnetic tape, using a D2020 tape control. This forward path, thus far, is essentially a 4,096 channel P.H.A.

The gain, or more correctly, the transfer function of the system may be changed electrically in two ways. First, the gain may be changed by a variable

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gain amplifier which effects a gain change by changing an analog voltage level applied to on F.E.T. acting as a variable feedback resistor.

Second, the spectrum may be shifted "en masse" up or down by another analog voltage applied to a pedestal adjustment in the linear gate. The linear gate is open only when a desired γ-ray passes through the beam telescope and also produces a pulse in the timing preamp. These two methods of effecting a transfer function change are used to stabilize the transfer function against drift by employing feedback from the computer as the data is being entered into storage. Previous systems have used a variable gain amplifier only and have been referred to as "gain stabilized systems."[1],[2] This particular system employs both gain and bias stabilization.

This method of stabilization utilizes a naturally occurring peak in a γ-ray spectrum, commonly obtained for calibration purposes from a small radioactive source. The peak is known theoretically to a high degree of accuracy and is, of course, absolutely invariant. Since this reference right at the beginning of the system is used, the stabilization with reference to this peak compensates for drift in any amplifier and includes even the rundown circuitry in the ADC.

A linear transfer curve is convenient for visualizing the stabilization process. Generally, channel zero does not correspond to zero volts input because, first of all, there is always noise present and to eliminate storage of this noise, a threshold voltage V_t is set (Fig. 2), or secondly, a bias "cut" may have been made to select only the upper portion of spectrum to analyze.

Suppose, for example, that the gain increased, as shown by the dotted transfer line in Fig. 2, then the computer recognizes the peak shift, within the limits of a window, W, and makes a correction by decreasing the gain a fixed small amount with the variable gain amplifier for each pulse that is analyzed until the peak is back to its desired position. The mechanism for this feedback is shown in Fig. 3. A reversible scaler, normally reset to 512, is continually monitored by an D/A whose output is the actual correction voltage for feedback. Say, for example, the gain has increased; then for every count which falls between P and P + W, including P, the PDP-5 sends a "minus" pulse to the reversible scaler which then effects a decrease in gain by a small fraction of a channel; conversely, when a count is obtained between (P - W) and P, excluding P, the gain is decreased, thus, the net effect of a peak shift due to gain drift increasing is a decrease in count on the reversible scaler, although this net effect is achieved in a

Continued . . .

random three-steps-forward-one-step-back type of process. When the peak is stabilized, the scaler continually jitters about a certain count by a few counts because of the gaussian distribution of the counts in a naturally occurring peak.

The zero adjustment or pedestal feedback is accomplished in a manner similar to that of the gain; Fig. 4 shows this effect. The gain is an angular control about an origin; the bias is a parallel motion and the combination, is in effect, a polar coordinate system which defines the straight line transfer function. Note that a change in bias affects both the bias reference peak and the gain reference peak by the same amount; a shift in gain, however, affects the bias peak less then the gain. It is difficult to imagine the simultaneous effect of these two dependent corrections upon each other and a computer program was written to simulate the behavior of this system using the straight line transfer function as a model; the model predicted two types of behavior later verified in operation. First, it predicted a piecewise linear correction rate to a step response, and secondly, an unstable system if the lower energy reference peak (the bias peak) effected much more feedback (channel shift per count), than the gain peak. The simultaneous correction is illustrated in Fig. 5.

In actual practice, the γ-rays come from two sources. First, there are γ-rays from a target which captures the pi mesons; these γ-ray spectra are of prime interest to the experimenter. Second, there are γ-rays from two calibration sources; these sources actually emit a pair of γ-rays in opposite directions. One passes into the main detector for stabilization; the second passes into an adjacent lower quality Si detector which produces a timing pulse. This timing pulse is used to mark or tag the second source of γ-rays from the target γ-rays. Thus, actually, two complete and independent 4,096 channel spectrums are produced at the same time: One for calibration which has a minor percentage of the total counts and one for primary data. Fig. 6 shows a block diagram of the system and shows the device numbers used for reading the various data and for producing reset pulses. The main input into the computer consists of the 12-bit data word and this may be accompanied by the two stabilization flags, all of which are read essentially in parallel by the computer every time an event occurs; thus, there are two types of data words. The primary data is distinguished from the stabilization data by the presence of a flag for the stabilization data. The only other inputs are an electrical turn on/off for gating the storage, and the two 10-bit scaler correction monitors, which may be used at the discretion of the operator.

Continued . . .

The interface hardware is essentially in three sections. First, there is an interface between the ADC and the PDP-5. Second and third are the bias and gain interface for feedback and these are very similar to each other. Fig. 7 shows the gain and bias feedback control block diagram. The stabilization trigger comes from the preamplifier for the stabilization (calibration) source. The overflow prevents the reversible scaler from exceeding its count capability; it gates off the minus or plus input when it has reached the empty or full count status, respectively.

The feedback levels numbered 1 through 4 are actually:

FEEDBACK CHANNEL CHANGE/COUNT IN REVERSIBLE SCALER

Switch Position	Gain	Bias
1	0.047	.065
2	0.173	.184
3	0.47	.357
4	2.9	--

A convenient setting for the experiment has been gain at position 3, and the bias position at 2. This will vary with the resolution of the detector and energy window being looked at.

The correct feedback setting depends upon the resolution of the detector and the energy window as expressed by kev/channel; the channel change per count of feedback should be much less then the (resolution)X(channels/kev). Using this criterion, measurements indicate that the effect of feedback upon the system resolution is negligible.

Referring to Fig. 1, the block diagram labeled "detector"[3] refers to the cryogenic chamber which contains the detector, liquid nitrogen cooling system, vacuum system, and three F.E.T. stages; this is shown in Fig. 8.

Timing resolution of the various detectors presented somewhat of a problem initially since a narrow gate was desired to exclude the large quantities of background noise from the beam. Timing resolution on the order of 20 ns has been achieved although this depends upon the signal to noise and the type of detector used. This figure is under improvement at present.

SOFTWARE

As noted above, the software serves three basic functions:

1) Storage of data on tape.
2) Scope display.
3) Feedback to gain and bias settings on amplifier.

Continued . . .

Tape Storage

Since the incoming data could fall in any one of 4096_{10} channels, it was not practical to consider pigeon-holing of the data as it arrives, (i.e., incrementing the contents of address 6427_8 when a datum falls in channel 6427_8), as the PDP-5 memory also has only 4096_{10} words. Instead, incoming data is merely stored sequentially in a buffer of 3000_8 (1536_{10}) words, and this buffer is transferred to magnetic tape when full. The disadvantages of this approach are, of course, the increased quantity of tape necessary, and the increased analysis time of the tape on the CDC6600. Advantages are that the increased redundancy makes it impossible for a noise error on the tape to invalidate the data, and that "marker words" can be used to distinguish between different types of data. Specifically, a "7777_8" in the data buffer signifies that the datum following it corresponds to a γ-ray from the stabilizing source and not from the target source. An 8192_{10} channel memory just for data storage would have been necessary to provide this capability if pigeonholing has been used.

