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HIGH DENSITY DISC RECORDING DEVELOPMENT PROGRAM

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HIGH DENSITY DISC RECORDING DEVELOPMENT PROGRAM

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General Dynamics/Electronics Division

[redacted]

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FOREWORD

The program objective is to apply the technology which has been employed in the General Dynamics' UNIversal DAta Recorder, UNIDAR(TM), system utilizing magnetic tape to the disc-type magnetic recorders. The recording technology applicable to magnetic tape and magnetic discs is similar, however, the techniques of one cannot be directly applied to the other without considerable investigation. The technology is a method of coding binary information into a format which greatly increases the equivalent packing density of data on tape. The program goal is to increase the disc recording track data density above that which is currently achieved with standard systems while maintaining an error rate of approximately one in 10^{11}.

This interim report compares various encodings, identifies the UNIDAR technology code as being the best approach, and specifies the in-contact disc requirements for high density data recording. Described are three channels of UNIDAR hardware and the versatile disc test bed which have been procured. A novel error detector which has potential error correction is also described.

The project engineer greatly appreciates the assistance of R. W. Freytag in the study program and his major contributions to this report.

Information contained in this report concerning UNIDAR technology is restricted to the extent described in the Data Clause on the title page. UNIDAR is a registered trademark of the General Dynamics Corporation. Paragraphs marked with an asterisk contain proprietary information.

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RADC Project Engineer

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GLOSSARY OF TERMS

BCT	Binary Coded Ternary
B_{rs}	Saturation Remanance of the Media
Byte	A group of adjacent bits operated upon as a unit and usually shorter than a word
$\frac{d\emptyset}{dt}$	Derivative of $\emptyset$ with respect to time
f_c	Nominal upper cutoff frequency
$Fe_2 0_3$	Ferric Oxide
FM	Frequency Modulation
H_c	Coercivity
HDDR	High Density Disc Recorder
MnBi	Manganese Bismuth
NiCo	Nickel Cobalt
NRZ	Non Return To Zero
ØM	Phase Modulation
PM	Period Modulation
PST	Paired Selected Ternary
S/N	Signal-to-Noise
TTL	Transistor-Transistor Logic
UNIDAR	UNiversal DAta Recorder
VCT	Voltage Coded Ternary

1.0 SUMMARY

This program is to establish the feasibility of transferring the methods and techniques employed in General Dynamics' UNIDAR technology on magnetic tape recorders to disc type magnetic recorders. The program goal is to increase the linear bit packing density on a disc to a minimum of 10,000 bits per inch while maintaining an error rate not to exceed 10^{-11}. The current UNIDAR tape recording technology achieves a bit packing density of 33,000 bits per track inch at an error rate of 10^{-6}.

* The existing UNIDAR technology converts binary information through special encoding circuits to the UNIDAR three level code. The three possible states of the UNIDAR codes are +, 0, and -. The codes are combined in such a manner that the algebraic sum of the components over a four bit interval always add to zero. This feature allows inherent error detection and potential error correction. The signal is filtered and shaped so that its spectral distribution closely matches that of the recorder response. Direct analog recording techniques using a high frequency bias signal are employed to transfer the data stream to the tape. During reproduction, equalization techniques compensate for amplitude and phase distortions introduced by circuit, gap, and spacing effects. Polarity and level threshold detection techniques are used to discriminate between the three possible states. Decoding logic converts the UNIDAR data stream into the original binary information.

During the study portion of the disc program, the primary objective was the design of an adaptable disc recorder test bed suitable for the evaluation of the recording efficiency and compatibility of UNIDAR and other binary or multi-level encoding techniques. Disc parameters such as track density, linear packing density, S/N bandwidth requirements, error rate, equalization, clocking, recording technique and format, error detection and correction and system properties were all investigated. Justifications for the selected disc properties were established and a performance specification for the test bed was prepared.

Only three disc manufacturers displayed an interest in this wideband in-contact instrumentation recorder specification. Two of the three manufacturers responded. The third could not meet the limited price and delivery schedule as specified. A trade-off analysis between the two remaining manufacturers was conducted and upon the completion of the trade-off, the disc was ordered from Data Disc Incorporated. Delivery of the disc is expected on 15 May 1970.

Fabrication and checkout of three channels of the UNIDAR electronics is completed.

2.0 ENCODING

Encoding for the high density disc recorder (HDDR) provides maximization of the packing density of the digital signals for a given error rate. The available bandwidth and the signal-to-noise ratio determines the theoretical data or Shannon limit [1] for error free transmission. This is defined as:

$$C = W \log_2 \left(1 + \frac{S}{W N_O}\right) \quad \text{bits/sec} \qquad (1)$$

where:

C = channel capacity
W = channel bandwidth
S = the average signal power
N_O = the Gaussian noise power in a one cycle band

Most systems attain only a small fraction of this capacity due to the extremely complex signaling system required. Minimization of the complexity of the signaling system is based on economic feasibility, required error rate, spectrum match of the signal to the channel, and the amount of non-white noise.

The encoding limit is affected by both electrical and mechanical parameters of the HDDR system. Three forms of encoding modulation are applicable for recording; they are phase, frequency, and amplitude.

The encoding process should transform the digital signal spectrum into the spectrum of the recorder which is zero at dc, rises at 6 dB per octave to a maximum and falls off rapidly beyond the cutoff frequency. There are few encodings which match this spectrum shape. This program has studied the codes to determine their efficiency, practicality, and insensitivity to the error sources of the disc system. At present, the UNIDAR code is considered to contain the properties best suited for application to disc operation.

* 2.1 UNIDAR Concept and Operation

UNIDAR resulted from a study of encodings to find a better spectrum match between the signal and the response of the recorder. The main feature of the UNIDAR encoding and decoding technique is that it causes a serial stream of binary information to be converted to a voltage coded ternary (VCT) analog signal for recording, and coverted back again after playback. The UNIDAR ternary signal is formed by separating the input binary sequence into four bit bytes. Each byte is encoded into a unique four-bit, tri-level, zero average format word as shown in Table 1, UNIDAR Encoding/Decoding. The set of four three-level bits contain 3^4 or 81 members, eighteen of which have the zero average property. Since a four-bit binary word has 2^4 or 16 possibilities, a unique encoding process can be established with two spare ternary words available for framing and synchronization in the playback decoding process. The recorded signal is formed from the sequential series of the zero average words.

* 2.2 Applicability of the UNIDAR Code to Disc Recording

For the disc program, the judicious choice of the available UNIDAR combinations creates a ternary code which has the following desirable properties:

1) A narrow spectrum whose power requirement closely matches the unequalized disc head response which is minimal at dc and increases with frequency.

2) A high encoding efficiency in terms of bits encoded per bandwidth required.

3) A self-clocking code which provides bit integrity and synchronization of the disc on both an inter and intra track basis.

4) A code whose transmitted sequence is history independent. This eliminates the occurrence of error bursts caused by single errors.

5) A zero average per four bit word encoding. This allows word as well as bit timing information. It also allows an error detection and potential for error correction. Redundancy exists in that any three bits of the four ternary bit format word uniquely specify the transmitted word; the fourth bit allows parity check per word.

6) Two extra code words; the first, or frame word, is used to indicate beginning and end of data blocks. This identifier provides the control for block erasure and transfer testing. The other word is unique for any desired assignment. It is normally used to identify binary input data which has poor quality. It will have value to both the disc test program and the on-line system.

7) An alterable spectrum; the encoding alphabet is arbitrary and its order may be changed by simply rewiring the input and output lines.

With respect to the alterable spectrum feature of the UNIDAR code:

* The ternary assignments, Table 1, can be easily changed in 384 ways by reorder of the input wiring to the encoder card. The reorder causes a change in the order of the "alphabet" of the ternary code. It is recognized that little or no spectral variation results from the reorder encoding of the pseudo or truly random binary data and that this condition creates the "worst case match" for test purposes. However, in the "real world" the probability of occurrence of various events and their digitized number is not constant. One may use this number-density-distribution to select a best case spectral match for the encoded binary data. If the application employs binary-coded decimal data, a wider choice of spectrum is available.

*Table 1. UNIDAR Encoding/Decoding

DECIMAL	BINARY (2 level)	TERNARY (3 level)
0	0 0 0 0	- + + - *
1	0 0 0 1	+ 0 0 -
2	0 0 1 0	0 0 - +
3	0 0 1 1	+ 0 - 0
4	0 1 0 0	0 - + 0
5	0 1 0 1	+ - + -
6	0 1 1 0	0 - 0 +
7	0 1 1 1	+ - 0 0
8	1 0 0 0	- + 0 0
9	1 0 0 1	0 + 0 -
10	1 0 1 0	- + - +
11	1 0 1 1	0 + - 0
12	1 1 0 0	- 0 + 0
13	1 1 0 1	0 0 + -
14	1 1 1 0	- 0 0 +
15	1 1 1 1	+ - - + *
FRAME WORD		+ + - - *
SPARE		- - + +

* Arbitrary codes

TRUTH TABLE

Binary	01	10	00	11
Ternary	-	+	0	0

* The proper order selection permits potential error performance advantages. The selected wiring order should be the one which produces the closest match to the unequalized spectral response of the disc system. This best match minimizes the equalization requirement.

The successive digits of most encodings are statistically independent; that is, the state of each digit is equally probable. This is not true of UNIDAR and the advantage can be realized in the form of error correction schemes. Because the value of this rewiring feature requires careful statistical evaluation, it has been given only cursory study. It has been outlined for the record because it offers potential toward the error performance goal of one bit lost per 10^{11} (100 billion) bits processed.

2.3 Comparison With Other Codes

Several codes including UNIDAR which transform raw binary data into signal spectra which better match the unequalized disc response are identified in this section. The comparison of these codes requires careful evaluation of the code parameters, their availability, and necessity, which are all relative to the disc system requirements. The encodings are either two or three level.

Poly-binary encodings [3] above the third level may be considered for disc recording at a later date. The higher level encoding will be more sensitive to intersymbol interference and the direct recording amplitude modulation which is approximately ±10 percent. Each encoding listed in Table 2, Code Comparison Chart, could be used on the disc, but each contains fewer of the previously identified UNIDAR code advantages. No additional encoding advantages are recognized by the non-UNIDAR codes studied.

Several observations can be made by studying the Code Comparison Chart. 1) The codes are listed in the order of their value to the disc program. 2) All of the three level encodings have higher encoding density than the two level codes. 3) Most of the codes are self-clocking and these codes will not require a separate disc clock track to maintain their intra- and inter-track correlation requirements. 4) The non-self clocking codes are easier to implement with the hardware. 5) All of the codes have a dc null and spectrum shaping advantage over the non-return-to-zero (NRZ) encoding which is the basic disc recording code.

Both the Partial Response and the Paired Selected Ternary lack the advantage of history independence. In order to receive their particular data streams, the correctly received pulse amplitude of past signals must be known.

* Of all codes, the Paired Selected Ternary (PST) [2] is the closest to and has been included within the UNIDAR Technology. The relative deficiencies of the PST code include:

* T

Code	Encoding Scheme	Numb of Co Leve
NRZ	Non Return to Zero	2
Patent No. 2,972,735	Type of Bi-phase	2
3,434,131	Period Sensitive	2
3,276,033	Type of Bi-phase	2
3,299,414	Type of Bi-phase	2
3,356,934	Double Frequency	2
3,374,475	2 Bits/1.5 Cycles	2
3,226,685	6 Digit Binary/ 8 Digit Ternary	2
3,274,611	3 Digit Binary/ 4 Digit Ternary	2
Partial Response -	0 - -1, 0, +1 1 - -1, 0, -1	3
Di-Code 5	00, 11 - 0 01, 10 - +, -	3
Bi-Polar 5	1 - +1, -1 0 - 0, 0	3
Paired Selected Ternary 2	See Text	3
UNIDAR	See Text	3

1

* Table 2. CODE COMPARISON CHART

Number of Code Levels	Encoding Density Bits/Cycle of Bandwidth	Self Clocking Code	dc Null	Encoding History Independent	Word Frame and Surplus Code Characters	**Inherent Parity**
2	2	No	No	Yes	No	**No**
2	1.0	Yes	Yes	Yes	No	**Yes**
2	1.0	Yes	Yes	Yes	No	**No**
2	1.0	Yes	Yes	Yes	No	**No**
2	1.0	Yes	Yes	Yes	No	**No**
2	1.0	Yes	Yes	Yes	No	**No**
2	1.33	Yes	Yes	Yes	No	**No**
2	1.5	Yes	Yes	Yes	No	
2	1.5	Yes	Yes	Yes	No	
3	2	Yes	Yes	No	No	
3	2	No	Yes	Yes	No	**No**
3	2	No	Yes	Yes	No	**No**
3	2	Yes	Yes	No	Yes	**Yes**
3	2	Yes	Yes	Yes	Yes	**Yes**

1) A variable word-length null-sequence which allows possible but difficult in-service error performance monitoring. This monitoring capability is probabilistic and encode sensitive. Consequently, error detection/correction capability for PST is minimal.

2) A difficult framing procedure. The variable word length null-sequence is used to control selection of one of two truth tables used for the PST decode to binary.

* The relative complexity of the PST and the UNIDAR truth table is shown below:

Binary	PST		UNIDAR
	+Mode	-Mode	
00	-+	-+	0
01	0+	0-	-
10	+0	-0	+
11	+-	+-	0

* An example of the encodings is shown below. Notice that UNIDAR always has a fixed null-sequence (4 bits) where the PST null-length is variable.

