THE DESIGN AND IMPLEMENTATION OF A DIGITAL MAGNETIC TAPE SYSTEM

THE DESIGN AND IMPLEMENTATION OF A DIGITAL MAGNETIC TAPE SYSTEM AND ITS APPLICATION IN RADIO-ISOTOPE SCANNING

By

Leon Stephen Blum

A Thesis

Submitted to the School of Graduate Studies

in Partial Fulfilment of the Requirements

for the degree

Master of Engineering

McMaster University

November, 1972

MASTER OF ENGINEERING (1972) McMaster University

(Electrical Engineering) Hamilton, Ontario

TITLE: The Design and Implementation of a Digital Magnetic Tape System and its Application in Radio-isotope Scanning

AUTHOR: Leon Stephen Blum, B. Sc. (Eng.) Rand

SUPERVISOR: Professor T. J. Kennett

NUMBER OF PAGES: viii, 119

SCOPE AND CONTENT:

This thesis outlines the design and implementation of a digital magnetic peripheral tape unit. This unit utilizes a novel recording format which, by allowing two tracks to interact, permits an effective increase in the data rate. A portable unit compatible with the peripheral unit is also described and its application to radio-isotope scanning used in Nuclear Medicine is outlined.

Results from the system are described and fundamental work towards image enhancement is undertaken.

ABSTRACT

This thesis is divided into two general sections. The first deals with the theory of digital magnetic recording and surveys the more common techniques used in digital magnetic tape recording. A new recording format is described which leads to a greater data rate at normal recording densities. The design and implementation of a recording system using this technique is described.

The second section outlines the design of a portable digital recording system compatible with the peripheral unit described in section 1. The application of this system to the acquisition of data from a radioisotope scanner used in nuclear medicine is described and some basic results obtained from the system are demonstrated. Fundamental work towards image enhancement is outlined.

ACKNOWLEDGEMENTS

I would like to thank Dr. T. Kennett for his constant encouragement and assistance during the preparation of this thesis.

I would also like to thank Mr. B. Kenyon of the Department of Nuclear Medicine for his excellent work as well as Dr. F. Vajda for his advice and interest. Finally, the financial support of the Department of Electrical Engineering is gratefully acknowledged.

TABLE OF CONTENTS

LIST OF ILLUSTRATIONS

SECTION 1

INTRODUCTION

There are many applications of digital computers where a very large storage capacity is required. This has led to the development of a great variety of techniques for data storage and accessing. Magnetic tape units are one type of device that have been of considerable prominence in this field. There has been a great deal of effort to try and increase the storage density, decrease the access time and improve the reliability. A great deal of these improvements have been achieved by placing closer tolerances on the mechanical design and fabrication techniques and this mechanical improvement has resulted in vast improvements in magnetic tape operation.

There is continuing work looking to the development of other and better media for mass storage, but at this point, there does not appear to be any technique which will replace magnetic film storage in the immediate future. Further, magnetic film recording densities now in use are well below the upper magnetic bit density limit for magnetic recording surfaces. There is, thus, considerable improvement which can be achieved and there will undoubtedly be a great deal of progress in the foreseeable future.

CHAPTER 1

THE MAGNETIC RECORDING PROCESS

(References 1 and 2)

1.1 Fundamental Considerations

The process of magnetic recording relies on the interaction between a magnetic head (the transducer) and a magnetic storage material in relative motion. During the writing process, the head magnetizes the medium which then, on reading, produces an induced voltage in the head, reflecting the rate of change of magnetiziation.

The basic requirements for the medium are that it should be capable of storing magnetic states related to the applied field from the head. This magnetization pattern should be stable and should change only through rerecording.

The head should provide an intense localized field at the surface of the medium during writing and should provide a path to link the flux arising from the magnetized states on the medium during reading. This suggests a high permeability magnetic path with a short non-magnetic region in the vicinity of the tape--simply a magnetic core with a gap and a wound coil.

The basic head-surface configuration in the recording process is shown in Figure 1.1a. It is possible to magnetize a thin strip of magnetic material in any of three possible directions: longitudinally, along its length; transversely, along its width; or perpendicularly, in the direction of its thickness. Practical considerations relating to head design and attainable resolution make longitudinal magnetization the most feasible.

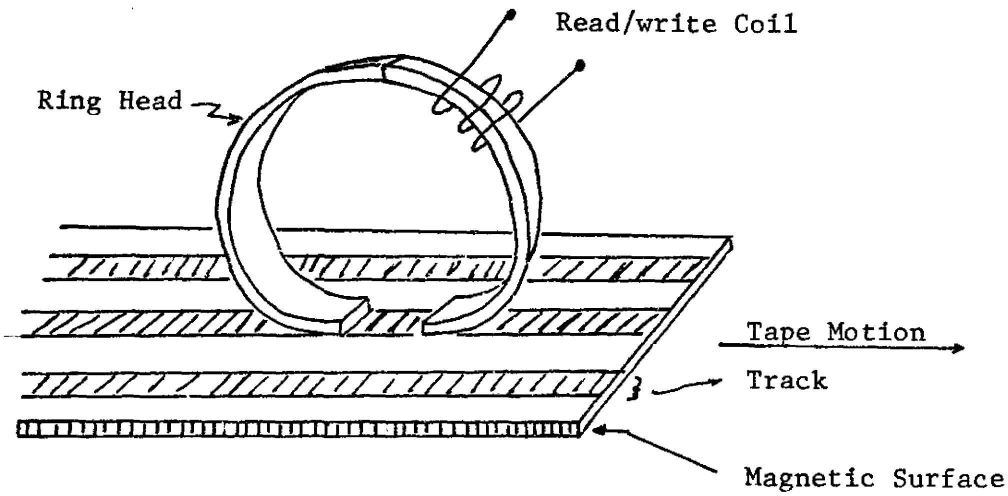


FIGURE 1.1a HEAD-SURFACE CONFIGURATION.

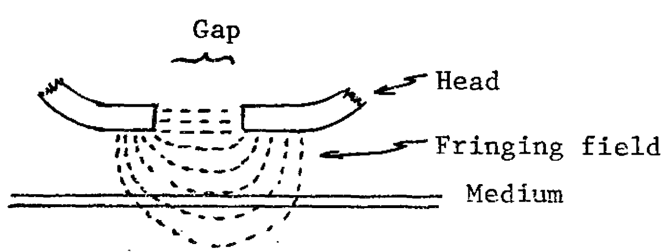


FIGURE 1.1b FRINGING FIELD.

The alternative methods are seldom used and will not be considered.

The head shown in Figure 1.1a is generally referred to as a ring head. The core is laminated and is usually made in two halves for convenience in fabrication and winding. There is a front gap over which the recording medium passes and generally a back gap. The windings are used to generate the flux necessary for recording and to detect the magnetization state of the tape on playback. The path generated along the medium by the magnetic head is called a track, a track thus being parallel to the direction of relative motion.

In digital recording, information is stored in a binary form customarily utilizing two opposite senses of magnetic saturation of the recording medium. These states of saturation are established in terms of the write current in the write coil. The write current thus has one magnitude and two possible directions, corresponding to positive and negative saturation magnetization of the storage medium. Differentiation is inherent in the readback process giving rise to a voltage pulse for each change in direction of saturation magnetization. The level of the write current is determined by the current level at which further increases in current amplitude do not provide an appreciable increase in the output voltage.

The magnetic head to surface coupling which exists with a ring head is shown in Figure 1.1b. The gap shows the gap field with its surrounding leakage flux; the fringing field which extends into the magnetic recording surface being the actual field of utility and interest.

The magnetic properties appropriate for a storage surface for digital recording can be enumerated. The storage surface should have a fairly large value of the maximum energy product (BH)max. H is the magnetic field intensity and B is the flux density. The product (BH)max is a measure of the magnetostatic energy which may be stored in a unit volume of the material. The induced voltage from the magnetic head on read back is nominally proportional to Br, the remanence, and hence a large value for this is desirable.

The coercive force, Hc, of the medium should also be reasonably high to enable the magnetization operation to proceed with a minimal influence on the region of the track just previously recorded. A relatively large ratio for Hc/Br will tend to minimize the susceptibility of the surface to demagnetization effects.

The magnetic properties of materials employed for magnetic heads can also be enumerated. The upper frequency range of the head should be sufficient to give a minimum of waveform distortion. For reading, the initial permeability should be large; this process involving the very weak fields set up by the magnetized surface. For writing the head should have a high saturation flux density, in order to ensure that the magnetic surface saturates before the head core. The residual induction of the head should also be small, so that the head acts as though it is demagnetized when it is not energized.

Figure 1.2 shows a typical set of waveforms encountered in a digital recording system.

1.2 The Magnetization Process

A rigorous treatment of the magnetic recording process is highly complex and while a fairly accurate model of the readback process has been described, there is still considerable doubt as to the actual analysis

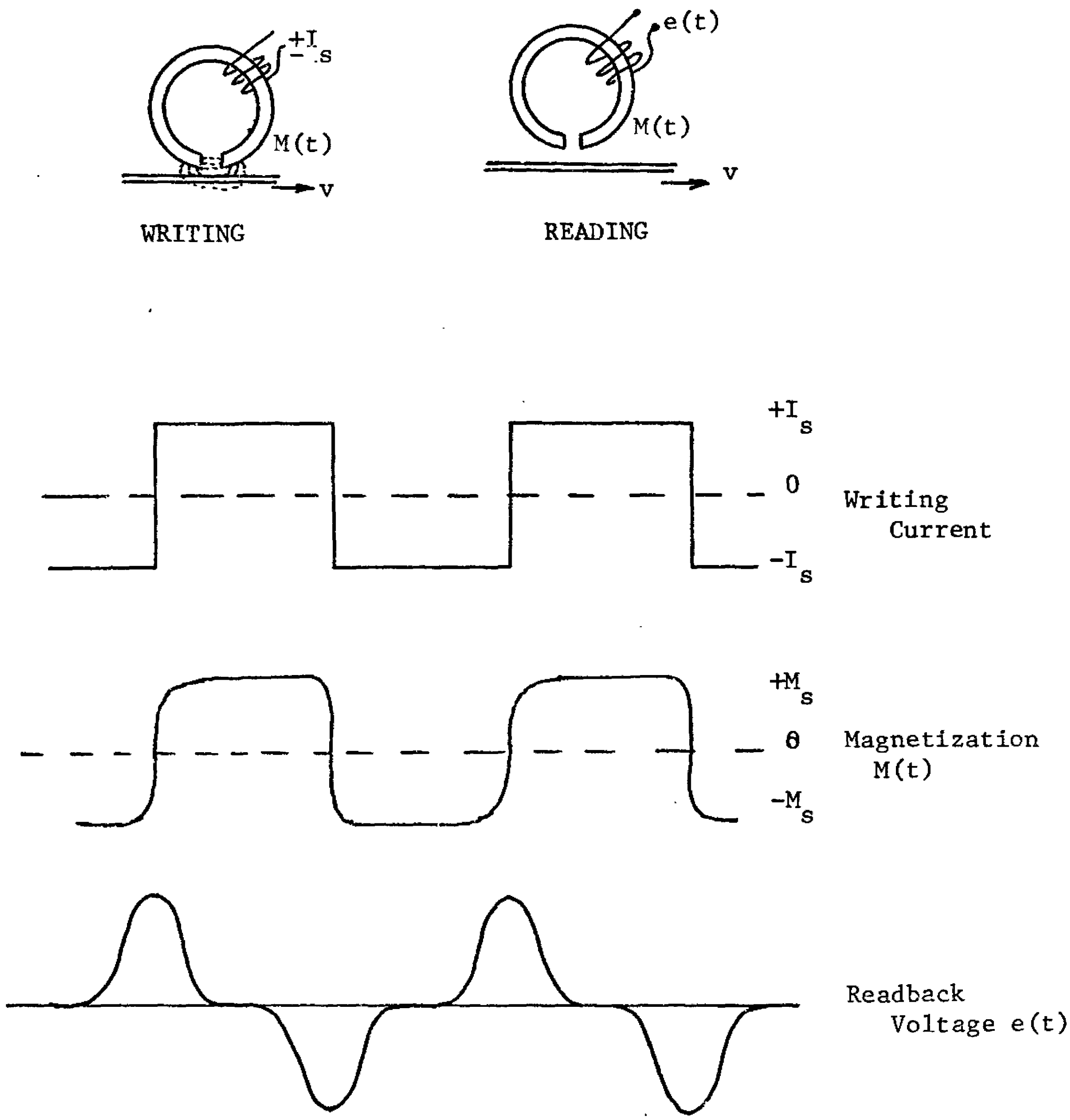


FIGURE 1.2 TYPICAL RECORDING WAVEFORMS.

of the writing process and there has to date been no widely accepted analysis relating all the variables involved in the recording process. This is due to the fact that linear approximations which can be applied to the playback process cannot be applied to the highly nonlinear recording process. Analysis is further complicated by the fact that the individual magnetic surface regions are actually acted upon by a time varying vector field as they leave the vicinity of the magnetic head. The process of magnetic recording and playback will be qualitatively discussed and the results of a more rigorous treatment quoted where of interest. For a more detailed analysis, the reader is recommended to read Hoagland's text (reference 2) where this subject is excellently described.

Magnetic recording media occur in the form of magnetic oxide coatings and metallic magnetic films. Magnetic oxide surfaces are composed of iron oxide particles dispersed in a suitable binder. The oxides used are synthetic oxide γ-Fe_2O_3 (red) or magnetite Fe_3O_4 (black). The red iron oxide being by far the most commonly employed.

The magnetic behaviour of these ferromagnetic materials may be understood through the nature of the magnetic domain substructure. An actual ferromagnetic specimen is composed of a number of small regions called domains, within each of which the atomic magnetic moments are held in parallel alignment. For this reason, the domain represents a saturated region of magnetization. The directions of magnetization of different domains need not be parallel. The net magnetization of the magnetic specimen represents the integrated effect of these elemental domains. An unmagnetized specimen consists of a somewhat randomly oriented set of domains, in a pattern which tends to minimize the total energy.

The increase in magnetization of a specimen in an applied field takes place by two independent processes: a growth of the domains favourably oriented with respect to the applied field at the expense of the unfavourably oriented domains; and rotation of the directions of magnetization toward the direction of the field. Figure 1.3a illustrates these two methods by which the resultant magnetization may change. In weak fields magnetization usually proceed by domain boundary displacements. In stronger fields, a rotation of the direction of magnetization of the domains occurs. Figure 1.3b shows a typical magnetization curve, designating the regions in which each process is dominant. For weak fields the boundary displacements are reversible. Once the applied field causes a local energy threshold to be overcome, an irreversible boundary displacement occurs. If the magnetic material is cycled by an alternating magnetic field sufficiently strong to saturate the sample, we get the familiar hysterisis curve of Figure 1.3c. The various conventional magnetic parameters; Hc - coercive force, Br - residual induction and Bs - the saturation flux density, are defined by means of this diagram.

1.3 Writing on Tape

In digital recording, the design goal for writing performance is to achieve as closely as possible a step change in magnetization on switching the direction of writing current. It is also desired that any further changes in the writing current direction should have no

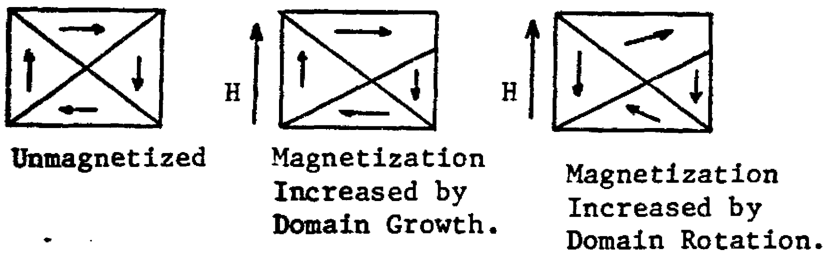


FIGURE 1.3a THE DOMAIN STRUCTURE.

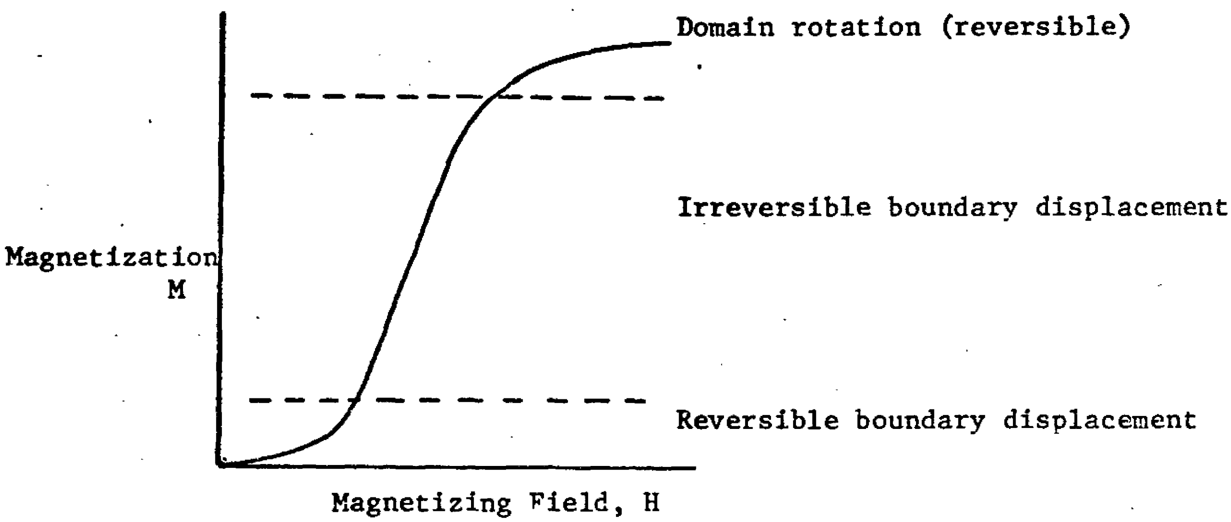


FIGURE 1.3b TYPICAL MAGNETIZATION CURVE.

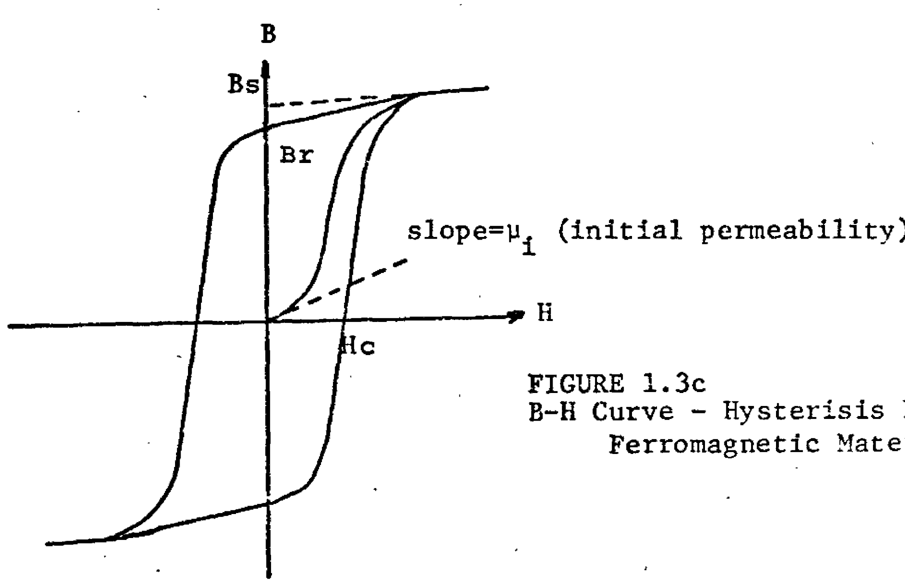


FIGURE 1.3c
B-H Curve - Hysterisis Loop
Ferromagnetic Material.

effect on the region of the surface just recorded. If these objectives could be met there would be no limit as to the number of saturation reversals that could be recorded, and the performance of the magnetic recording system would be entirely governed by the characteristics of the read operation. In practice it is found that while these objectives cannot be met, the limitations imposed by the read process are more severe than those of the write process. The practical limit in density thus occurs at a value lower than write considerations would dictate.

The actual mechanism by which a step change in writing current results in a change in medium magnetization and the shape of the transition region which can be expected can be obtained from the following graphical model.

Figure 1.4b shows the pole tips of a magnetic recording head. For a step-like change in the magnetizing field, only the surface region under the trailing edge need be considered. All the magnetic regions of the track passing the head gap centreline traverse the same magnetizing field and hence will be uniformly saturated. By the graphical procedure illustrated in Figure 1.4a it is possible to construct a curve of magnetization as a function of distance.

Before application of a current change, the surface is being uniformly saturated. Assuming an instantaneous reversal in the writing field, the resultant magnetizing field is graphically projected onto the recording medium characteristic to yield the resultant curve for the recorded transition zone. At the gap centre the magnetizing field, H, is sufficient to completely reverse the direction of saturation. The magnetizing field diminishes with x (direction of motion) until, when projected on the "demagnetization" curve of the magnetic surface material, no modification of existing saturation state occurs. Each surface point on the trailing leg side of the head gap is exposed to the maximum magnetizing field, tending to reverse its direction of saturation at the initial instant of switching. As an elemental volume leaves the region of the head, it passes through a continuously diminishing field (having a constant general orientation). Therefore, a reasonable first order simplification is to assume that the final transition boundary between magnetic saturation states is the same as that holding initially. This procedure provides a meaningful approximation from which several deductions can be qualitatively made.

The resulting magnetization change is actually displaced from the gap centreline, by x' (see Figure 1.4a) in the direction of surface motion. This displacement will depend on the magnitude of the write current, since the magnetizing field is proportional to this current, and hence slight voltage pulse displacements can result from differing levels of saturation current. The greater the fringing field gradient and/or the more rectangular the magnetic properties of the storage medium, the closer will the magnetization transition width approach a true step. Also, it can be seen that the actual size of the writing gap will not have a sensitive influence on the recorded magnetization change. The actual transition width x_t is difficult to measure in practice. In Figure 1.4a x_t is taken as the distance between 10% and 90% saturation change points. The transition width is considerably less than the width of the fringing field coupling zone. This fact is indicated by comparing the curve of magnetization with that of magnetizing intensity

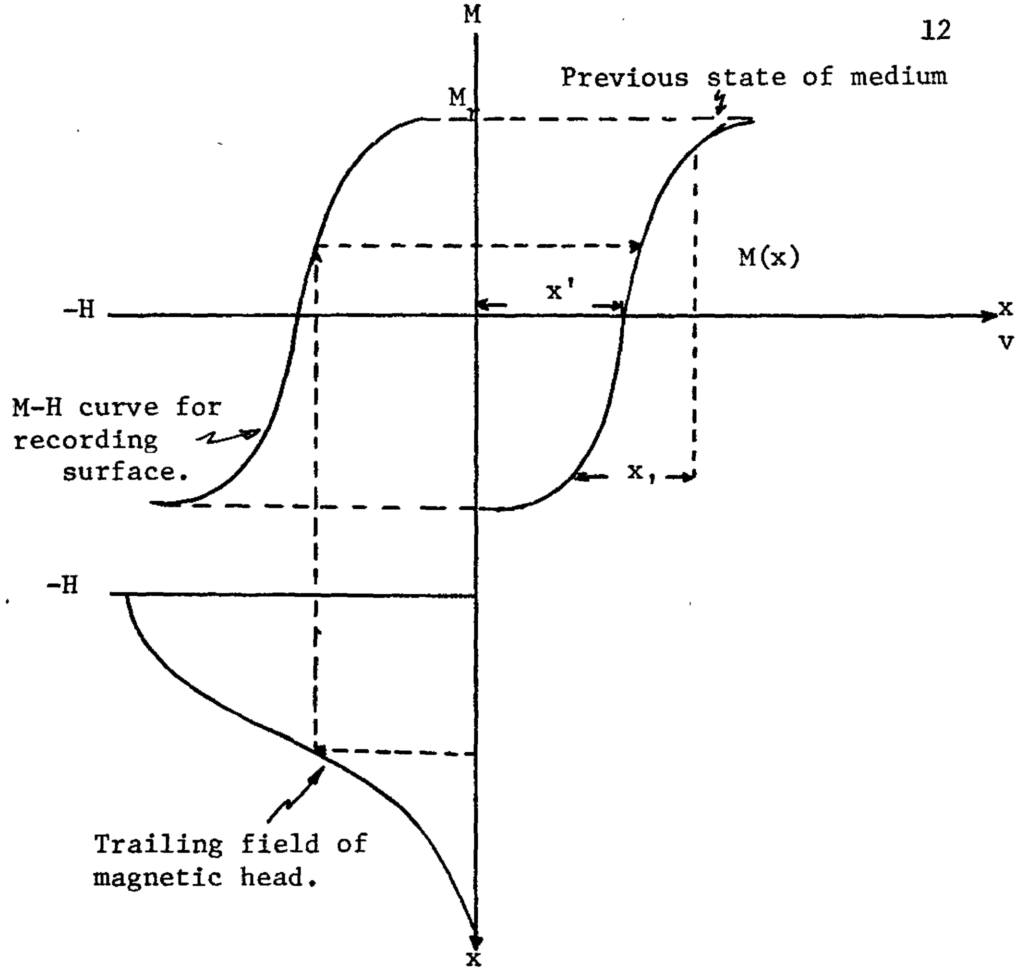


FIGURE 1.4a GRAPHICAL DETERMINATION OF M(x).

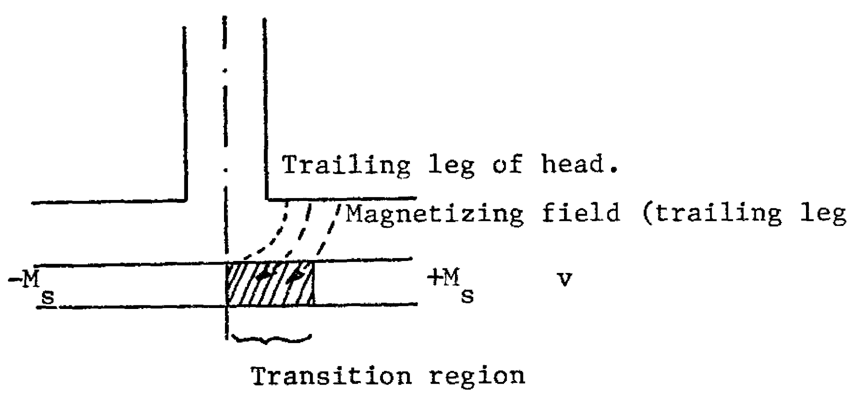


FIGURE 1.4b SATURATION REVERSAL

and can be seen as a result of the nonlinear saturation characteristic of the magnetic storage medium. The output pulse from a step change in magnetization is found to be proportional to H, the magnetizing field and therefore in practice the o/p signal will not differ significantly from that determined on the basis of a perfect step change in saturation.

As well as considering the saturation transition width it is also of interest to determine the density at which step-like changes can be recorded. To preserve a step-like change just written, the surface should move at least a distance $x_{\prime}$ before another magnetization change is initiated. This displacement will move that edge of the transition region, which has just been saturated in the reverse sense at the gap centre, out beyond the range of the effective magnetizing field. As mentioned earlier, this limit is not approached in practice as the reading process imposes more severe restrictions on this minimum distance.

1.4 Reading from Tape

Due to the differentiation of the magnetization waveform, the output voltage for a step change in magnetization is a pulse. In binary recording a continuous writing current consists of a sequence of alternating current steps. This gives rise to an alternating pulse sequence with one pulse for each change in the current polarity. The maximum value of the output voltage signal will be given by the peak amplitude of the basic voltage pulse from a single current reversal. (See Figure 1.5a).

In reading we are particularly interested in the spread of the fringing field which couples the head, since this factor sets the actual

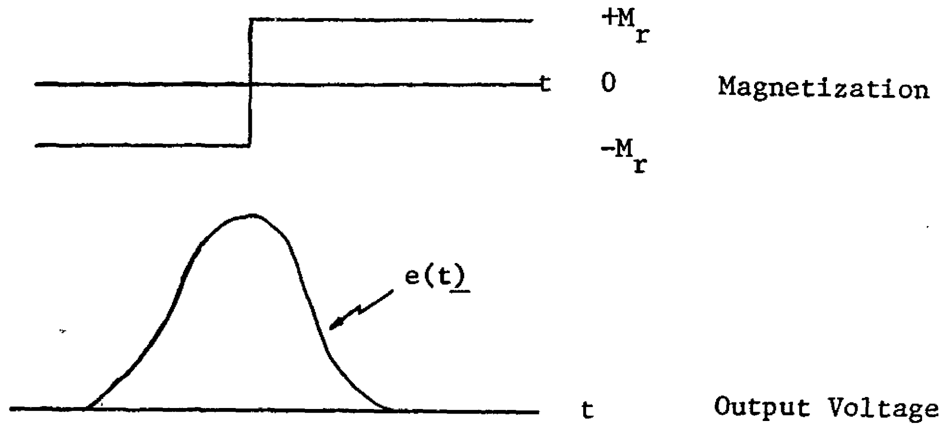


FIGURE 1.5a RESPONSE TO A STEP CHANGE IN MAGNETIZATION.

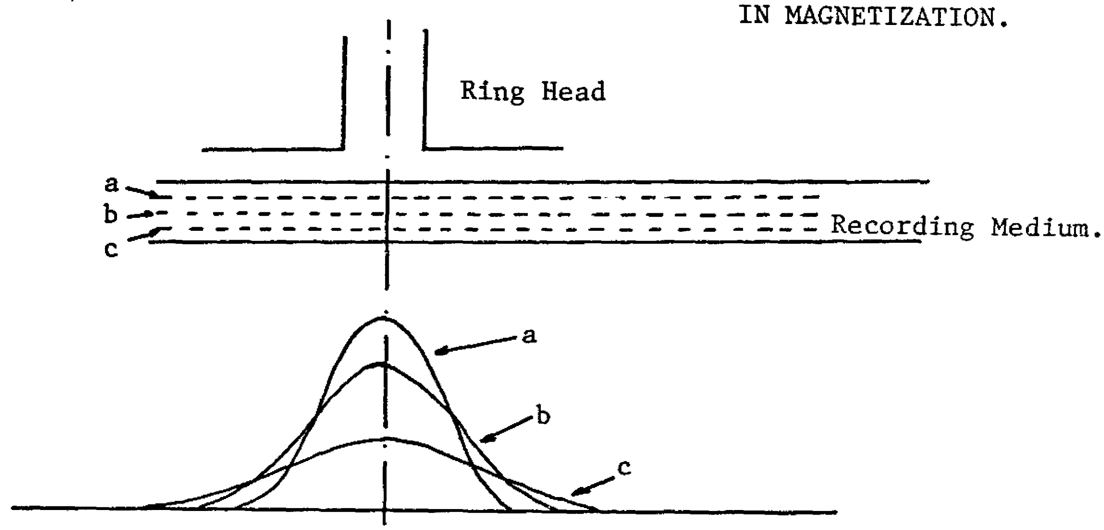


FIGURE 1.5b EFFECT OF MEDIUM THICKNESS IN OUTPUT PULSE.