Scope Display

The scope display buffer occupies 1000_8 (512_{10}) addresses in memory. Unlike the data buffer, it is pigeon-holed. The subsequent reduction in resolution from 4096 to 512 channels (on full scale display) is not objectionable because the scope is not capable of distinguishing more than 512 channels in any case. In order to set the peaks on which the gain and bias settings will be made, it is necessary to be able to tell on the scope where a peak falls with considerable accuracy (within a few channels). This is achieved by having three separate display scales. Since the PDP-5 stores numbers in octal, the reduction in scale of the scope display is by a factor of 8. The scope screen is divided into 8 octants, and with the teletype, the operator can select any one of the octants for a closeup display. Then the resulting octant may be further broken down into 8 octants. Thus, the full $10{,}000_8$ (4096_{10}) channels can be broken down into 100_8 (64_{10}) displays of 100_8 channels each. On each such display, a visual resolution of one channel is easily obtainable. (See Fig. 9)

In order to minimize the reaction time of the computer to incoming data, the scope display takes place, one point at a time, only when the computer has checked to see if there is an incoming datum and has found nothing. See the flow chart in Fig. 10.

Continued . . .

Stabilization

The feedback function of the program is activated when the computer receives a trigger signal at the same time as a datum. The datum is then assumed to come from a stabilizing source, and is compared with the peak center previously selected by the operator. If the datum is larger than the selected peak, a pulse is generated which decreases the gain (or bias); and vice versa. Since the only instability in the system is usually a slow drift, stabilizing data does not need to be inputted too frequently (several per second is sufficient, compared with an overall data rate of several hundred per second).

Keyboard Controlled Options

In addition to the functions noted above, the program also contains a number of options controlled from the teletype keyboard, which provide different modes of operation to facilitate initial setup of equipment, checking out, and so on.

The storage in tape memory can be suspended during set-up or while tape is changed, and a special end of tape marker can be written when data storage on a particular tape is complete. Four words of the tape memory buffer are reserved for a title to identify the data tape after analysis. These are filled in with a keyboard option.

The scope display, besides having the different scale options already mentioned, can be reduced vertically by half, either manually, or automatically when it grows to the top of the screen. Options can also select whether the display includes stabilizing data or not, and whether the display occurs while data acquisition is taking place, or without concurrent data acquisition to provide a faster display time for better visibility.

The peak centers for gain and bias stabilization are typed in via the keyboard, and the operator may also turn either stabilizer on or off, or cause stabilization to occur without triggers.

Other keyboard characters cause the status of all options to be printed out, lock the keyboard to prevent accidental activation of undesired options, and unlock it.

DEADTIME CONSIDERATIONS

A problem of some concern in the design of the program has been the minimization of "dead time," or the time the computer is unable to record an incoming event, because it is still busy handling the previous one. Clearly

Continued . . .

the deadtime should be less than the average rate at which data arrives, if the percentage of data lost is to be kept low.

A formula has been derived[4] relating deadtime, data rate and the percentage of events recorded (efficiency). As applied to the present experiment, this formula is:

$$a = \left[\nu A - (1 - e^{-\nu A})\right] + \frac{1}{N}\left[\nu B - 1\right]$$

Where a = the ratio of events recorded to events lost

ν = the average input data rate

A = the deadtime following each event, during which the ADC and the computer perform their analysis and storage functions

B = the period of deadtime during which the computer suspends normal data taking while it is outputting onto magnetic tape

n = the number of data processing cycles (A) between each tape storage cycle (B).

ν is typically about 500 events per record. A is about 800 μs; n, which is equal to the word size of the tape storage data buffer, is 1535_{10}; B is 220 msec. Using these values in the formula gives

$$a = 500/\text{sec}.800\ \mu\text{s} - (1 - e^{-500/\text{sec}.800\mu\text{s}}) + \frac{1}{1535}\ (500/\text{sec}.220\ \text{msec} - 1)$$

$$a = 0.070 + 0.068$$

$$a = 0.138$$

The efficiency is then $\frac{100}{1+a} = 87.7\%$

Working out the formula for various values of ν gives the theoretical curve shown in Figure 12. As can be seen, the measured results are in good agreement with the formula.

Figure 11 represents a measured probability distribution of an "effective deadtime." This is a deadtime Q such that multiplying it by the frequency will yield the same quantity as the first term in a, above. Thus

$$\nu Q = \nu A - (1 - e^{-\nu A})$$

Q is logically equivalent to the time when the following conditions obtain: 1) The computer has not yet reset the ADC, and 2) an event is stored in the ADC waiting to be read. Calculation of the average effective deadtime Q from the centroid of the graph in Fig. 10 provides a rough check on the effectiveness of the efficiency formula. In the case shown, the average effective deadtime Q is about 295 μs, as compared with the actual deadtime of 800 μs. The reduction is made possible by the ability of the ADC to "store" a new datum while the computer is still calculating. It can therefore be seen that for processing random data, a temporary storage buffer of one or two words between computer and ADC is just as effective as a large increase in calculating speed.

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In summary, the system has proven effective and easy to use, and the flexibility of the PDP-5 and ADC combination has greatly facilitated making modifications since the experiment began.

Acknowledgement

We would like to acknowledge the help and cooperation we received from Dr. David Jenkins.