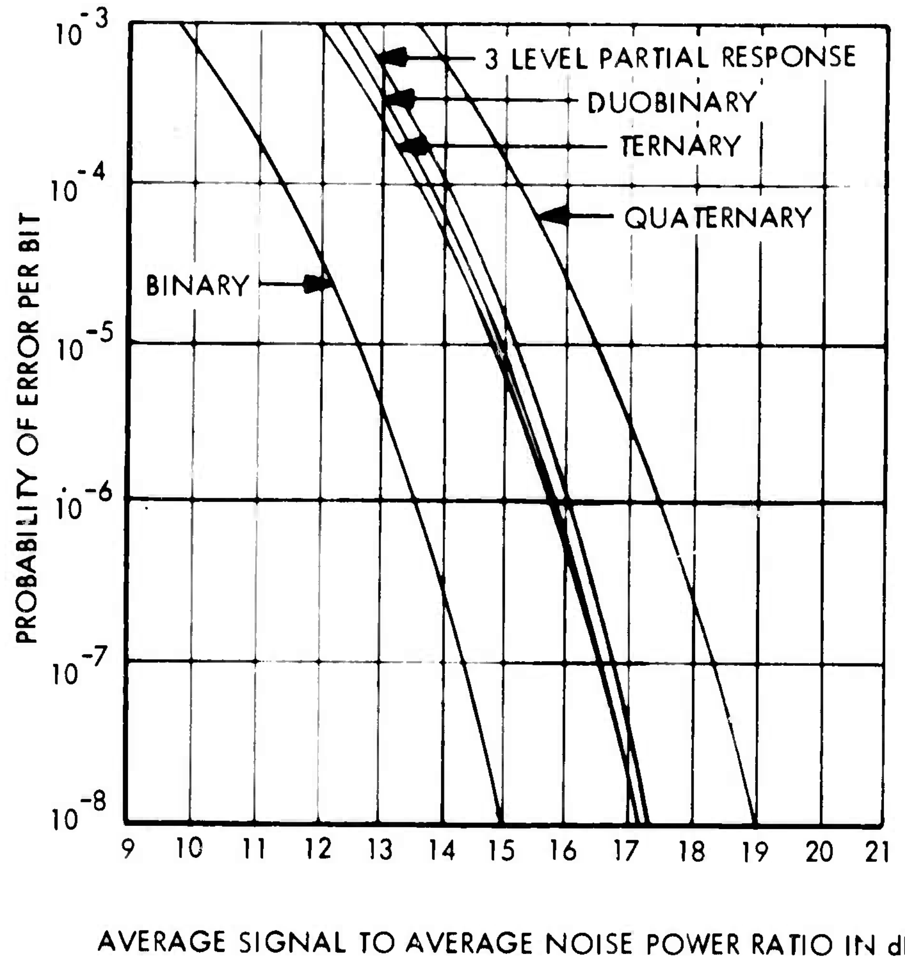
Binary	1001	0001	1101
PST	+00-	-+0+	+ -0-
UNIDAR	0+0-	+00-	00+-

* In conclusion, it is important to point out that only the UNIDAR code provides an error detection capability which pin-points the location of the error to within a four bit interval or word time. Figure 1 identifies the error rates for idealized systems transmitting at a constant 2-bit per cycle of bandwidth. This graph shows the error probability advantage of the two level raw binary over the three level encodings. Observations from the graph may be made:

* 1) The signal-to-noise ratio required for a given error rate continues to increase with the number of encoding levels.

2) The response requirements of all three level encodings (including UNIDAR) are closely similar.

3) Bandwidth efficiency can be increased by choosing the number of encoding levels which just meets the minimum data quality requirement, in terms of probability of error-per-bit.



ASW 10551

Taken from Polybinary Data Transmission by Robert Howson, IEEE Transactions on Communication Technology, September 1965

Figure 1. Error Rate Graph (IEEE)

3.0 HIGH DENSITY DISC RECORDER (HDDR) SYSTEM REQUIREMENTS

The program goals of the HDDR contract are to increase the linear data packing density to better than 10,000 bits per inch while maintaining error performance of 10^{-11}. In addition, the system must have sufficient versatility and adaptivity for recording and reproducing a variety of signals by either analog or digital recording techniques. Although all UNIDAR tape techniques are not directly applicable to the disc system, the concepts of reduced bandwidth, inherent clocking, parity, and negligible low frequency components are directly applicable to high data density recording.

For testing purposes, the disc system should have a capability for multi-speed operation, redundant recording, and external synchronization. The availability of at least several track widths, both moving and fixed head assemblies, control of track spacing, sufficient S/N, and proper bandwidth are necessary to achieve these minimum requirements.

The areas which must be investigated are equalization, erasure, cross talk, error failure modes, error performance versus bit density, effects of intersymbol interference, and error correction and detection techniques. The disc characteristics such as head-to-disc interface, medium thickness and composition, frequency limitations, servo drive control and track access time will influence the performance in these areas.

3.1 Disc Characteristics

A disc recorder has several advantages over a magnetic tape recording system. The disc is rigid which minimizes timing errors and provides an excellent base for the deposition of a magnetic film whose characteristics of thickness, surface roughness, and composition may be closely controlled. Consequently, the medium has a potential for high signal-to-noise ratios and therefore excellent error performance. The access rate is several orders of magnitude higher which offers a capability of single write and repetitive read on a continuous scanning basis. Unlike the tape system which has drive requirements, such as fast start and stop, fast rewind, and tape tensioning limitations, the disc is driven at a single speed and is quite amenable to precision servo speed control. The disc also has a capability for high frequency operation, high track densities, and operation with a large number of coherent parallel channels.

The main disadvantages of the disc system are the effective spacing between head and disc which limit the linear packing density and the variation in effective surface speed as a function of radius. It is this latter factor which limits the performance for direct recording and requires equalization techniques which are a function of head position.

3.1.1 Head-To-Disc Interface

The vast majority of available disc systems are not capable of high data density disc recording. They are digital machines using saturated recording techniques and 'flying head' principles where the write and read head flys from 50 to 200 μ inches above the surface of the disc. A few manufacturers have recently marketed high performance disc systems which operate with the head in-contact with the disc. The head is actually spaced a finite distance from the medium due to the thickness of the hard protective coating deposited over the magnetic storage film and the surface roughness. This coating is generally a Rhodium flash and is less than 10 μ inches thick. A scaled comparison of both systems is shown in Figure 1.

The 'flying head' principle is based on the aero-dynamic property that the layer of air dragged along the surface of the disc under the head pad approaches the incompressible state and a force must be applied to the head to maintain uniform head-to-disc spacing. Surface roughness, surface speed, restraining force, and the area of the pad determine the flying height. Unfortunately, the 'flying head' machines are quite susceptible to permanent damage to both head and disc when operated in an atmosphere containing particles which can become embedded between the head pad and the disc. To insure stability, the area of the head pad is relatively large and a large restraining force is required to maintain a given flying height. These factors, however, increase the probability of permanent damage. Even if the disc is operated in a controlled atmosphere, extra tracks are provided should certain tracks become inoperative.

The 'in-contact' systems have less of a problem due to the small surface areas in contact with the disc, the resultant light pressure applied to maintain contact, and the toughness of the protective film. Advantages of an 'in-contact' system are lower modulation in the head-to-disc spacing, and excellent cross talk properities. The disadvantage of this system is the higher wearing rate.

Modulation of the head-to-disc spacing results in amplitude modulation of the recorded signal. This causes phase errors as well as amplitude variations for systems requiring zero-crossing detection and affects the threshold for direct recording techniques requiring amplitude level detection. This amplitude modulation is at least 6 dB lower for the 'in-contact' systems.

Cross talk is a measure of the amount of isolation of one track from adjacent tracks. It is a function of the spacing between the head gap and the recorded elements. During the record cycle, fringing fields at the gap extremities tend to disturb recordings on adjacent tracks. This is more serious for direct linear recordings and longer wavelengths especially where pre-emphasis is used. Long wavelengths which are more susceptible to cross talk pickup are normally attenuated by the unequalized response characteristic. These characteristics are absent in the UNIDAR signal. Careful head design is required to minimize this effect. Some digital systems use a split-gap erase head which erases a narrow strip on both sides of the data track immediately after write-in. Most systems, however, erase a wider track just prior to recording.

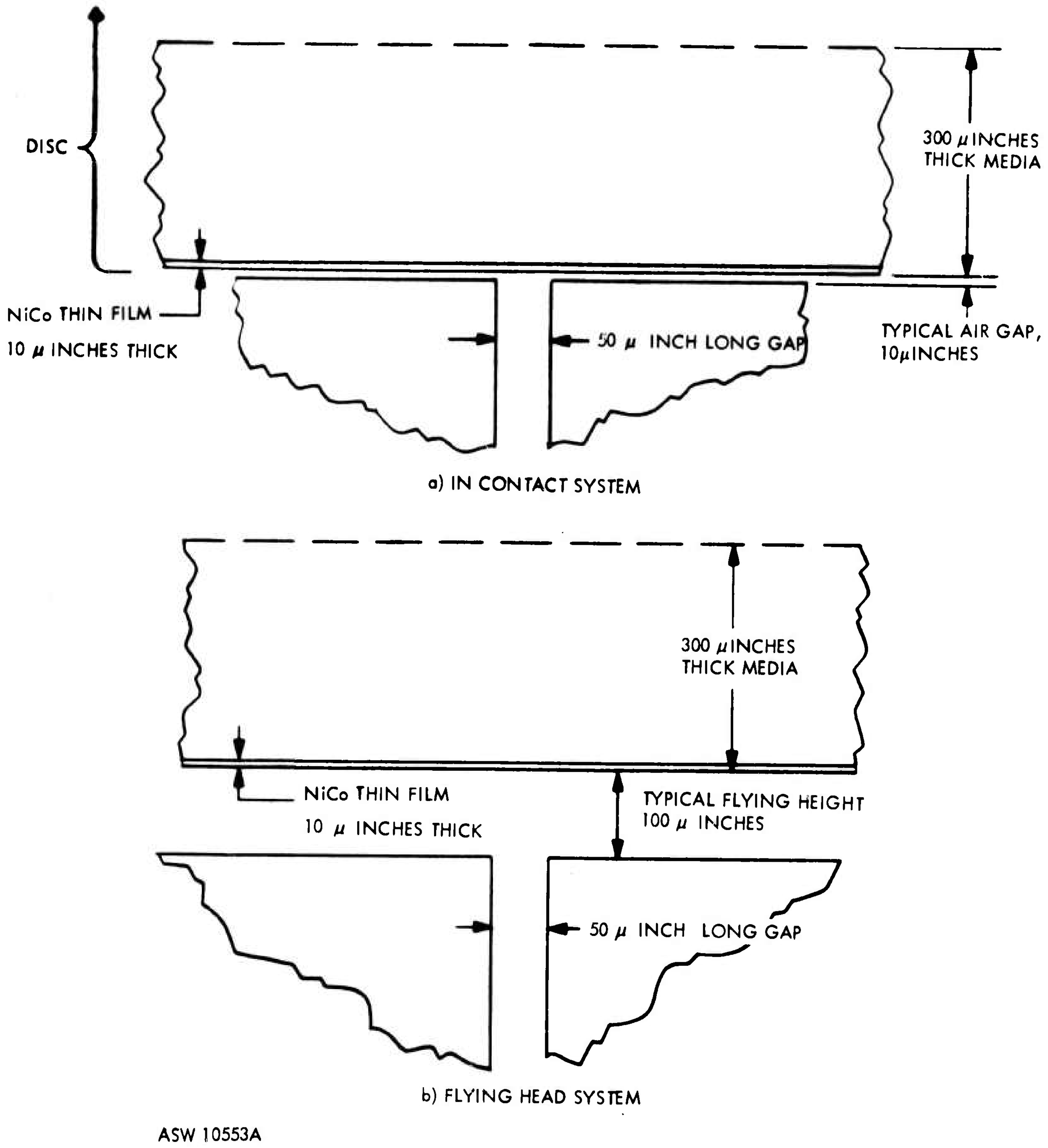


Figure 2. Head-to-Disc Interface Comparison

During the reproduce cycle, recorded elements on adjacent tracks may cause noise interference with the reproduced data track. Parameters such as gap height, head-to-disc spacing, medium thickness and head width can affect the magnitude of cross talk. Special head configurations such as notched heads, have been used to minimize its effect. In-contact systems have head widths which are 500 to 1000 times as large as either the head-to-disc spacing or the thickness of the medium, therefore the distance between tracks can be reduced to less than 1.5 mils with cross talk down by 30 dB. It is obvious that little can be gained with head widths of 5 to 10 mils by recording the tracks any closer than 1 mil. Another form of cross talk known as head-to-head interaction is common to tape systems where heads are adjacent. Situations requiring simultaneous write and read can be accomplished in a disc system by spacing the heads around the periphery of the disc.

The wear associated with 'in-contact' systems is a function of surface roughness of both head and disc, surface speed, and head pressure. For those systems where the heads are not retracted during disc speed-up and slow-down, the wear rate is also a function of the number of times the machine is shut down. The life of a disc normally is based on the worst case condition of one head assembly mounted in a fixed position on a single track for the life of the disc. Thus, additional heads per track will increase the wear rate across the disc. It is interesting to point out that a fixed head system with retractors mounted on the heads could extend the life of an 'in-contact' system considerably if only those heads which were being used were left in contact.

3.1.2 Disc Medium

The magnetic coating of the disc is primarily available in either a thick particulate Ferric Oxide (Fe_2O_3) coating or a thin electroplated Nickel Cobalt (NiCo) film. The oxide coating is similar in many respects to that placed on flexible tape. The thickness may vary from less than 100μ inches to over 400 μ inches, on a particular disc, with a surface roughness of about 4 μ inches. The surface roughness, and relatively soft characteristics of the film eliminate any possibility of operating the head 'in-contact' with the disc surface. The NiCo plating which was developed for drums and discs can be made as thin as 3 μ inches. Table 3 summarizes some of the average characteristics of the two media, assuming optimized operation.

Although a thin medium is a requirement for high density saturation recording, it tends to limit the performance of direct linear recording due to the restriction on bias amplitude. For dc bias, the bias current should be set such that only one-half the thickness is magnetized. Superposition of the signal causes depth modulation and a linear transfer characteristic can be obtained. Excessive signal distortion will occur if the signal amplitude is allowed to push the modulation beyond the far side of the medium. This may be difficult to avoid if the head-to-medium spacing variations are of the same order as the medium thickness. Linear recording using ac bias should be less susceptible to spacing variations especially if a larger bias amplitude can be employed. The amount of linearization is dependent on the record head field decrement and as such is not presently known. Recording parameters using bias techniques are discussed in Section 3.6.