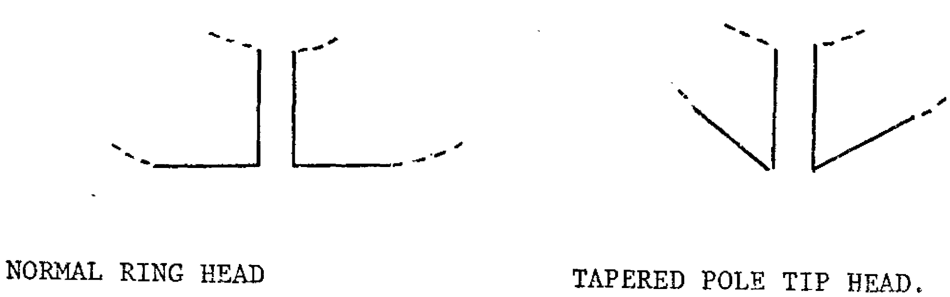


FIGURE 1.5c

bit resolution of the recording system in reading. This field distribution determines both the shape and the pulse width obtained from discontinuous changes in the magnetization.

Because the magnetic field of the recording surface giving rise to flux in the magnetic head is small, it is possible to obtain satisfactory results by assuming the magnetic readback process to be linear. The principle of superposition can then be applied so that the net voltage (or flux) caused by a sequence of saturation changes on the recording medium is obtained by the linear combination of their individual voltage (or flux) contributions. This principle of superposition is valid as long as the density of saturation reversals does not exceed the limit for the writing of independent saturation reversals.

Figure 1.5a illustrates the shape of a typical output voltage pulse in response to a step change in magnetization. The actual width and size of the pulse as a function of the distance of the recording medium layer from the head is shown in Figure 1.5b. The shape of these pulses are essentially the same as the fringing field H, at these spacings. For the overall recording surface indicated, the next output pulse can be approximated to a reasonable degree by the linear addition of the component signals produced by the three strata shown. The farther a given stratum is from the magnetic head, the smaller its corresponding output signal amplitude and the broader its pulse width. Thus, for the highest pulse resolution, a very thin surface is required, unless it is practicable to use non-saturation recording techniques which can confine the magnetized layer to the upper region of the surface.

In either case, increasing pulse resolution means the acceptance of an appreciable reduction in pulse amplitude.

As was mentioned, the shape of the pulse is essentially the same as the shape of the fringing field. The factor which is most predominant in its influence over the shape of the fringing field is the gap width. A reduction in the gap width gives an almost proportional reduction in pulse width for a step change in magnetization. The actual minimum gap width is a function of the amplitude required (will reduce with reducing head gap) and the physical limits dictated by the head fabrication process. It can also be seen that the head-tape spacing is directly related to the shape and amplitude of the output pulse. In magnetic tape recording, the largest single source of error is caused by "dropouts" which are temporary losses of signal due to an increase in head to tape spacing. This can be caused by fluctuations in the thickness of the magnetic surface coating, by dirt or dust particles or by imperfect tape drive or feed mechanics.

Improved pulse resolution can be obtained by modification of the idealized ringhead, so that the pole tips are slightly tapered. It is found that gains obtained from this technique are more pronounced in non-contact recording, such as that used in discs and drum stores, than in contact recording which is used in magnetic tape recording (Figure 1.5c).

1.5 Density Limitations Set by Pulse Crowding

In digital recording a large number of output pulse patterns can arise. At low density of magnetic saturation reversals each pulse is individually resolved and has the shape of the typical output pulse as in Figure 1.5a and repeated in Figure 1.6a where its width w is indicated. When the density is increased, the pulses are no longer individually resolved and pulse crowding (or intersymbol interference) occurs. Using the principle of superposition it is possible to synthesize the readback waveform for arbitrary binary sequences. For convenience we show the waveforms as a function of distance along the tape, x. This is directly related to the time response by the tape speed ($x=vt$) and provides a better indication of the density limitations. In Figure 1.6a we also define the parameter h, the cell length, that is, the minimum spacing between current reversals. In this case, the number of cells or pulses per inch (ppi) = 1/h. Figure 1.6b gives a curve of the peak output voltage versus ppi, obtained by the principle of superposition. This is valid as long as the density considered is not above the density limit imposed by the recording of magnetization reversals in the writing process. If each pulse is to have its individual integrity preserved then

$$h \geqslant w \qquad \text{(see Figure 1.6)}$$

$$\text{or} \quad ppi(max) = 1/w$$

The output voltage peak amplitude will remain constant above this point until adjacent pulse interference extends to the pulse centres, this point occuring for ppi = 2/w. Figure 1.7 shows the effects of two different binary sequences undergoing pulse crowding.

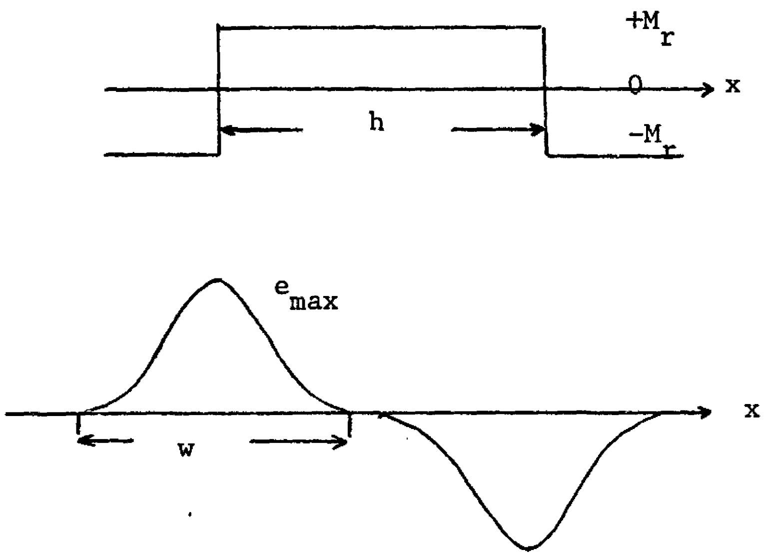


FIGURE 1.6a REVERSALS WITH NO INTERSYMBOL INTERFERENCE.

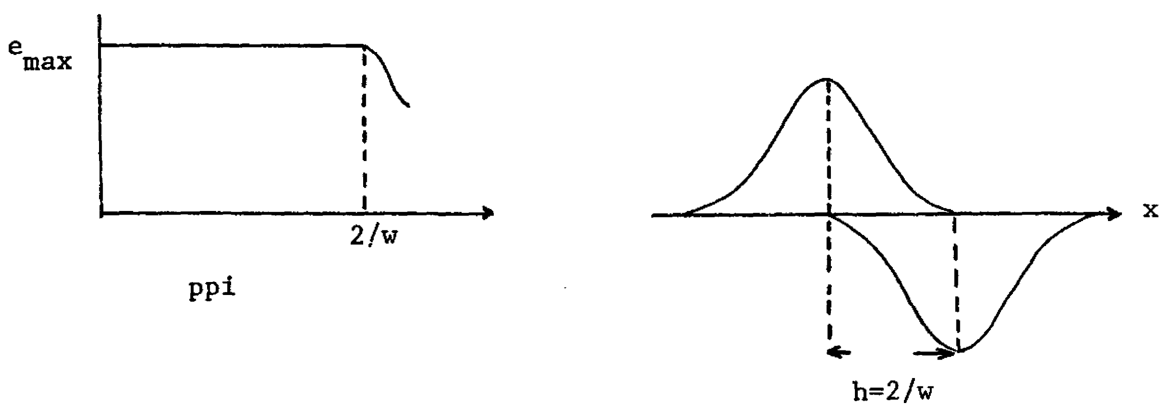
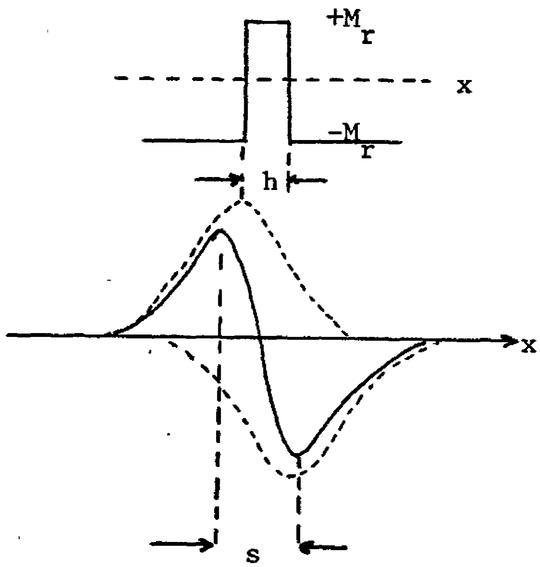


FIGURE 1.6b EFFECT OF DENSITY ON OUTPUT PULSE AMPLITUDE.

The individual pulse from each reversal is shown as well as the resultant waveform obtained by superposition of the individual pulses. In Figure 1.7a two adjacent saturation reversals are considered. These are considered to be isolated from any other reversals but the distance h (cell spacing) is considerably less than the width w (the pulse width). As can be seen, there is a peak shift effect produced by pulse interference, indicated by the fact that the separation between the peaks of the output voltage is greater than h, the separation between the corresponding reversals in write current. This peak displacement phenomenon gives rise to a discrepancy in pulse location timing with respect to the original clock time period on writing.

Figure 1.7b shows the output signal with pulse crowding when four successive reversals are recorded. In this case, because of symmetry the two outer pulses are the same amplitude and the two inner pulses are also equal in magnitude. The inner pulses are surrounded by two adjacent pulses of opposite polarity and therefore are reduced in amplitude to a greater extent than the pulses on the waveform extremities. The net effect is to give the waveform the appearance of a "droop" as shown. There is also base line shift.

From these waveforms it can be seen that as the degree of pulse crowding becomes more pronounced, the problems of detection and timing will become more severe. This is discussed further in a later section of the text.



h Current Reversal Separation.
s Pulse Peak Separation.

FIGURE 1.7a OUTPUT SIGNAL FROM TWO ADJACENT SATURATION REVERSALS.

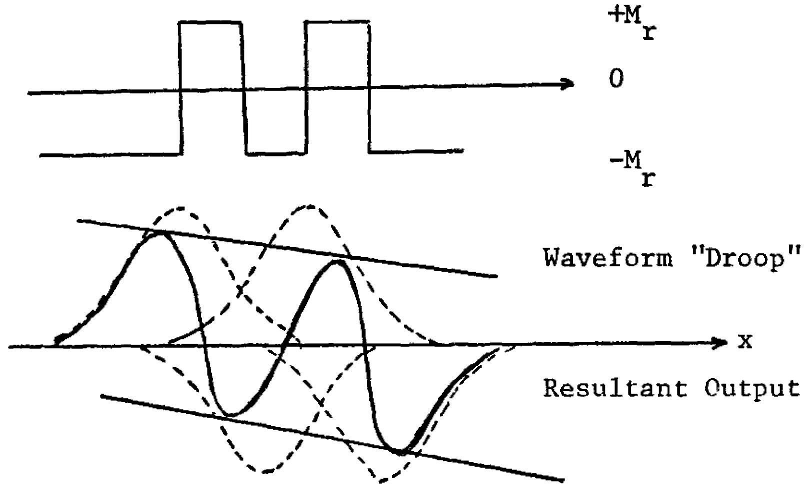


FIGURE 1.7b OUTPUT SIGNAL FROM FOUR ADJACENT SATURATION REVERSALS.

FIGURE 1.7 EFFECTS OF PULSE CROWDING

CHAPTER 2

REVIEW OF DIGITAL RECORDING TECHNIQUES

Having described the process by which information is recorded on magnetic tape we can now survey some of the more common formats used to record digital information on magnetic tape. All these methods require that the binary digits 0 and 1 be converted into their respective states of magnetic surface saturation and/or saturation reversals. (References 2, 3 and 4)

2.1 Return to Zero Method (RZ) Figure 2.1a

This is probably the most straightforward method of recording digital information. The magnetic surface is initially erased and at bit times a binary 1 is recorded by a short current pulse in one direction; a binary zero by a current pulse in the opposite direction. Since the input current is a pulse the playback output voltage will be a dipulse, a recorded "1" being the same as an inverted "0". Due to the fact that the magnetization changes only from zero to positive or negative saturation, as well as the fact that there are effectively two magnetization reversals per bit time (one recorded by the leading edge of the head gap to other by the trailing edge) the o/p voltage using this method is less than one half that which can be obtained by swinging between positive and negative saturation. Also due to this characteristic the RZ method is subject to pulse crowding at lower densities than the non return to zero method to be described.

A serious handicap of this method is that it is necessary that the tape be pre-erased before it is recorded on, unless very precise timing in current pulsing can be achieved.

Advantages of this method are that it provides an output signal for every bit recorded. A further advantage of this discrete pulse method, which is used in some applications, is that it is possible to write selectively and thus a single bit within a recorded sequence can be altered.

2.2 Return to Bias Method (RB) Figure 2.1b

In order to eliminate the necessity that the surface be initially erased, the return to bias method was introduced. In this method, the tape is continually saturated in one direction except when a "1" is to be recorded. At these times, a short current pulse reverses the direction of saturation. In this way, only recorded "1's" provide output signals. Again, as in the case of the RZ method the output dipulse is broader than the pulse from a single step change of current, so that successive "1's" will produce a similar degree of interpulse interference at higher densities. It is again possible to insert single changes in the bit sequence but this method does not provide an o/p signal for every recorded bit, so that it is not basically selfclocking. However, an odd parity recorded on a group of tracks will ensure an output pulse from one of the tracks at every bit time. Both of the above methods are not used to any great extent at present due to their severe limitations at higher densities.

2.3 Non-Return to Zero (NRZ) and Modified Non-Return to Zero (NRZ1)

The most common methods of digital recording are the NRZ and NRZ1. The relation between the binary data and the writing current is shown in Figures 2.1c & d. In the NRZ method, the write current polarity is reversed for every change in the sequence. This can also be considered as a 1 having one direction of write current associated with it and a 0 the other direction. The name NRZ indicates that the pulses lose their individuality and the writing current does not return to zero between successive data bits. The magnetic surface is continuously saturated in one direction or the other so that pre-erasure is not necessary.

The NRZ1 method is essentially the same as the NRZ method as regards the digital recording process, but in this scheme the current is reversed every time a "1" is to be recorded. A "1" is thus indicated by either a positive or a negative reversal and a "0" by no reversal. The two methods will thus be the same in their basic input/output signal characteristics but the NRZ1 method has certain advantages over the NRZ method. If in the NRZ1 technique a bit is misread, only that bit will be in error; with the NRZ technique a misread bit will propogate through the entire record. Further, in parallel recording on a group of tracks, an odd parity count per data frame will ensure that there is a magnetic saturation reversal every frame, thus ensuring a readback signal from at least one of the tracks every bit period. In both these techniques signal polarity is not a factor in interpreting the readback voltage, thus simplifying interpretation when bidirectional surface motion is used. NRZ and NRZ1 techniques use at a maximum one saturation reversal per bit of information. This maximum occurs under the NRZ system when an alternating sequence of 0's and 1's is recorded and under the NRZ1 system when a continuous sequence of 1's occurs. This is of importance in pulse crowding considerations. Not every bit is identified by a pulse, and therefore an accurate clocking system is necessary to correctly interpret the output waveform, particularly to read those data bits where an output signal may not be sensed over several bit periods.

2.4 Phase Modulation, Figure 2.1e

This method also employs a continuous writing current and the relationship between the binary data sequence and the associated write current waveform is shown in Figure 2.1e. A "1" is written by a positive change in the writing current at the bit data time, while a "0" is denoted by a negative change at this time. It can be seen that if the sequence requires adjacent 0's or 1's it is necessary to insert an extra midtransition in order to meet the requirements. The output signal sequence will thus be a series of positive and/or negative pulses at each of the bit times with possible extra pulses at the mid bit times which can be ignored in the readback process, as they are superfluous to the reconstruction of the data sequence. This coding technique can be regarded as a phase modulation process where the current square wave with one cycle per bit has one phase for 1's and the opposite phase for 0's. This form of coding provides more redundancy in the waveform than does the NRZ or NRZ1 methods, since every data bit provides an output signal. With phase modulation recording, the discrimination between a 1 and a 0 involves only the detection of pulse polarity.

The maximum number of input current reversals per bit is equal to two and occurs when there is a continuous sequence of either of the binary levels (i.e. 00 or 11), i.e. bits per inch (bpi) $\leq$ pulses per inch (ppi) $\leq$ 2 bpi

$$\text{bpi} \leq \text{ppi} \leq 2 \text{ bpi}$$

The number of current reversals in phase modulation is thus greater than that in the NRZ methods. The phase modulation method will thus encounter pulse crowding before the NRZ method with increasing bit density. However, an examination of the waveforms for phase modulation shows that the presence of a nearly symmetrical alternating pulse environment surrounding any output pulse tends to minimize the problem of pulse location timing. With the phase modulation method, every bit gives a pulse with its rise and fall sharply delineated by zero crossover points, which are the best preserved waveform feature with considerable pulse interference. This makes this technique very amenable to higher density applications.

Further, since both 0's and 1's provide output pulses there is at least one output pulse per bit interval. This feature allows a clocking signal to be continuously generated from the output, advantageous for coping with bit synchronization problems in readback.

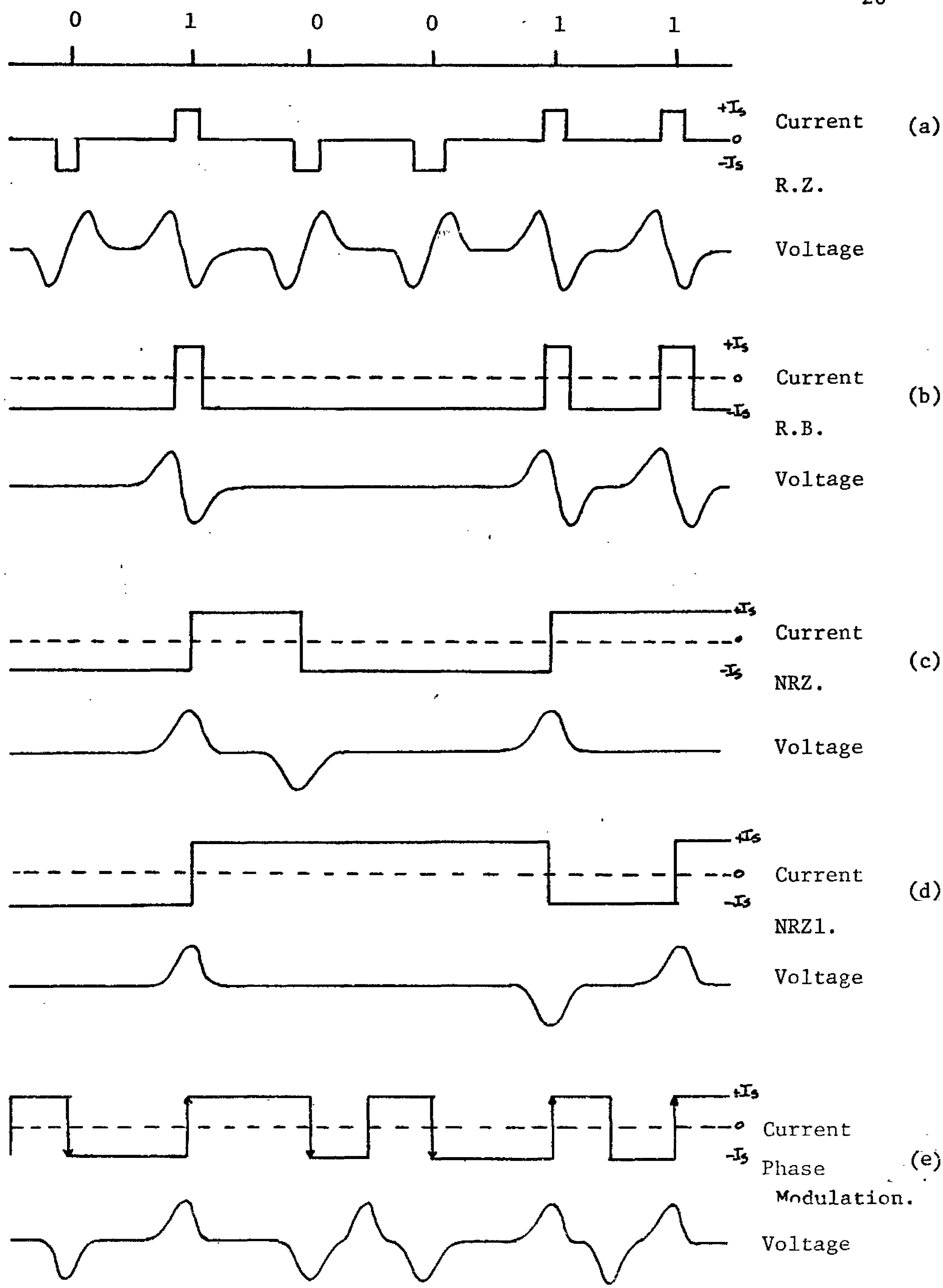


FIGURE 2.1 RECORDING TECHNIQUES.

2.5 The Three Level Nature of the Output Signal

Before introducing a new technique for high density recording proposed by Kobayashi and Tang (reference 5) it is necessary to show how the pseudo ternary method of coding used in communications systems can be applied to digital recording.

A set of rules assigning a three level signal to a binary message is called a pseudo ternary code. Generally these codes are utilized because of their ability to shape the frequency spectrum and the elimination of a dc component in particular. They are also used at times in preference to binary transmission in order to facilitate clock recovery, to introduce redundancy for error checking or to increase the data rate. Typical examples of this form of coding is the bipolar code and the duobinary code. Ternary partial response is another example of this form of coding. These codes are all formed by allowing a controlled amount of intersymbol interference and fall into the class of linear pseudo ternary codes.

A pseudo ternary code is said to be "linear" if it can be linearly derived from the binary message:

$$a_n = \sum_{k=0}^{K} b_{n-k} \alpha k$$

where the coefficients αk define the code, while $a_n = -1,0,+1$ is the ternary code level and bn = -1,+1 is the binary encoded data. A single example, that of the twinned binary code can be used to demonstrate the coding technique.

For twinned binary coding $\alpha_o = -1/2$, $\alpha_1 = +1/2$

The code is thus

$$a_n = \sum_{k=0}^{1} b_{n-k}\alpha_k = b_n\alpha_0 + b_{n-1}\alpha_1$$

$$a_n = \frac{-b_n}{2} + \frac{b_{n-1}}{2} = \frac{b_{n-1}-b_n}{2}$$

Figure 2.2a shows the encoding of a typical input sequence.

If we now consider the same input sequence to be encoded in a NRZ recording system and observe the o/p waveform it can be seen that the squared up waveform is identical to that of the twinned binary output.

Further, the NRZ 1 recording method can be seen to produce the same results where the input sequence is precoded according to

$$b_n = c_n + b_{n-1} \bmod 2$$

where: c_n is the binary input sequence (= 0,1)

b_n is the precoder output (=0,1)

This is shown in figure 2.3 for a similar input sequence. From these two illustrations, it can be seen that the output voltage waveforms in the NRZ and NRZ1 methods are really three level signals. This three level character is not exploited in conventional detection techniques where the waveform is typically full wave rectified and threshold detected on readback.

Kobayashi and Tang (reference 5) propose that this inherent redundancy of waveform should be exploited either for error detection or to achieve an increase in the data rate. As well as proposing an error detection scheme for the NRZ1 scheme they also propose a new recording format which utilizes the three level nature of the waveform

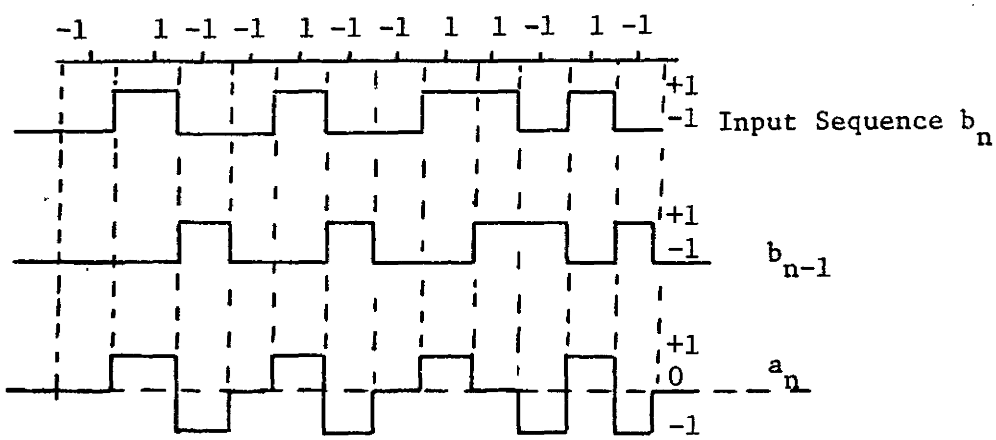


FIGURE 2.2a TWINNED BINARY ENCODING.

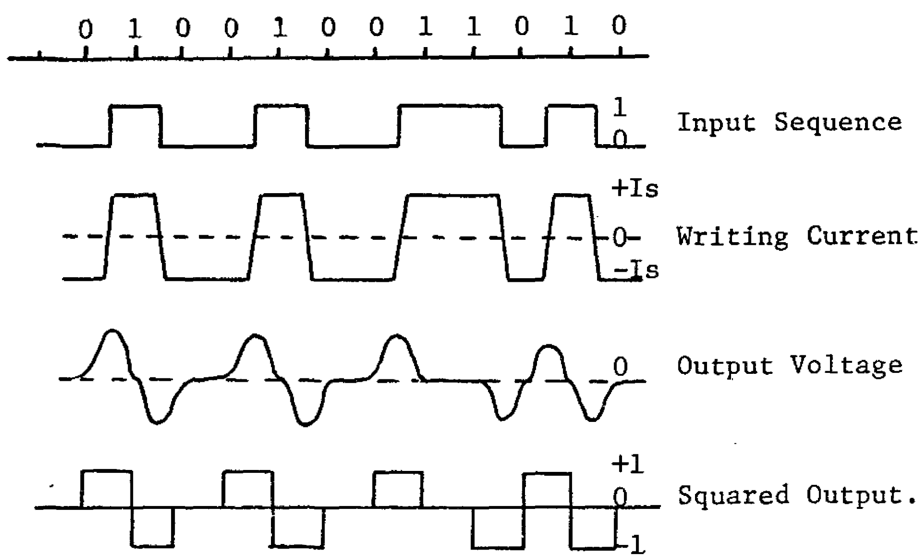


FIGURE 2.2b NRZ RECORDING.

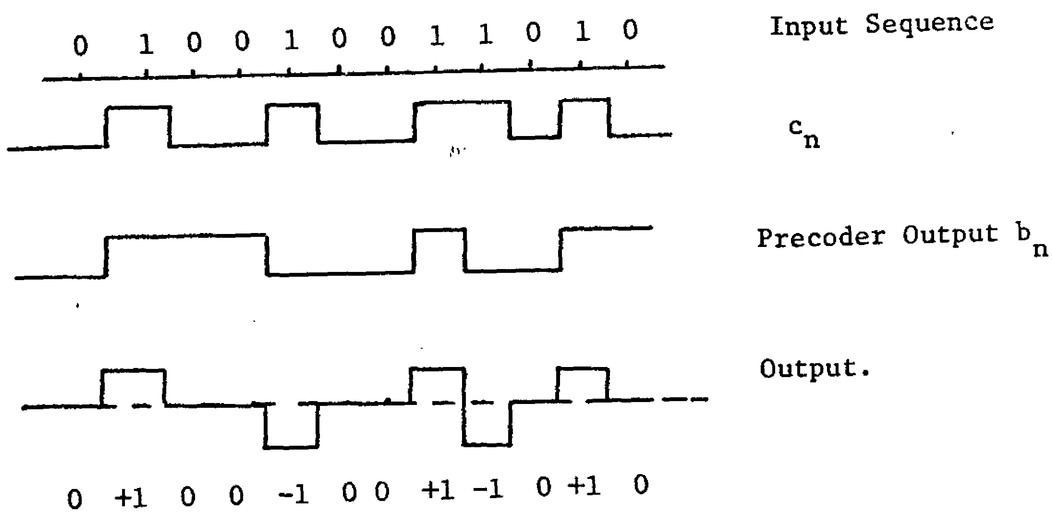


FIGURE 2.3a TWINNED BINARY WITH PRECODING.