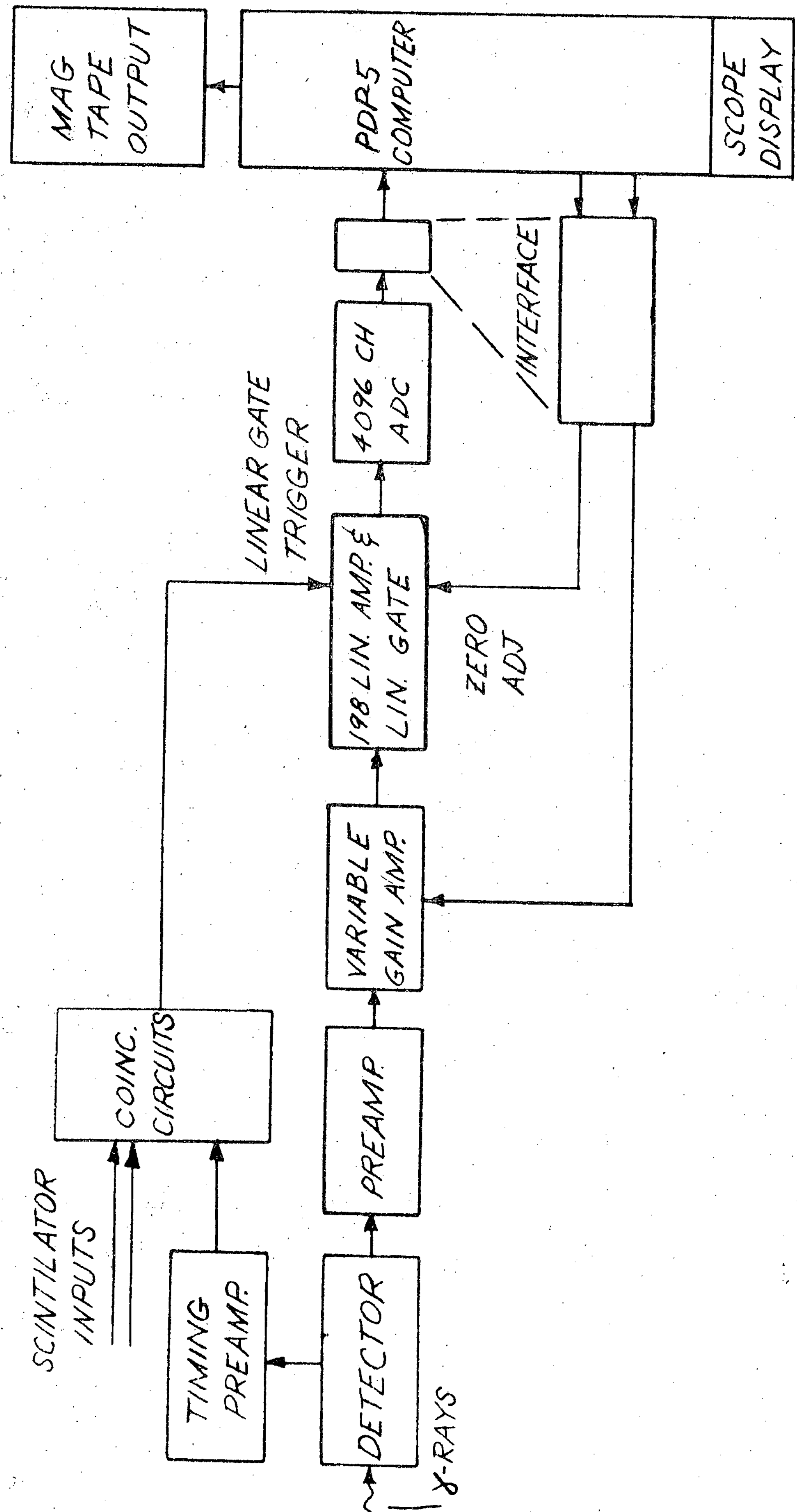
References

[1] An Electrically Controlled Variable Gain Pulse Amplifier Using Different Controlled Elements
H. Arque Almaraz- Lawrence Radiation Laboratory, University of California, Berkeley, California 30 July 1964 Instruments and Methods 32 (1965)

[2] A Digital Gain Stabilizer For a Multiparameter Pulse-Height-Recording System
M. Nakamura and R. L. La Pierre, Lawrence Radiation Laboratory, University of California 30 July 1964 Instruments and Methods 32 (1965)

[3] A Preamplifier With 0.7 keV Resolution for Semiconductor Radiation Detectors
Emanuel Elad September 7, 1965 UCRL-16390 University of California Lawrence Radiation Laboratory, Berkeley, California

[4] On the Events Lost During a Nuclear Counting Experiment
Paul Concus - Lawrence Radiation Laboratory, University of California Berkeley, California April 7, 1966 (Unpublished)



SYSTEM BLOCK DIAGRAM

Fig. 1

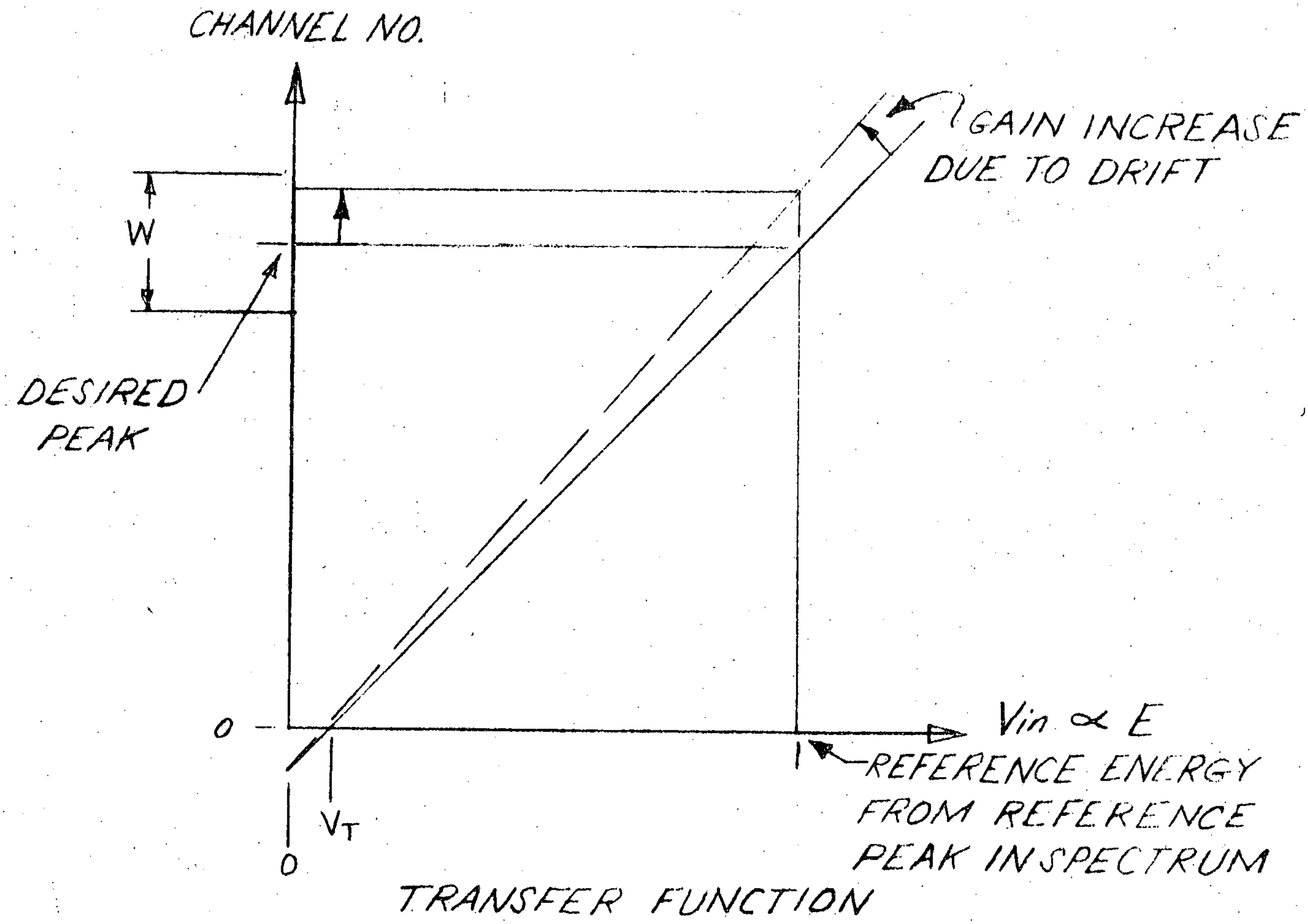

CHANNEL NO.
GAIN INCREASE DUE TO DRIFT
W
DESIRED PEAK
0
Vin ∝ E
REFERENCE ENERGY FROM REFERENCE PEAK IN SPECTRUM
V_T
0
TRANSFER FUNCTION