Table 3. Disc Medium Characteristics

Parameter	Symbol	Fe_2O_3	NiCo	Units
Remanence	Br	1900	8000	Gauss
Coercivity	Hc	280	400-800	Oersted
Thickness	t, nom (min)	300 (75)	10 (3)	μ inches
Spacing	d, nom (min)	100 (40)	10 (in-contact)	μ inches
Surface finish	-	3.5	0.4	μ inches AA
Medium life	-	10^5	2500	Hours

3.1.3 Access

The access time for a disc system depends upon the position of the head relative to the selected word location, the speed of the disc, and the recovery time of the switching matrix. A head per track system has the fastest access time dependent only on the fraction of one revolution for the head to reach the storage location. For 3600 rpm, this amounts to an average access time of about 8 ms. For faster access, additional heads may be mounted to scan each track but at greater expense. Cost, therefore, is a significant deterrent for fixed-head-per-track systems where high capacity or exceptionally high access time is required. Increasing the linear storage density should diminish the cost but only within the bounds imposed by the frequency limitations of the system. Unless head cost can be reduced substantially, a fixed-head-per-track system is not recommended for a high capacity 'in-contact' recording system where head life is limited to less than 5000 hours. For larger capacity systems, a moving head system is usually employed where access times of the order to 500 ms may be tolerated.

Access is controlled by a stepper motor assembly. The stepper motor assembly which was selected moves the heads incrementally by counting sequentially from a reference track. The accuracy of this technique is much higher than other techniques and is less than ±0.5 mil for a track 8.5 mils wide. Figures are not available for the deviation resulting from the inherent hysteresis in the tracking system, but it is believed to be quite low. The total error or inter-channel time base error is less than ±20 ns which includes head-to-disc spacing variations. Besides faster access, a fixed head system provides the opportunity to match the head design to that particular track response. A hybrid system where the head moves over a very limited region would also simplify the equalization requirements.

* 3.2 Bandwidth Requirements

The project goal of 10,000 bits per inch for the HDDR corresponds to a minimum bandwidth requirement which is dependent upon disc surface speed. The minimum diameter of the recording zone on the test bed is 8 inches corresponding to a circumference of approximately 25 inches. Although the nominal bit packing efficiency of the UNIDAR code is 2 bits/cycle, it has been determined that the equalized third harmonic component of 0.5 fc (where fc is defined as the nominal upper cutoff frequency) should not be lower than 12 to 15 dB below midband to properly reproduce the UNIDAR signal. For example, a sequence consisting of alternate ++ -- has a spectral line at 0.5 fc. Sampling occurs at the center of each bit cell and the threshold level detector must be adjusted accordingly. Figure 3 represents an in-phase third harmonic component of 0.5 fc which is required to reconstruct the original waveform. This establishes the equalized 6 dB upper cut off frequency of the passband at 1.3 fc. Linear phase must be maintained through 1.5 fc. This simplified waveform synthesis shown for a system with a maximum flat frequency response and a linear phase does not minimize intersymbol interference but it is instructive in determining approximate bandwidth requirements. A system employing linear-phase and maximum flat time delay response will minimize intersymbol interference at the expense of bandwidth. The final system requirement will depend on the encoding technique which is selected.

Table 4 shows the required bandwidth corresponding to an inside diameter of 8 inches for 10,000 bits per inch at various disc speeds for UNIDAR.

3.3 Bit Packing Density

The first disc file introduced by IBM 14 years ago had a linear bit packing density of only 4000 bits/track. The majority of disc systems currently available have packing densities that are typically 1000 bits per inch for phase encoding or 2000 bits per inch for NRZ.

Table 4. Bandwidth Requirements

Disc Speed (rpm)	Bit Rate (Mbits/sec.)	fc (MHz/sec.)	1.3 fc (MHz/sec.)	1.5 fc (MHz/sec.)
900	3.75	1.875	2.44	2.81
1200	5.0	2.5	3.25	3.75
1800	7.5	3.75	4.87	5.12
3600	15.0	7.5	9.75	10.25

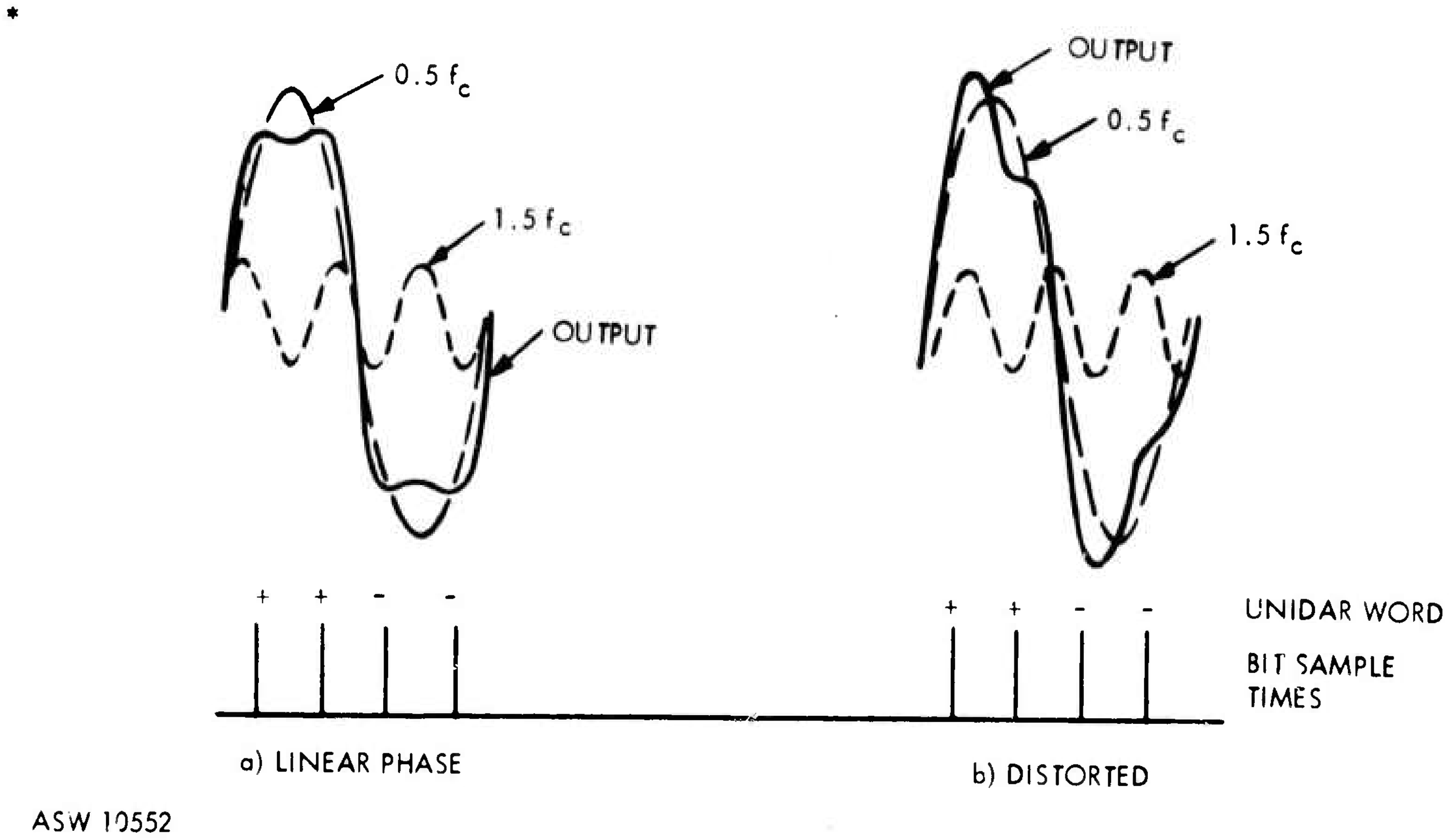


*Figure 3. Simplified Waveform Analysis Indicating Bandwidth Requirement

The lateral packing density or track density is generally 30 to 50 tracks/inch for a fixed-head-per-track system and 50 to 100 tracks/inch for a movable head system. The corresponding packing density is approximately 200,000 bits/inch^2. Error performance is typically 5 in 10^{10}. All of these systems are digital machines generally employing flying head techniques and saturation recording [6]. The project goals of increasing the linear packing density and the error performance by an order of magnitude is also intended to show a capability of increasing total packing density by more than an order of magnitude.

3.3.1 Linear Bit Packing Density

The factors which limit the maximum bit packing density of a recording system are:

1) Demagnetization characteristics of the medium.

2) The reproduce head gap length.

3) The field decrement at the trailing edge of the record head.

4) Head-to-disc spacing.

5) Rise time of the recording current.

6) Method of recording or modulation technique.

7) Thickness of the media.

8) Amplitude and phase distortion.

9) Vertical field component.

10) Frequency losses.

Demagnetization is dependent upon the saturation remanance of the media, B_{rs}, coercivity H_c, and the shape configuration of the recorded zone. In general, a low ratio of B_{rs}/H_c and a large ratio of recorded wavelength to cross sectional area is desired although a shape factor must also be considered. Lowering the B_{rs} or reducing the thickness of the media, however, reduces the amount of flux lines that can be coupled to the reproduce head during readout which consequently affects output voltage level. Increasing H_c, makes it more difficult to switch the media during the write process. The longitudinal recording field on the gap axis, at a distance equal to the gap length, is only 35% of the field between the pole tips. This neglects the influence of media permeability on the recording field. For flying head systems, a requirement for a larger number of turns or higher current places considerable constraints on the record head driver to achieve the necessary rise time for high density storage. This becomes more important where high disc surfaces speeds are required. Since the recording is effectively accomplished at the trailing edge of the record gap, the field gradient should be as sharp as possible. For 'in-contact' systems, the maximum field at the trailing edge is in a vertical plane. In most cases this field component is neglected, but at high densities it has been shown to influence the writing process and has been proposed to facilitate the switching of high coercivity films. The demagnetization of Fe_2O_3 films using high density UNIDAR recording techniques can be considered as negligible since only a very thin surface layer is effectively magnetized. The demagnetization characteristics of NiCo films, however, cannot be neglected due to the much higher ratio of B_{rs}/H_c of the recording media. These ratios are typically as high as 10 to 20 and unless the thickness is correspondingly reduced, the demagnetization could be a limiting factor. It is estimated that wavelengths as short as 30 μ inches can be supported for saturation recording on the NiCo surface of the test bed disc medium. The write/read gap length has been optimized at approximately 60 μ inches since the combined head design is a compromise between requirements for efficient recording characteristics during the write process and reproduction of short wavelengths during the read cycle. The well known relationships for gap and spacing losses are respectively:

$$\text{Gap Loss} = 20 \log \left[\frac{\sin \frac{\pi l}{\lambda}}{\frac{\pi l}{\lambda}} \right] \text{dB} \qquad (2)$$

$$\text{Spacing Loss} = 54.6 \frac{d}{\lambda} \text{ dB}$$

Where:

l = Length of the reproduce gap
d = spacing between gap and media
λ = wavelength of recorded signal

The gap loss for a sinusoidal wavelength that is twice the length of the gap is approximately 4 dB and corresponds to a wavelength of 120 μ inches on the test bed. The spacing loss for a similar wavelength and a flying height of 100 μ inches would be 45 dB. For an 'in-contact' system where the finite air layer, surface roughness, and the rhodium flash cause a nominal spacing of 10 μ inches, the spacing loss still amounts to 4.5 dB. The required wavelength corresponding to the 6 dB frequency response must be 154 μ inches as outlined in Section 3.2. Frequency losses will be minimal for the initial phase of this program since operation will be limited to a 4 Megabit/sec rate.

3.3.2 Track Density

The three factors which determine the track density are the read/write head width, the erase head width, and the guard bands between tracks. Reduction of the head width is limited by the fabrication capabilities, the positioning resolution of the actuator for moving head system, the loss in the signal-to-noise ratio, and the loss in signal amplitude. Since the signal amplitude is directly proportional to head width (neglecting fringing and head efficiency) the signal-to-noise ratio is reduced by 3 dB for every 6 dB of signal loss. It has been estimated that the head width could be reduced to about 1 mil before very serious problems of head construction occur, since the gap height and the back core structure must also be reduced along with the width. The much higher signal-to-noise ratio found at the outside diameter of the disc could be used to advantage in this respect by grading the head width in accordance with the required signal-to-noise ratio. Thus, a sacrifice in signal-to-noise could be made to increase packing density on the outer recording zones. Cost and resolution of the actuator, which for the Data Disc System is ±0.5 mil on a 8.5 mil wide track, will restrict this potential. Reduction of the guard band is not practical beyond the present 1 to 1.5 mil between tracks for an 'in-contact' system due to actuator performance and cross talk criteria. The guard bands for a 'flying head' saturated mode disc recorder are typically 5 mils.

3.4 Error Performance

The error performance for the disc system can be predicted for a given data density. The prediction is dependent upon the signal-to-noise ratio of the channel, the number of levels and spectral response of the encoded signal, the spectral distribution of the noise, the amount of intersymbol interference resulting from amplitude and phase distortion found in band limited channels, and the modulation or recording method which also determines the detection mode. The signal-to-noise ratio will be higher if the medium thickness, head width or the number of turns on the head is increased, but these signal enhancing parameters also effect the data density. Minimization of media non-uniformities and head to medium spacing variations are process variables and will cause shifts in the noise spectrum as a function of the radial position of the head on the disc. Characteristics which affect this portion of the noise spectrum are uniformity of the thickness and magnetic characteristics of the films, uniformity of the head-to-head characteristics, and surface roughness. The process variables are controlled by the disc manufacturer and are considered only for the purpose of identifying possible sources of noise. Other noise dependent factors are jitter, the method of erasure, and the track position.