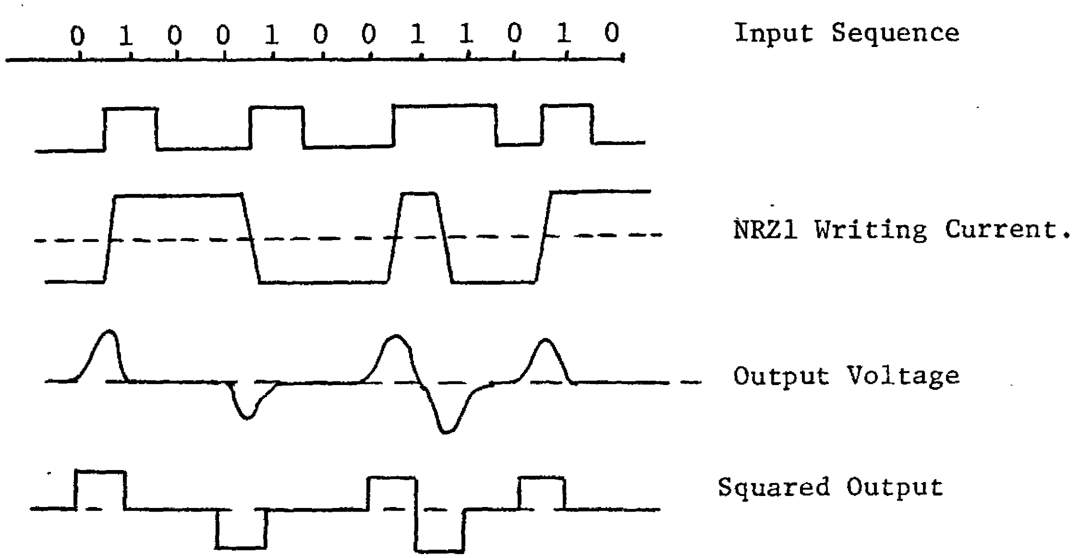


FIGURE 2.3b NRZ1 RECORDING

and a controlled amount of intersymbol interference to obtain a high density recording scheme known as Interleaved NRZ1.

2.6 Interleaved NRZ1

Figure 2.4a shows the already described output response to a step change in magnetization. The interval T shown is the interval which must be maintained between successive magnetization reversals in order to avoid excessive intersymbol interference. The Interleaved NRZ1 technique exceeds this limit by a controlled amount in order to increase the density.

Figure 2.4b shows the same response as that in Figure 2.4a but the sampling rate has now been increased by 50%, i.e. sampling is now performed every T^1 seconds where $T^1 = 2/3T$.

The input binary sequence, a_k, is precoded so that the input is related to the precoder output, b_k, by:

$$b_k = a_k + b_{k-2} \bmod 2$$

and sampling takes place at intervals T^1.

Consider the following input sequence and precoder output:

$$a_k = 0\ 1\ 0\ 1\ 1\ 0$$

$$b_k = 0\ 1\ 0\ 0\ 1\ 1\ 1$$

Figure 2.4c shows the waveforms associated with the recording and playback system.

The function f(t), Fig. 2.4c(v) shows the time scale of reference of the response to the step change in magnetization. By the principle of superposition this is modified to give the output voltage waveform shown in Figure 2.4c(vi).

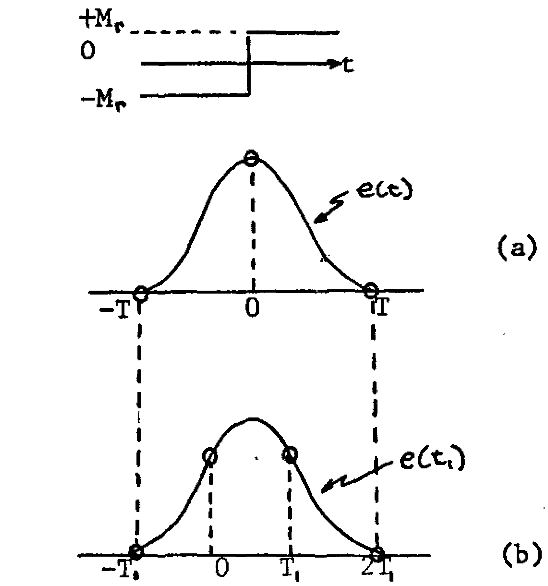


FIGURE 2.4a AND 2.4b
WAVEFORMS FOR INTERLEAVED NRZ1 SCHEME.

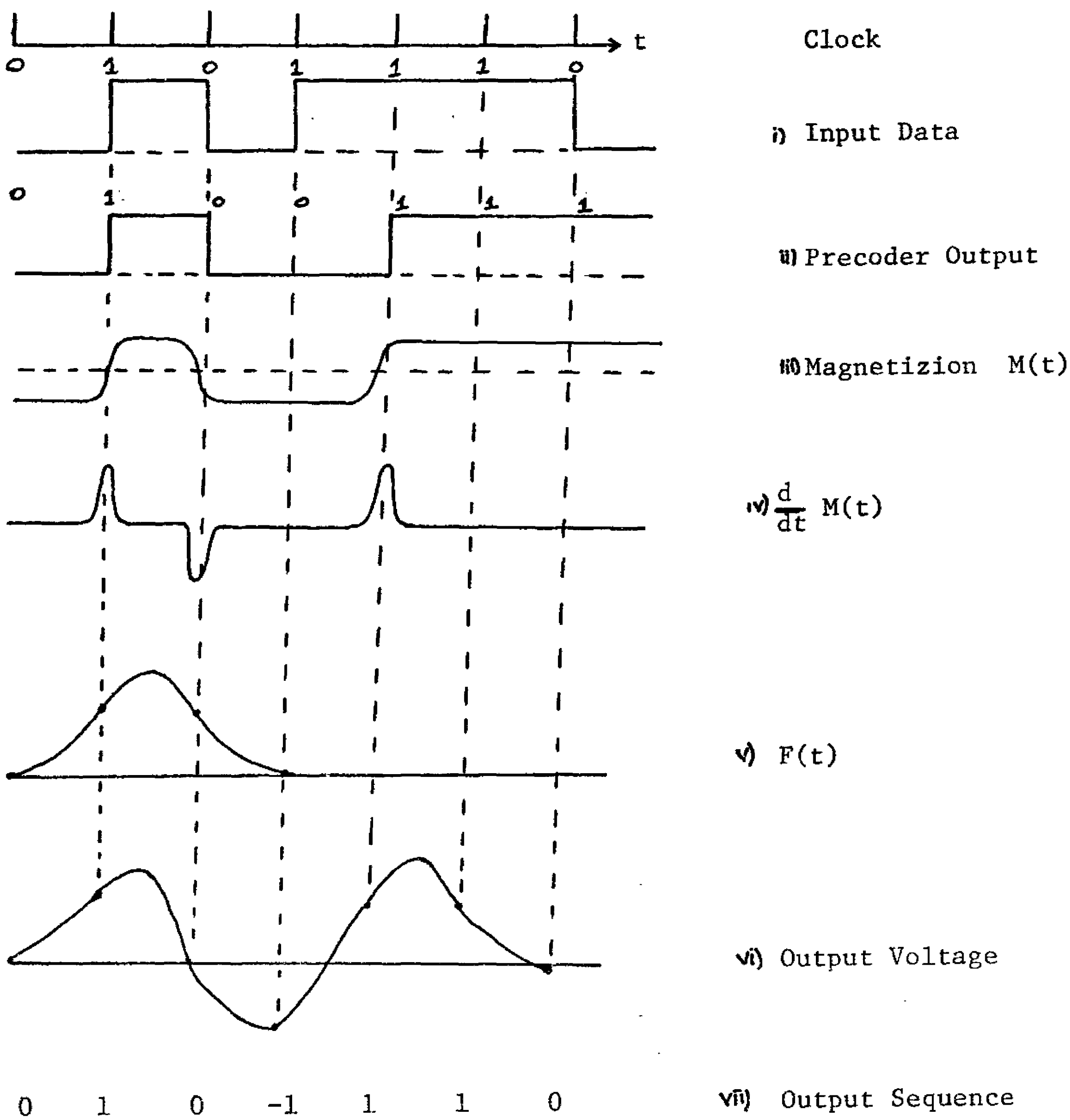


FIGURE 2.4c INTERLEAVED NRZ1 RECORDING WAVEFORMS.

Although this technique has not been implemented in practice it appears to have a number of possible advantages for high density recording.

1. The recording density can be increased substantially by using this technique.

2. Precoding can be used to prevent propogation of errors, and this can be implemented by means of simple digital circuitry.

3. Error detection and correction methods have been developed by Kobayashi and Tang (reference 5) and can be used.

4. In parallel recording on a group of tracks, an odd parity count per frame will guarantee an output signal from one of the tracks in every two bit period.

5. Because signal polarity is not a factor in interpreting the readback voltage voltage, readback is simplified when bidirectional motion is used.

It is important to note that up to this point the interleaved NRZ1 method has not been implemented in practice and there are many practical problems in the implementation of such a system. These problems are largely in the fields of detection and synchronization.

2.7 Proposed Technique - Two Track Pseudo Ternary Coding

A technique is now proposed which also takes advantage of the inherent three level nature of the output signal to increase the effective recording density but does not depend on the intersymbol interference in order to achieve this. The effective increase is achieved by encoding data onto two tracks in parallel.

As indicated previously, at any bit time during readback in a digital recording system it is possible to have either a positive voltage pulse, +1, a negative voltage pulse, -1, or no pulse at all, 0.

By allowing two tracks to interact the following combinations are then possible:

Track 1	Track 2
+1	+1
+1	-1
+1	0
-1	+1
-1	-1
-1	0
0	+1
0	-1
0	0

If the system is to be selfclocking, we require that a voltage pulse should be present on one of the tracks at every data time. The combination 00 thus becomes invalid leaving 8 or 2^3 possible combinations.

Before introducing the overall coding scheme, the method used to obtain the required o/p signal pulses can be demonstrated. Consider a ternary sequence

$$a_k = +1\ -1\ 0\ +1\ +1\ 0\ -1\ 0\ -1$$

In order to record this sequence, we require that at a clock time the transition in the magnetizing current should match the data, i.e.

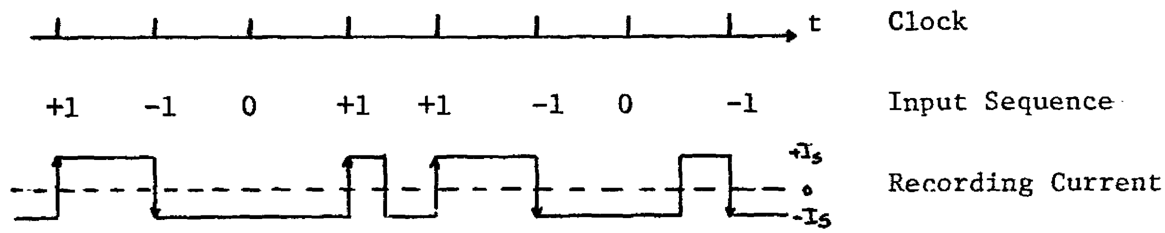


FIGURE 2.5a ENCODING A TERNARY SEQUENCE.

Octal	Binary msb lsb	Transition left	Transition right
0	0 0 0	+1	+1
1	0 0 1	+1	0
2	0 1 0	+1	-1
3	0 1 1	0	-1
4	1 0 0	0	+1
5	1 0 1	-1	+1
6	1 1 0	-1	0
7	1 1 1	-1	-1

FIGURE 2.5b
TWO TRACK PSEUDO TERNARY RECORDING.

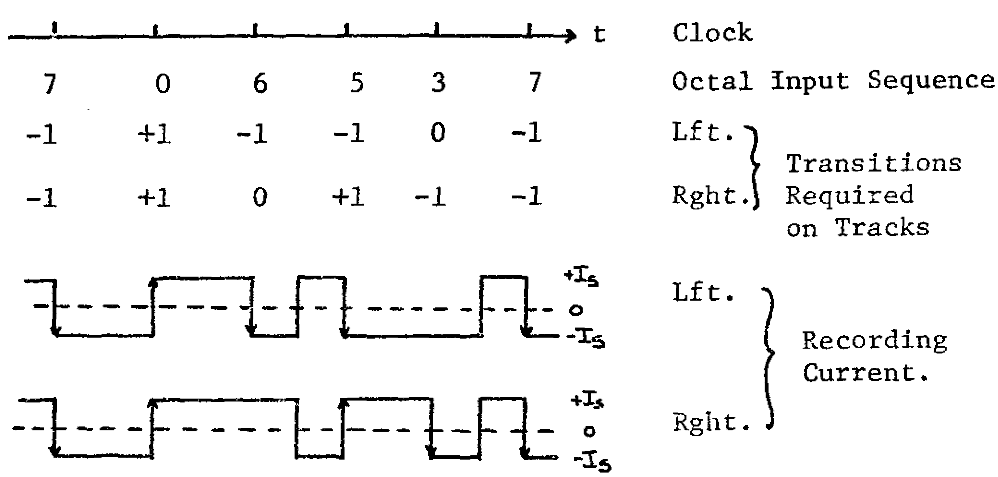


FIGURE 2.5c RECORDING WAVEFORMS

if the data is a +1 then at the clock time the magnetizing current should change from its negative polarity to positive polarity. Figure 2.5a shows the writing current waveform for the sequence a_k. Note that if the data sequence requires that there be two consecutive +1's or -1's then it is necessary to insert a midclock transition in a similar way to the technique used in phase modulation encoding. It can also be seen that if the sequence requires a zero between two identical non-zero transitions, (eg. +1 0 +1) then a midtransition is also required. This can be seen in the final three data values in the sequence shown in Figure 2.5a.

There are many possible pseudo-ternary which can be used, the code selected is shown below:

Octal	Binary Data	Pseudo Ternary Code	
		Left	Right
0	000	+1	+1
1	001	+1	0
2	010	+1	-1
3	011	0	-1
4	100	0	+1
5	101	-1	+1
6	110	-1	0
7	111	-1	-1

As the combination 00 is not used there will be an o/p pulse from at least one of the two tracks at each clock time which can be used for synchronization purposes.

Figure 2.5c shows the encoding of a typical octal input sequence. The two tracks are designated left and right.

CHAPTER 3

THE PERIPHERAL TAPE UNIT--BASIC CONSIDERATIONS

3.1 Introduction and Basic Design Considerations

There were two basic aims governing the design of the tape unit to be outlined. Firstly, the system should utilize the pseudoternary recording format outlined in the previous chapter so that the practical problems involved in such a technique could be better studied. Secondly, the unit should be inexpensive and simple even if this would require forfeiting a certain amount of speed. This second requirement arises from the need to have an inexpensive, relatively slow rate data logging device which would provide a reliable mass storage facility less bulky than conventional paper tape devices.

3.1.1 Storage Device

It was felt that a commercial audio tape cartridge or cassette recorder could be used to meet these requirements. There are at present three different commercially available audio recording devices which are suitable for such an application. These are the compact cassette, 4-track cartridge and 8-track cartridge systems.

Commercial audio cassette recorders have a nominal tape speed of 1 7/8 inches per second and a nominal track width of ~.025 inches. The 8-track and 4-track continuous loop cartridge systems both have a nominal speed of 3 3/4 inches per second and both utilize lubricated

1/4 inch width magnetic tape. The 4-track system has a track width of ~.05 inches, double that of the 8-track system. The wider track 4-track system would thus appear to be more desirable than the 8-track system as its wider track implies a larger output signal and thus better signal to noise ratio and immunity to dropouts. However, the 4-track system was immediately discarded as the present trend seems to indicate that the 4-track systems are soon to become obsolete.

The 8-track continuous loop cartridge was selected in preference to the cassette system for the following reasons:--

i) The nominal speed ratio of two-to-one gives the 8-track a better signal O/P and thus an inherently greater reliability at these nominal speeds. It is possible to operate either of these systems at higher speeds, but it was felt that tape life and reliability would be affected. Further, at higher tape speed the acceleration tension on the tape in order to bring it up to speed in as short a time interval as possible would require either excessive start up delay or the risk of tape stretching and wear. A portable tape unit is to be designed which is compatible with the peripheral unit. Since this portable unit is envisaged to operate in a start/stop stepping type mode, the time required for the unit to attain rated speed is an important consideration.

ii) The 8-track system is a continuous loop system, so that rewind operation is not required, simplifying the control electronics. The heads are mechanically shifted to 4 different positions on the tape surface. In this way a tape which runs for 4 minutes can store 16 minutes of data by switching between the 4 positions.

iii) The 1/4 inch lubricated tape used in these cartridges can be obtained in 600 foot reels and it is relatively simple to load a cartridge with the amount of tape required. Blank tapes are also available in many different lengths so that by correct selection of tape length access time can be minimized.

3.1.2 Stop/Start Motion Control

In any computer application it is important that the tape reach rated speed consistently in as short a time as possible and similarly it should stop in a short time period. This imposes severe demands on the start/stop control circuitry and mechanically on the magnetic tape itself. The design should take these factors into account and should attempt to minimize start/stop time without undue wear on the tape.

3.1.3 Writing Frequency

There are two major factors which for a given tape speed limit the attainable writing frequency. These factors are pulse crowding and tape skewing.

i) Pulse Crowding

The effect of pulse crowding on the voltage waveform has already been outlined. Pulse crowding distorts the shape of the voltage waveform and can lead to timing and level detection difficulties. As the magnetic head used is an audio playback head it can be expected that pulse crowding will take place at densities well below those encountered when a head designed specifically for digital recording is used. The effects of this should be investigated.

ii) Tape Skew

There are two forms of tape skew which must be taken into account:--

a) Static Skew--this form of skew is caused by the mechanical tolerances in the alignment of the head gaps in a multitrack system and by the possible misalignment of the head relative to the tape.

This misalignment leads to a decrease in the voltage pulse amplitude and a widening of the pulse. A more serious problem is that tapes recorded on another recorder and played back on a unit having static skew are subject to phase and timing differences, which occur between tracks which are intended to be in phase. Static skew can be minimized by the proper adjustment of the azimuth and if necessary it can be compensated for by incorporating delays in both the read and write logic which allow a time delay for each individual track sufficient to bring the tracks into alignment.

b) Dynamic Skew--this phenomenon is a far more difficult problem to overcome as it is not possible to compensate for it by electronic methods. Dynamic skew is a result of the inability of mechanically achieving a perfect tape guide system. The tape passing over the head does not remain perfectly normal to the head gap and tends to wander up and down the pinch roller causing what is in effect a fluctuating phase difference between tracks. As this effect is not constant it cannot be compensated for and it is necessary to make allowance for this problem in the design. This can be done either by allowing each track to run independently having its own clock or to ensure that the skew is sufficiently

CHAPTER 4

OUTLINE OF THE SYSTEM

4.1 Operation

The peripheral unit is a digital magnetic recorder consisting essentially of an 8-track stereo cartridge transport, motion control logic, Read/Write Electronics and load point sensing.

For a WRITE operation, tape motion initiated and after a time delay which ensures that tape reaches rated speed, data is requested from the CPU in 3 bit bytes and recorded onto tape in the format described in chapter 2.7. At the end of a record the tape is stopped by program control. Record length is variable under program control, with interrecord gaps inserted by the stop/start time delay.

For a READ operation, tape motion is initiated and after a delay somewhat shorter than the write delay, the detector circuits are enabled and the read process commences. The first output signal from the tape enables the read clock which is then kept in synchronization with the data which is self clocking. The data is transmitted to the CPU in 3 bit bytes where it is reconstructed into its original 18 bits. The end of a record can be obtained either under program control or by sensing an interrecord gap flag.

To find the start of the tape, a load point search is initiated. The tape is driven until the conducting strip on the tape is sensed at which point the tape immediately stops and a LOAD POINT FOUND SIGNAL is transmitted to the computer.

small (or the bit period sufficiently long) that all voltage signals across the tape occur within the time allotted for them. This will be further illustrated in the detailed design.

3.1.4 Reliability

It has often been stated that the largest cause of error in digital magnetic tape recording is dropouts. These are loss of signal caused by a temporary increase in tape-head spacing as a result of dust or dirt etc. or due to defects in the tape. There has been very little quantitatively written on this subject (ref. 6) so that it was not known what sacrifice in reliability would be made if ordinary commercially available audio quality magnetic tape was used instead of the computer quality tape normally used in these applications. A further test of the system should thus be on its reliability.

4.1.1 Recording Technique

This has been outlined previously but is repeated for the sake of completeness in Figure 4.1 together with typical waveforms. The data is recorded using a 2-track pseudoternary scheme, the write current and readback waveforms of which are illustrated in this figure. The first three bit data word is fixed and carries no information as it is used to synchronize the readback operation.

4.1.2 Tape Transport Mechanism (Figure 4.2)

The tape transport contains the capstan and drive motor, read/write head, track change solenoid and the load point sensor. Each cartridge is in the form of a continuous loop and has its own pinch roller. When the cartridge is inserted, it is pulled firmly against the capstan by a spring mechanism. The same magnetic head is used for both read and write operations.

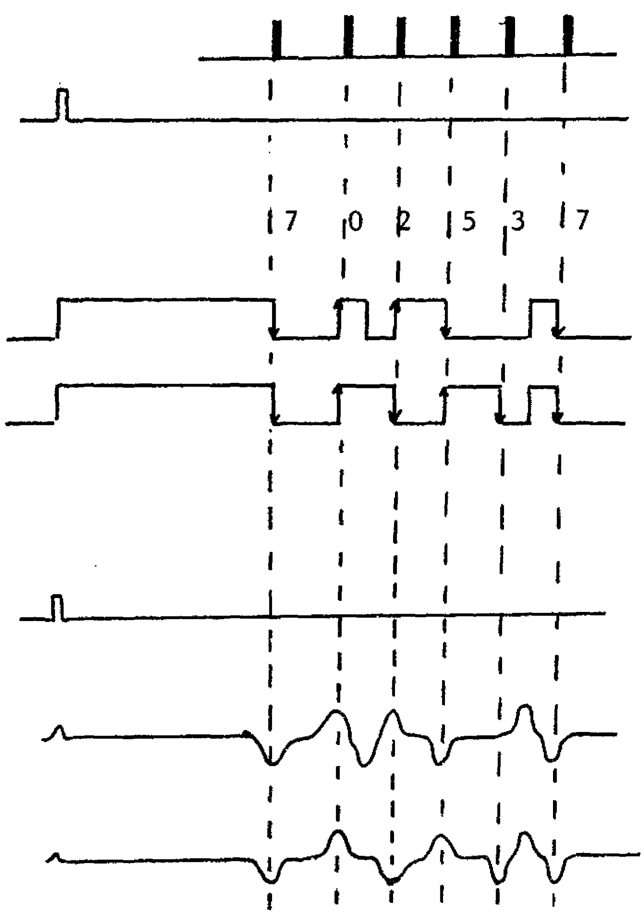
4.2 Computer Interfacing

The tape unit is interfaced to the program controlled transfer lines of a PDP-15 computer. The PDP-15 is an 18-bit word computer and under program control, 18 bits of data can be moved between a selected device and the accumulator. This transfer is initiated by means of an input/output transfer (IOT) instruction which has the following format:

1. An OPERATION code of 70_8 which indicates that an I/O function is to be performed (bits 00 through 05).

BINARY INPUT msb lsb	OCTAL	TRANSITION REQUIRED left track	right track
0 0 0	0	+1	+1
0 0 1	1	+1	0
0 1 0	2	+1	-1
0 1 1	3	0	-1
1 0 0	4	0	+1
1 0 1	5	-1	+1
1 1 0	6	-1	0
1 1 1	7	-1	-1

PSEUDOTERNARY ENCODING



Clock

Start Write Instruction

Octal Data Sequence

Left Track Write Waveform

Right Track Write Waveform

Start Read Instruction

Left Track Output Waveform

Right Track Output Waveform.

FIGURE 4.1 PSEUDOTERNARY ENCODING AND WAVEFORMS

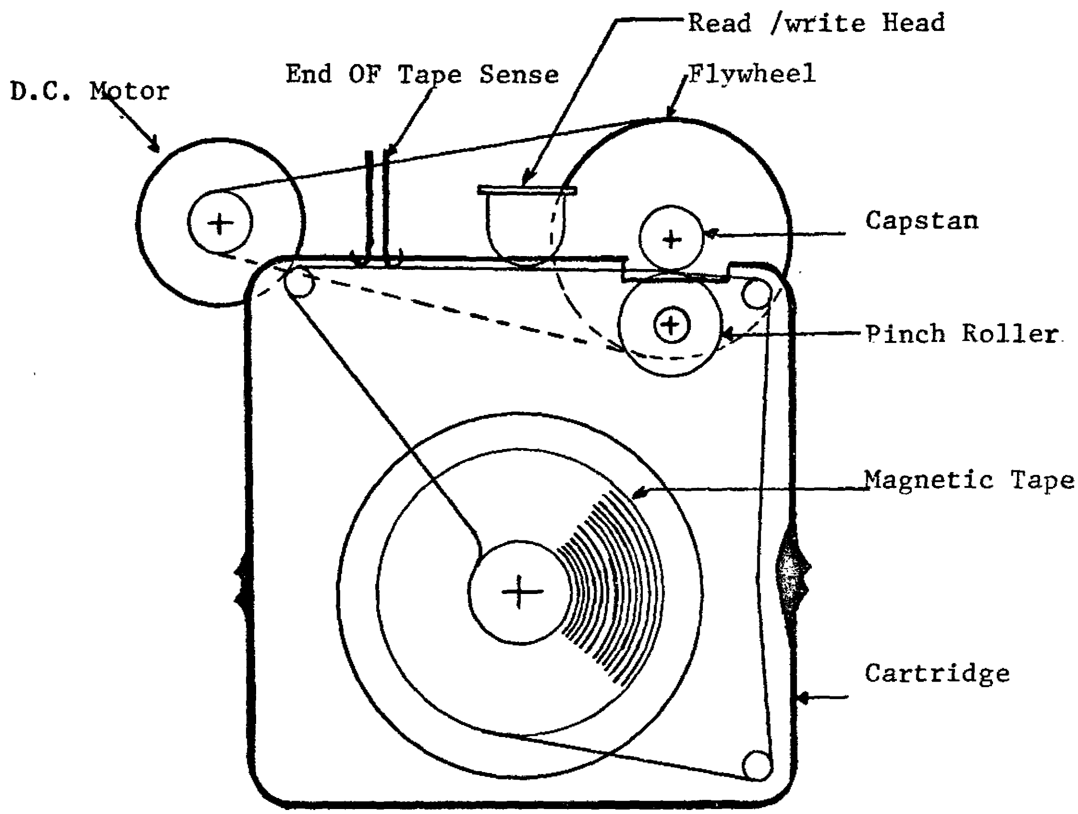
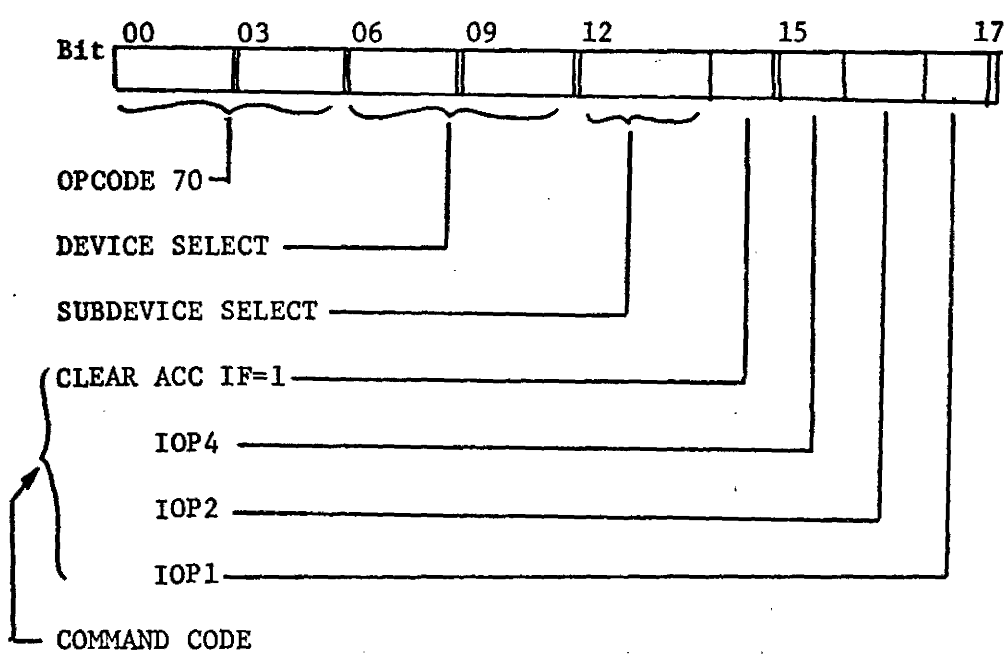


FIGURE 4.2 TRANSPORT MECHANISM.

2. An 8-bit device selection code to discriminate between the devices on the I/O lines. Each device interfaced to the program transfer lines posses-ses selection logic in its I/O bus interface, which will cause it to respond only to its preassigned code. Normally, bits 06 through 11 perform the primary device descrimination (tape unit has device code 14_8) and bits 12 and 13 are coded to select an operational mode or subdevice.

3. A command code (bits 14 through 17) capable of being microprogrammed to clear the accumulator and issue up to three pulses via the IOP lines of the I/O bus (IOP1, IOP2 and IOP4)



Communication between the computer and a peripheral thus proceeds in the following way:

When during program execution an IOT instruction is encountered, the device and subdevice code is transmitted along the device and subdevice lines. Only the device having the corresponding device and subdevice code will be able to decode the instruction and respond to the IOP pulses transmitted.

The conventional use of the IOP pulses is as follows:

IOP1 is normally used in an I/O skip instruction to test a device or flag.

IOP2 is usually used to transfer data to or from the device to the computer, or to clear a flag.

IOP4 is usually used to transfer data from the computer to the device.

If the device requires CPU attention, there are two ways in which this can be accomplished.

1. Without program interrupt, the program must test the device flag at regular intervals, by means of an IOT SKIP instruction. When this device requires attention, a skip will be generated which the program can then handle.

2. With program interrupt, the device notifies the computer of its need for attention by posting a program interrupt. Since all devices share the same program interrupt line, it is then necessary to determine which device caused the interrupt. This is done by skipping on the flags of those devices capable of generating program interrupts until the interrupting device is identified.

All the tape unit flags which can require servicing by the computer are OR'd together and the output is tied to both the program interrupt and the skip lines. The unit can thus be operated using either of the above methods.

4.3 Circuit Description

In order to perform all the i/o control and status functions on the tape unit an excessive number of computer instructions would be required. For this reason the concept of function and status registers is employed. In this way a relatively few instructions can perform all the necessary input/output.

4.3.1 Instruction Set

Nine instructions control the tape unit; these are:--

Mnemonic	Function
DFR	Deposit accumulator in function register
EXCT	Execute the function in the function register
DDW	Deposit Acc. in data register and clear flag
RDD	Transfer data from tape unit into Acc. and clear flag
SOT	Skip on tape unit flag
STOP	Stop
CLINT	Clear tape unit flags
CDPT	Clear dropout/interrecord gap flag
LSR	Load Status Register into accumulator

DFR Bits 00-04 of accumulator are transferred into the tape unit function register. This controls all the functions which the tape unit can perform and serves to select the function required.