Fig. 2

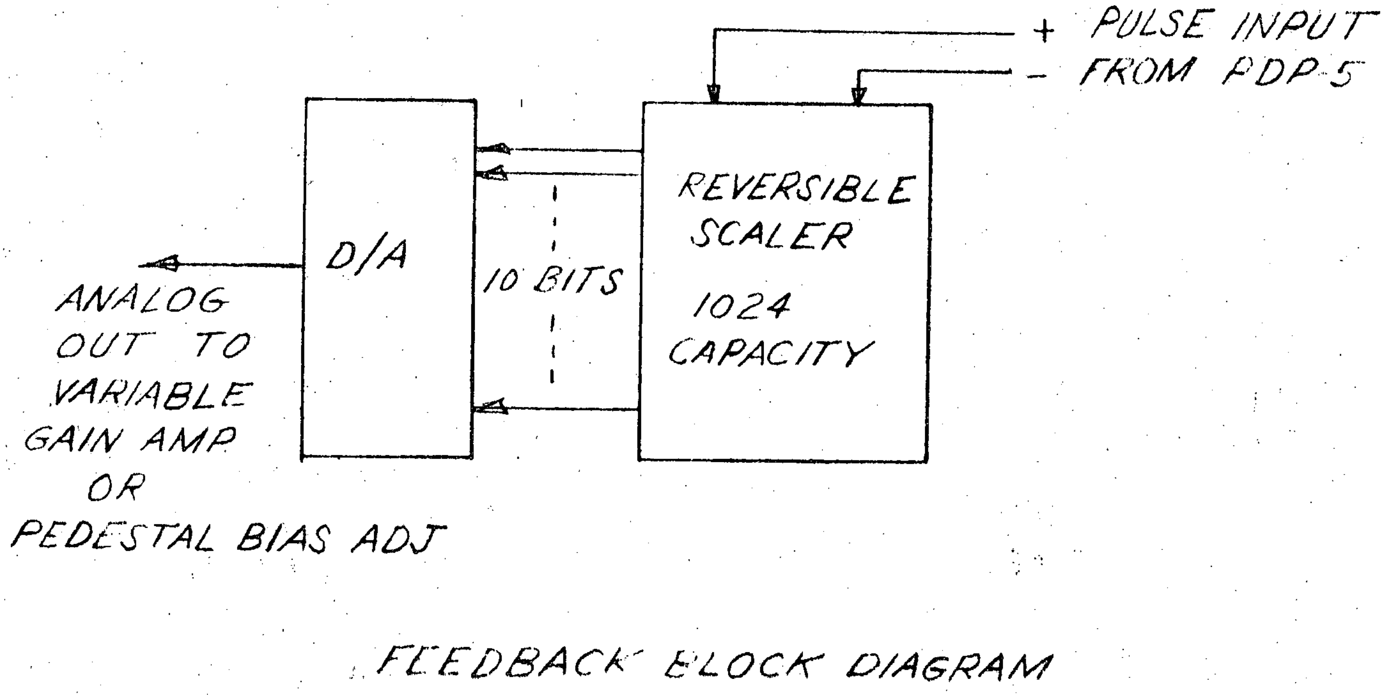
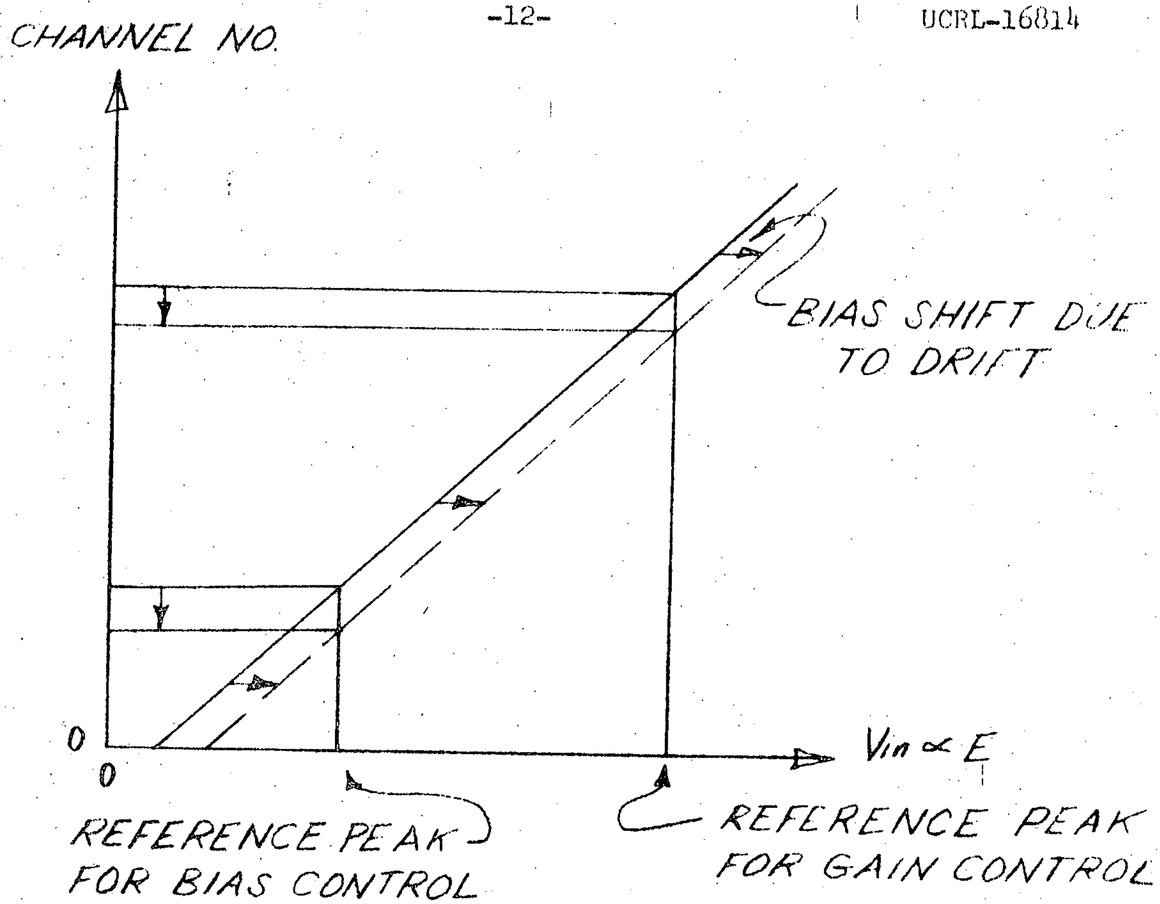
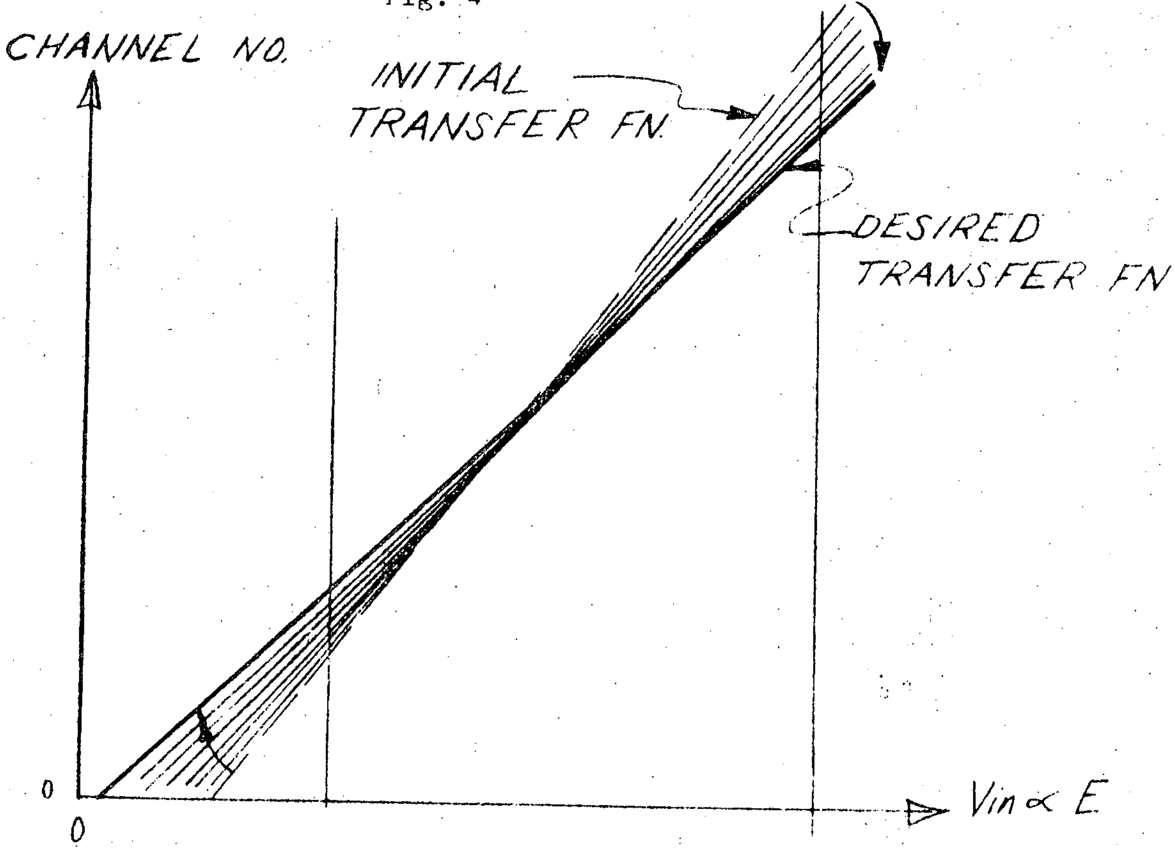