* For a fixed maximum data rate, the signal-to-noise ratio will be approximately 12 to 15 dB higher at the outside diameter than at the inside track. This results from higher surface speed and longer wavelengths at the outside track where error rates will be quite low. A plot of error probability vs S/N is shown in Figure 1 for multilevel signals. The curve for the three level UNIDAR signal would fall near the center grouping for the other

three level codes. An extrapolation of the curves to an error probability of 10^{-11} indicates that less than a 19 dB signal-to-noise ratio is required. Further extrapolation indicates that two orders of magnitude improvement in error performance may be obtained for a S/N improvement of only 1.2 dB. The assumptions which define this set of curves are:

1) the noise is white, additive, and Gaussian

2) the noise power is measured in a band equal to the bandwidth of the signal spectrum

3) any level of the signal has an equal probability of occurrence

4) the channel has no distortion

Conditions 1 and 2 are reasonable assumptions. Condition 3 is only partially met and condition 4 depends on the complexity of the equalization.

* For example, assuming a random occurrence of the 16 UNIDAR words, the probability of occurrence for + (or -) to appear in the first bit position is 0.31, while for a 0 it is 0.37. If a + occurs in the first bit location, the probability of occurrence for a + in the second bit location is zero, for a 0 it is 0.4 and for a - it is 0.6. The third symbol of the UNIDAR word is then heavily dependent upon the state of the first two symbols and completely defines the word. The fourth symbol is therefore defined by the first three and could be eliminated at the expense of losing the built in redundancy and bandwidth characteristics. This conditional probability of occurrence for any of the three possible states in the second, third and fourth bit positions may be used to advantage.

The flux pattern stored on the media during the record process may have a very high resolution with negligible intersymbol interference. It is during the reproduce process that the aperture effects of the read gap, spacing losses, etc., causes intersymbol interference which without proper equalization may cause an excessive error rate. The Data Disc Period Modem system uses linear-phase maximally flat time delay response to minimize intersymbol interference. At 1800 rpm the signal-to-noise ratio for a 4 MHz signal using the Modem system at a radius of 5 inches is 32 dB.

* The 4 MHz signal is down 7.5 dB from the signal level at midband. The bandwidth requirements place the 6 dB down point at $1.3\ f_c$. The frequency corresponding to $1.3\ f_c$ in the 4 MHz system is 3.7 MHz, thus, f_c is 2.85 MHz and the corresponding bit rate is 5.7 Megabit/sec. Full utilization of the available signal-to-noise ratio would permit a packing density of 6000 bits/inch. Assuming negligible intersymbol interference and using the minimum signal-to-noise requirement of 19 dB, a packing density of 10,000 bits/inch would be possible with an error performance of 10^{-11}.

* With direct saturated recording techniques and assuming a channel having no distortion, a signal-to-noise ratio of 19 dB would provide a packing density of approximately 17,000 bits/inch.

* Better utilization of the redundancy in the UNIDAR code could be employed with the Period Modem system by recording the UNIDAR word on four parallel channels instead of the serial format presently used on the tape systems. This technique involves dividing the recording surface area into four concentric zones. The width of each zone would be equal. The most significant symbol in the UNIDAR word would be written in the outer zone where the signal-to-noise ratio is the highest and the error probability the lowest. The second and third most significant symbols would be written respectively in the following two zones. The fourth symbol is used as a parity check and stored on the inner most zone representing 25% of the recordable surface. If the error performance is 10^{-11} on the outer three zones and only 10^{-8} on the inner zone, errors would be detected at an average rate of 1 error in every 10^8 words. Automatic correction of the last bit to achieve a zero average condition would correctly identify the word 999 times out of 1000, but could not identify the one word in 10^{11} which was actually in error. The next most likely source of error would be on the inner portion of the third zone while errors would occur very seldom in the outer zones. Matching of the tracks in the third and fourth zones could achieve better error performance in particular applications.

* Insertion of parity bits at discrete intervals in each zone around the circumference of the disc would indicate the column in which the error occurred. Single level errors ($+ \rightarrow 0$, $0 \rightarrow +$, $- \rightarrow 0$, $0 \rightarrow -$) or double level errors ($+ \rightarrow -$, $- \rightarrow +$) would be detected and corrected using either odd or even parity. During the recording process, the number of + bits in each column would be counted and a binary 1 or 0 generated depending upon the parity used. The binary parity word would be converted to the UNIDAR word, recorded on the disc, and reproduced in the proper time slot. The same procedure would be used for the - bits, thus, two word locations would be required for each parity check.

* It is important to note that although the disc response is matched with the Modems, the signal response on each channel could go to dc if a string of identical words were to occur. The Modems do provide dc response. Clocking information which is normally derived directly from the UNIDAR signal would be taken from either a clock track, the carrier frequency, or by a special 'ring' shifting of the UNIDAR bits. Table 5 shows the format as it would appear on the four tracks for the latter technique.

Table 5. Recorder Track Format

Word No. \ Track No.	1	2	3	4
1	A	B	C	D
2	D	A	B	C
3	C	D	A	B
4	B	C	D	A
5	A	B	C	D

In conjunction with this format, the time interval of occurrence for errors at different error rates for a given data rate is important. Assuming an input/output rate of 16 megabits/sec from the four parallel tracks, the following error intervals would occur for continuous operation:

10^{-10}	10.5 minutes
10^{-11}	1.7 hours
10^{-12}	17 hours
10^{-13}	7.2 days
10^{-14}	2.4 months
10^{-15}	2 years

Thus for direct recording of the UNIDAR word in the normal serial format, only the inner tracks would require redundant recording.

3.5 Equalization

A property unique to the disc system is the variation in relative head-to-disc speed over the recording zone. Both tape and drum recorders have a fixed head to medium speed. The speed variation in a disc system is usually kept less than a factor of 2 and is directly proportional to the ratio of the outside to inside diameters of the recording zone. Consequently, for a fixed input data rate, the wavelength of the recorded signal may vary by a factor of 2 over the recording zone. Since the unequalized head response is basically wavelength dependent at the upper end of the response characteristic (neglecting high frequency loss components), the frequency response curve would be shifted to the right at the outside diameter. The response would not change appreciably at the lower end of the response characteristic over the recording zone since the head responds to only the rate of change of the flux. Very long wavelength losses caused by the head configuration can be neglected for the narrow band signals like UNIDAR. Equalization, therefore, becomes not only a problem of equalizing for a given head but also is a function of head position. It is in this respect that modulation schemes such as frequency (FM), period (PM) or phase (ØM) modulation which utilize zero crossing detection techniques can be used to advantage at a sacrifice in bandwidth. Techniques currently used on UNIDAR tape recording systems maximize the linear bit packing density capability of tape recorders by direct recording of the UNIDAR signal onto the media. Thus, maximum utilization of the available bandwidth is achieved. For these reasons every effort will be pursued to explore all possibilities of direct recording on disc recorders.

The most direct approach for a fixed head per channel system would be separate equalization netwocrds for each head or group of heads. However, most disc systems which satisfy mass memory requirements employ a minimal amount of channel electronics and use a switching matrix for access to the proper head. If a single equalization network were designed for a group of heads which covered a certain zone on the disc surface, two levels of switching would have to be provided to select the correct head and the proper equalization network. If enough channels were provided to adequately cover the disc, only one level of switching would be required. For a moving head system, several possibilities exist:

1) the address of the track selection matrix could be used to switch to a suitable equalization network;

2) the basic equalization network could be altered with respect to the head position: or

3) the movement of the heads could be restricted over a range which did not exceed deviation tolerances prescribed for optimum equalization within a zone.

Several factors which may be used to offset the equalization requirements are:

1) Graded gap lengths where the reproduce gap length would be longer at the outside track.

2) Variable head-to-disc spacing with a larger spacing at the outside radius. This normally does occur to some extent due to the aero-dynamics of the head and disc and the increased disc speed at the outside radius. Additional control could be obtained by increasing the thickness of the protective film from the inside to the outside diameter.

3) Use of a flux responsive head such as the Hall effect pickup. Balancing networks to eliminate the residual ohmic voltage, temperature compensating circuits and careful layout of the Hall cell and connecting leads to minimize $d\phi/dt$ pickup are required. The amplitude and phase response would then be flat up to the point where wavelength dependent losses occur and would be subject to the aperture effects caused by the finite gap length. Equalization, however, at the high end should be simpler and is not required at the low end of the response. General Dynamics Electronics division holds several patents covering Hall effect reproduce heads one of which is capable of minimizing the gap effect.

Considerable emphasis will be placed on the utilization of transversal filters in the equalizer design. Given the impulse response of the system, a computer program is available to determine the required R, L, and C components for the transversal filters required in each zone. Both amplitude and phase equalization can be handled with transversal filters.

3.6 Digital/Analog Recording Techniques

The thickness of the media on the test bed is nominally 10 inches. The spacing between the head and disc varies from 5 to 15 inches depending upon the head configuration, the head position, the head pressure, and the speed of the disc. The variation in the spacing for a fixed set of conditions would appear on a single tone recording as amplitude modulation. It is known that the combination of media non-uniformity, spacing modulation and media thickness variations do not affect the amplitude of the signal by more than ±10%. This appears within the tolerance required for direct recording provided AGC circuits are effectively utilized.

3.6.1 Bias Recording

Examination of the recording process is necessary to better understand the limitations that are involved for biased recording. A model for the biased recording process is described below. In the simplest case, particle interaction effects and perpendicular switching fields are neglected. Mees [7] has shown that under these conditions for long wavelengths, a cylindrical volume exists directly beneath the gap where complete switching occurs within the volume and zero switching outside of it. The radius of the cylinder is directly proportional to the recording current (bias current and signal current) and inversely proportional to the switching field threshold of H_c. As the media traverses the recording gap, the cross section of the cylindrical volume alternately changes polarity at the frequency of the bias and changes size as a function of the signal amplitude. For dc bias only the size of the volume changes. Keeping in mind the hysteresis characteristic of the medium, the recorded pattern in either case consists of overlapping saturated volumes which tend to linearize the transfer characteristic. This model although not extremely accurate at high frequencies is useful in illustrating the mechanics of the recording process and the occurrence of distortion as the bias amplitude is increased. For example, consider the case for zero bias. The non-linear transfer characteristic of the magnetization curve causes a recording of only the peaks of the signal on the surface layer causing 'dead space' between recorded areas. When the bias is increased such that the minimum amount of bias plus signal current is sufficient to magnetize the surface layer, the condition for optimum distortion (<5%) exists. Further increase of the bias will increase the distortion. The signal also increases as more of the depth of the medium becomes magnetized. As the bias amplitude penetrates through and beyond the remote surface of the medium, the total harmonic distortion again falls and may fall to less than 2%. These figures are dependent upon the amplitude and frequency ratios of signal-to-bias and the signal frequency. The UNIDAR tape system uses a bias amplitude which just magnetizes the surface layer. For the disc recorder with its thin medium, the larger bias amplitude would be considered. For dc bias, the bias must be adjusted to magnetize not more than one-half the medium thickness. The signal level must then be adjusted such that the peak excursions do not penetrate either surface. The recording is then a form of depth modulation.

The factors which disturb this model especially for the disc are:

1) The medium has a finite permeability which affects the field pattern at the pole tips.

2) The requirement that bias frequencies be 3 to 5 times the top signal frequency will cause considerable eddy current losses in the thick aluminum substrate. This will effectively load the head and force more of the field into the top layers of the surface.

3) The field vector at the trailing gap edge is oriented at 45^{o} to the medium and at 90^{o} to the field vector at the leading edge. In addition, the point of maximum field shifts from the gap center plane for medium elements located at a distance or spacing of one-half the gap length to the gap edges for surface elements. Consequently, for the thin medium and high frequencies, the recording takes place beyond the trailing edge of the record gap.

4) Domain interaction effects especially at short wavelengths can disturb the recorded pattern.

3.6.2 Non-Bias Recording

Some of the factors which effect direct recording were included in the previous section. Several techniques which permit the recording of a three level code such as UNIDAR using binary recording techniques is discussed below. One method uses dc erase but requires the use of a special head, namely a bifurcated record head with separate balanced windings. Two tracks are written simultaneously side by side. Each track contains binary information of either + or - in an NRZ format. Track one of width W writes both + and 0 as + and writes - as -. Track two of width W writes both - and 0 as - and writes + as +. A common reproduce gap of width 2W is then used to read both tracks simultaneously. The output level of the +'s and -'s is equivalent to a track width of 2W. Zeroes are formed by the cancellation of the equal but opposite polarity recordings common to the reproduce head.

A second technique takes advantage of the dead space which is recorded during sinewave recording using zero bias. By varying the shape and the level of the input signal: i.e., predistortion of the input signal, the UNIDAR signal could be directly recorded on the disc. By using AC erasure any signal below the switching threshold of the film would remain in the zero or erased state. However, the pulse width of the recorded signal would be sensitive to record current amplitude, spacing, and medium non-uniformities.

3.7 Erasure

Erasure of the medium may be defined as any technique which removes all traces of previously recorded signals and places the medium into a uniform, predictable, magnetic state ready to accept the recording of new data. In general, there are two accepted states; saturation where all domains are aligned in the same direction and demagnetization or zero remanance where domain orientation is random such that no external induction is detectable. Present UNIDAR tape recording technology requires a zero remanance erased state for the direct recording of the three level word.

Ideally, thermal demagnetization would produce the most complete erasure; i.e., domain orientation would be random in the plane of the film. This is accomplished by raising the temperature of the film above its Curie point where the medium changes from a ferromagnetic to a paramagnetic state. During cooling in the absence of an external field a highly random magnetization is achieved which is determined only by the random distribution of the internal fields. High density Curie point writing has been achieved at low rates on Manganese Bismuth (MnBi) films 700A thick by using a pulsed laser beam and optics to record spots approximately 40 μ inches in diameter [7] . The Curie point of MnBi is 360° C and recorded areas appear stable and unaffected by repeated recording cycle. However, a number of formidable problems exist for a system employing Curie point erasure on present thin film disc systems. For example, NiCo compositions normally used for disc media have Curie points of up to 800° C. The melting point of the aluminum substrate is only 700° C. The large track width of 10 mils and the thermal time lag associated with the heat dissipation and heat capacity of the materials would determine the maximum thickness of the media. No external fields, fringing from adjacent tracks or head magnetization can be present during cooling due to the high sensitivity of recording just below the Curie point during the cooling cycle. Protective non-oxidizing coatings might also be necessary. There are also problems of implementation, temperature sensitivity of the write-in process, partial erasure of adjacent tracks, large strains generated in the media by non-compatible thermal coefficient of expansion between medium and substrate, and stability of medium over repeated cycles. These problems indicate that the gain in Signal-to-Noise performance achieved by thermal demagnetization would have to be offset by a careful redesign of the medium processing.