EXCT The function which was loaded into the function register by a DFR instruction is executed.

DDW In response to a write data request flag from the tape unit bits 00-02 of the accumulator are transferred into the data register and the data request flag is cleared.

RDD In response to a read data request from the tape unit, the contents of the tape unit output data register are loaded into bits 00-02 of the accumulator and the flag is cleared.

SOT All interrupt flags of the tape unit are OR'd together into a single interrupt request flag. If any of the possible interrupt generating flags requires servicing this flag will be set. When operating the system with the program interrupt facility enabled the SOT instruction allows identification of the tape unit as the interrupting device. If the program interrupt is not enabled then a polling sequence would use the SOT instruction during a polling routine.

STOP The function being performed is halted, tape motion suspended, but the status of interrupting flags is retained.

CLINT All flags on the tape unit are cleared and the system is reset. This is the equivalent of a power clear or system reset but is applied only to the tape unit.

CDPT The absence of data during a read operation sets a dropout/ interrecord gap flag which produces an interrupt. The CDPT instruction clears this flag but has no effect on the status of the unit--the read operation can thus be continued if desired.

LSR The status register of the tape unit is loaded into the accumulator bits 00-08. Status can then be determined by examination of the accumulator contents.

4.3.2 Function Register

The function register is a 5 bit register which is loaded under program control with the contents of accumulator bits 00-04. The basic functions which are performed are:--

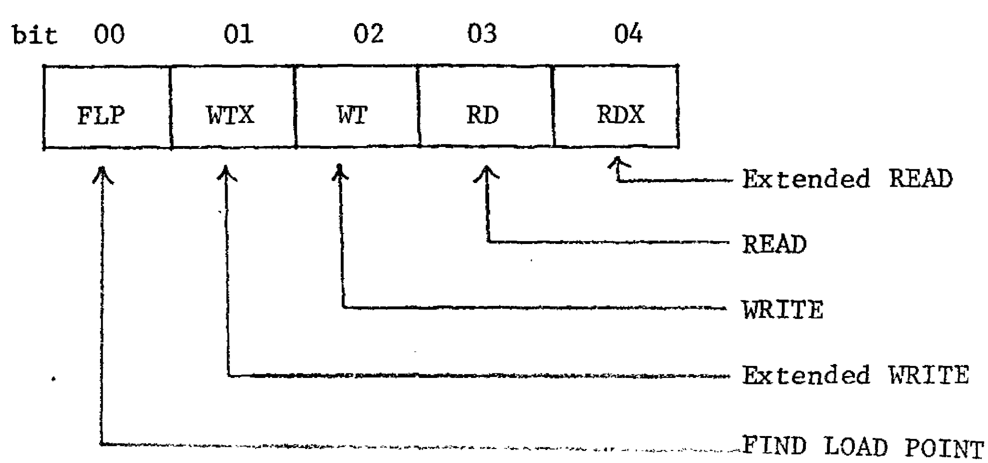
i) WRITE

ii) READ

iii) FIND LOAD POINT (start of tape)

The load point is detected by means of a 1/2 inch conducting strip on the tape. A sensor which rests on the tape detects the conducting strip and signals the computer. As the conducting strip is located on the recording surface and is detected in front of the recording head in the direction of motion, it is necessary to ensure that this has cleared the recording head when writing or reading is initiated. This delay is longer than the delay necessary for the tape unit to attain rated speed, so that in order to utilize the tape fully, this longer delay should only be implemented for the first record at the load point. For this reason two additional functions, read extended and write extended are included to introduce the extra delay prior to reading or writing from the load point.

<u>Function Register</u>



4.3.3 Status Register

This is a nine bit register which indicates the status of the unit.

bit	Flag Indication
00	Error
01	Dropout or Interrecord gap
02	READ DATA REQUEST
03	WRITE DATA REQUEST
04	LOAD POINT FOUND
05	WRITING
06	READING
07	READY
08	LOAD POINT SEARCHING

Description:--

Error--this condition indicates that during reading or writing the load point strip has been encountered. The function being performed is halted, tape motion suspended and the error flag raised. In order to reinitiate the unit a CLINT, CAF or Power Clear instruction is required. This facility prevents the overwriting of the tape during writing (tape is a continuous loop) and indicates the absence of a particular record on the tape or end of data during reading.

DPT or Interrecord Gap--once reading has commenced the absence of data at a bit time raises the flag, indicating either that a dropout has occurred or that an interrecord gap has been found.

WRITING	)	
READING	)	Function being performed
LP SEARCHING	)	
READY		Indicates that all flags are cleared, a cartridge is loaded and the unit is ready to execute a function.

bit	00	01	02	03	04	05	06	07	08
	ERROR	DPT GAP	RDREQ	WTREQ	LPFND	WTG	RDG	RDY	FLP

4.3.4 TTL Logic

The digital hardware used throughout this thesis (except for the MOS Registers in Section 2) has been Texas Instruments TTL Integrated Circuits. Both small scale integration (SSI) and medium scale integration (MSI) are used. Throughout the work, a logical "1" or true level implies a high TTL voltage (2.5v to 5v) and a logical "0" a low TTL voltage (0v to 0.4v). An input which is held permanently in a high state is labelled, Vcc, the integrated circuit supply voltage.

CHAPTER 5

DETAILED DESIGN

5.1 Bit Density Measurements

Skew measurements performed on the tape unit using a calibrated tape showed the effects of static skew to be negligible (10 μsec) providing that the azimuth was correctly adjusted. Dynamic skew on the other hand was found to be considerable due to the relatively poor mechanical construction of the 8-track unit. The dynamic skew was found to be of such severe proportions that it was necessary to limit the recording density at a value well below that at which pulse crowding of any proportion takes place.

The method of determining the dynamic skew is outlined. A series of saturation reversals is recorded in phase on the two tracks. The tape is then readback and the output pulses are peak detected. If no dynamic skewing occurs, then the two tracks will have coincident peaks and the relative shift between the two tracks is an indication of the skewing. If we define the cell time, as previously defined, as the minimum time between output pulses, w, then in order to ensure that the o/p from either of the tracks does not occur in the incorrect cell time relative to the other track, it is necessary that the cell time, w, be greater than the maximum shift in either direction due to skewing. The dynamic skewing was found to be within 0.75 msec. in either direction (see Figure 5.2a) thus imposing a minimum cell time of 1.5 m secs. In order to allow time for gating and strobing this is increased to 2.0 msecs. As there can be two voltage outputs in one clock period (mid-transition and clock transition) the minimum clock period is twice this, or 4 msecs. This data rate is thus three bits every 4 msecs or 750 bits per second. The effects of pulse crowding were also examined and it was found that at this frequency very little pulse crowding was evident. Decreasing the cell time below 1 msec. caused the voltage pulse amplitude to be effected, indicating that the peaks were interacting at this point.

5.2 Motor Control Circuit

The tape transport mechanism was illustrated in Figure 3.1. The d.c. motor drives the flywheel and capstan which has the form of a long spindle. Each tape cartridge has its own pinch roller which is pulled against the capstan, with the tape in between, thus driving the tape. The tape is in the form of a continuous loop with the tape motion drawing tape from the centre of spool and winding on to the outside of a spool. The objective of any motion control circuit is to attain rated speed as quickly as possible, and to keep it at a constant speed once it has been accelerated. The acceleration must not be too severe or distortion and stretching of the tape can occur. It was found that with a full reel of tape (i.e. maximum inertia), the tape could be brought up to rated speed in 150 msec. with no harmful effects to the tape.

The speed control circuit utilized is essentially a negative impedance converter the operation of which can be understood from the basic configuration shown in Figure 5.1b.

The electromotive force developed by the motor is linearly proportional to its speed.

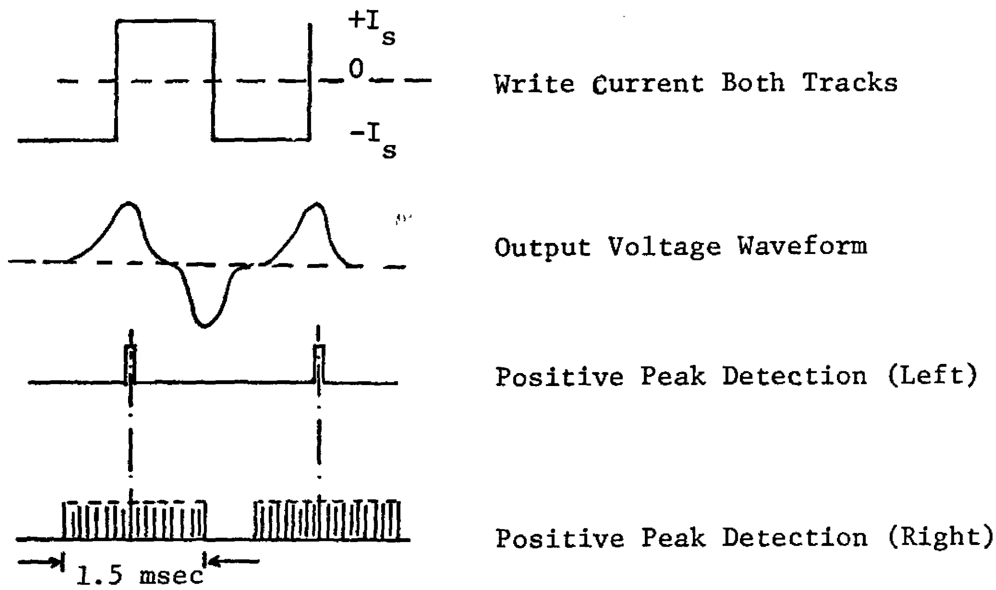


FIGURE 5.1a DYNAMIC SKEW MEASUREMENT

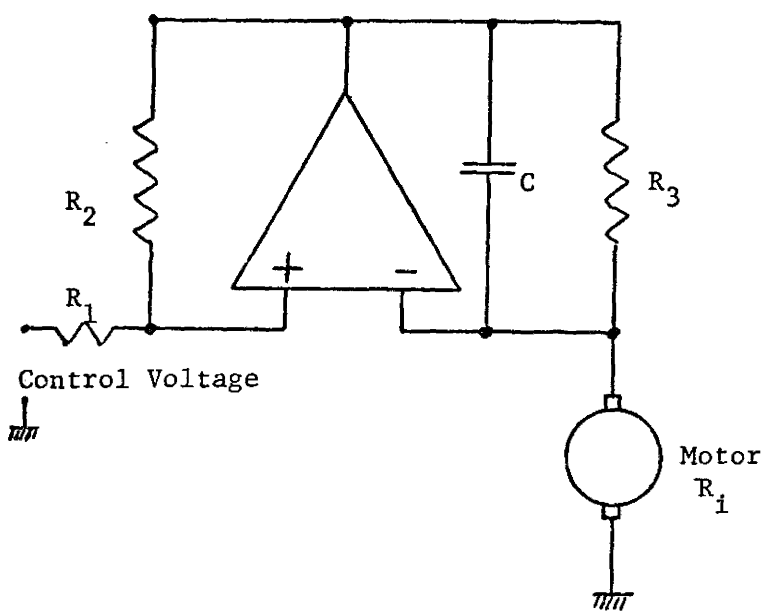


FIGURE 5.1b SPEED CONTROL CONFIGURATION

$E = KN$ where K is a constant

N is the motor speed

If the motor has a winding resistance equal to Ri ohms and is driven by a voltage source, v_s, with internal resistance R_s, then the speed is given by

$$N = \frac{v_s - I(R_s + Ri)}{K}$$

If R_s can be made to be negative and equal to Ri then the speed becomes dependent solely on the applied voltage v_s. Using an operational amplifier with both positive and negative feedback as in Figure 5.1b this can be achieved.

The source resistance presented to the motor, which is placed between the inverting input and ground is controlled by the ratio - $-R_1R_3/R_2$. Capacitor C serves to stabilize the circuit, preventing oscillation. The response of the circuit can be varied by varying the positive feedback resistance.

Figure 5.2 shows the overal circuit--a true level from a TTL gate is sufficient to start the motor and rated speed is attained in approximately 150 msecs. A similar time is required to stop the motor.

The power operational amplifier is achieved by the circuit shown in Figure 5.3. A unity gain compensated SN 72709 operational amplifier feeds a wide band current booster. The open loop gain is approximately 60,000 and current limiting occurs at approximately 1.5 amps.

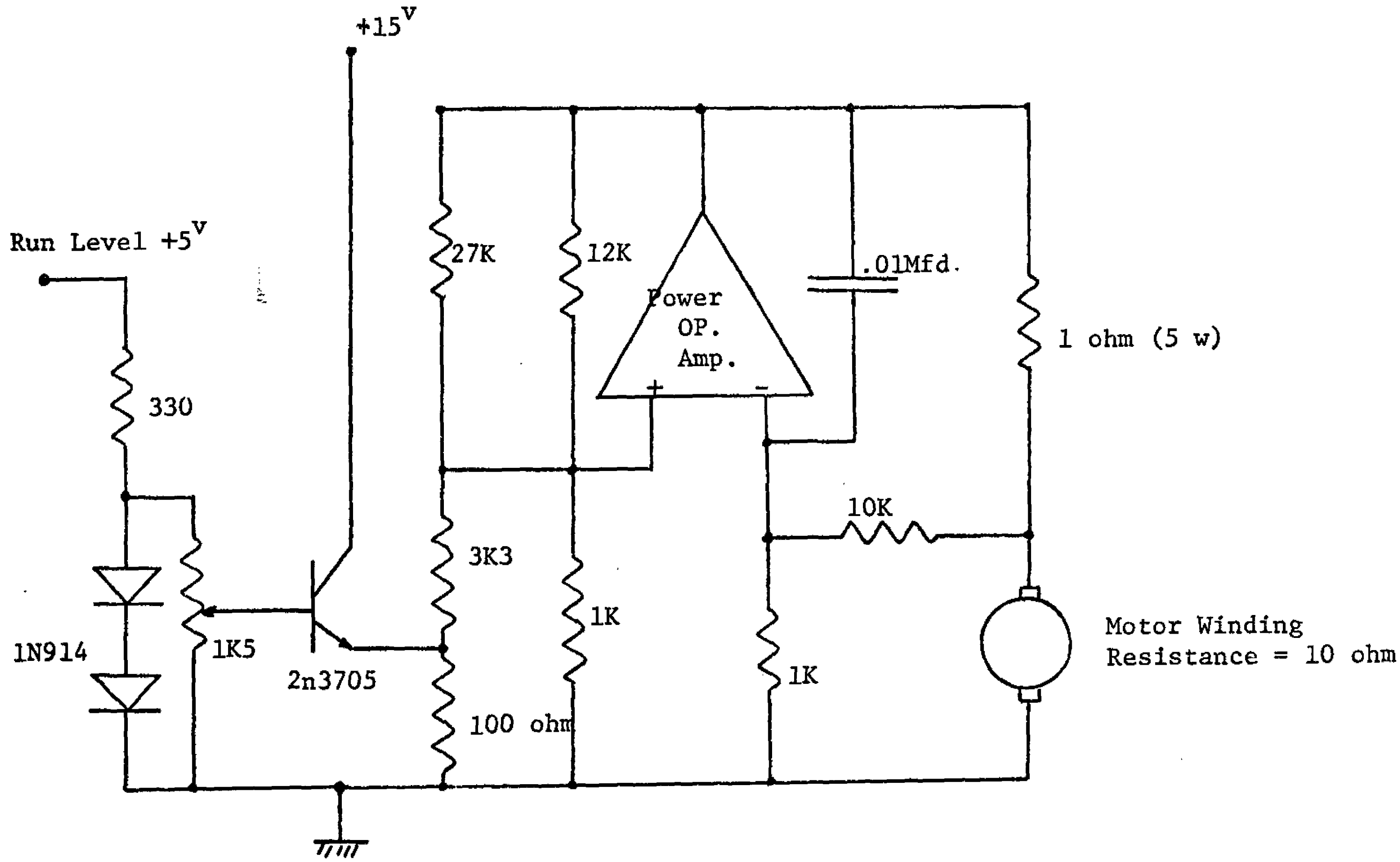


FIGURE 5.2 SPEED CONTROL CIRCUIT.

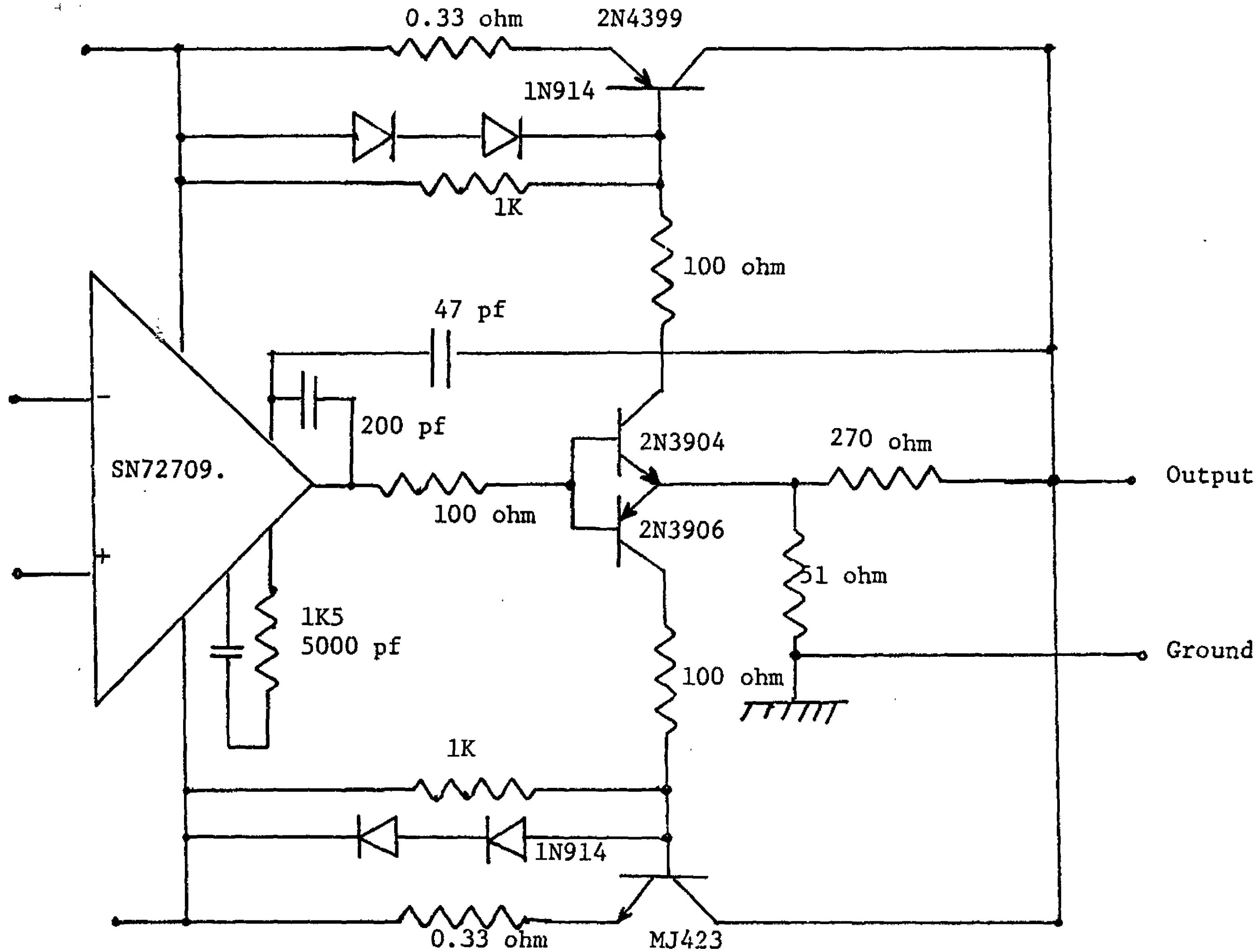


FIGURE 5.3 POWER OPERATIONAL AMPLIFIER.

5.3 Write Electronics

The write electronics contains write control and timing logic, write encoding logic and write driver circuits. A block diagram of the write system is shown in Figure 5.4.

The write control and timing logic synchronizes the write operation and is outlined first.

5.3.1 Write Control and Timing Logic

The operation of this section can be understood from the schematic in Fig.5.5 and the write timing chart of Figure 5.4b. With the system initially reset WRITE or WRITE EXTENDED is loaded into the function register by means of an IOT DFR instruction. An execute instruction (IOT EXCT) sets the writing status line high. This line performs a number of functions:

i) tape motion is initiated

ii) writing status constitutes bit 05 of the status register indicating that writing is in progress

iii) the output AND gates which supply the WRITE DRIVER CIRCUITS are enabled. The WRITE LEVEL FLIP FLOPS are set simultaneously by WRITE DELAY and this ensures that the tape is erased up to the point where the record is to start.

For a normal WRITE operation, a delay of 200 msecs. occurs, to ensure that the tape reaches rated speed (800 msecs. in the case of an EXTENDED WRITE operation). After this time, the write clock is enabled and this in turn starts the count sequence. The clock has a period of .4 msecs. and this together with the BCD counter and decimal decoder

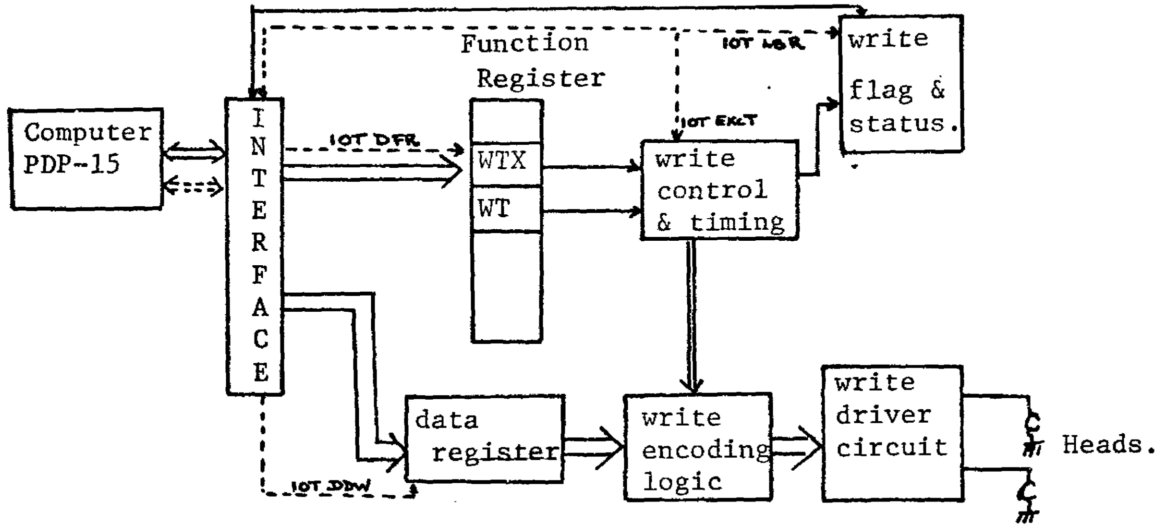


FIGURE 5.4a BLOCK DIAGRAM OF WRITE OPERATION.

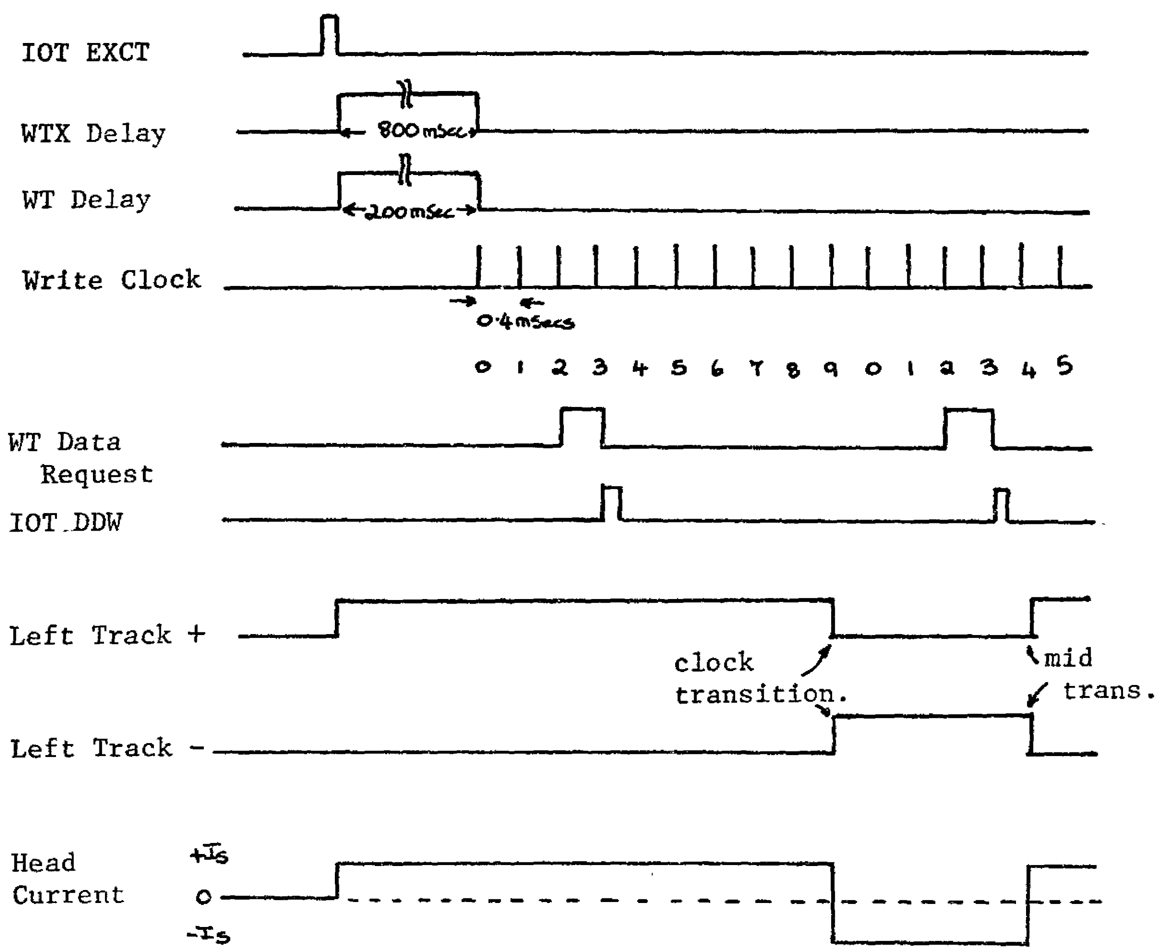


FIGURE 5.4b WRITE TIMING.

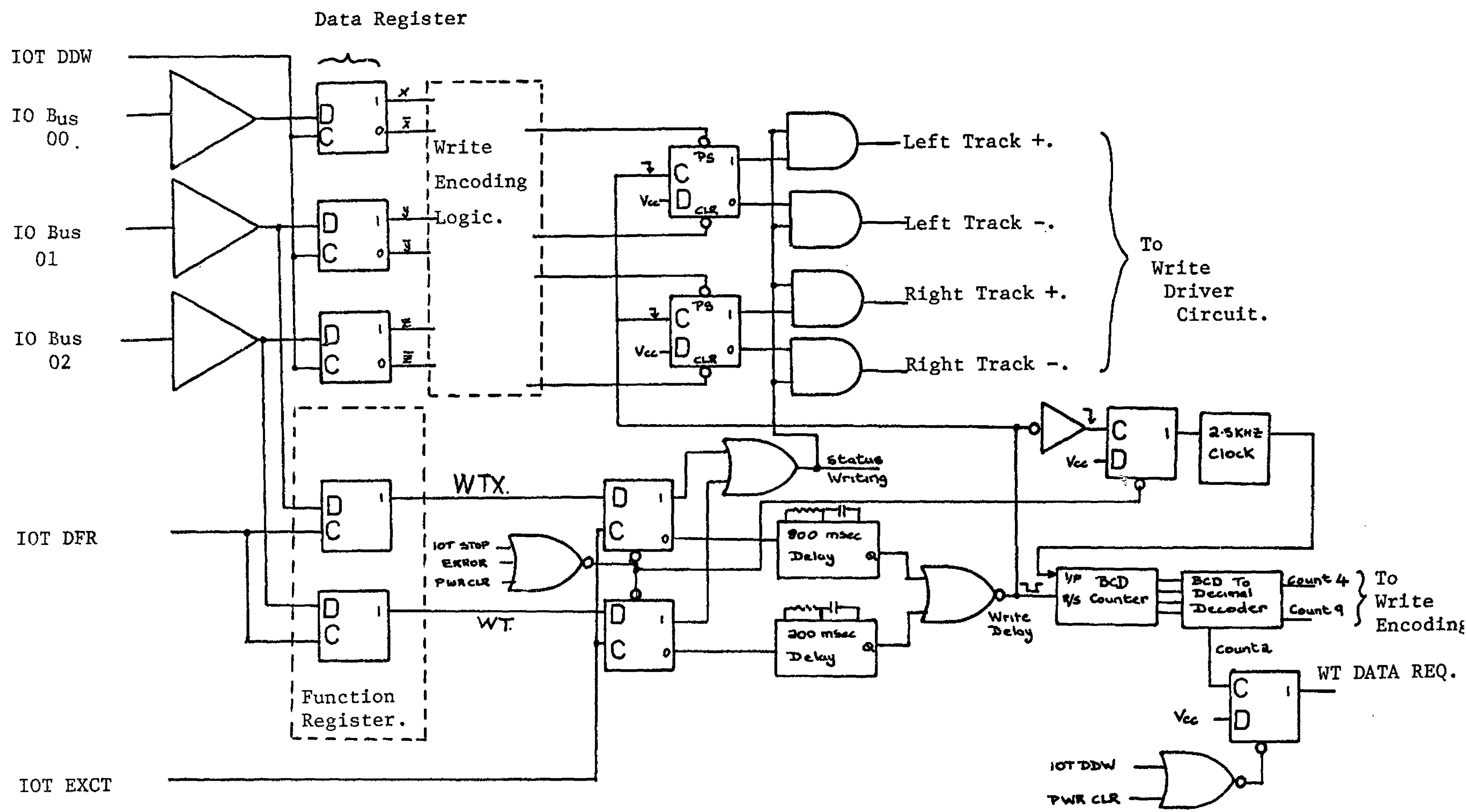


FIGURE 5.5 WRITE CONTROL LOGIC

serve to sequence the write operation. When the BCD counter reaches a count of two, the WT DATA REQ flip flop is set. This generates a program interrupt requesting a transfer of three bits of data from the computer into the data register. Data is loaded into the data register from the accumulator by means of an IOT DDW instruction which also clears the interrupt flag. At a count of four, a decision is made on the basis of the data in the data register as to whether a midtransition must occur. Two msecs. later, at a count of nine, the actual clock transition occurs. As the tape is saturated with a positive writing current during the initial start delay, and in order to synchronize the read clock during the read operation, the first octal digit of data recorded is prescribed and carries no information. The data which is loaded into the data register in response to the first WT DATA REQ flag must be the octal digit 7 which results in no midtransition occurring and a negative transition at the actual clock time. (See Write Timing Chart, Figure 5.4b)

5.3.2 Write Encoding Logic

This consists essentially of 2 D type flip flops with preset and clear inputs, and 8 AND-OR-INVERT gates (Figure 5.6a). The outputs of the flip flops are gated through the output AND gates and the state of the flip flop reflects directly the direction of current saturation when the output AND gates are enabled. (If the Q output of the flip flop is high then the tape is positively saturated.) In order to obtain a positive transition in the saturation write current it is thus necessary to change the state of the Q output from a low to a high level, (logic 0 to logic 1).