+ PULSE INPUT
– FROM PDP-5
REVERSIBLE SCALER
1024 CAPACITY
10 BITS
D/A
ANALOG OUT TO VARIABLE GAIN AMP OR PEDESTAL BIAS ADJ
FEEDBACK BLOCK DIAGRAM

Fig. 3



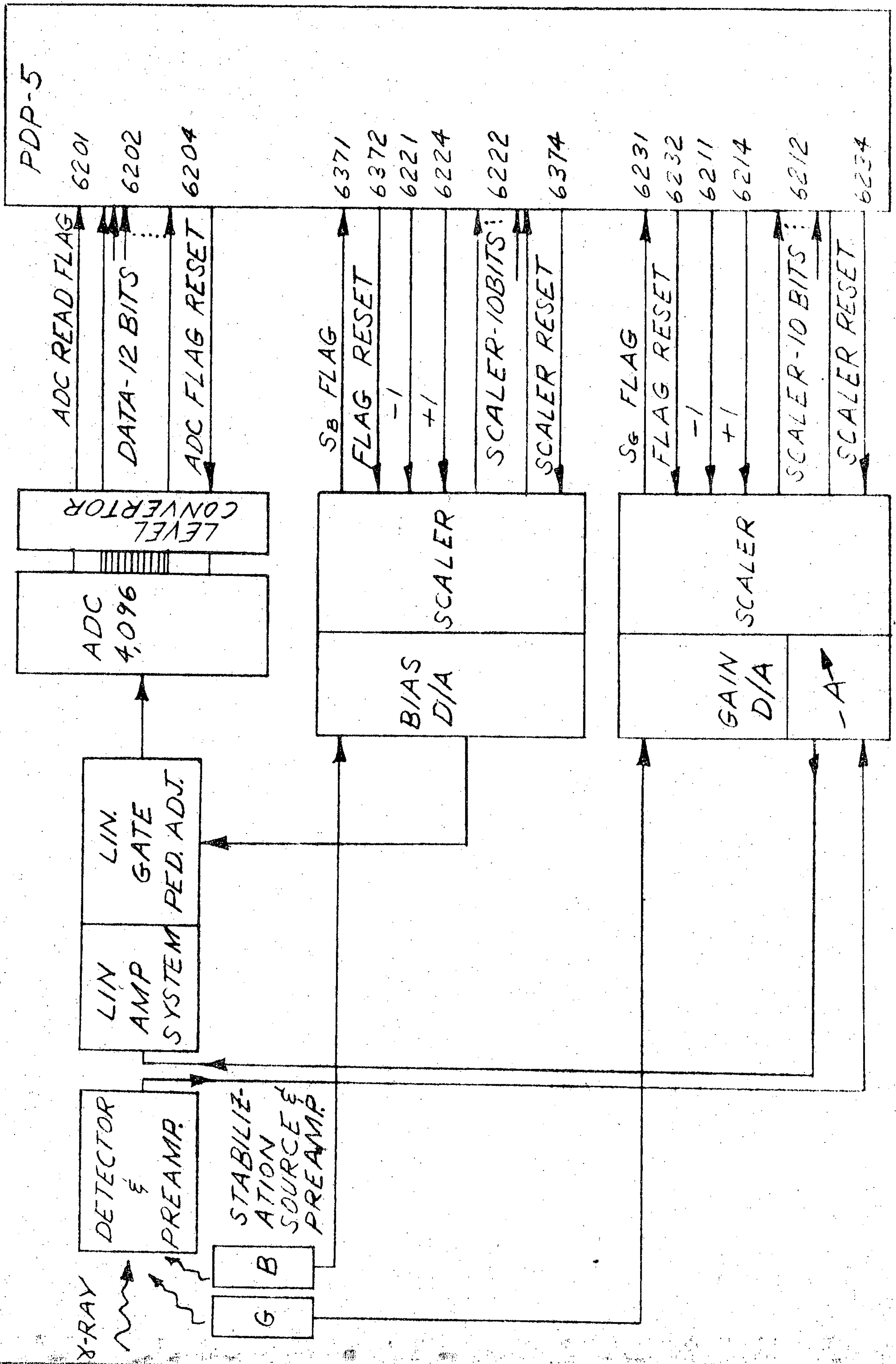
TRANSFER FUNCTION

Fig. 4



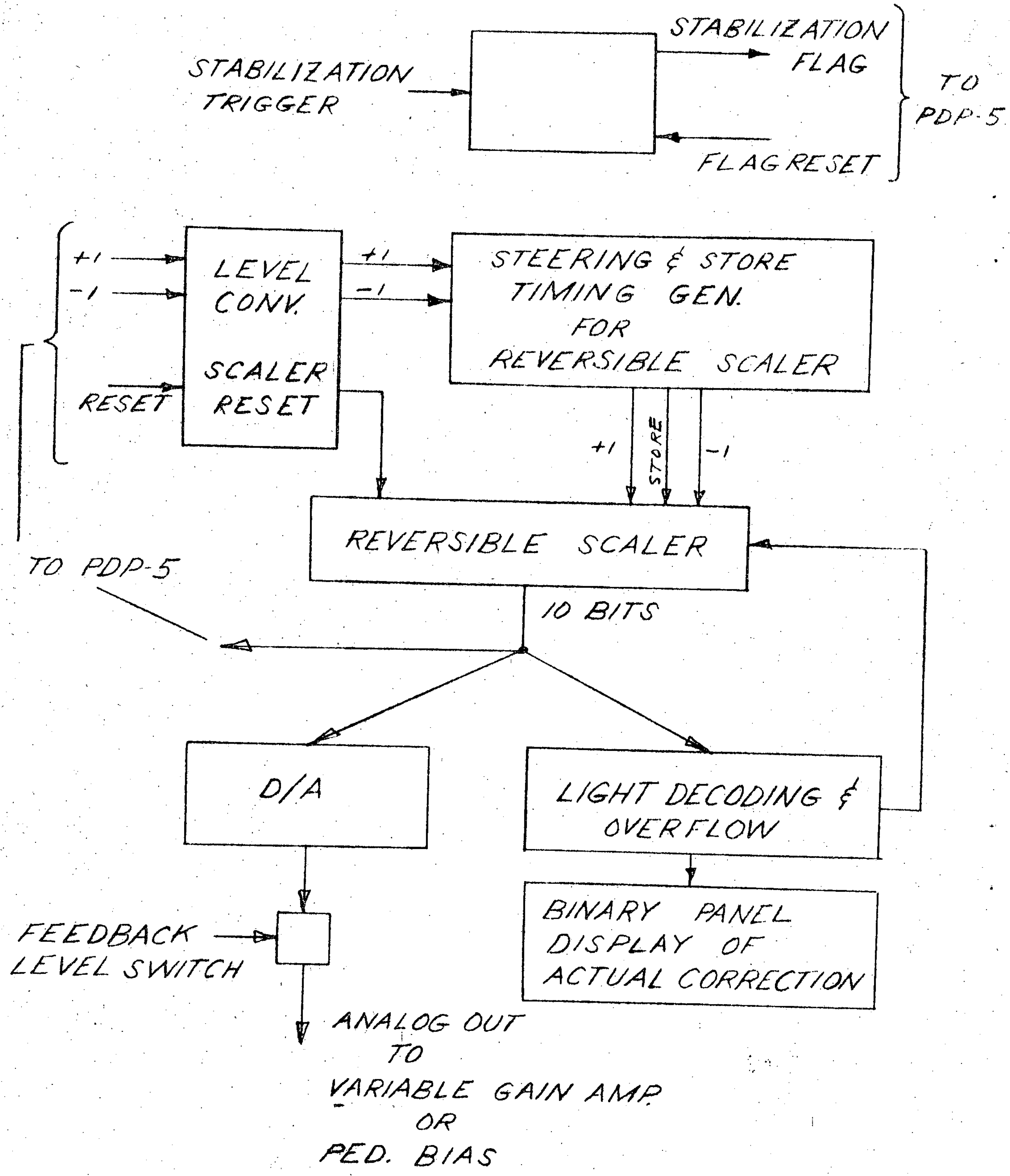
STABILIZATION PROCESS

Fig. 5



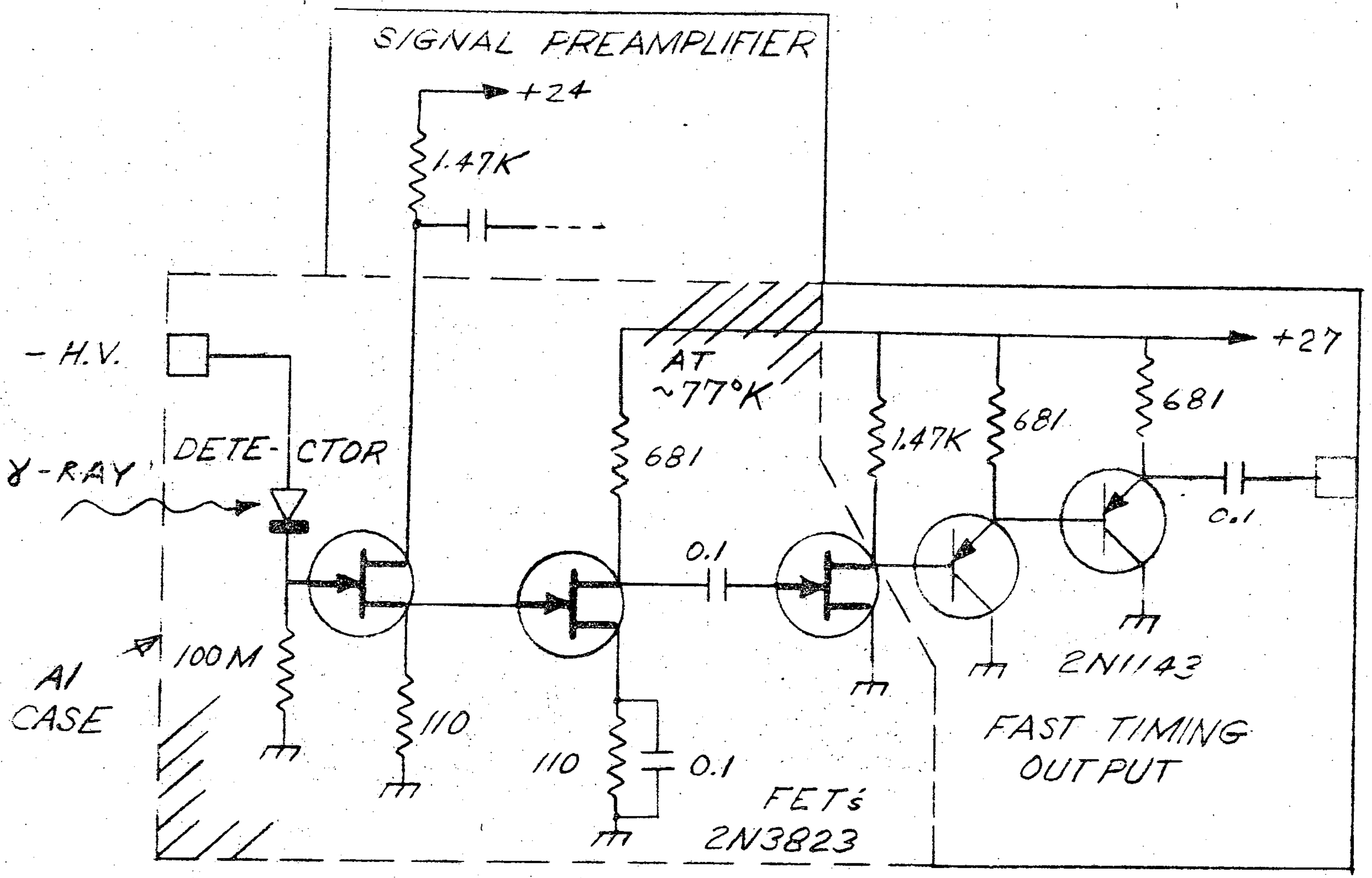
SYSTEM BLOCK DIAGRAM