A technique commonly referred to as AC erasure also places the medium in a state of zero remanance although the particle or domains are randomly oriented only in the direction of the applied field. The procedure for AC erasure consists of stabilizing the domains initially with several cycles of a saturating field which is then followed by anhysteretic erase. This involves slowly reducing the field to zero during which time the domains undergo only a small change from cycle to cycle. The erase signal should have no asymmetry which would tend to leave the medium in a biased state. The medium moving past an erase signal should have no asymmetry which would tend to leave the medium in a biased state. The medium moving past an erase head for a given frequency and medium speed constitutes a means for slowly reducing the field to zero. Alternatively, bulk erasure, whereby the medium is slowly removed from the field (or the field slowly reduced to zero by a variable control) may be used. Bulk erasure is the most effective method of erasure on magnetic tape reels and is commonly used on instrumentation tapes but cannot be used where selective updating is required.

Erasure by means of an AC erase head has the following minimum requirements:

1) The erase gap must be long enough and the frequency high enough for each element of the medium to experience a number of cycles of a saturating field before it passes beyond the vicinity of the gap.

2) The erase signal must be beyond the response of the reproduce head.

3) The field should be large enough to saturate all portions of the media.

For tape systems where the media is thick and has a high coercivity, high frequency losses in the head may cause excessive heating. For a disc system, the large, highly conductive aluminum substrate places an additional burden on the AC erasure techniques due to eddy current loading. The simplest technique is DC erasure where all domains are saturated and oriented in the same direction. This technique is used in all saturating digital systems where only two levels are recorded. In many cases new digital data may be written directly over old data. DC erase is normally used in systems employing modulation techniques such as FM, PM or ØM and in direct recording situations where DC bias may be used.

The big disadvantage of DC erase on tape is the much higher noise level which may be as much as 6 to 10 dB higher than that of the AC erasure. This is primarily due to the modulation noise or that portion of the noise which is a function of the magnetization level. Some of the sources of this noise are variations in the head-to-media spacing, jitter, surface defects, inhomogenities in the media and thickness variations. It is expected that this portion of noise will be considerably lower for the disc system than a tape system due to a much improved media uniformity and surface characteristics.

4.0 HARDWARE DEVELOPMENT

Many of the parameters and inter-relationships which control the performance of the HDDR have been identified in the previous sections. The goal of the hardware development is the design of a skeletonized machine which tests the performance limits at minimum cost. The equipment under development has sufficient flexibility in its design to:

1) Permit data recording on a minimum of four hundred selectable tracks.

2) Vary the data density to assess the trade-off between bit packing density and error performance.

3) Change the encode/decode alphabet and resultant equalization networks with a minimum of hardware change.

4) Permit the assessment of multiple head or channels as a means of redundant recording.

The design goal for this equipment is an effective data bit packing density of 10K bits per track inch, having an error rate of one per 10^{11} bits. When compared to most saturation-type disc recording systems, this performance goal is an order of magnitude better in both bit packing density and error performance level. Figure 4 shows a block diagram of the HDDR hardware which is being built or being purchased to assess the potential of recording the UNIDAR code on the disc. Two areas of hardware development are required. These include:

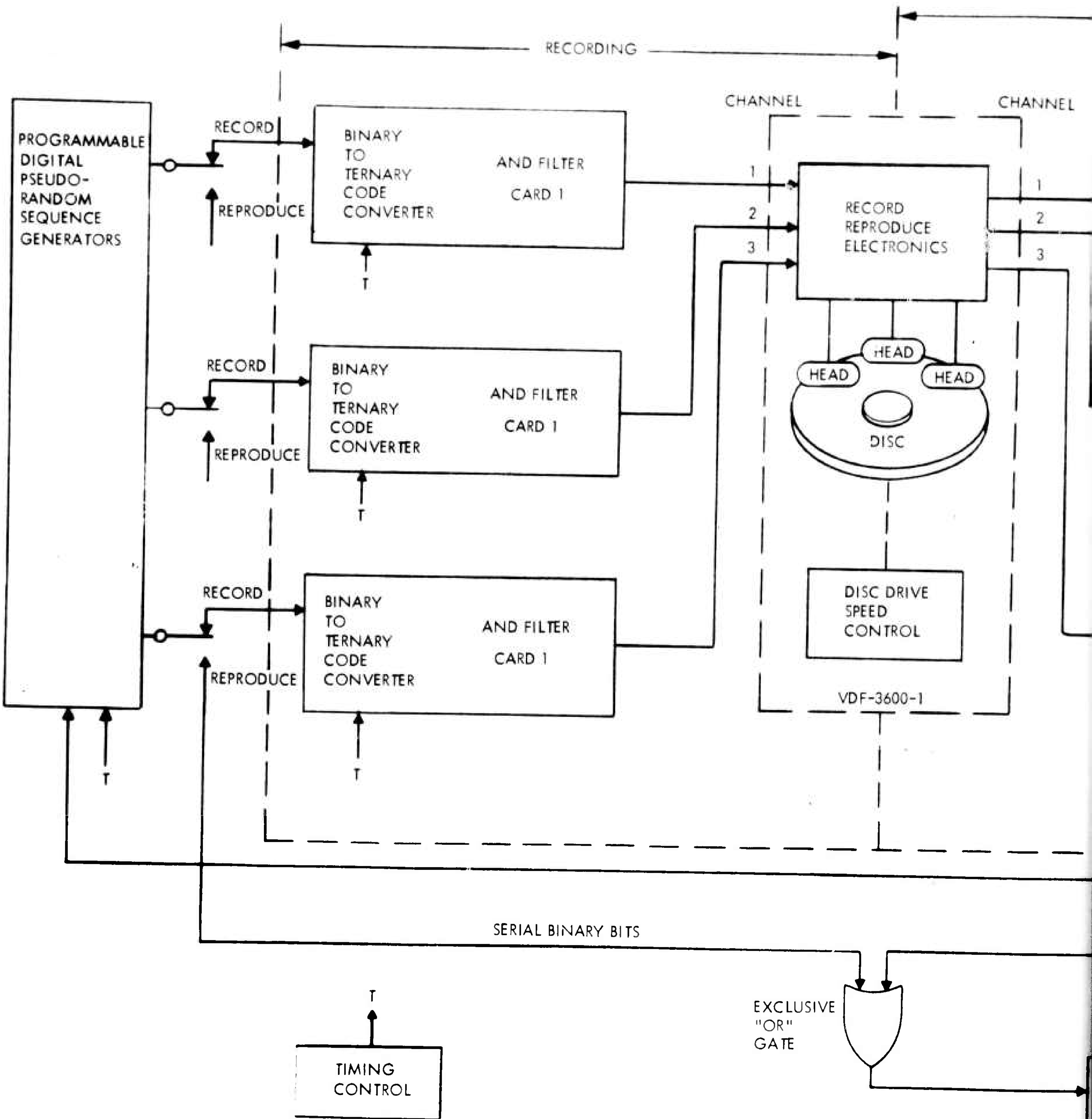
1) The three channels of UNIDAR electronics that will encode/decode the raw NRZ binary data into/from the better matched disc signal. This equipment, with the exception of the equalizer, has been manufactured and tested in a closed-loop system. The equalizer card has been tentatively designed and laid out. Its final design, build and test effort will be completed after delivery of the disc system.

2) The skeletonized disc test bed that will be used to analyze the parameter trade-offs which affect high density recording. This disc is a custom Data Disc Model VDF-3600-1 scheduled for delivery on May 15, 1970.

4.1 UNIDAR Electronics

4.1.1 Background

The digital logic and design principles required to implement and test the UNIDAR code on the disc system (figure 4) is essentially complete, since the encoding technique has


RECORDING
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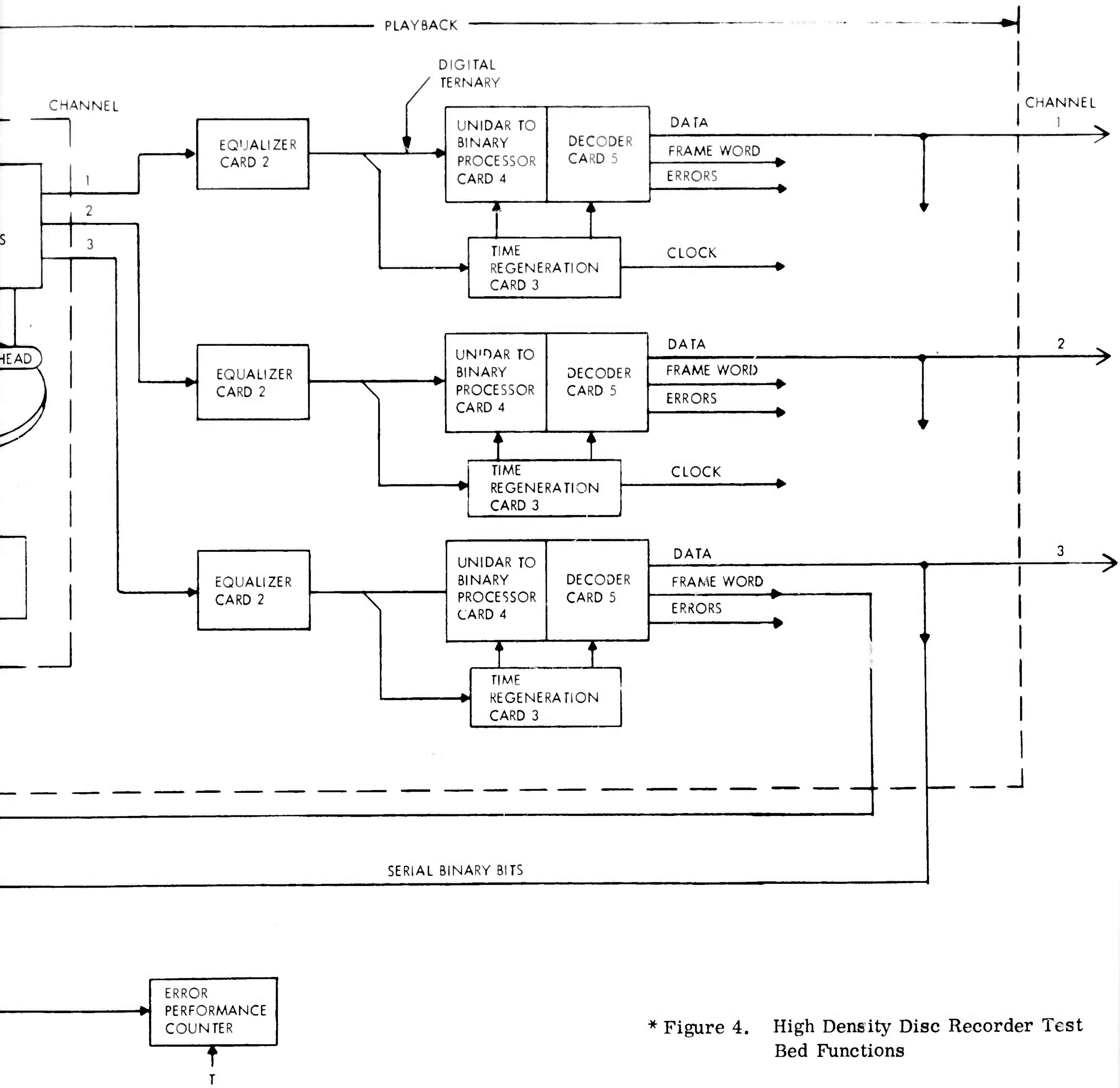


* Figure 4. High Density Disc Recorder Test Bed Functions

been tested on a magnetic-tape recording system. However, the lower frequency response of the magnetic-tape system logic will limit its direct applicability to disc hardware implementation unless disc diameter and/or disc speed can be reduced. Redesign of the UNIDAR digital electronics was undertaken that doubled the bit rate to 4 mega bits per second (2 MHz). Higher data rates corresponding to higher disc speeds are achievable. This will be necessary to minimize disc data access time, but it is not being developed at present.

To accept the 4 mega bit per second data rate the disc system is designed for operation at 1200 RPM. Its speed is controllable at any fixed rate between 900 and 3600 RPM with a minimum amount of hardware change and at practically no additional cost.

Thus, the UNIDAR disc project can take advantage of the UNIDAR tape developments with minimum redesign. For example, all of the UNIDAR card layouts and most of the electronics components common to the tape system can be used on the disc project. Also, at the lower disc speed, the signal bandwidth and spectral requirements of the disc and tape are similar. This allows extrapolation of the tape system equalization design to the disc with minimum change.