Thus, if the data in the data register is such that at an actual clock time a positive transition in the writing current is to take place, then it is necessary to ensure at the mid transition time (count 4) that the Q output is set to a logical 0 so that the transition can take place. This is achieved by directly strobing the preset and clear inputs at these times.

Consider the following binary representation of the possible transitions:

Actual Clock Time Transition Required	Representation		State to which Q Output should be set at Mid-transition time	State to which Q Output should be set at Actual Time
	A	B	Q	Q
+ (negative to positive)	1	0	0	1
- (positive to negative)	0	1	1	0
0 (No change)	0	0	Q	Q

In order to achieve these transitions, levels A and B are generated by the encoding logic from the data present in the data register. At the midtransition time, A is applied to the clear input of the flip flop while B is applied to the preset input. At the actual transition time, this is reversed with A being applied to the preset input and B to the clear input.

The actual design procedure and Kamaugh maps are outlined:

Data x y z	Transition Required Left	 Right	Binary Representation Left JK	 Right LM
0 0 0	+	+	10	10
0 0 1	+	0	10	00
0 1 0	+	-	10	01
0 1 1	0	-	00	01
1 0 0	0	+	00	10
1 0 1	-	+	01	10
1 1 0	-	0	01	00
1 1 1	-	-	01	01

J

xy \ z	0	1
00	1	1
01	1	
11		
10		

$J=\overline{x}\overline{y}+\overline{x}\overline{z}$

K

xy \ z	0	1
00		
01		
11	1	1
10		1

$K=xy+xz$

L

xy \ z	0	1
00	1	
01		
11		
10	1	1

$L=x\overline{y}+\overline{y}\overline{z}$

M

xy \ z	0	1
00		
01	1	1
11		1
10		

$M=\overline{x}y+yz$

The implementation of this is shown in Figure 5.6a. The mid-transition clock pulse which occurs at a count of four is indicated by "4" and the actual clock transition which occurs at a count of nine is indicated by "9". The gating of the outputs to the preset and clear inputs is achieved by means of and-or-invert gates.

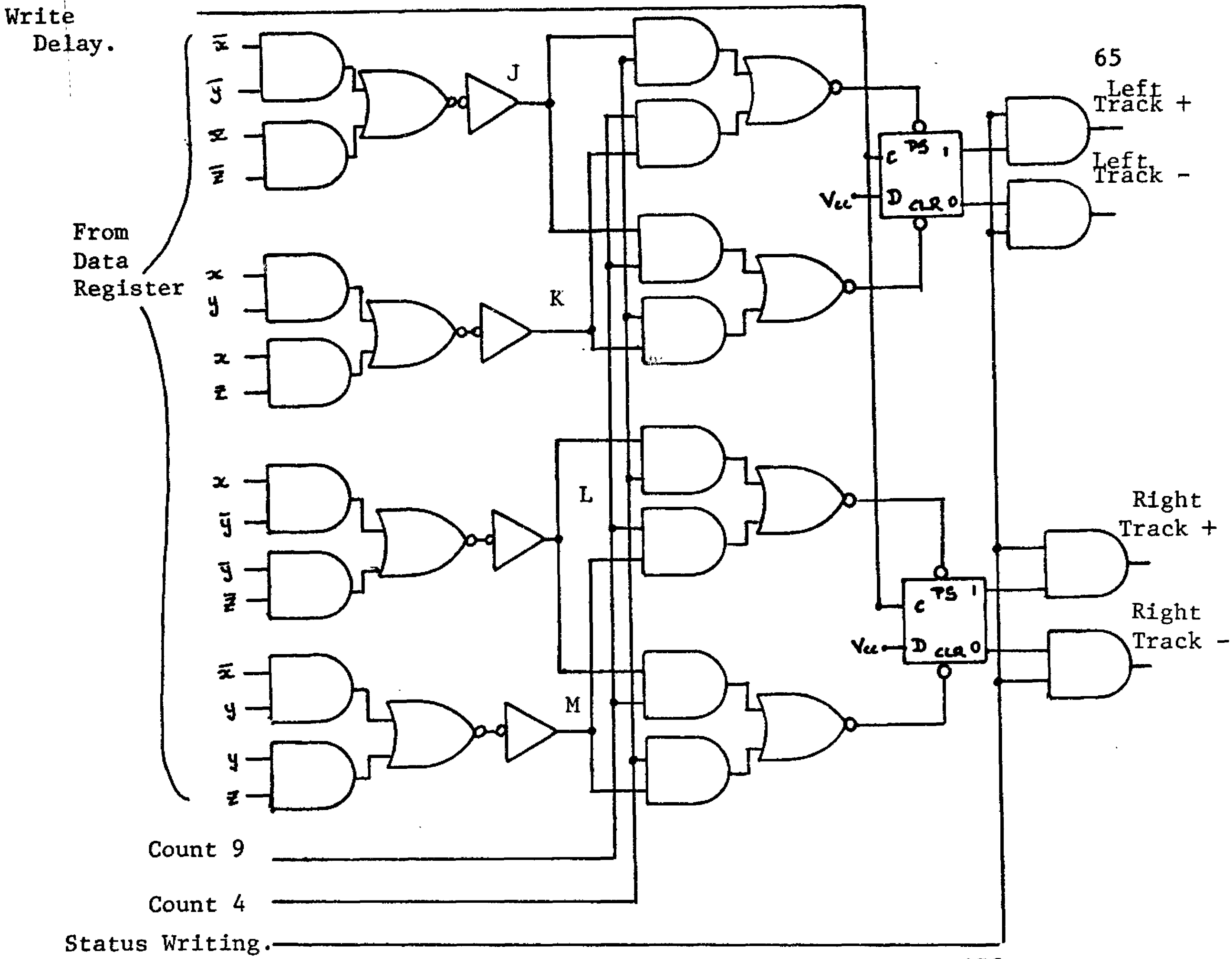


FIGURE 5.6a WRITE ENCODING LOGIC.

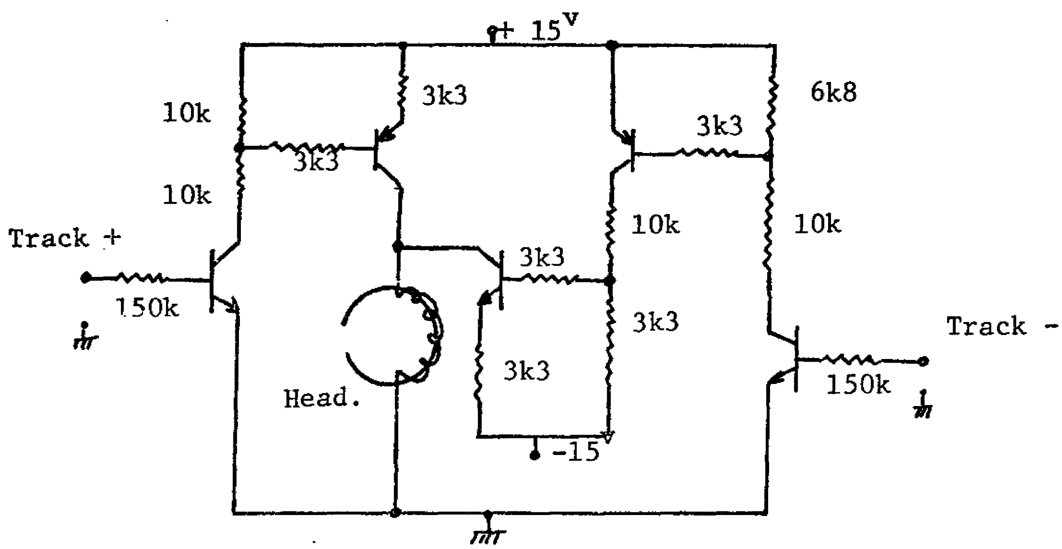


FIGURE 5.6b WRITE DRIVER CIRCUIT.

5.3.3 WRITE DRIVER Circuit

This circuit is shown in Figure 5.6b. When either of the inputs goes high, current is driven through the head, the magnitude of which is established by the emitter voltage and resistance in the output transistor. When neither of the inputs is high, the circuit presents a high impedance to the tape head so that the write driver can be connected to the head during the playback operation. In order to obtain the optimum recording current, the emitter resistance is decreased until no appreciable increase in o/p voltage is obtained for further decrease in resistance. It is necessary at this point to ensure that the write current is sufficient to ensure complete erasure of previously recorded data, requiring possibly a further small decrease in the emitter resistance. The inputs are driven directly from the outputs of the output AND gates of the write encoding section.

5.4 READ Electronics

The READ electronics contains the playback amplifier and peak detection circuits, read control logic, read decoding logic and read clock circuitry. This is shown schematically in the block diagram of Fig. 5.7.

5.4.1 Readback Detection

As the recording density is sufficiently low that peak shift effects do not occur, the most accurate form of detection in terms of the synchronization of the data is to use peak detection. The readback detection circuitry is illustrated in Figure 5.8. The head output is amplified using a Texas Instrument SN 72709 operational amplifier resulting

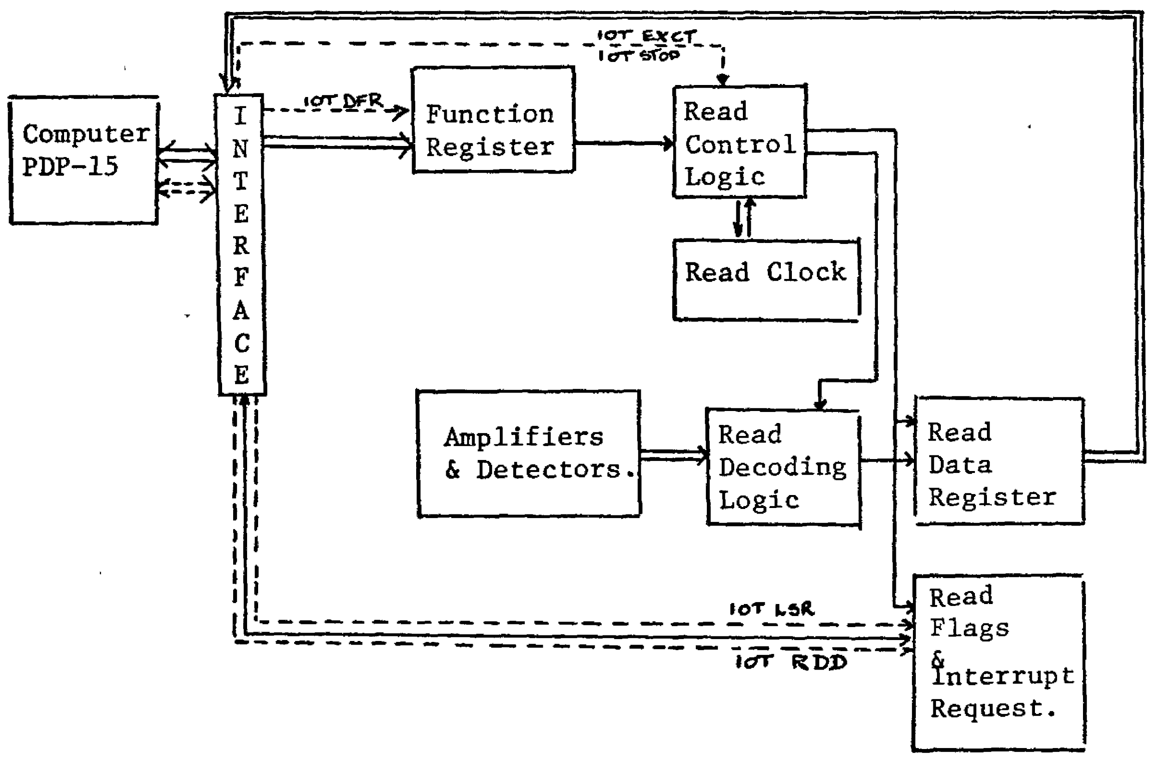


FIGURE 5.7 BLOCK DIAGRAM OF READ OPERATION.

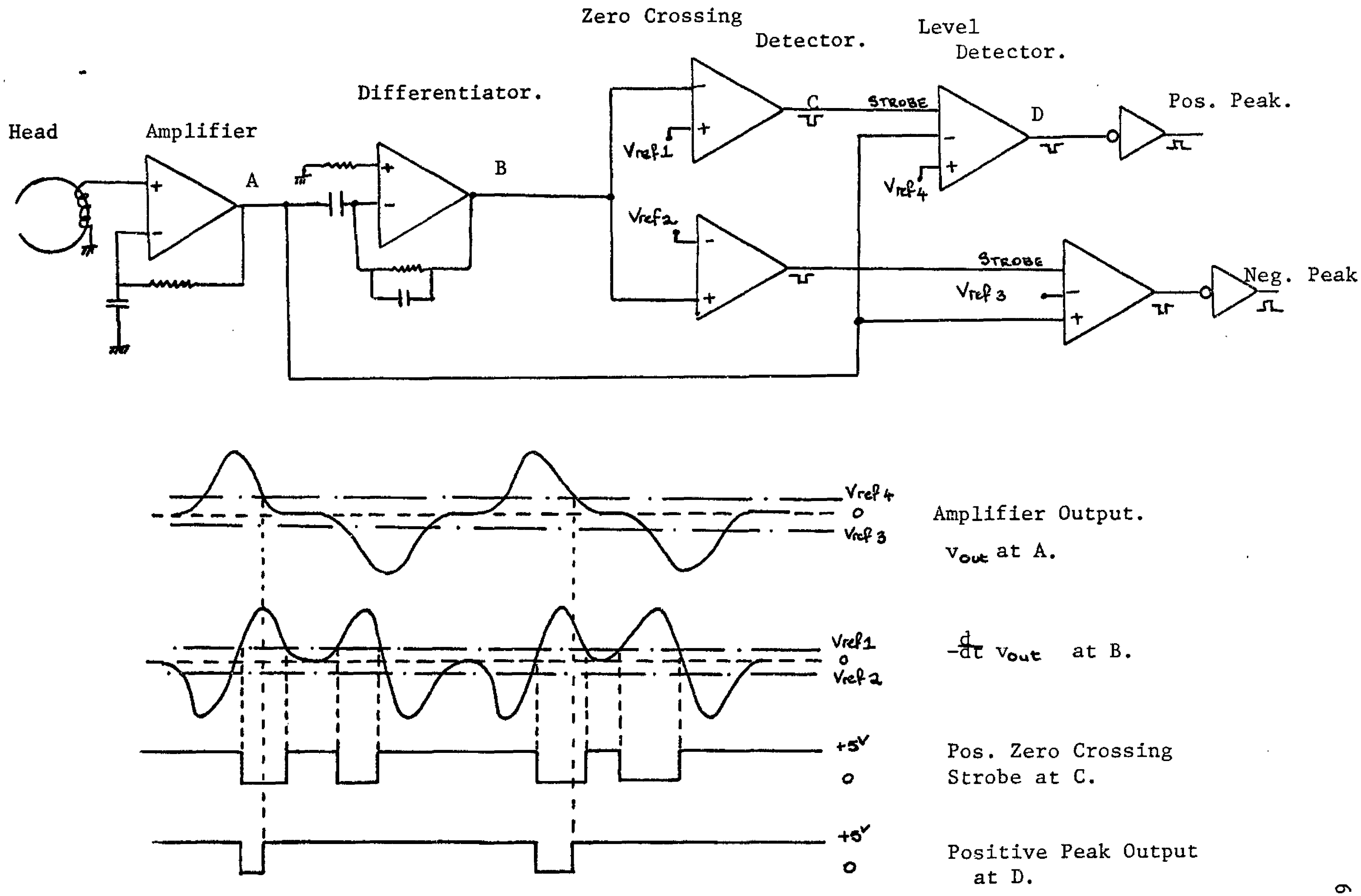


FIGURE 5.7 READBACK DETECTION

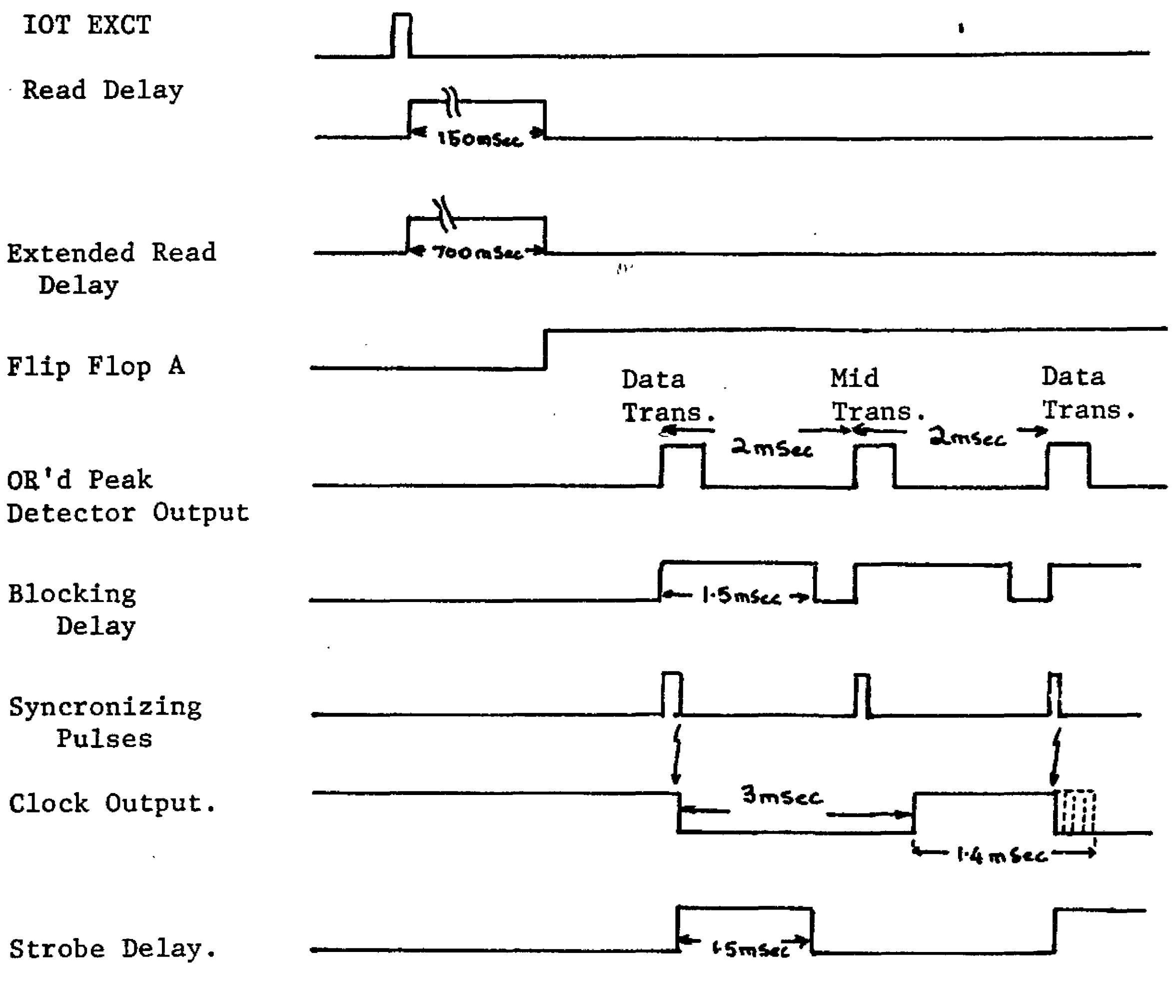


FIGURE 5.9a READ TIMING.

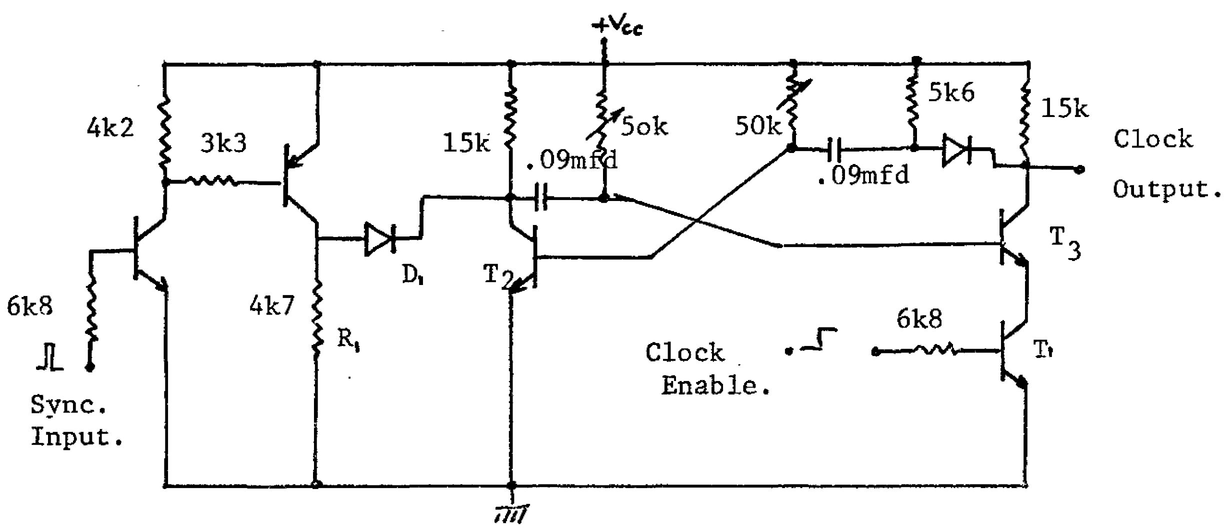


FIGURE 5.9b READ CLOCK.

in a pulse peak amplitude of approximately 10 volts. Peak detection is achieved by differentiating the output waveform and then detecting the zero crossings. Noise considerations make it necessary to limit the high frequency response of the differentiator; this being achieved by the small capacitor in the feedback loop. A similar consideration requires that the reference level applied to the zero crossing detectors be raised above the noise level. As can be seen from the waveforms at the output of the positive zero crossing detector in Figure 5.8 outputs will occur from the detector both when the readback voltage signal has reached a positive peak and is returning to zero and when it crosses the threshold level going negative. The amplitude detector is enabled at both these times but will produce an output only when the output voltage pulse has the correct polarity.

5.4.2 Read Logic and Decoding

The operation of the read logic circuitry can be understood from Figure 5.10 and the read timing chart of Figure 5.8

With the system initially reset, READ or READ EXTENDED is loaded into the function register by means of an IOT DFR instruction. An IOT EXCT instruction initiates the tape motion via the READING status line, which also constitutes bit six of the status register indicating that reading is in progress.

For a normal read operation, a delay of 150 msecs. occurs (700 msecs. for a READ EXTENDED) during which time the control logic is disabled. After this delay, flip flop A is set which enables the first detected output from the tape through the four i/p OR gate to start the

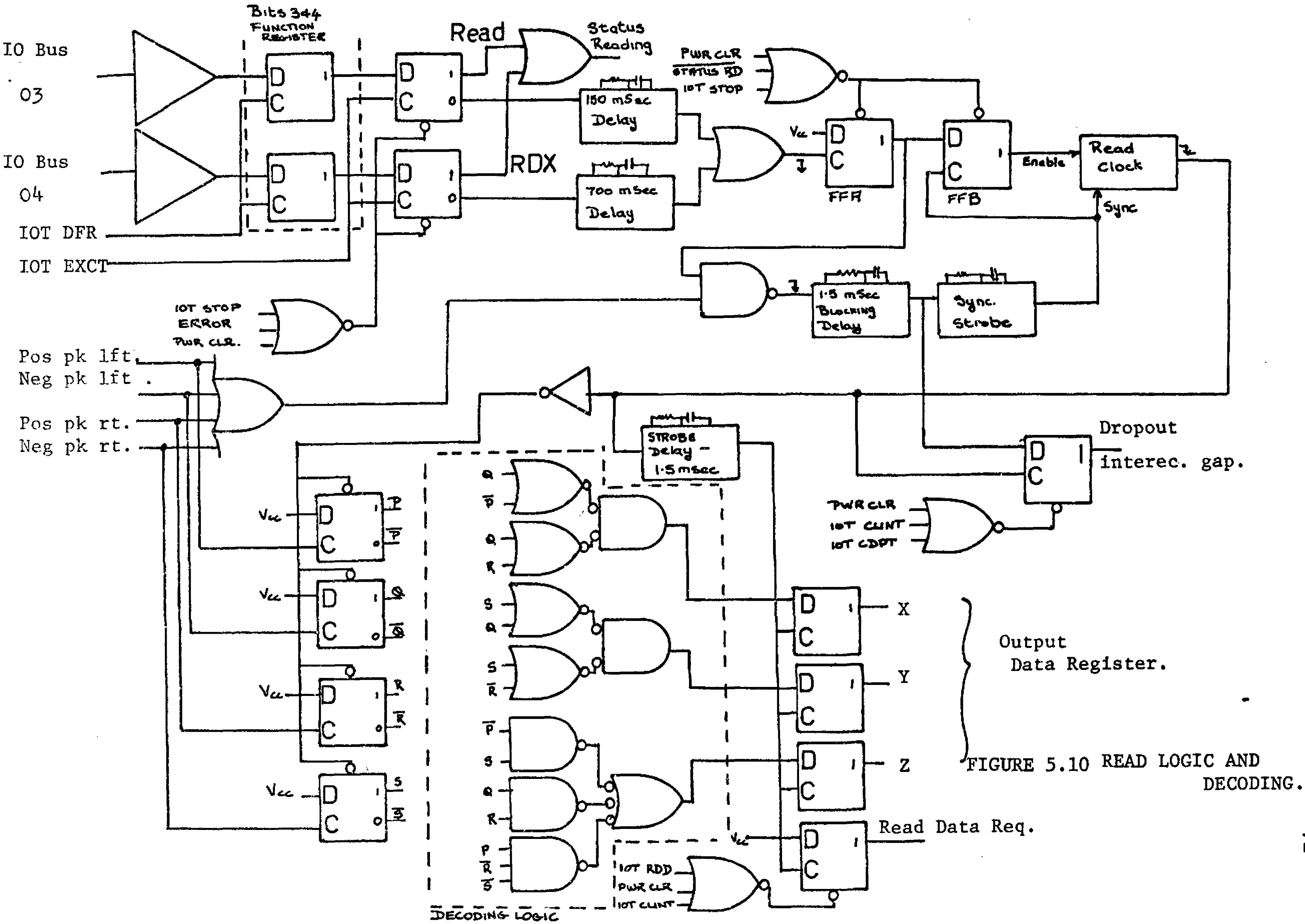


FIGURE 5.10 READ LOGIC AND DECODING.

READ clock. The read clock has a free running period slightly longer than the data period (4.4 msecs.) but is pulled into step by the arrival of the synchronizing pulses. Because of the dynamic skewing present in the system, it is necessary to insert a blocking delay to ensure that phase differences between the two tracks do not result in the generation of extra synchronizing pulses. The arrival of a synchronizing pulse, while the clock output is high, terminates the cycle and resets the o/p to a low level. The clock is to be reset to a low level with the arrival of every actual clock transition recorded on the tape. As the presence of midtransitions on the tape will also generate synchronizing pulses, it is necessary to ensure that these do not effect the timing. For this reason, the clock has an uneven mark/space ratio. The clock is at a low level for 3 msecs. and is high for 1.4 msecs. During the time that the clock is low, synchronizing pulses have no effect on the clock period.

Thus, data arriving from the tape terminates the clock cycle causing it to return to its low level. This transition is delayed by 1.5 msecs. to ensure that the data from the other track has also arrived, at which time the output of the decoding logic is strobed into the output data register and a READ DATA REQUEST INTERRUPT is generated requesting the transfer of three bits from the tape unit to the computer.

If no data has arrived by the time the clock reaches its free running negative transition time (4.4 msecs. from the previous data arrival) indicating either that a dropout has occurred or the end of a record has been reached, the Dropout Gap Interrupt will be set to indicate this condition. This flag can be cleared while the read process continues by means of an IOT CDPT instruction. In this way, it is possible for the computer to take cognizance of the fact that an error has occurred while continuing to read the rest of the record.

READ Decoding

The outputs from the peak detector are stored in flip flops P,Q,R and S of Figure 5.10. The table below indicates the state of the flip flops for the possible data combinations.

Original Data			Recorded Transition		Correct State of Flip Flops on Readback	
			Left	Right		
x	y	z			PQ	RS
0	0	0	+	+	10	10
0	0	1	+	0	10	00
0	1	0	+	-	10	01
0	1	1	0	-	00	01
0	0	0	0	+	00	10
1	0	1	-	+	01	10
1	1	0	-	0	01	00
1	1	1	-	-	01	01

The decoding logic is somewhat simplified by the Don't Care conditions JK=1, RS=1 and $\bar{P}\ \bar{Q}\ \bar{R}\ \bar{S} = 1$ which exist due to the fact that a track cannot have both positive and negative transitions in the same bit time (without error) and the state $\bar{P}\ \bar{Q}\ \bar{R}\ \bar{S} = 1$ indicates a dropout or inter-record gap which is detected by the read logic circuitry.