Fig. 6



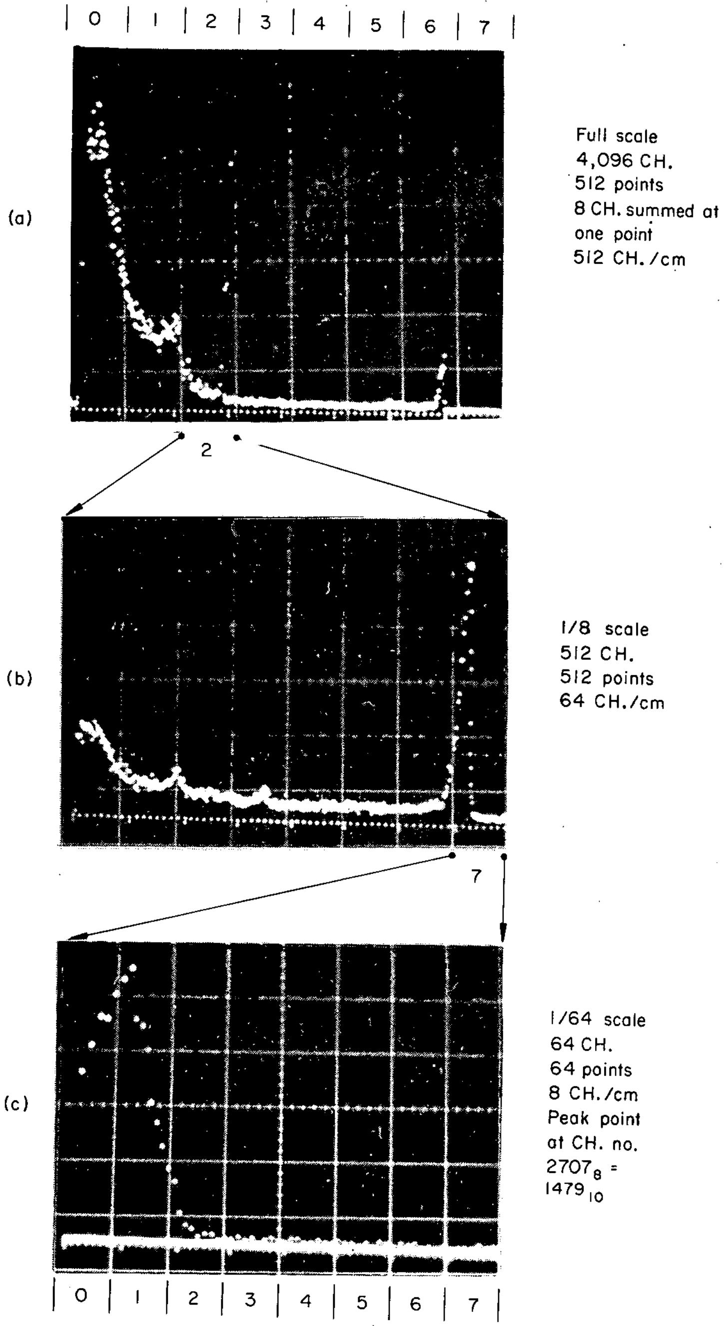
GAIN AND BIAS FEEDBACK BLOCK DIAGRAM

Fig. 7



DETECTOR BLOCK DIAGRAM

Fig. 8


0
1
2
3
4
5
6
7
(a)
Full scale
4,096 CH.
512 points
8 CH. summed at
one point
512 CH./cm
2
(b)
1/8 scale
512 CH.
512 points
64 CH./cm
7
(c)
1/64 scale
64 CH.
64 points
8 CH./cm
Peak point
at CH. no.
2707_8 =
1479_{10}
0
1
2
3
4
5
6
7