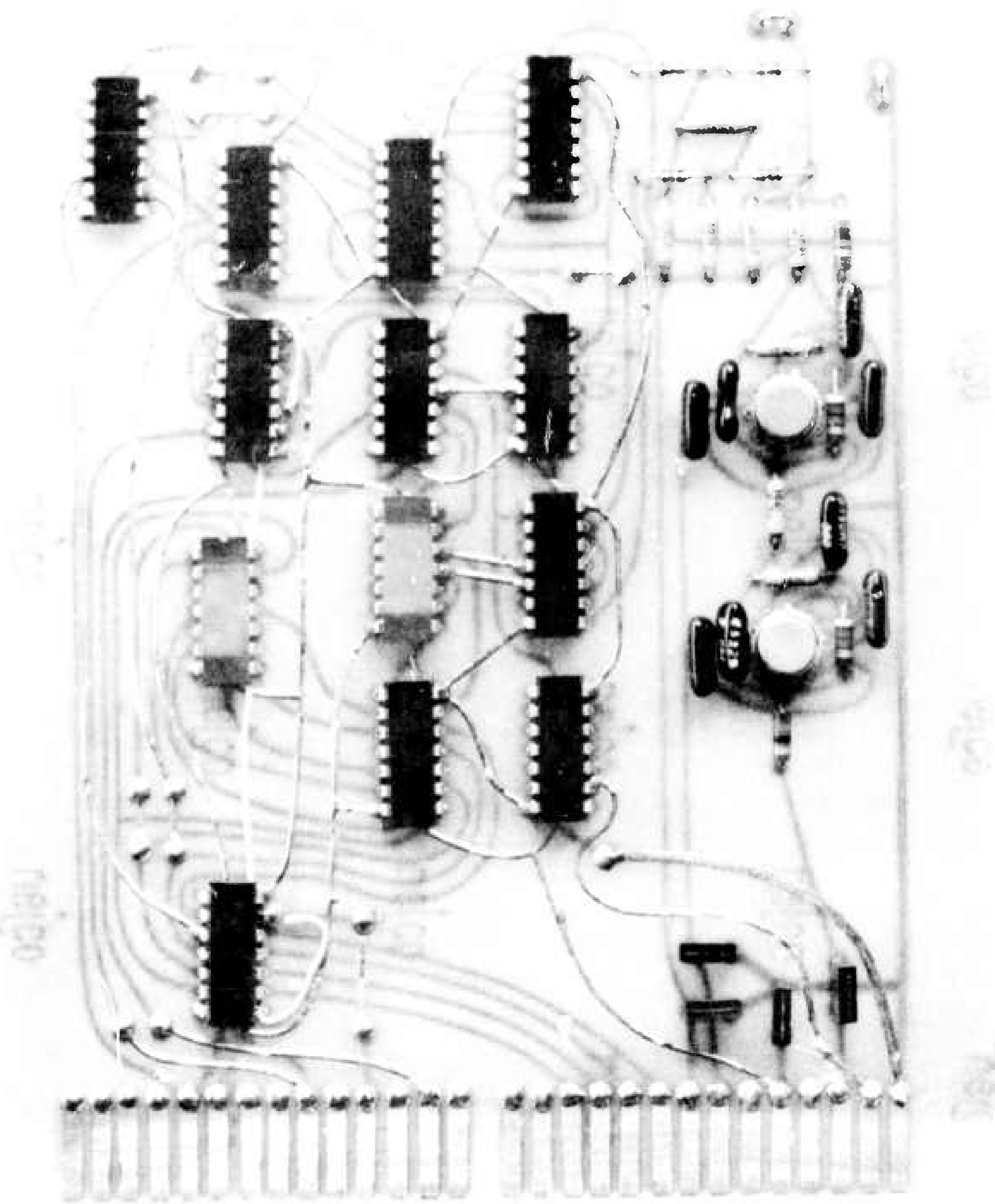
4.1.2 UNIDAR Encode Logic for Recording

Each of the three channels of the HDDR system (figure 4) requires one encoder subassembly card (figure 5). This card converts a channel of binary input into the UNIDAR three level waveform in conformity with the UNIDAR encoding/decoding alphabet shown in Table 1.

The block diagram of the encoder process is shown in figure 6. Features related to UNIDAR encoding for disc recording application and signal flow through the sections of the encoder card are identified in the following paragraphs.

The input to the encoder card is a continuous binary data stream. For test purposes, a consecutive sequence and a pseudo random word sequence are available from the pseudo random generator (PRG) card. Both cards have been built and tested for operation at a throughput rate of 4 mega bits per second.

* The binary data stream is accepted into the encoder in the form of a four bit byte. The encoder converts the four bit binary word into a unique four bit, tri-level, zero average format word. The encoding process is unique but arbitrary. The set of four VCT bits contains 3^4 or 81 members, 18 of which have the zero average property. Since the four-bit binary word has only 2^4 or 16 possibilities, two extra ternary words are available. These two are used in framing and synchronization in the playback/decoding process. The recorded signal is formed from the sequential series of four bit three level zero average words.



ASW 10234

*Figure 5. Encoder Subassembly Printed Circuit Card

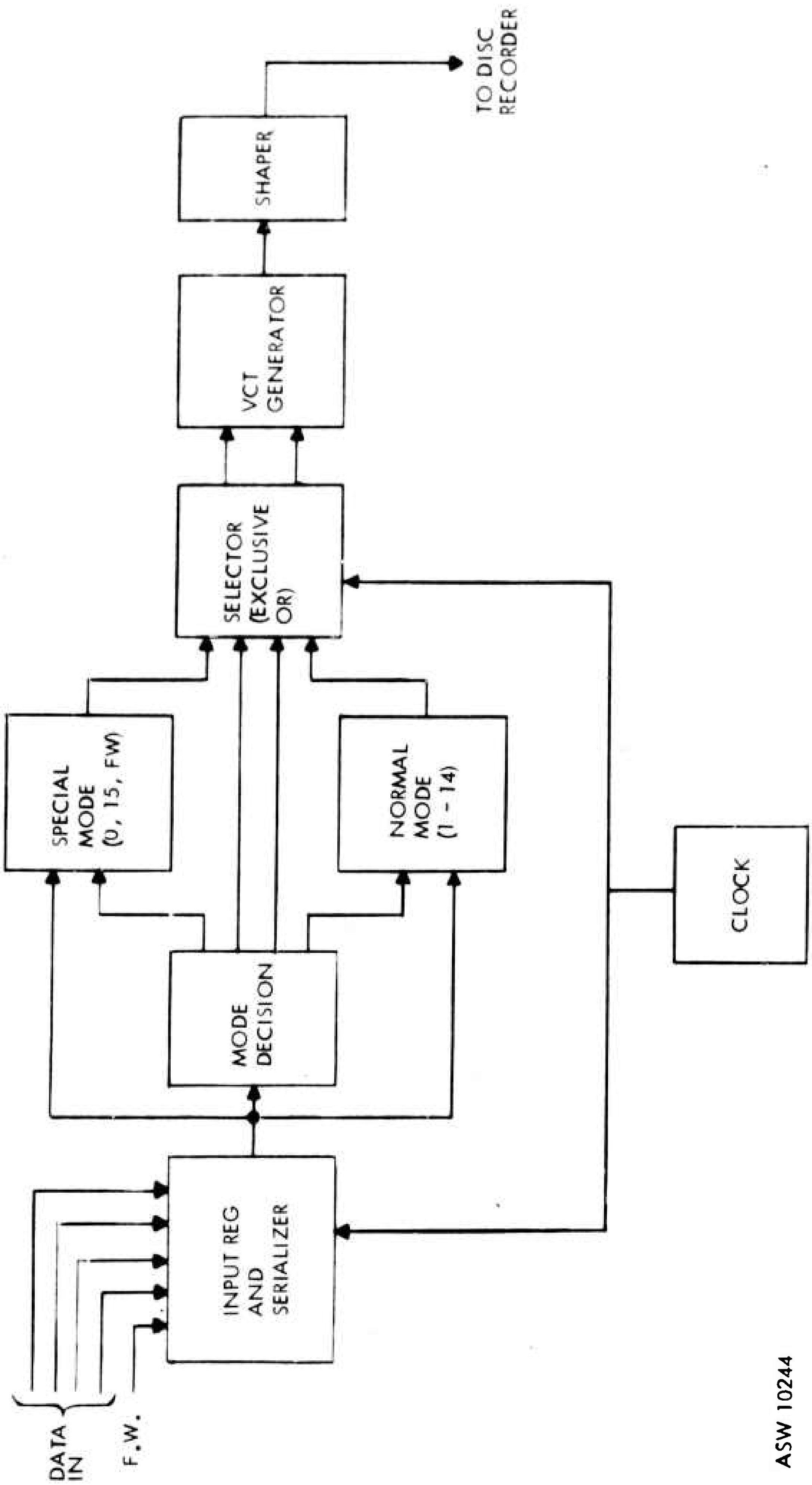


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Figure 6. Encoder Subassembly Block Diagram

4.1.3 UNIDAR Decode Hardware for Playback

Figure 4 is a first level block diagram showing the High Density Disc Recorder Test Bed functions. These playback functions will simultaneously reproduce: (a) the data of two tracks from a 400 track selection and (b) the data from one fixed track.

Figure 7 shows the playback functional block diagram of one channel that is typical of the three required playback channels. Each channel requires the four cards shown in figure 8. The UNIDAR playback cards serially process the ternary level analog signal from a selected track to reconstruct the original binary data. All cards (excluding equalizers) have been built, tested, and system wired (figure 5) to show three channels of system operation at a 4 mega bit per second rate.

Sequential functions of cards 1 through 4 are required in the playback decoding of a UNIDAR channel. The following paragraphs provide a detailed functional description of each card.

4.1.3.1 Amplitude and Phase Equalizer, Card 1 - One equalizer card is required per track. Its function is to remove phase and amplitude distortion from the analog signal as it comes off the track.

Figure 8 (card 1) is a photograph of the equalizer as it is used on the UNIDAR tape system.

Although the bandwidth and unequalized response of the tape and disc systems are generally similar, the exact equalizer design for the disc system requires measurement of the amplitude and phase response of the disc reproduce heads. Relative to the tape system, the equalization design should be eased because disc flutter and jitter are under better control ($<$ 50 nano sec.). However, variations in the signal response characteristic will be greater on the disc. These are affected by head to disc spacing ($> 10\mu$ inch) which changes with radius and the spacing itself which represents a greater percentage of the disc medium thickness.

* In the present tape equalizer, the raw playback signal is applied directly to a transversal filter. Outputs from taps on the filter are adjusted for amplitude and combined to create a high frequency boost without introducing additional phase distortion. Additional high frequency peaking is provided and a simple RC network is used to extend the low frequency response.

* Following the amplitude equalizer section, five cascaded, split-load phase shifters are used to provide envelope delay correction. At this point, the properly equalized UNIDAR signal is routed to the sampler/timer card.

GENERAL DYNAMICS
Electronics Division

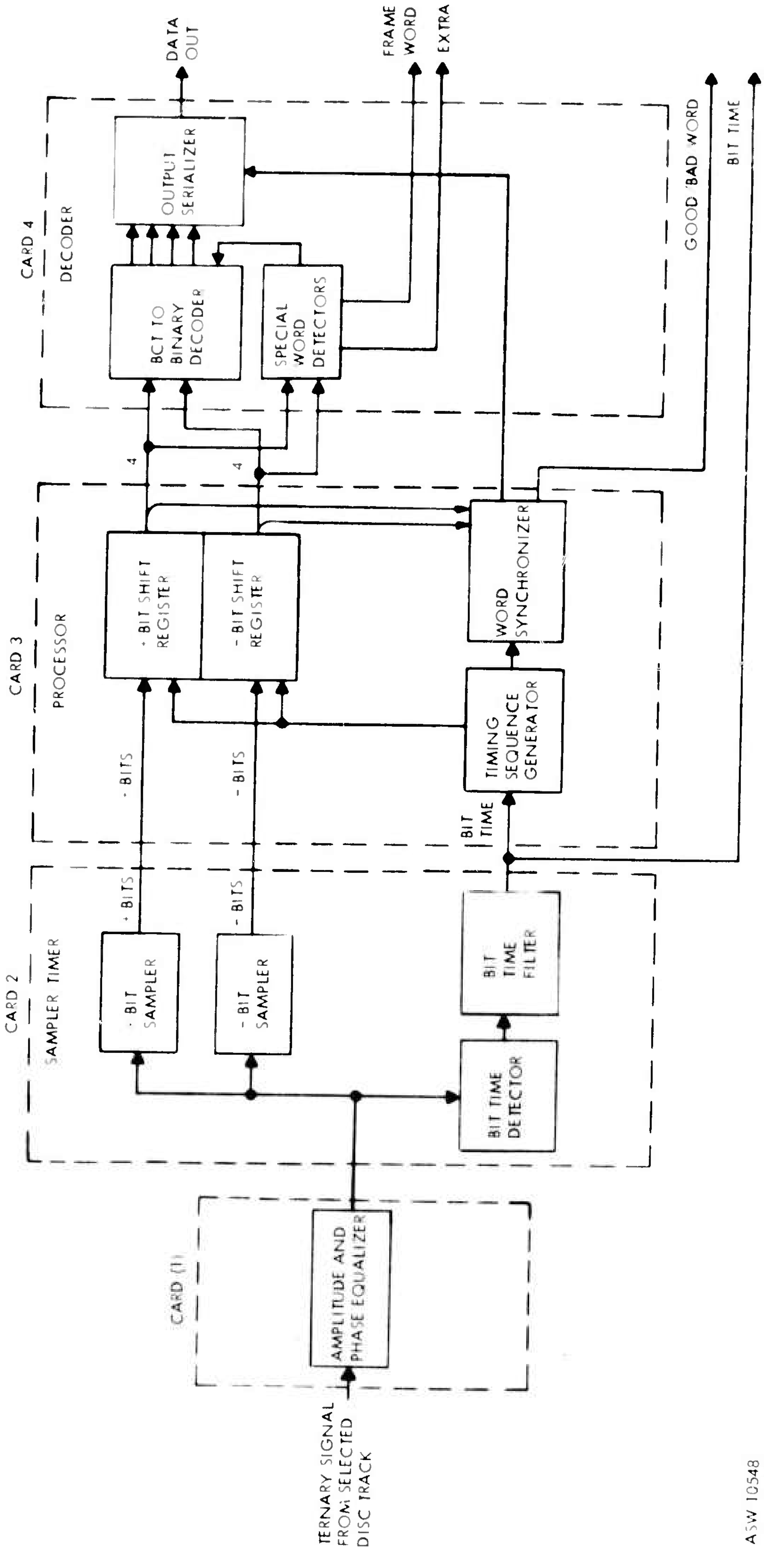
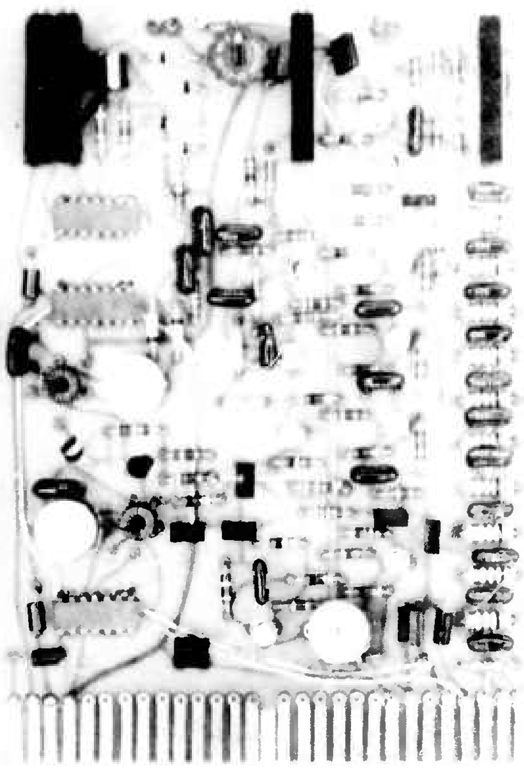
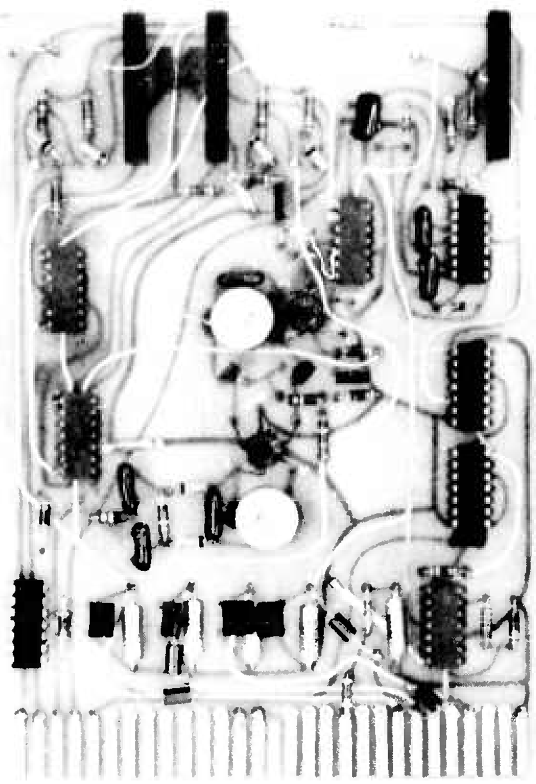