The expressions for the read decoding and the Karnaugh maps are given below.

x

PQ \ S R	S=0, R=0	S=1, R=0	S=1, R=1	S=0, R=1
00	x		x	1
01	1	1	x	1
11	x	x	x	x
10			x	

y

PQ \ S R	S=0, R=0	S=1, R=0	S=1, R=1	S=0, R=1
00	x	1	x	
01	1	1	x	
11	x	x	x	x
10		1	x	

z

PQ \ S R	S=0, R=0	S=1, R=0	S=1, R=1	S=0, R=1
00	x	1	x	
01		1	x	1
11	x	x	x	x
10	1		x	

X = Don't Cares

$x = Q+\bar{P}R = (Q+\bar{P})(Q+R)$

$y = S+Q\bar{R} = (S+Q)(S+\bar{R})$

$z = \bar{P}S+QR+P\bar{R}\bar{S}$

5.4.3 Read Clock

The read clock is shown in Figure 5.9b. This is simply a collector coupled astable multivibrator. Transistor T_1 enables the clock and ensures that it comes on in the correct state. A positive pulse at the collector of T_2 brings T_3 out of cut off thus synchronizing the clock and data. A synchronizing pulse occurring while T_3 is conducting (i.e. at a midtransition time) will not effect the timing. Diode D_1 prevents the capacitor from discharging through R_1. The natural clock period is 4.4 msecs.

5.5 End of Tape Sense and Miscellaneous Operations

Figure 5.11 illustrates the end of tape sense logic and those signals not directly involved in the READ or WRITE cycles. In order to search for the load point, bit 00 of the function register is set by means of an IOT DFR instruction. An IOT EXCT instruction initiates tape motion by setting flip flop FLP which also constitutes bit eight of the status register indicating the load point search is in progress. When the load point is located, the load point found interrupt is generated and tape motion halted. If the load point is sensed during a read or write operation indicating that the continuous loop has cycled completely an error flag is raised which also suspends tape motion.

In order to load either the status bits 00-02 or the three bits of data into the same accumulator locations the multiplex circuit is required. The signal RD REQ L indicates to the computer that the data transfer is from the peripheral into the accumulator.

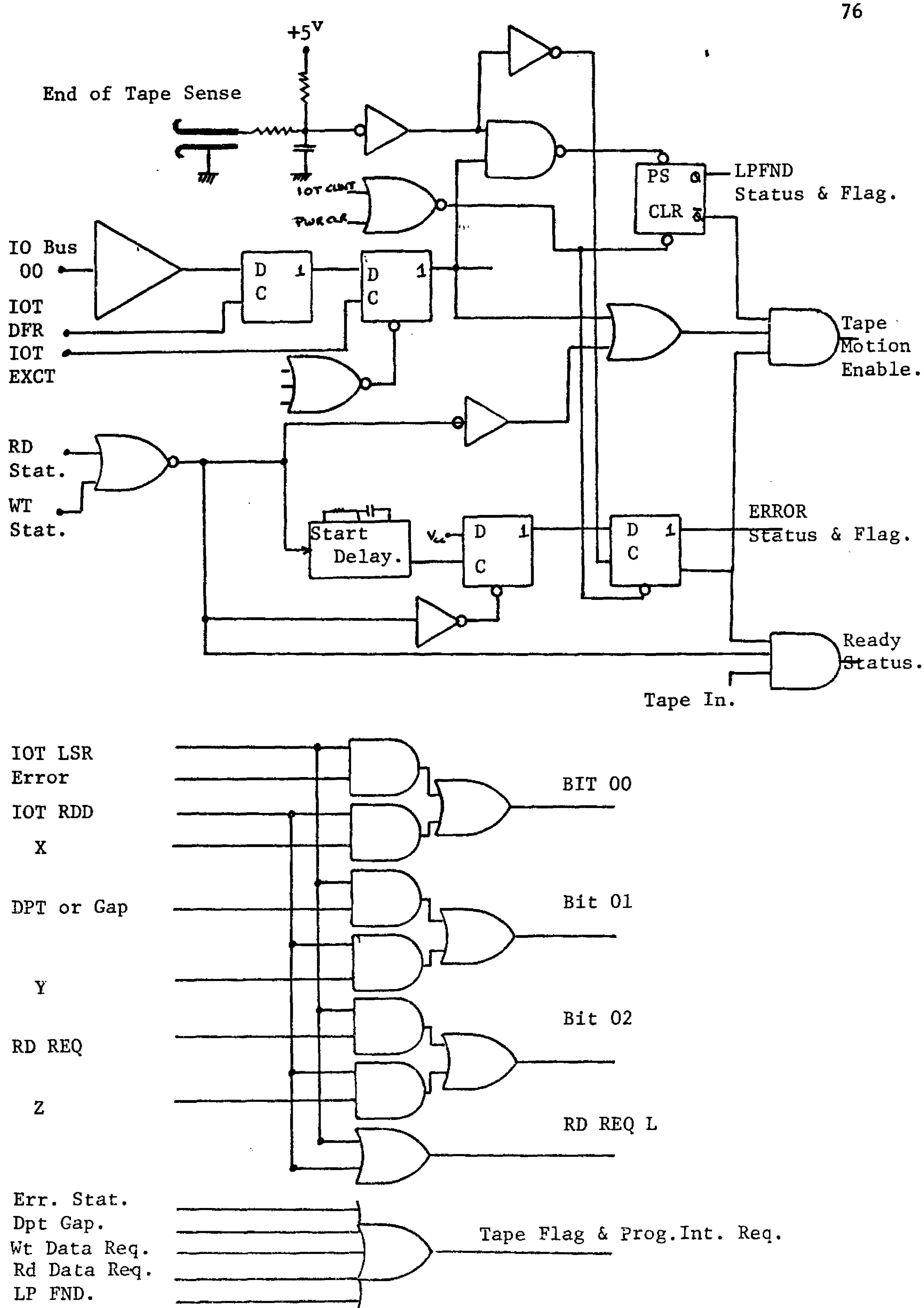


FIGURE 5.11 LOAD POINT DETECTION

CHAPTER 6

PROGRAMMING AND RELIABILITY

Programming of the tape unit is illustrated by means of two sample programs.

6.1 Program to Write Onto Tape

This program searches for the start of the tape and then writes out the contents of specified core locations onto tape. The word length in the computer is 18 bits, thus requiring that each word be written in six write cycles. The flow diagram is shown in Figure 6.1.

6.2 Program to Read from Tape

This program searches for the start of the tape and then reads tha data from tape, reconstructs it into 18-bit words and stores the words in specified core locations. When the specified number of words have been read, the program halts. The flow diagram is shown in Figure 6.2.

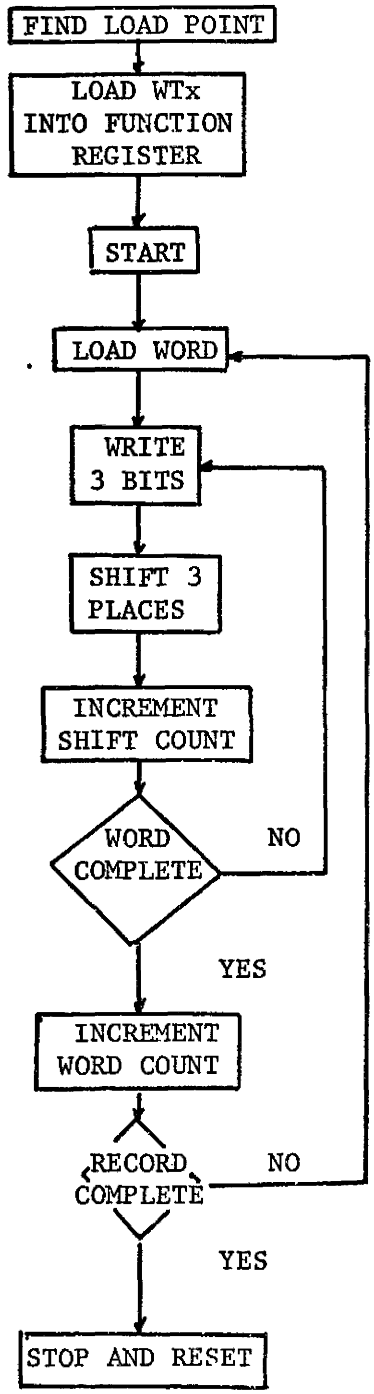


FIGURE 6.1 WRITE FLOW DIAGRAM

```
START   CAF             /RESET
        LAC  LP         /CODE FOR LOAD PT SEARCH
         DFR /DEPOSITED IN FN REG AND
         EXCT           /EXECUTED.
         SOT /SKIP ON TAPE FLAG
         JMP -1
        LSR             /LOAD STATUS REGISTER
         RTL             /ROTATE ACC. 2 LEFT. IF LP FOUND
                          /THEN LINK =1
         SNL            /SKIP ONLINK
        JMP ERROR  /IF NOT. ERROR HAS OCCURRED
         CLINT          /RESET LP FLAG
          CLX           /INITIALIZE FOR WRITE. CLEAR INDEX REG.
        LAC  WDCNT  /NO. OF WORDS TO BE DUMPED
        PAL             / DEPOSIT THIS IN LIMIT REG.
        LAC WTX           /AT LP THUS EXTENDED WRITE
        DFR             /DEPOSIT IN FN REG AND
        EXCT            /EXECUTE.
NUWD    LAW -6          /NO. OF SHIFTS PER WORD TO BE DUMPED
        DAC BCNT        /18 BIT WORD WRITTEN IN 6 3 BIT BYTES
FLAG     SOT              /SKIP ON FLAG
        JMP -1
        LSR             /LOAD STATUS REGISTER
        RTR             /STATUS MUST BE WT DATA REQUEST     /
        RTR         /IF SO, LINK =1
        SNL         /IF NOT ERROR HAS OCCURRED
        JMP ERROR  /
        LAC STAL,X  /THE START ADDRESS INDEXED IS LOADED
         /AND WRITTEN MOST SIGNIFICANT BYTE FIRST
        DDW         /BYTE DEPOSITED IN TAPE REG. & FLAG CLRD.
        DAC TEMP  /WORD SAVED IN TEMP. LOCATION
        ISZ BCNT /HAS WORD BEEN COMPLETED?
        JMP CONT /NO, FINISH WORD.
        AXS +1        /YES.HAS RECORD BEENCOMPLETED?
        JMP NUWD    /NO. JMP TO NEW WORD
        LSR         /YES, LOAD STATUS AND HALT
        STOP
        HLT
CONT    LAC TEMP     /LAC PRESENT WORD
        RTL          /SHIFT IN NEXT THREE BITS
        RAL          /FOR WRITE OPERATION
        LAC TEMP
        JMP FLAG  /RETURN FOR REST OF WORD
ERROR   LSR      /IF ERROR HAS OCCURRED EXECUTION HALTS
        STOP    /WITH ACC. DISPLAYING THE INCORRECT INTERRUPT
        HLT     /IF SUCCESSFUL THE ACC. WILL DISPLAY STATUS
        JMP START  /AS WRITING.
```

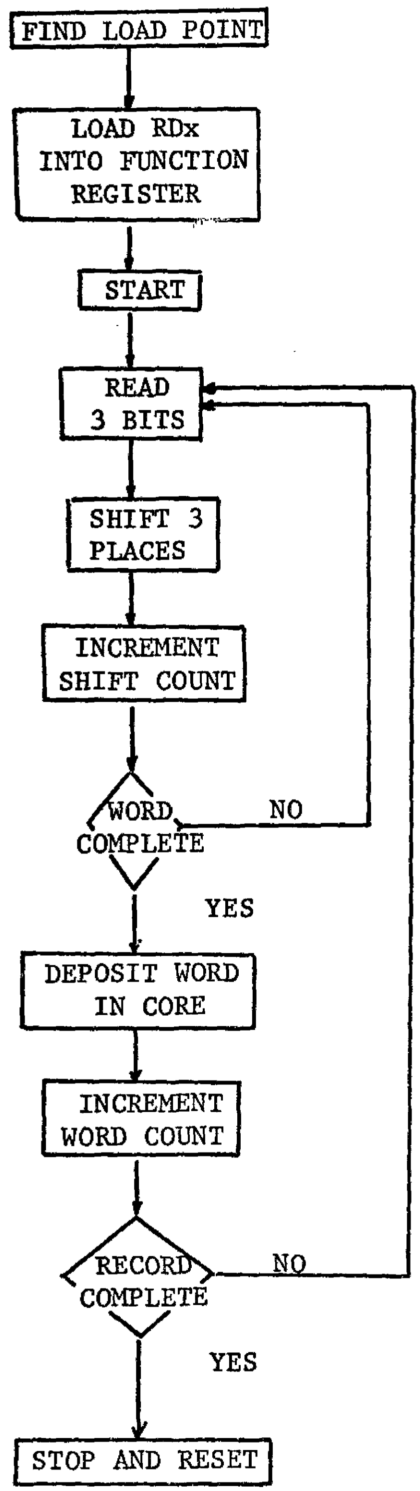


FIGURE 6.2 READ FLOW DIAGRAM

```
START       CAF           /RESET
            LAC LP        /LOAD CODE FOR LP SEARCH.
            DFR           /DEPOSIT IN FN REG. AND
            EXCT          /EXECUTE.
            SOT           /SKIP ON TAPE FLAG
            JMP -1
            LSR           /LOAD STATUS REG.
            RTL           /SHIFT LP AND STATUS BIT INTO LINK
            SNL           /IS LINK = 1?
            JMP ERROR     /NO, ERROR HAS OCCURRED ILLEGAL INT.
            CLINT         /YES,CLR FLAG & PREPARE FOR READ
            CLX           /CLEAR INDEX REG.
            LAC WDCNT     /LOAD NO. OF WORDS TO BE READ
            PAL           /PLACE IN LIMIT REG.
            DZM DRPTS     /SET NO. OF DETECTED ERRORS = Ø
            LAC RDX       /AT LP., THUS EXTENDED READ LOADED
            DFR           /DEPOSIT IN FN REG. AND
            EXCT          /EXECUTE.
NOWD        LAW -6        /18 BIT WORD RECONSTRUCTED IN 6 3BIT BYTES
            DAC SHIFT
            DZM TEMP      /DUMMY LOCATION USED IN RECONSTRUCTION
RETURN      SOT           /SKIP ON TAPE FLAG
            JMP -1
            JMS READ
            ISZ SHIFT     /INCREMENT SHIFT COUNT, HAS WORD BEEN COMP
                          /COMPLETED?
            JMP CONT      /NO, PREPARE FOR REST OF WORD
            LAC TEMP      /YES, DEPOSIT WORD IN INDEXED START ADDRESS
            LAC STAD,X
            AXS +1        /HAS RECORD BEEN COMPLETED?
            JMP NOWD      /NO, PREPARE FOR NEW WORD
            STOP          /YES, STOP TAPE MOTION
            LAC DRPTS     /LOAD NO. OF DETECTED ERRORS
            HLT           /STOP PROGRAM EXECUTION
            JMP START     /RETURN FOR REPEAT
CONT        LAC TEMP      /COMPILED WORD IS SHIFTED TO MAKE
                          /ROOM FOR REST OF WORD
            RCL
            RTL
            DAC TEMP
            JMP RETURN
READ        0             /RETURN ADDRESS FROM SUBROUTINE
            LSR           /LOAD STATUS REG.
            RTL           /SHIFT DROPOUT BIT INTO LINK
            SZL           /IS IT A DROPOUT?
            JMP DRT       /YES, JUMP TO DROPOUT HANDLING
            RAL           /NO, ROTATE READ REQUEST BIT INTO LINK
            SNL           /IS IT A READ REQUEST?
            JMP ERROR     /NO, ERROR HAS OCCURRED
DATA        RID           /YES , READ DATA AND CLEAR FLAG
            RTR           /ROTATE 3 BITS READ INTO BOTTOM OF ACC.
            RTR           /THROUGH THE LINK
            AND MASK      /AND WITH MASK
            TAD TEMP      /ADD TO PARTLY ASSEMBLED WORD
```

```
        DAC TEMP     /RESTORE TO TEMP LOCATION
        JMP* READ     /JUMP BACK VIA RETURN ADDRESS
DPT     LAC  DRPTS   /LOAD DROPOUTS COUNT
        IAC            /INCREMENT COUNT
        DAC DRPTS     /REPLACE
        CLRDPT        /CLEAR DROPOUT FLAG
        JMP DATA      /CONTINUE PROGRAM EXECUTION
ERROR   LSR           /LOAD STATUS REG.THIS WILL SHOW
        STOP         /CAUSE OF ERRONEOUS INTERRUPT
        HLT          /STOP TAPE MOTION AND PROGRAM EXECUTION
         JMP START
LP      400000       /CODE FOR LP SEARCH
RDX     020000       /CODE FOR EXTENDED READ
MASK        7    /MASK
WDCNT   1000          /NO. OF WORDS IN OCTAL TO BE READ
```

6.3 Reliability

To obtain a statistical figure for the tape unit reliability is rather difficult. This is because of the variation in tape quality which occurs both between tapes manufactured by the same company and due to variations between different manufacturers. Also the life of the tape tends to depend to a large extent on its handling and environment. In order to obtain a general indication of the reliability of the tape unit, the following program was used.

Two identical records of 1500 computer words were written onto tape. The tape was then read back and the output compared with the record which was recorded. If an error occurred it was noted and after completion of the two records, another attempt (or second pass) was made to read the record correctly.

This cycle was then repeated with a new set of data. In order to determine whether errors were random or occurred in the same region of the tape, all errors were identified by their location within the record. A single tape was used and 1000 write/read cycles of 3000 words per cycle were procured.

This constitutes $3x10^6$ computer words or $18x10^6$ write operations. During this period, five 3-bit errors occurred on the first pass read and these errors were all recovered on the second attempt.

This is an average first pass error rate of one 3-bit error in $3.6x10^6$ 3-bit words recorded. Assuming a Poisson distribution, this can be interpreted as an error rate of 5^{+4}_{-3} 3-bit errors with 90% confidence in $18x10^6$ operations.

There were, however, no irrecoverable errors within this period, but unfortunately the duration of the experiment (~ 40 hrs.) precluded further searching for an irrecoverable error.

SECTION 2

INTRODUCTION

There are a large number of electronic instruments in use at the present time whose output is by nature essentially digital. This characteristic is frequently encountered in Nuclear Instrumentation where the process may involve the counting of discreet events. The digital characteristic is often not fully exploited despite the fact that in many cases the power of the instrument could be greatly enhanced if some means were available of entering the information from the instrument into a digital computer.

Punched paper tape has often been used in such applications but its cost as well as the inconvenience of working with paper tape, make an inexpensive, compact form of data storage very desirable.

With this in mind, a portable magnetic tape unit, compatible with the peripheral unit described in Section 1 has been designed and successfully interfaced to a radio-isotope scanner used in Nuclear Medicine.

Because of the wide variety of applications envisaged for this unit, the design philosophy was to keep the unit itself as simple and flexible as possible, and to allow the particular system specialties to be built into the interface between the tape unit and the device.

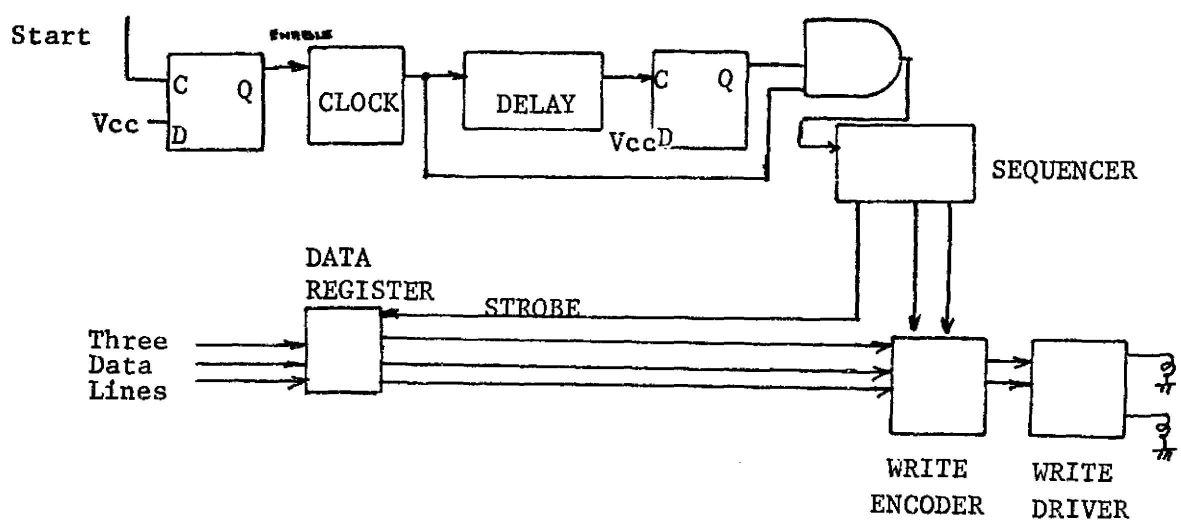
This section describes the design of the unit and its interface when applied to the field of radio-isotope scanning.

CHAPTER 7

THE PORTABLE TAPE UNIT

The portable unit is identical to the peripheral unit described previously as far as write format, writing speed and compatibility are concerned. The unit does not have a readback facility though, so that it is considerably simpler. Further, the absence of the computer to provide control makes it necessary that all control functions be either hardwired or manually set. Another minor difference in the hardware design is that noise immunity considerations have prompted the replacement of monostable delays with delays derived from counting circuits.

A block diagram of the tape unit is shown in the figure below.



The write encode logic, write driver circuitry, and motion control electronics are identical to that used in the peripheral unit. For the schematics of these sections, refer to:

Write Encode Logic - page 62

Write Driver Circuit - page 66

Motion Control Circuit - page 54

In the portable unit, pushbutton switches enable the following functions:

1. Search for start of tape (FIND LOAD POINT).
2. Set for first record--identical to the write extended function in the peripheral unit. When this function is set, an 800 msec. delay occurs before writing commences to allow the load point strip to pass the tape head (normal start delay is 200 msecs.).
3. Reset tape unit. Clears system.

In addition to this, eight status lights indicate the status of the unit. These lights are:

1. Power Supplies ON. ($+15^V$, -15^V and $+5^V$).
2. READY. (No Function being executed).
3. LOAD POINT searching.
4. SET for first record. (This is set when writing commences from the load point marker. Both the READY and FIRST RECORD lights should be on before recording starts.)
5. MOTION (Indicates that voltage is being applied to the motor windings.)
6. WRITING

The tape unit requires the following control signals and data from the device to which it is interfaced:

1. Three data lines
2. Start writing
3. Stop writing

The tape unit provides a pulse to the interface (called SHIFT) indicating that the data present on the data lines have been accepted and that another three bits can be loaded.

Two boards, the function control and the write timing boards control the whole unit. These are fairly straightforward as shown in Figures 7.1 and 7.2 and are discussed jointly.

A start signal from the device interface initiates tape motion and enables the write clock which has a period of 400 μsecs. The start signal, as in the case of the peripheral unit, also causes the tape to be saturated ensuring erasure of previous records. The clock feeds a synchronous BCD counter which provides two functions. At start up, it serves purely as a divide by ten counter to divide the 400 μsecs. clock down to 4 msecs; after the start delay it is used as a sequencer for the write operation. At start up the 4 msec. clock from the counter feeds further divide by 10, divide by 5 and divide by 4 counters. The output of the divide by 5 counter is then a 200 msec. clock required for normal start delay and the output of the divide by 4 counter is an 800 msec. clock required for a write extended (or first record) start delay. The applicable delay is obtained from the and-or delay selector. The o/p from the delay selector sets a flip flop providing control line RECORD (and $\overline{\text{record}}$). Thus, after the correct start up delay, the record line goes high enabling the 4 to 10 line decoder outputs to start the write sequencing. The BCD counter at this point is at a count of zero. At a count of one, the data present on the data lines is strobed into the data register from where it passes to the write encode logic. Note that it is necessary that the interface electronics provide the correct header

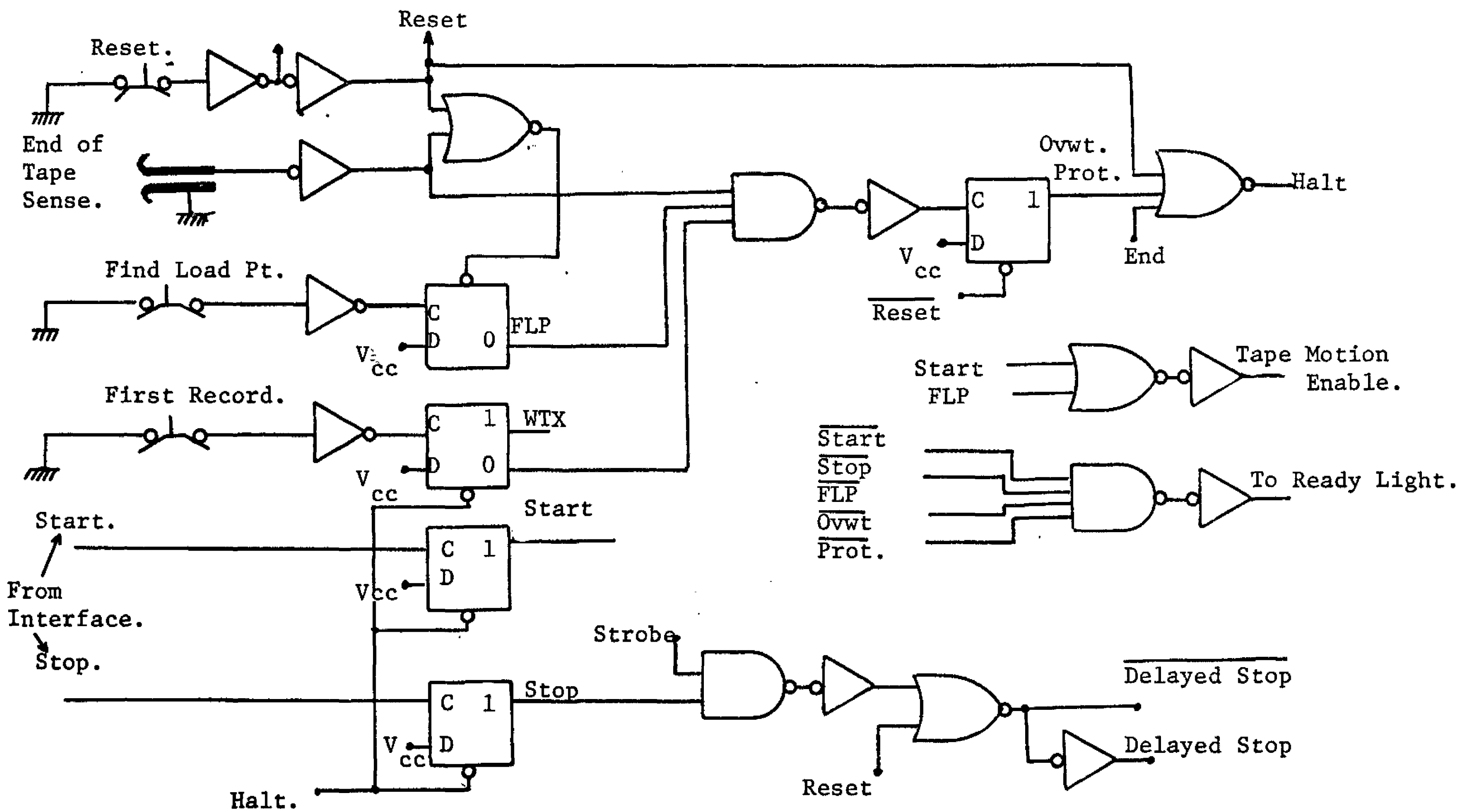


FIGURE 7.1 FUNCTION CONTROL LOGIC

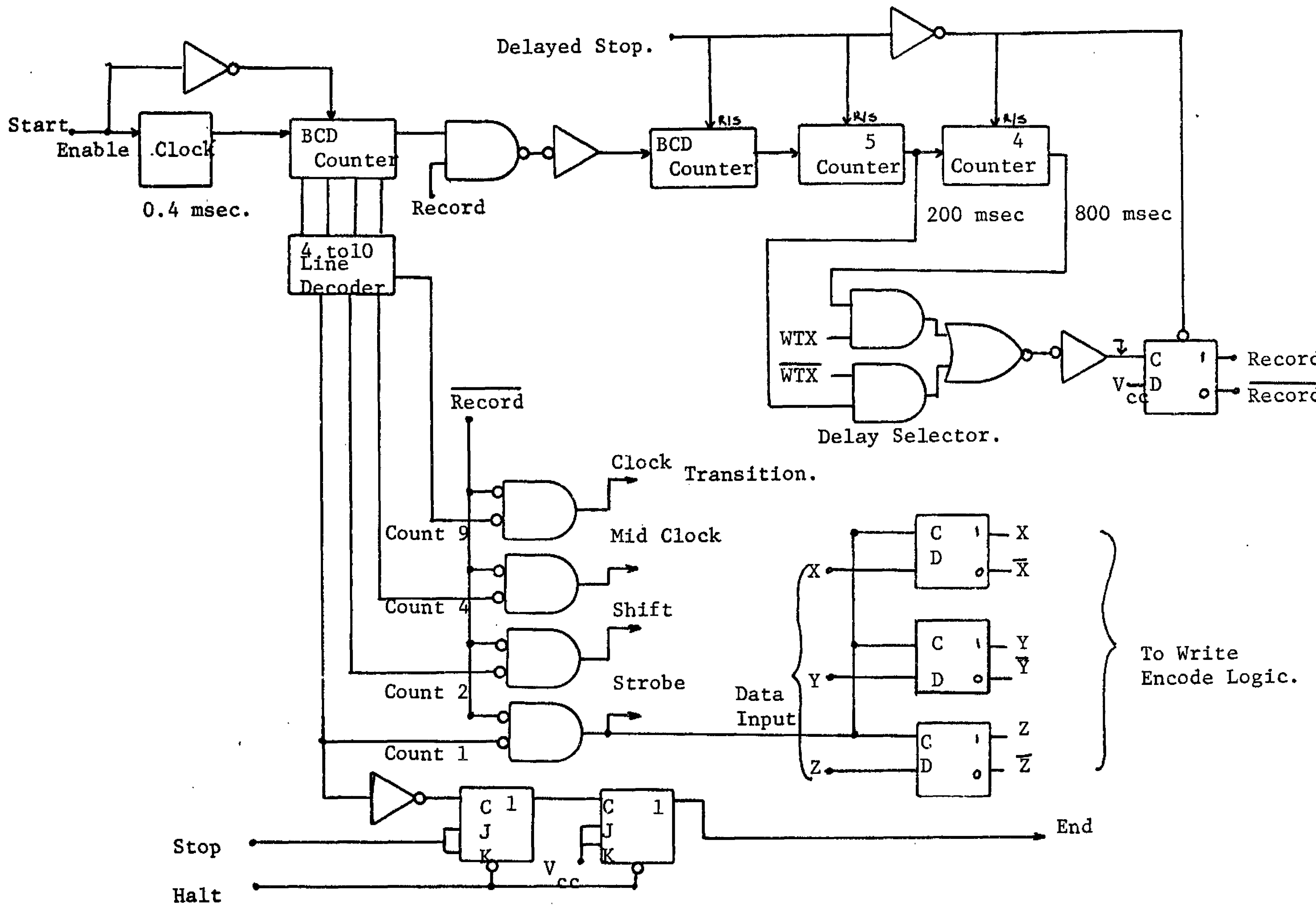


FIGURE 7.2 WRITE CONTROL AND TIMING LOGIC

to ensure the correct first two transitions of tape magnetization, i.e. the first and second data words of a record must be octal seven and octal zero respectively. After the data has been strobed on a count of one, a pulse is sent to the interface on a count of two indicating that the data presently on the lines has been accepted and another three bits should be loaded. Counts 4 and 9 are as in the peripheral unit, the midtransition and actual clock transition pulses. Having accepted the final 3 bits of data of a record (count 1) the interface will respond to a shift request (count 2) with a stop pulse. The unit then completes the write cycle recording the data which has been strobed at count 1. When the counter reaches a count of 1 again the delayed stop signal occurs. This signal clears the RECORD flip flop disabling further write current transitions and resets the FIRST RECORD flip flop so that future records will require only 200 msecs. start delay. The tape motion continues with the tape held in the state in which it was after the last data write transition. It is held in this state until the counter reaches count 1 again when the last recorded data transition is clear of the area of the head. At this point, the STOP DELAY flip flops produce the signal END which results in the Start and Stop flip flops being cleared and tape motion halted and the ready light enabled.