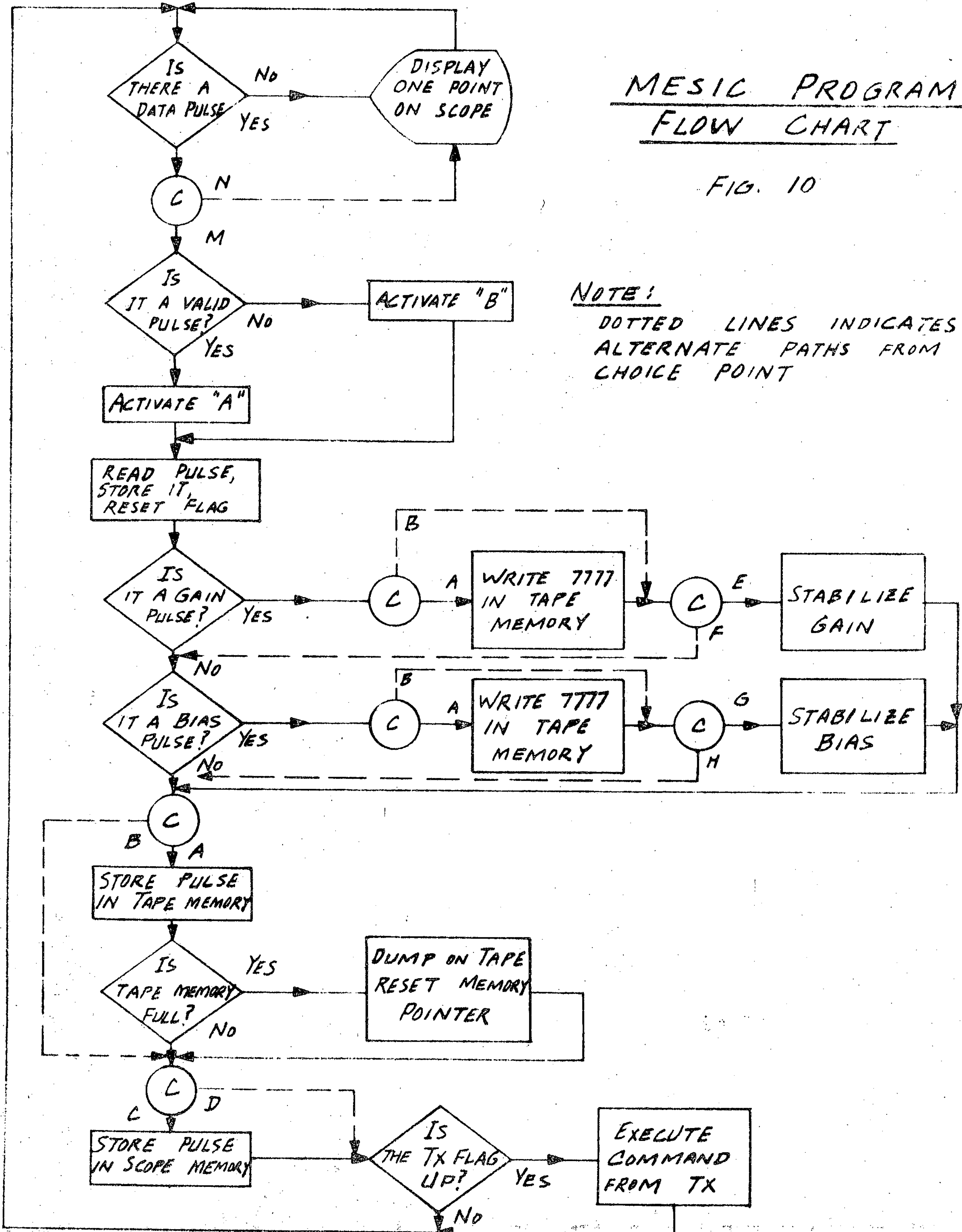
ZN-5999

Fig. 9

MESIC PROGRAM FLOW CHART

FIG. 10

NOTE:
DOTTED LINES INDICATES ALTERNATE PATHS FROM CHOICE POINT



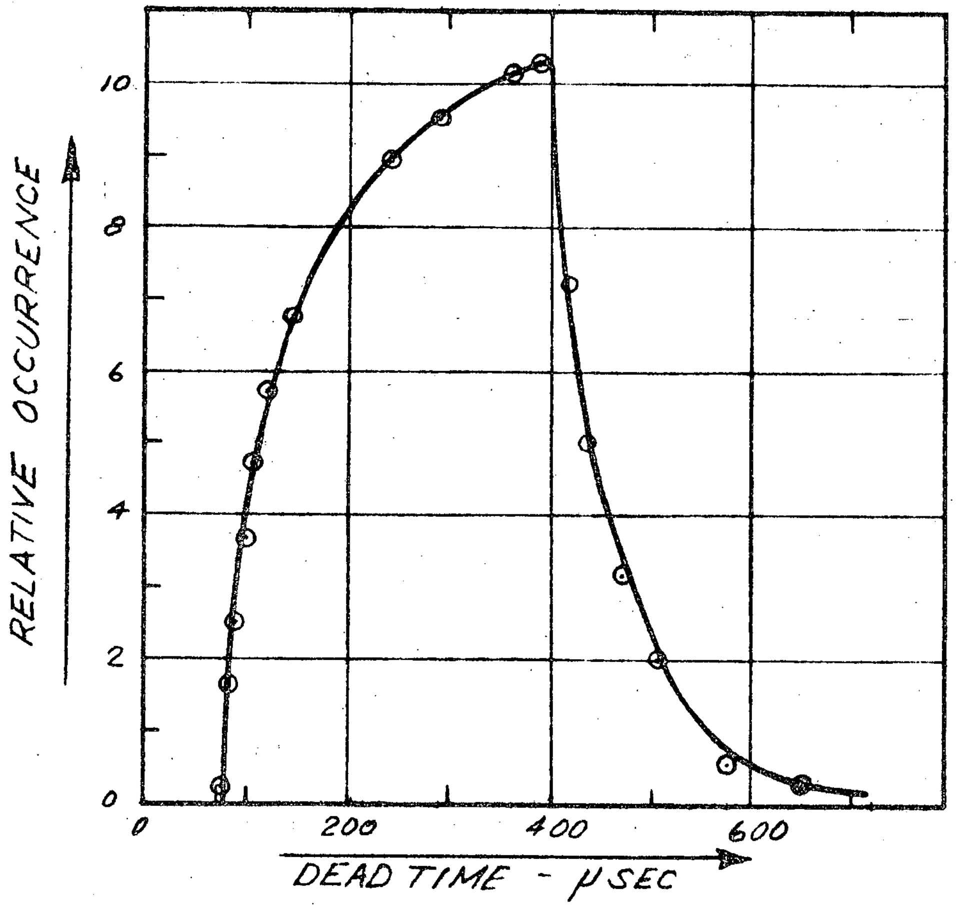

10
8
6
4
2
0
RELATIVE OCCURRENCE