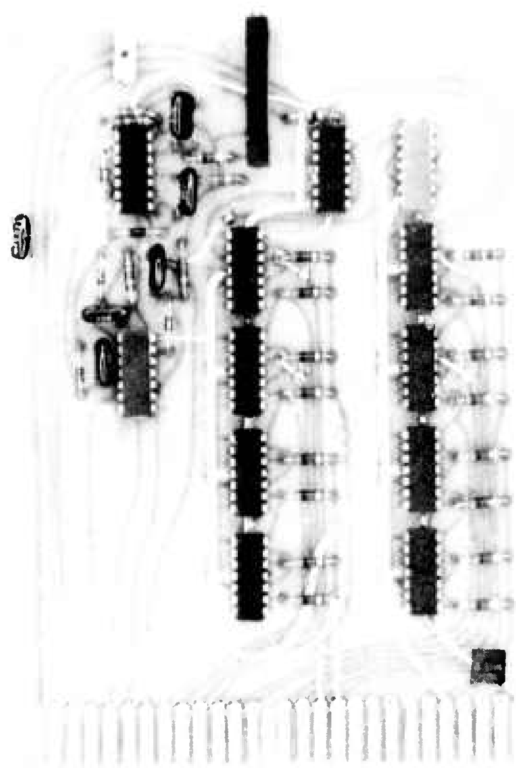
Figure 7. One Channel Playback Functional Block Diagram



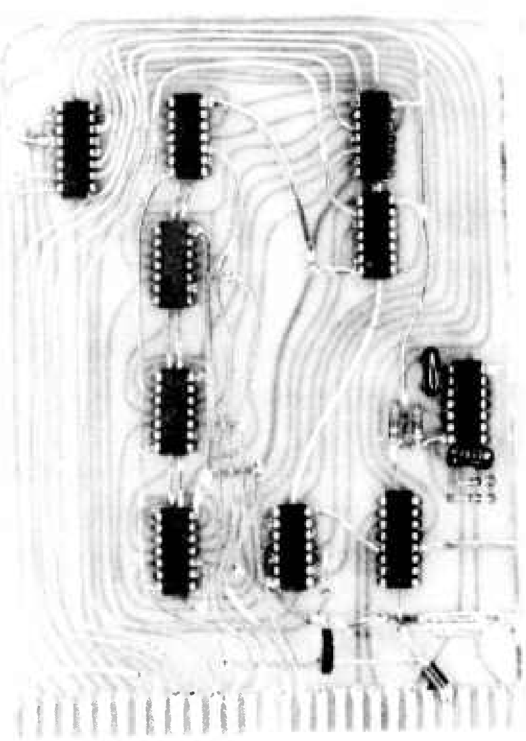
(1) Equalizer Card



(2) Sample Timer Card



(3) Processor Card



(4) Decoder Card

ASW 10549

*Figure 8. One Channel Playback Function Printed Circuit Cards

4.1.3.2 Sampler/Timer, Card 2 - The equalized data stream is converted into digital logic levels for ultimate reassembly into word groups. The data stream will have amplitude variations due to disc variations, imperfect head contact, dirt, etc., so it is not practical to compare the data stream against a fixed reference value. Instead, a floating or variable reference will be derived from the data stream itself by detecting the peak levels of both + and - ternary digits as these values are averaged over a short period, e.g., 10 words. One-half the averaged peak level establishes the threshold for each of the bit samplers. The data signals and the threshold levels are then applied to a comparator. In this manner, the + ternary digits above the threshold will be detected and appear as logic ones at the output of the card. Likewise, the - ternary digits will appear as logic ones at the output. The data at this point is the UNIDAR ternary code which is split up onto two lines in an interim binary-coded-ternary format. The signal is then routed to the processor card.

* The disc has an available outside timing track which will be necessary to re-time playback data for non-self clocking codes. UNIDAR however is self clocking. It will re-establish a stable time reference based on the data stream. This can be used for timing the data sampling process as well as synchronizing the disc recorder to an external system clock by means of phase lock techniques.

* To derive this time reference, it is necessary to detect the peaks of the data signal both + and -, remove the DC components and apply the residual AC component to a narrow filter. As detected, the bit rate AC component is approximately 20 dB above the surrounding clutter. After filtering and amplification, this value is approximately 60 dB. A level detector is used to detect the zero crossings that slices the sine wave signal into a square wave, to sharply define the sampling points for the BCT data output. This bit detector and time generator is also located on the sample/timer card.

4.1.3.3 Processor, Card 3 - Three signals (+ and - BCT bits and bit time) are routed from the sampler/timer to the processor card and are used to perform the following two functions:

1) Assembly of the serial data stream into parallel format

2) Examination of the data for zero average word groupings

* The BCT data from the samplers is presented continuously to the processor shift registers, and is entered under the control of the shift pulses from the timing sequence generator. With each successive shift pulse, the BCT data is moved along the line until all bits of the word are correctly positioned in the registers. When this occurs the complement of the + bits and the - bits sum in a resistor summing network to a specific voltage (approximately 2 volts). Thus, valid words are correctly positioned in the line whenever equal numbers of + and - bits are in the registers. The summation is repeated for a second word to reduce the likelihood of false zero indications to facilitate rapid synchronization.

* This word synchronizer subassembly is part of the processor card. Its main function is to examine the word groupings for the zero average condition. This information, along with a timing pulse, is the basis for a position validity decision of the data in the shift registers. However, in addition to valid four-bit sequences which average zero, it is possible to get the same result from an invalid four-bit sequence. The frequency of this occurrence is reduced by examining two adjacent words instead of only one. This does not affect operation after synchronization is attained but it does allow synchronization to be achieved more rapidly. Lack of dropout characteristics on a disc may reduce the complexity of the word synchronizer subassembly.

* Word synchronization is achieved in the following manner. Bit times from the timing generator are counted in groups of four. Each time a count of four is reached "good words" or 'bad words" are registered in separate counter. (Good words have a zero average; bad words do not.) When either counter registers a count, it clears the other counter. Thus, the counters in fact count sequential good and bad words.

* The "good word counter" is larger than the "bad word counter". Synchronization/ nonsynchronization occurs when a counter fills.

* When "word status bad" is indicated, the four-bit counter enters a search mode. This enables "good word status" to be recovered in the shortest possible time.

The design has been breadboarded and thoroughly tested.

* 4.1.3.4 Decoder, Card 4 - The following two functions are accomplished in the decoder card:

1) BCT to binary decoding

2) Special word detection

As UNIDAR 4 bit word interval times are detected by the word synchronizer, the BCT signal is decoded four bits at a time back to its original binary code. The conversion is via a simple decode matrix containing eight input lines between the processor and decoder. These input lines are re-assignable to conform with the arbitrary record encoding alphabet.

* The output of this four bit parallel decode function is serially converted to regenerate the original disc input data stream.

* The special words detected by the decoder are the 2 of a possible 18 zero average ternary codes that do not have the binary equivalent (see table 1). These are custom words having bi-level outputs on separate lines, that are defined by specific customer requirements.

4.1.4 Testing

Equipment has been developed to test for the following two forms of errors:

1) Incorrect interpretation by the electronics

2) Dropouts caused by dirt, bumps or inhomogenity of the magnetic medium

* The first category will occur randomly. Disc dropouts should not occur. However, a larger number of sequential words would be incorrect if the disc dropout does occur. During the recording/playback process on the disc these errors will be examined and compared with desired system standards to flag malfunctions and incorrect data. The logic which monitors these errors has been built and is similar to that which has been designed to flag malfunctions and incorrect data on the tape system.

* One visual method of examining large quantities of serial data by the oscilloscope is the eye pattern technique. Random binary or ternary data is observed on the oscilloscope by using a horizontal sweep covering a few pulse intervals, which is synchronized with the pulse rate. All possible random pulse amplitude and time positions become superimposed, giving a symmetrical pattern of open spaces and transition waveforms. The openings show the minimum margin for correct sampling decision. The vertical dimension of the openings indicates the minimum margin against noise when sampling the waveform. The horizontal dimension indicates the range of correct sampling time and the amount of peak distortion due to intersymbol interference. An observation of the eye pattern gives a quick indication of the effectiveness of equalization measures to combat display distortion and the general quality of the data channel and its signals.

4.2 Disc System

A major objective during Phase I of this program has been the selection of a suitable test bed having sufficient versatility and adaptability for use in the performance evaluation of the recording efficiency of UNIDAR and other binary and multi level encoding techniques. A literature search was conducted to identify current technology on disc recording techniques. Potential vendors were polled on cost, availability, delivery and performance of existing equipment. Parameters of the disc system and variables unique to high density recording were then established. These factors were classified in accordance with current and projected program objectives each of which were given a program impact weighting factor. These are listed in the Disc Evaluation Matrix shown in Appendix I.

4.2.1 Performance Specification

In general, the program objectives have required the following basic disc system characteristics:

1) In contact head-to-disc interface
2) Ultra thin, high remanance, high coercivity medium
3) Combination of movable and fixed head configuration
4) Two identical channels for redundant recording capability
5) Double loop servo control to maintain speed stability within ±50 nsec
6) Variable speed control
7) High resolution clocking capability
8) Erase-before-write capability
9) Minimum equivalent data rate of 4 m bits/sec
10) Wavelength resolution 200 inches
11) Cost below $25,000
12) Delivery within 90 days

A description and specification for an instrumentation disc recorder based on the preceding requirements is included in Appendix II.

4.2.2 Competitive Procurement

Potential vendors for the instrumentation disc recorder were established by telephoning the research, engineering and/or marketing departments of disc, tape and wideband instrumentation recording manufacturers. Each vendor was requested to identify his interest or manufacturing capability for a head-in-contact disc recording system. Three companies (Ampex, Data Disc and Data Memory Inc. (DMI)) expressed an interest in quoting on the equipment specified. None of the other companies contacted expressed an interest in bidding on a wideband instrumentation disc recorder specification.

The facilities of Ampex, Data Disc and DMI were inspected on Feb. 5 and 6 to determine quality of the product, credibility, and capability of the potential vendors. The personnel and facilities of both Data Disc and DMI were favorably impressive and extended the confidence that either manufacturer could deliver the equipment. Ampex was given the specification but declined to bit on the basis of their inability to meet the price and delivery schedule imposed by the contract requirements.

On Feb. 16, DMI provided a demonstration of a single channel version of their dual channel IDR-200 wideband instrumentation disc recorder at the Electronics division of General Dynamics. Their standard unit records on a continuous spiral track running from the outside to inside diameter of the recording zone for a period of 20 seconds at a track density of 200 tracks/inch.

This is not practical for digital disc applications because single track repetitive scanning is concentric. Consequently, it will only read approximately 75% of the track information due to the spirally recorded track. All of the stored information may be read if both record and read functions are performed in the concentric single scan mode. However, the trigger which supplies the once-around signal is derived from a dØ/dt detector located near the drive shaft. Rise time of this trigger signal is < 40 usec and is inadequate to supply a stable display. A separate clock track located at the outside radius was requested.

4.2.3 Bid Evaluation

Upon receipt of both manufacturer's proposals, a detailed evaluation process covering performance, availability and cost was undertaken. The program objectives and requirements listed in the disc evaluation matrix (Appendix I) were each given a normalizing factor. The parameters which affected these criteria were then listed within each group and given separate weights (1 to 10). Each manufacturer was then scored upon his capability within that group for each parameter. The scores were tabulated and normalized. The results show Data Disc was decidedly better suited for this application. The tabulation shows Data Disc outscored DMI 29 to 14 with 22 even out of 65 categories (see Appendix I).