Finally, in order to prevent the tape from being overwritten when the loop has cycled, since it is a continuous loop, the Overwrite Protect flip flop is set if the load point is encountered during a normal write operation. This halts the tape and the unit must be reset in order to continue recording.

CHAPTER 8

RADIO-ISOTOPE SCANNING

(Reference 7)

The technique of radio-isotope scanning is employed for the visualization of the distribution of radio-activity within an organ (such as the thyroid) or of a lesion (such as a brain tumour). A γ-ray emitting radio-active compound is injected into the patient, or the compound is taken orally. It has been found that certain compounds tend to accumulate in various organs, the most well known of these being the accumulation of iodine in the thyroid. Some time after the compound is administered to the patient, a detector scans the area and detects the distribution of radiation within the organ. An image is built up which reflects the distribution of the concentration of the compound. The image which is obtained by a number of possible printout techniques is then visually observed and analysed.

Although the instrumentation required for this technique is fairly complex and expensive, the visual image produced is in most cases rather poor and on occasions it is difficult to obtain a definite prognosis. It is felt that by applying more sophisticated and quantitative techniques to the readout system of this instrument, its utility could be greatly increased. Further, if the readout system can allow a more quantitative output, it is possible that detection of abnormalities could take place at an earlier stage, thus facilitating treatment.

8.1 Scanner Configuration

A radio-isotope scanner consists of a number of components, which are shown schematically in the figure below.

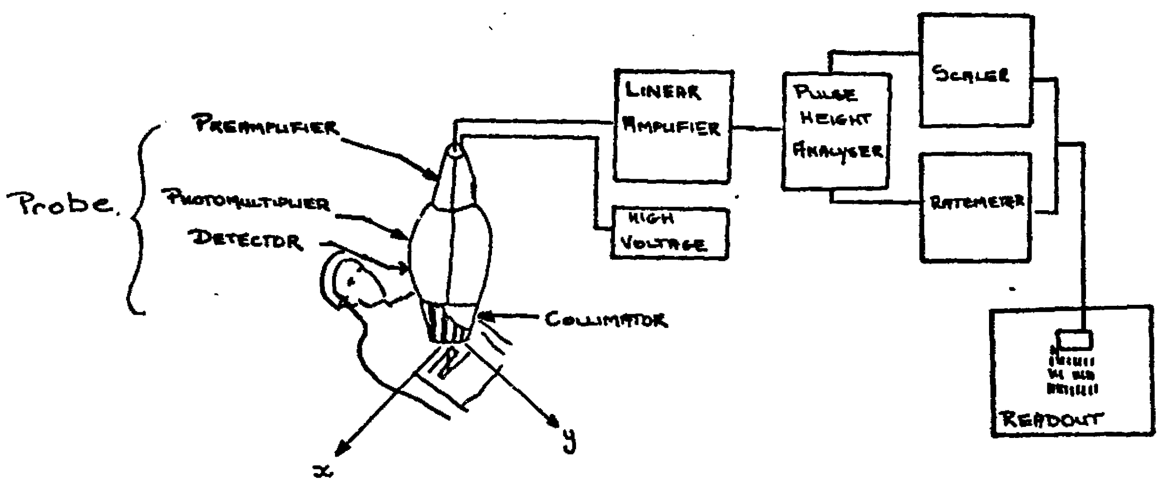


FIGURE 8.1 BLOCK DIAGRAM OF RADIOISOTOPE SCANNER.

The patient, having been injected with the isotope lies on the table with the focussing collimator situated above the area to be scanned. In some cases, a second detection system, identical to the system shown is placed below the patient. This allows correlation measurements to be performed between the two scanner outputs. The probe then moves continuously in the x direction, scanning the distribution of the radio-activity. The collimator transmits the γ rays from the source (patient) to the detector. The detector which is usually a NaI scintillation detector converts the radiation into light pulses which are then converted into electronic pulses by the photomultiplier tube. These pulses are amplified and processed by the electronic hardware resulting in a suitable optical readout system which can be visually analysed. When the probe reaches the extreme of its scan in the x direction it steps in the y direction and returns along the x direction. A system of stepping motors moves the detection system with respect to the patient and synchronizes the readout with the position of the detector.

There are two major problems which confront the designer of radio-isotope scanners. First, it is necessary to achieve sufficient sensitivity so that the distribution of the radio-activity can be determined with adequate statistical precision. Second, it is necessary that the detecting device be capable of sufficient resolution so that the distribution of radio-activity can be reproduced with adequate detail. As in the design of most instruments, these two requirements are in conflict and require a compromise.

The scintillation counter, usually a sodium iodide crystal, is a very sensitive detector which may record virtually all the radiation striking the crystal. The principal loss in sensitivity occurs in the collimating system, which is necessary to produce the desired spacial resolution. In general, the higher the resolution, the lower the sensitivity of the system.

The circuits used for pulse amplification, scaling and obtaining average count rates were introduced at an early stage in scanning development. The incorporation of a pulse height analyzer provided a substantial step forward in this field. With a radio-isotope that emits γ-rays of essentially one energy, pulse height analysis permits the exclusion of radiation which has been scattered in the source (i.e. the patient). As this scattered radiation will have originated away from the area of the focus, the suppression of this radiation results in sharper scans.

The speed with which the scanner moves and the steps between scans (or line spacing) is variable on all instruments. The OHIO Nuclear Scanner which was used employed scanning speeds variable between 20 to 760 cm/min. The scan speed will be varied depending on the concentration of radio-activity within the organ and the time available for completing the scan. Obviously, the slower the scanning speed the better will be the statistical accuracy of the scan.

A variety of readout systems offer several choices of display. The earliest and simplest method of scan presentation and one which is still used is the dot record. In this method, a stylus moving over a piece of paper stamps a dot or bar for every fixed number of input pulses from the pulse height analyser. The resultant scan shows a pictorial density variation proportional to the dot density and consequently to the count rate at that position.

Another common method, and that employed by the OHIO Nuclear Scanner is that of photoscanning. Xray film is used to record light flashes which correspond to individual detector pulses. The amount of film darkening produced by each light flash can be controlled by varying the brightness of the light flash or its duration, or sometimes both. The light source them moves in one to one correspondence with the scanner relative to the xray plate and produces an image such as the brain scan shown in Figure 8.2. In both of these readout systems described, the objective was to produce a finished picture at the conclusion of the scan. In each case, this requires some compromise in the readout system with the possible loss of valuable information.

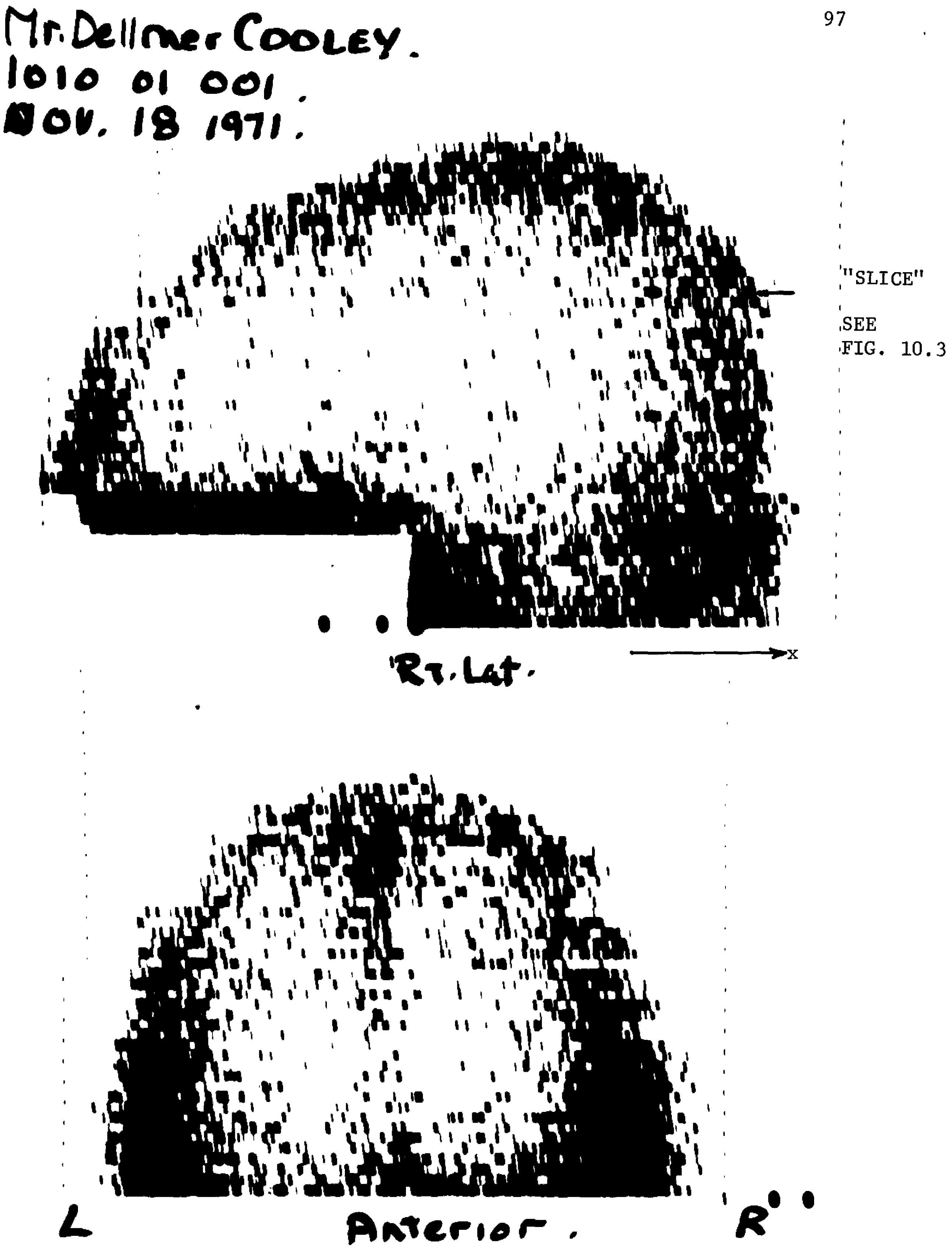
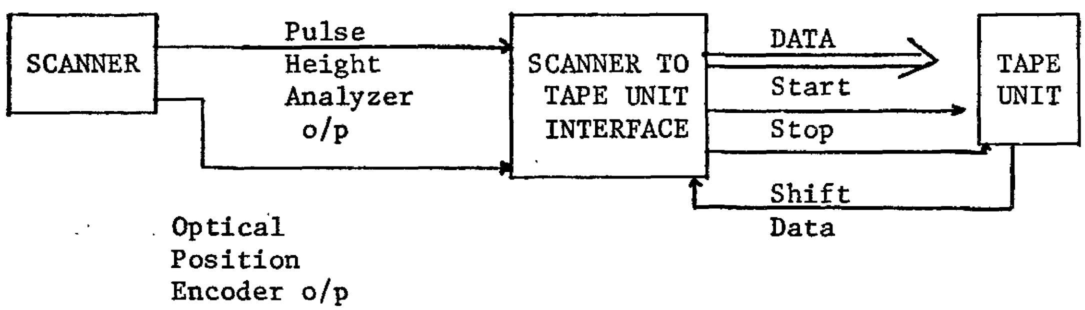


FIGURE 8.2 TYPICAL BRAIN SCAN

The ideal solution would be to preserve all the data accumulated by the detector in an accessible form so that it may be re-evaluated numerically or subjected to nonlinear transformations emphasizing the desirable information. Such data storage systems allow maximum flexibility of data handling, which is desirable for research applications. On the other hand, for routine scans, a simple, immediately available readout system has obvious advantages. With this in mind, a magnetic recording system which chould be interfaced to the scanner was designed.

8.2 Recording From the Scanner

A block diagram of the system is shown below.



Two signals are obtained from the scanner:

1. The o/p from the pulse height analyzer, one pulse being produced for each detected γ photon.

2. An o/p signal from the optical position encoder. This o/p is a square wave which has a period equal to the time taken for the scanner to move 1 mm. Since the scan rate is variable, the period of the square wave will vary accordingly.

The o/p from the pulse height analyzer is counted and the total number of pulses arriving within one m.m. of travel is recorded.

CHAPTER 9

THE SCANNER - TAPE UNIT INTERFACE

9.1 General

Up to this point, the radio-isotope scanner and the portable tape unit have been described. It is now necessary to provide an interface between the two which will convert the signals from the scanner into a form which the tape unit can accept.

The requirements can be summarized as:

i) From the scanner

  a) Pulses from the pulse height analyzer which are to be counted.

  b) Optical encoder signals indicating that the count total from the pulse height analyzer is to be stored and recorded and the counter reset.

ii) To and from the tape unit

  a) Signal to start writing

  b) Signal to stop writing

  c) Three bits of data to be supplied to the tape unit, with new data to be supplied after every shift pulse is received from the tape unit.

An important consideration in the interface design is the fact that while the tape unit writing speed is constant the data rate from the scanner is variable. Since the tape unit cannot be operated in a stepping mode, it is necessary that the interface provide a buffer to accommodate this variation in data rate.

Preliminary tests on the scanner showed that a maximum scan speed of 130 cm/min. should be allowed for and that a nine bit binary counter would easily handle the number of counts from the pulse height analyzer. In order to allow for the lower detector, a two 9-bit word or an 18-bit double word is to be dumped onto tape with the arrival of each optical encoder signal.

In order to handle these requirements, a dual buffer system is employed. In this way, one buffer is loaded with data. When this buffer has been filled, the mode changes and the second buffer is then filled while the filled buffer is written onto tape. The amount of buffer storage required is determined by the maximum data date and the writing speed.

Assume that the buffer length is n 18-bit words. Then every time we write onto tape we will write these n 18-bit words plus the tagword and header (another two 18-bit words). The time required to write n+2 18-bit words on tape is: T = start time of the tape unit + writing time + stop time of the unit. Ignoring the first record extra delay, the start time is 200 msecs. and the stop time is also 200 msecs. The writing speed is 3 bits every 4 msecs. or one 18-bit word every 24 msecs.

The total time T is thus:

$$T = 200 + (n+2)\ 24 + 200\text{msecs}$$

$$T = 24n + 448 \quad \text{msecs.} \qquad \text{-- (1)}$$

During this time, T, the second buffer, is being filled. At the maximum speed the second buffer will be filled and ready to be dumped just as the first buffer has emptied, i.e. in Time T.

$\therefore$ T = n x time between arrival of each word.

= n x ta

This ta is a function of the scanning speed. The optical encoder transmits a transfer signal for every 1 mm. of travel in the x direction. Thus, at the maximum speed of 130 cm/min. the time between transfer signals is :

$$ta = \frac{\text{distance travelled between optical encode signals}}{\text{speed of scanner}}$$

$$= \frac{1 \text{ mm.}}{130 \text{ cm/min.}}$$

$$= \frac{600}{13} \text{ msecs.}$$

$\therefore$ T = nta msecs.

$$= \frac{600\ n}{13} \text{ msecs.} \qquad \text{--} \quad (2)$$

$\therefore$ Solving for n from (1) + (2)

$$T = \frac{n600}{13} = 448 + 24n$$

gives n = 20 words

= 360 bits of storage

With the advent of mos LSI this does not present any severe problem. Using two dual 128-bit mos shift registers for each buffer, we will have a storage capacity of 512 bits or 28 words and 8 extra bits.

The header and tagword bring this up to 30 words; the time necessary to dump 30 words is 1.12 secs. The time taken to accumulate

28 words of data at the maximum rate is 1.3 secs. so that at the maximum rate the tape unit will be idle for 180 msecs. between 30 word dumps. The format of the data recorded on the tape will be blocks 30 words in length. Each word will contain two 9-bit words with the count from the scalers. The block diagram of the interface and illustration of tape format is shown in Figure 9.1.

9.2 Detailed Design

Each half of the interface buffer system operates in two cycles. The load cycle during which data is loaded into the selected mos buffer, and the write cycle during which the filled buffer is shifted out onto tape.

The overall shift register and scaler schematic is shown in Figure 9.1.

This can, for convenience, be described by the three major sections:

1. The nine bit input scalers and 18-bit input shift register.
2. The mos shift registers and TTL/MOS, MOS/TTL interface
3. The 24-bit o/p register and tagword scaler.

The flow of data through these sections is controlled by two control sections.

1. The 28 x 18-bit input shift control which controls the loading cycle
2. The 180 x 3-bit output write control which controls the write cycle

These two share a common 250 kc/s clock which controls all timing but are otherwise asynchronous.

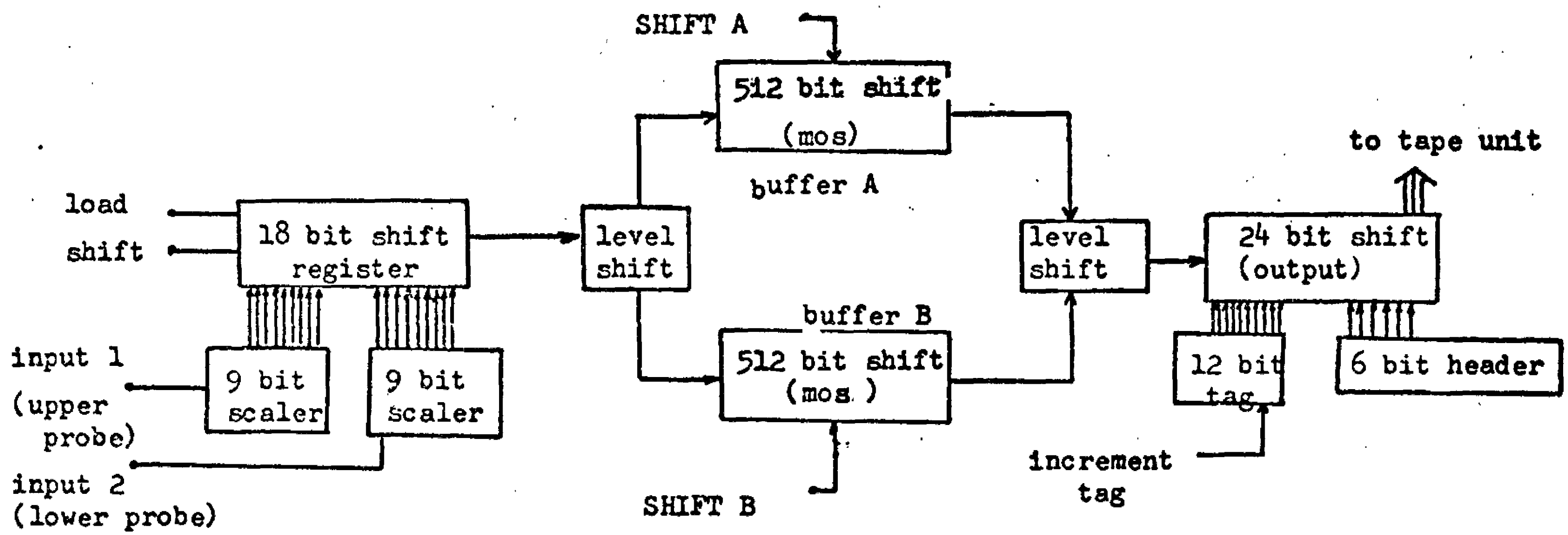


FIGURE 9.1a INTERFACE BLOCK DIAGRAM.

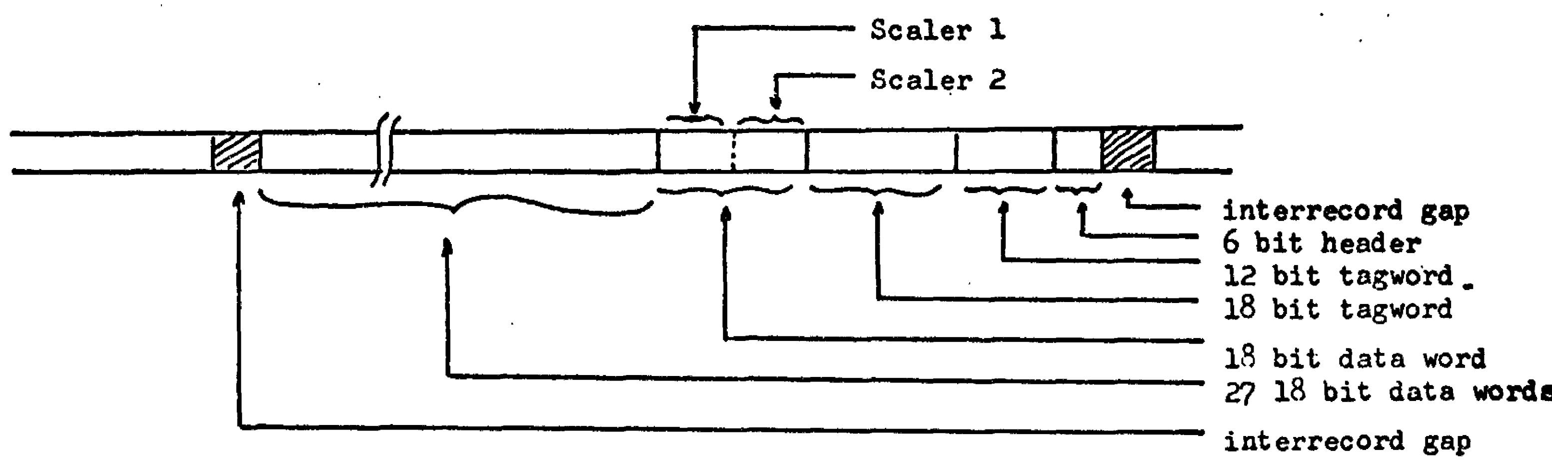


FIGURE 9.1b TAPE DATA FORMAT.

9.2.1 The Shift Register Configuration

The overall shift register section is shown in Figure 9.2 together with its logical subdivisions. To follow the flow of data through the interface, we assume that initially, buffer A is selected (i.e. Mos Register A will be loaded). The pulses from the two pulse height analyzers feed directly into inputs 1 and 2 of the input section. These pulses are shaped and as long as the enable line is high, feed into the 9-bit scalers. The enable line is held high at all times except during a transfer from the scalers to the 18-bit shift register. The two scalers are then parallel loaded into the 18 bit shift register. These data are then shifted out of the 18-bit register into the selected mos register (buffer A in this case) and the scaler count is reset to zero. When 28 words have been loaded into the mos register in this way, the register is full and ready to be transferred onto tape. The mode selection is then switched so that Buffer B is now to be loaded. The write control logic then increments the tagword count in the 12 bit tagword scaler and transfers both the count total and the header (70 octal) onto the 24-bit o/p register. A START WRITE signal is transmitted to the tape unit which then accepts data from the last three bits of the o/p shift register. After every 3 bits has been accepted by the tape unit, it transmits a shift pulse to the write control logic, which then shifts the contents of the mos and output registers three places to the right. This continues until all the data in the mos register has been accepted by the tape unit (30 words altogether = 180 three position shifts). At this point, the output cycle is completed and the tape unit is signalled

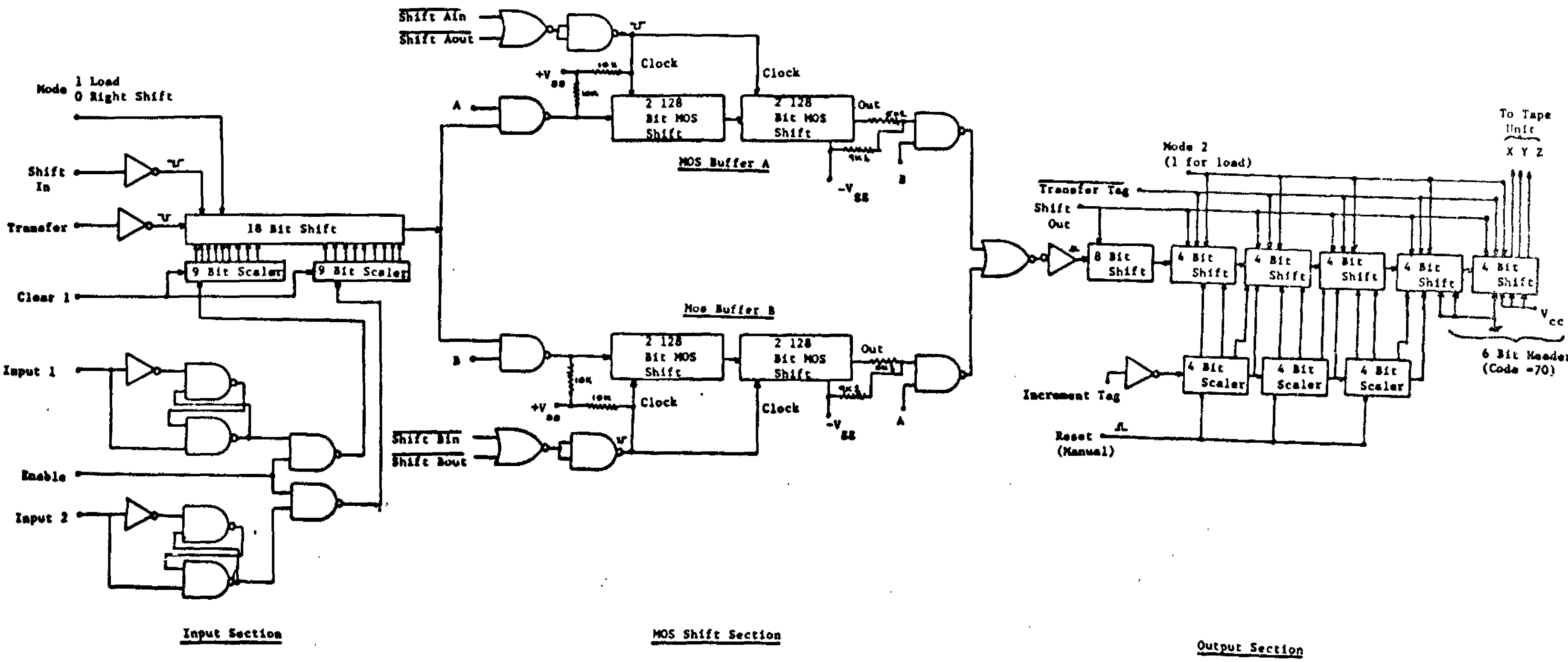


FIGURE 9.2 SHIFT REGISTER CONFIGURATION

to stop. When buffer B (which has been loading during this time) is filled, the process is repeated with the data in buffer B being shifted out and buffer A being selected for the load cycle.

9.2.2 Input Shift Control Logic

The input shift control is shown in Figure 9.3. All control signals are named and their function can be seen in the overall register schematic.

The arrival of an optical encoder signal indicates that the contents of the input scalers should be stored. After being shaped, the optical encode signal sets the JK flip flop which in turn loads a 1 into the continually clocked 4 bit shift register, and then resets the flip flop when it is loaded. At the same time, it generates levels MODE 1 and ENABLE. MODE 1 enables the 18-bit shift register for a parallel load and ENABLE which will be low prevents the scaler count from changing during this time. The next shift to the right produces the transfer from the scalers to the shift register. The final shift (CLEAR 1) before leaving the register clears the scalers, enables the signal inputs to the scalers and sets the mode of the 18-bit register for a shift right operation. This final shift (CLEAR 1) also resets the 5-bit counter in Figure 9.3. The o/p from the NAND gate A will then be high allowing clock pulses to enter the counter. Eighteen pulses occur until the NAND gate returns to the low state. These 18 pulses shift the data out of the 18-bit register and into the selected mos register. The transition back to the low state of NAND gate A is transmitted to the write control logic as a SHIFT DONE.