0
200
400
600
DEAD TIME - μSEC

FIG. 11

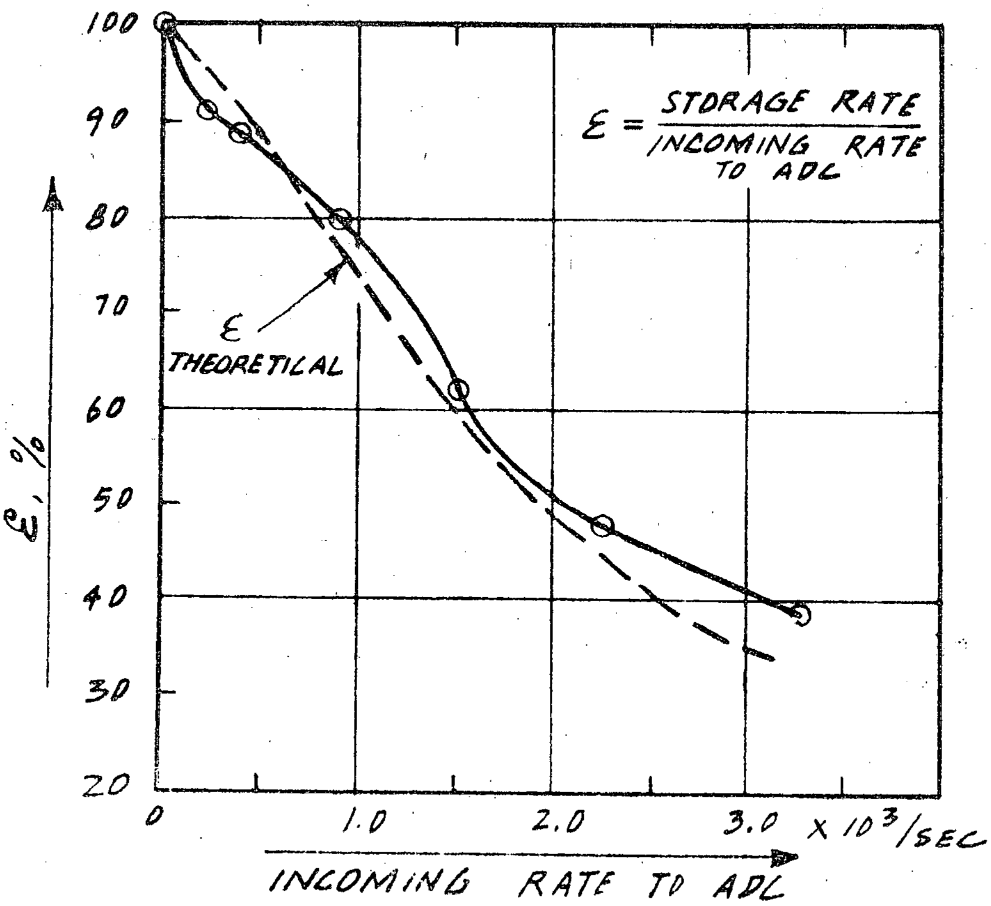

100
90
80
70
60
50
40
30
20
ε, %
ε = STORAGE RATE / INCOMING RATE TO ADC
ε THEORETICAL
0
1.0
2.0
3.0
x 10³/SEC
INCOMING RATE TO ADC

FIG. 12