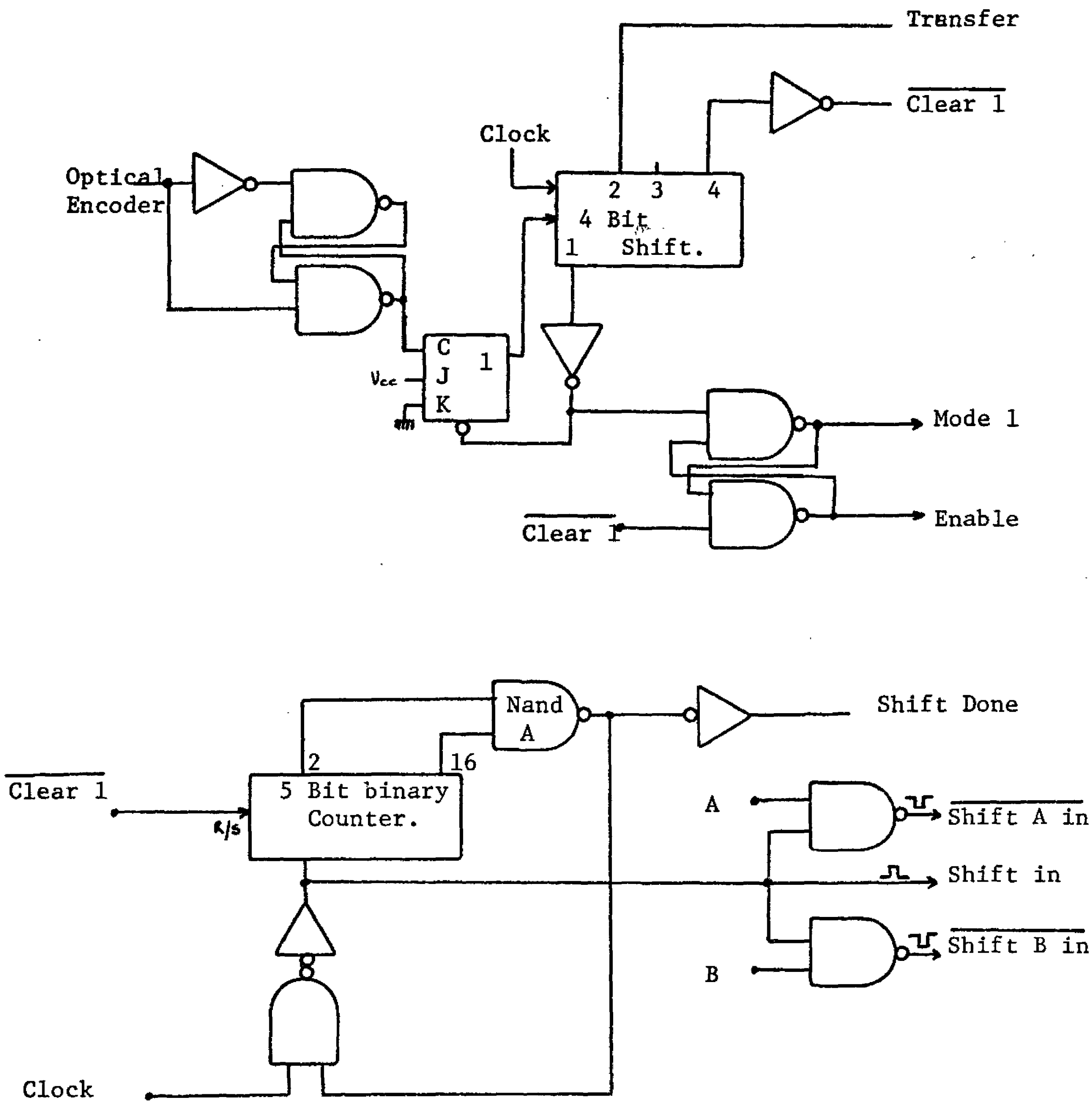
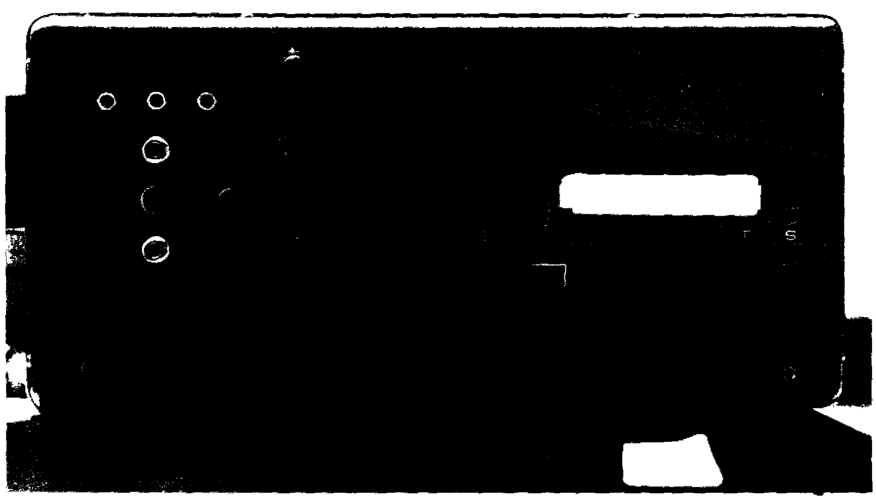


FIGURE 9.3 INPUT SHIFT CONTROL LOGIC

10.2.3 Write Control Logic, Figure 9.4

The SHIFT DONE signals are counted in the 5-bit counter. When 28 shift done pulses have occurred, the Mos Register has been filled. At this time, the o/p of NAND gate B will go low and results in a 1 being set in the 4-bit shift register. This resets the counter, and sets the 24-bit o/p register to accept parallel data. The first shift right produces Increment Tag which increments the count in the 12-bit tagword register and changes the mode so that buffer B is now selected. On the third shift, the 24-bit o/p register is parallel loaded with the tagword and hard wired header (octal 70). The final shift transmits the start write signal to the tape unit and this resets MODE 2 to shift right position. The arrival of the shift signal from the tape unit increments the count in the 8-bit binary counter and sets the first bit in the 8-bit shift register. The 8-bit shift register produces three shift pulses which shift the data from the Mos register through the 24-bit o/p register, 3 positions per shift signal from the tape unit. The 8-bit binary counter counts the number of shifts which have occurred. When this count reaches 180, the entire buffer has been shifted out to the tape unit. At this point, NAND gate C o/p goes low inhibiting further shift signals which might arrive and setting the first bit in the 4-bit shift register. In the same manner as before, the 1 shifted through the 4-bit register transmits a STOP WRITE signal to the tape unit and resets the 8-bit counter.

Radio-Isotope Scanner



Portable Tape Unit

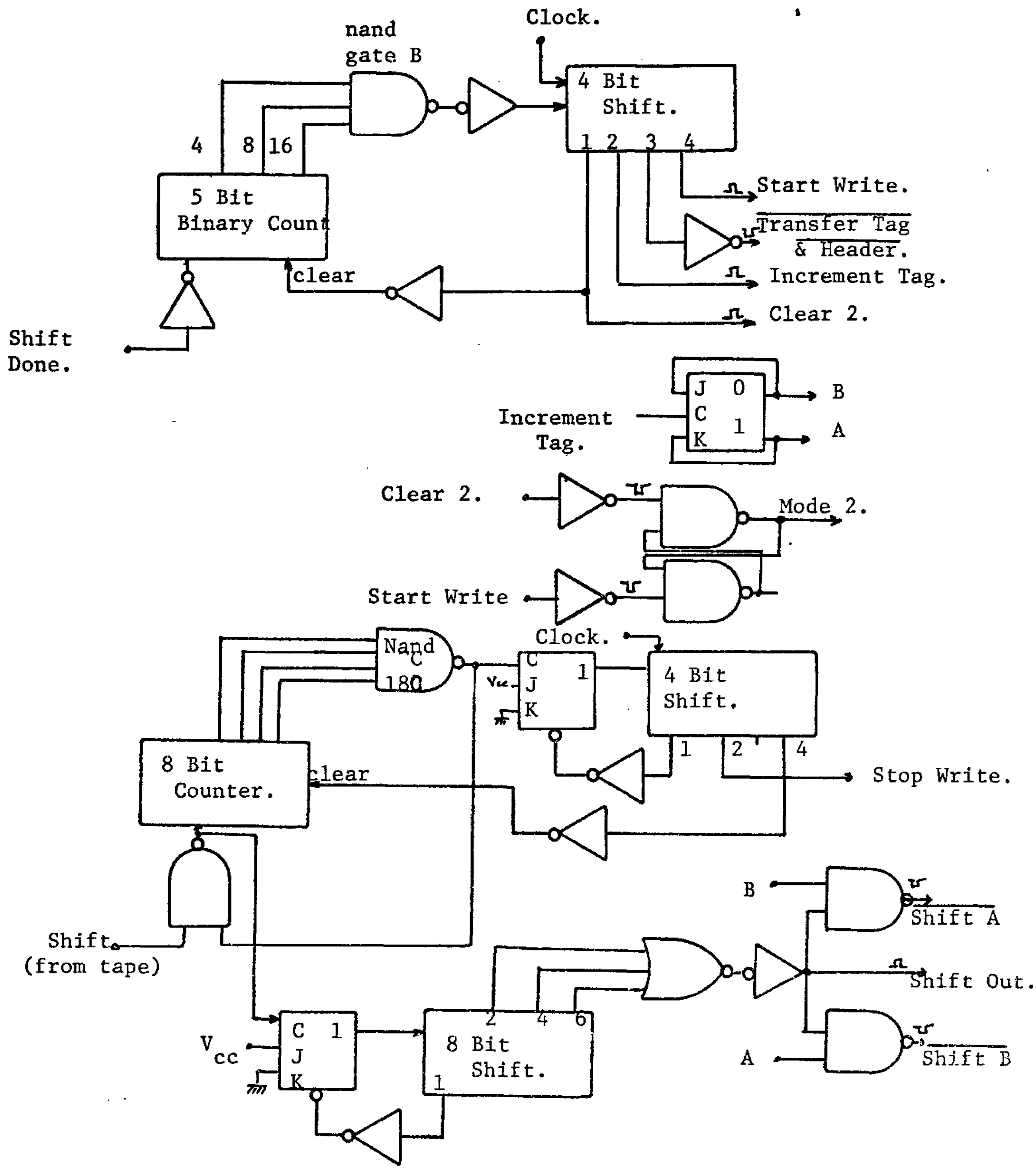


FIGURE 9.4 WRITE CONTROL LOGIC

CHAPTER 10

RECORDED SCANS

The initial work which has been done using the overall system involved the acquisition of data necessary for future research into resolution and image enhancement.

By scanning and recording the response of the system to a single line source of activity, the impulse response or overall transfer function of the scanner is obtained. Figure 10.1 shows the results obtained when a single line is scanned with the source placed at varying distances from the focal plane of the collimator. It can be seen from this scan that the focus occurs at a distance of approximately three inches. The resolution is greatest at this point and deteriorates as the collimator is moved in either direction from the focus. Fourier Transformation of this output gives the frequency response of the system, usually called the Modulation Transfer Function (MTF) in image enhancement work. The MTF can then be used for both matched filtering and deconvolution experimentation.

Note that the scan shows the variation in counts as the scanner moves in one direction, from front to rear or rear to front. In Figure 8.2 this was referred to as the x direction. When the probe reaches the extreme of its scan, it steps in the y direction and then returns. The ultimate objective in any image processing would thus be to obtain a contour map or two dimensional image of the count distribution. This is complicated by the fact that the steps taken in the x and y directions are not equal so that when filtering or smoothing is performed in two dimensions it will be necessary to take this fact into account. Preliminary work will consider the simplified case of a 1-dimensional situation of scanning in the x direction only. Results obtained in this way can then be extended to the two-dimensional case. For this purpose, the scan shown in Figure 10.2 was recorded. This shows the response of the system to a number of line sources of varying activity and spatial separation located at the collimator focus and scanned in the x direction. Attempts will be made to improve the resolution by means filtering or smoothing and then subsequent deconvolution (references 8 and 9).

Finally, Figures 10.3 &.4 show a typical "slice" of brain scan. The particular "slice" recorded is from the brain scan which was also recorded on photographic film and shown on page 97.

The "slice" or particular x direction scan is indicated in this picture. The trend of the scan can be more easily determined from the smoothed scan shown in Figure 10.4. This is the identical scan which has been subjected to a linear smooth (or weighted average).

The equation used for the smooth is:

$$\bar{c}_i = \sum_{j=i-2}^{j=i+2} \frac{(3-|i-j|)c_j}{9}$$

where $|i-j|$ = modulus i-j and

c_i is the point being smoothed.

This is equivalent to convolving the output spectrum with a triangle of height three units and width of five units. Comparison of this smoothed scan with the indicated "slice" of the brain scan on page demonstrates the rather small dynamic range of the photographic film.

This is witnessed by the relatively small difference in the number of counts between very dark and very light areas on the film.

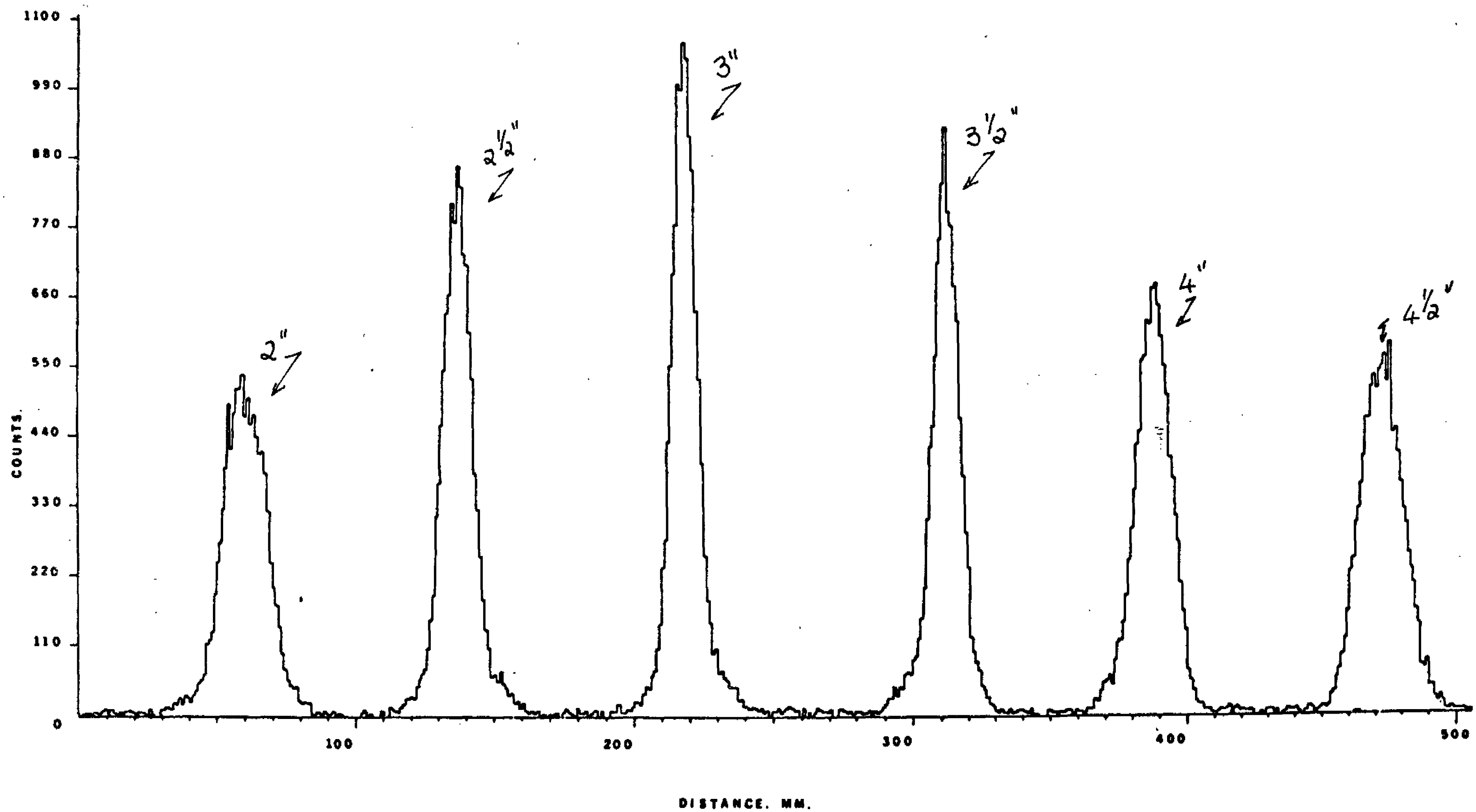


FIGURE 10.1 RESPONSE TO A SINGLE LINE SOURCE

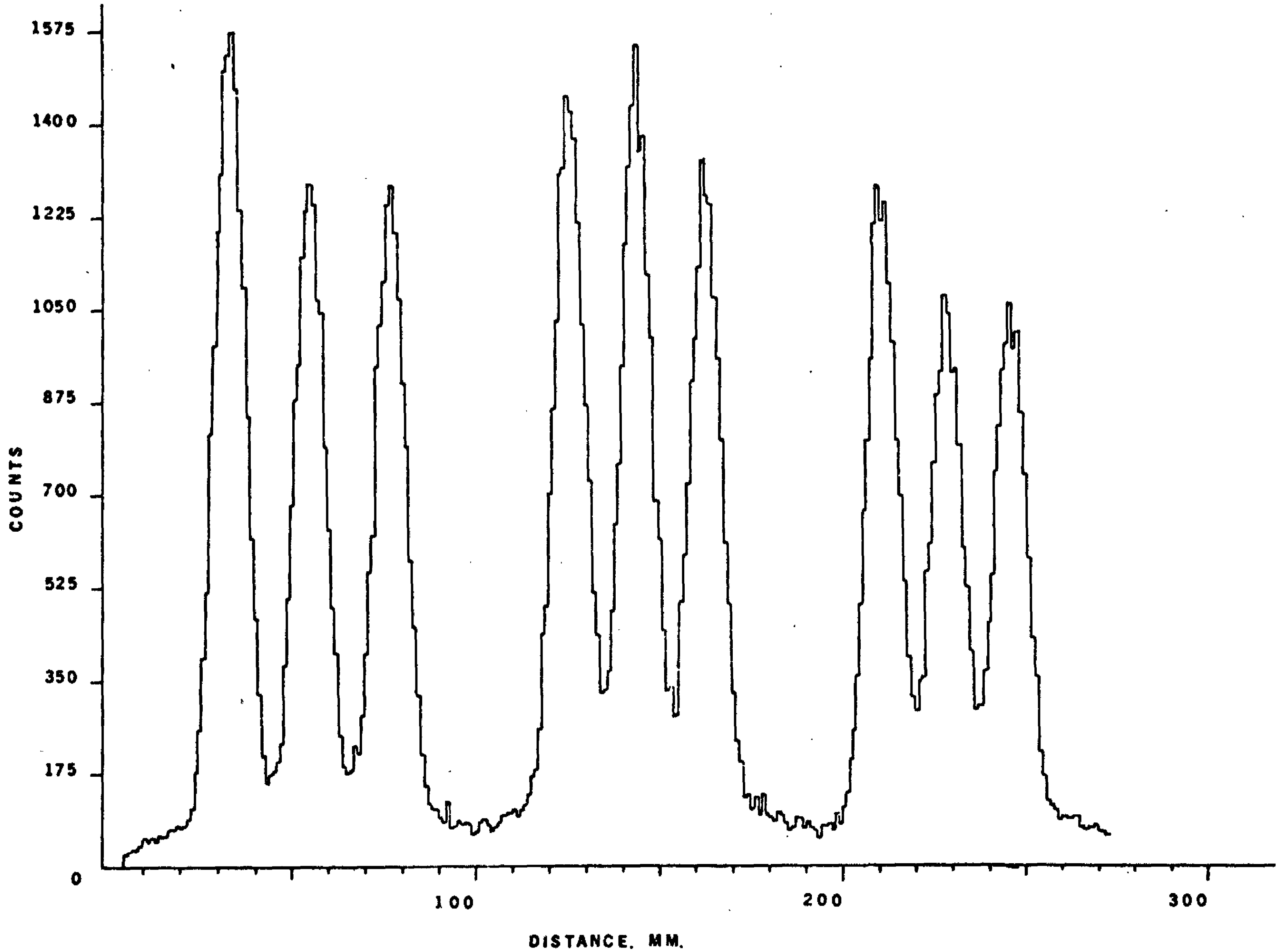


FIGURE 10.2 RESOLUTION CALIBRATION

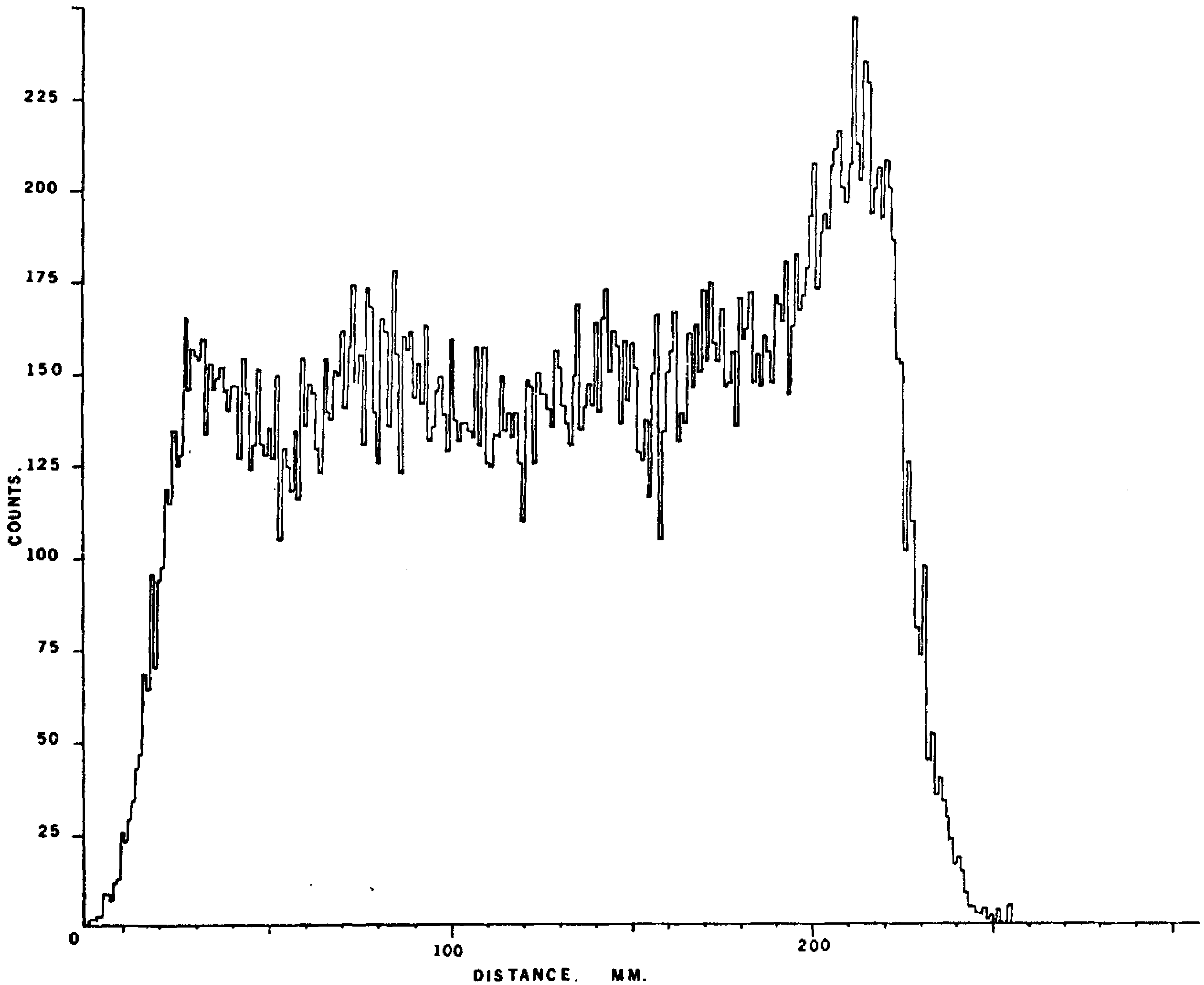


FIGURE 10.3 BRAIN SCAN

CONCLUSIONS

This thesis has outlined a pseudo-ternary coding technique which utilizes the three level nature of the output signal from a digital magnetic recording system in order to increase the effective data rate, when two tracks are used in parallel.

The design of a digital recording system using this technique has been described and the application of a portable system to radio-isotope scanning is illustrated.

There are many possible codes which can be used and future work in this field should investigate these possible codes with respect to error detection and correction.

It is felt that this technique warrants further investigation and it is felt that minor modification could make this form of recording extremely effective at high densities where phase encoding techniques of recording are normally employed.

The application of digital recording techniques to radio-isotope scanning provides a means for quantitative analysis of the scanning process. Future work in image enhancement, using this system, could produce a useful supplement to the conventional scan recording techniques.

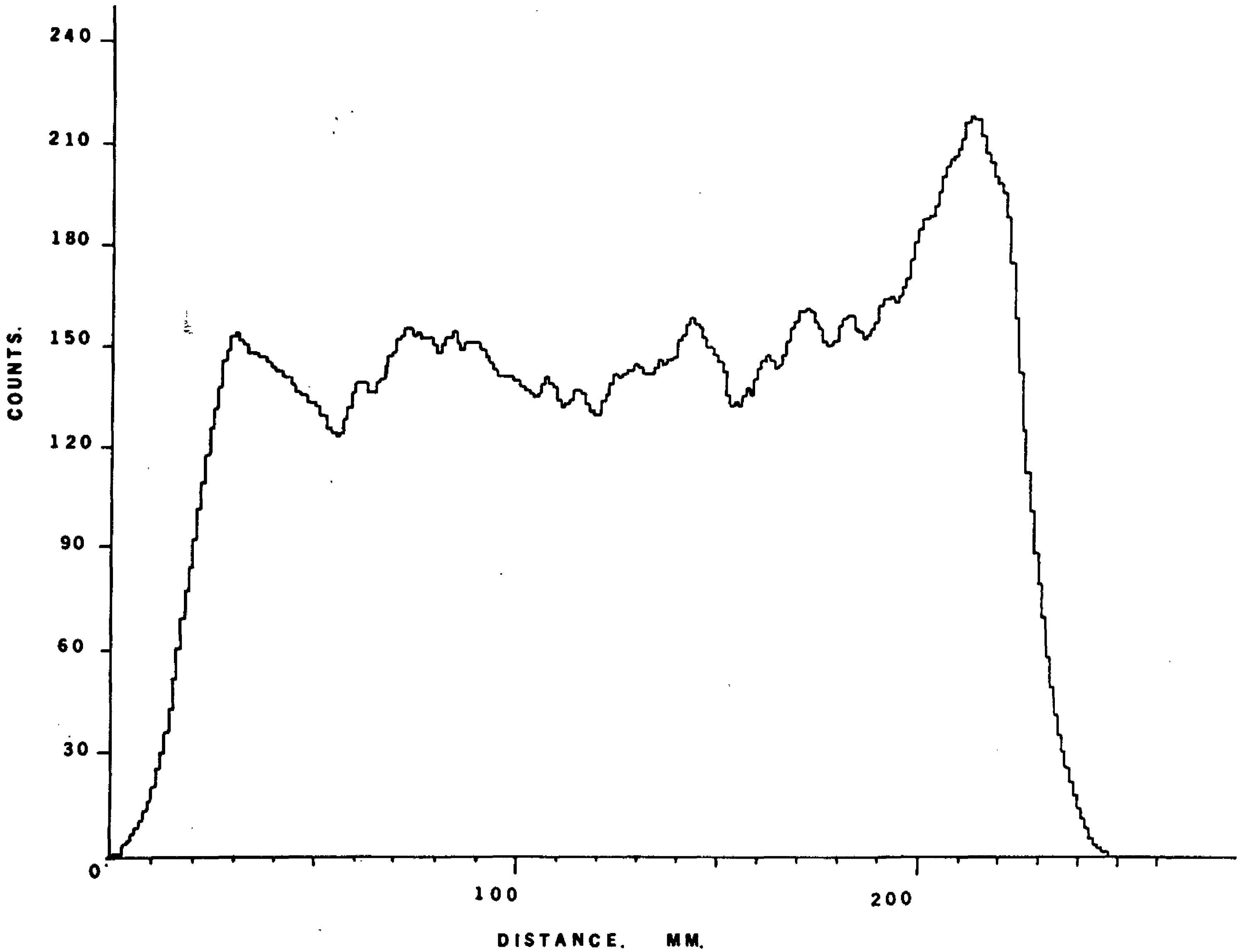


FIGURE 10.4 SMOOTHED SCAN

REFERENCES

1. Kraus, John D., Electromagnetics, McGraw Hill, New York, 1953.
2. Hoagland, Albert S., Digital Magnetic Recording, John Wiley & Sons, Inc., N. Y. 1963.
3. Richards, R. K., Digital Computer Components and Circuits, Van Nostrand Company, Inc., Princeton, N.J., 1957.
4. Dakin, C. and Cooke, C., Circuits for Digital Equipment, Iliffe Books Ltd., London, 1967.
5. Kobayashi, H. and Tang, D., Application of Partial Response Channel Coding to Magnetic Recording Systems, IBM Journal of Research and Development, July, 1970.
6. Carson, R., Dropouts in Magnetic Recording Systems, International Conference on Magnetic Recording, I.E.E. Electronics Division, London, July, 1964, pp. 20-23.
7. Hine, G. J. (editor), Instrumentation In Nuclear Medicine, Vol. 1, Academic Press Inc., N.Y., 1967, Chapter 15, MacIntyre, W., In Vivo Tracer Studies by External γ ray Counting.
8. Brownell, G. and Chesler, D., Basic Concepts of Resolution Enhancement, Quantitative Organ Visualization in Nuclear Medicine, edited by P.J. Kenny and E. M. Smith, University of Miami Press, 1971.
9. Iinuma, T., Image Enhancement by the Iterative Approximation Method, Quantitative Organ Visualization in Nuclear Medicine, edited by P.J. Kenny and E. M. Smith, University of Miami Press, 1971.

10. Croisier, A., Introduction to Pseudoternary Transmission Codes, IBM Journal of Research and Development, July 1970.

11. Applications Manual for Operational Amplifiers, Philbrick/Nexus Research, 1968.

12. The Integrated Circuits Catalogue, Texas Instruments, Inc. 1971.