4.2.4 Description of Disc System

The test bed identified as the Custom Three Track Video Disc File System Model VDF-3600-1 in figure 4 has been purchased from Data Disc Inc. It is scheduled for delivery on 15 May 1970. This equipment shown in figure 9, consists of components from the custom 3200 series Video Disc File and the custom 4000 series Fixed Head Disc Recorder. The system operates with the heads-in-contact with the disc surface. Two movable and one fixed head assemblies are provided to cover 400 tracks, at a track density of 100 tracks per inch. Two of the three clock tracks provide servo drive control. All head assemblies are mounted on the bottom disc surface. The system has capability of operating at any speed from 900 to 3600 r/min with simple resistor, capacitor combination changes on the servo control board. Signal response may be tailored from dc to 2 MHz at 1200 r/min or dc to 6 MHz at 3600 r/min using the Data Disc Modem system by simple changes in resistor capacitor combinations in the modems. Direct recording up to 10 MHz at 3600 r/min or 7.5 MHz at 1800 r/min is possible. Only two channels of Data Disc Period Modems have been purchased at this time with a capability of expanding the system at a later date. Any two channels are operable since card plug-in positions are interchangeable. This block diagram of the disc system is shown in figure 10.

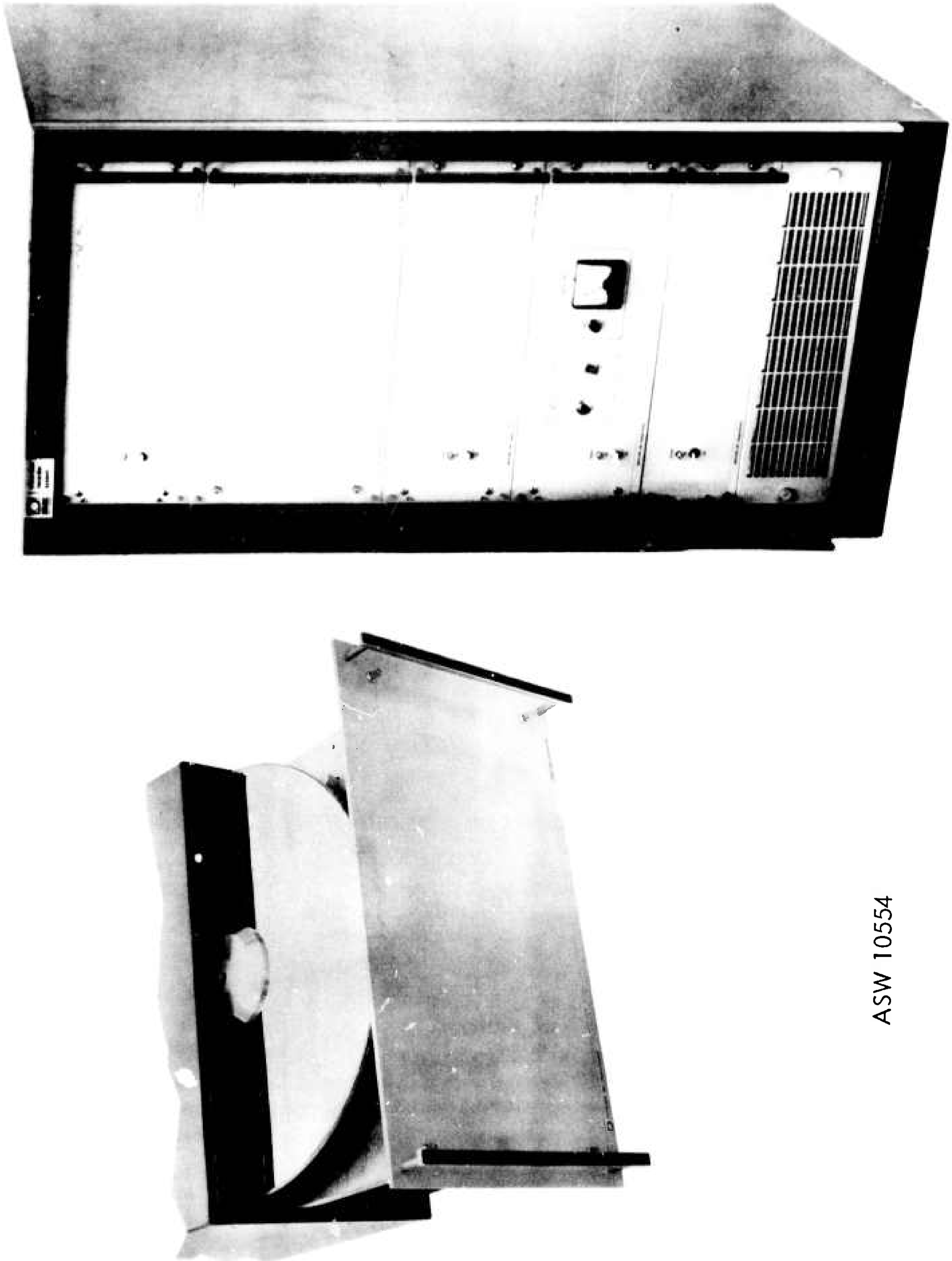


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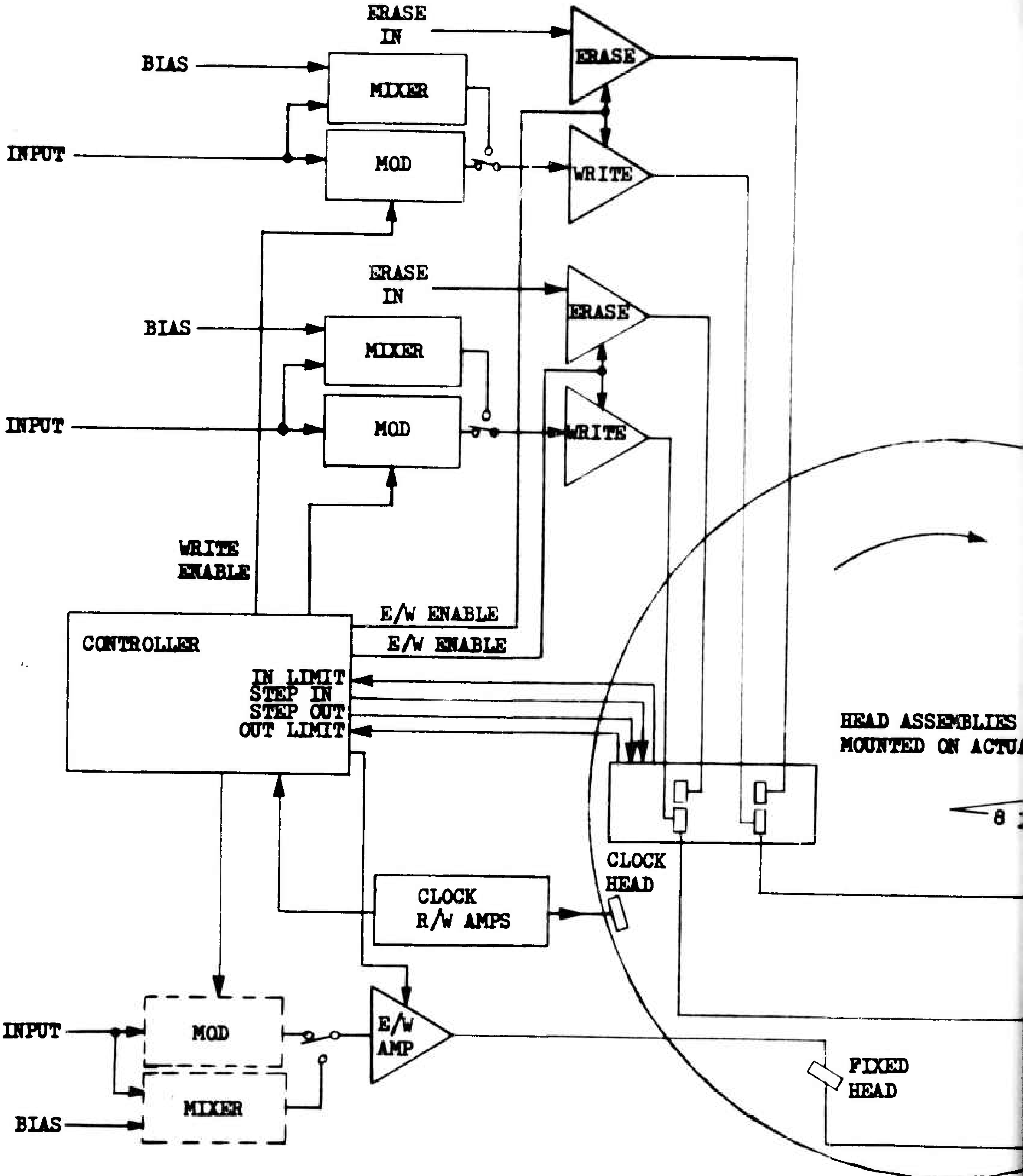
Figure 9. Data Disc Video Disc Recorder, Model VDF-3600-1


ERASE IN
BIAS
MIXER
INPUT
MOD
ERASE
WRITE
ERASE IN
BIAS
MIXER
INPUT
MOD
ERASE
WRITE
WRITE ENABLE
E/W ENABLE
E/W ENABLE
CONTROLLER
IN LIMIT
STEP IN
STEP OUT
OUT LIMIT
HEAD ASSEMBLIES
MOUNTED ON ACTU
CLOCK HEAD
CLOCK R/W AMPS
INPUT
MOD
BIAS
MIXER
E/W AMP
FIXED HEAD

ASW 10550

1

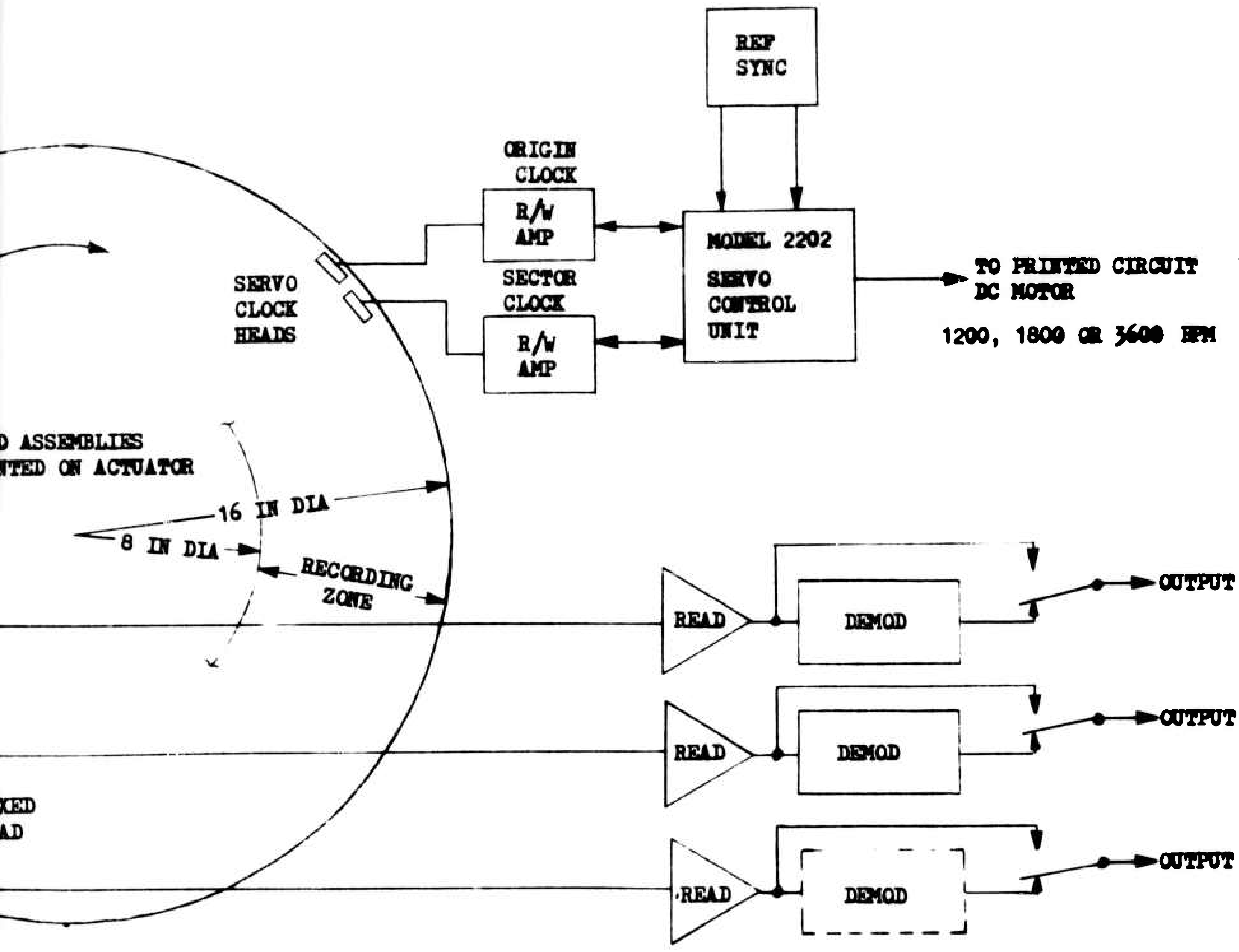


Figure 10. Custom Three Track Video Disc File VDF-3600-1

4.2.4.1 Disc Medium - The disc medium is a proprietary NiCo composition deposited on a pre-plated 0.25 inch thick aluminum disc. Nominal thickness of the medium is 10 micro inches. The disc is plated on both surfaces and consequently has two useful surfaces although one surface may not meet all specifications. A Rhodium flash, a few micro inches thick, has been deposited on top of the magnetic film to provide protection from corrosion and abrasion from head contact. The surface roughness is nominally 1 micro inch peak-to-peak averaged over 1 inch. The recording zone nominally extends from an outside radius of 8 inches to inside radius of 4 inches.

4.2.4.2 Head Configuration and Track Accessing - Two head assemblies are mounted on a single actuator. The actuator is driven by a TTL compatible stepping motor in sequential 10 mil steps at a 200 tracks per sec maximum slew rate. The actuator is automatically reset to the outer track when travel goes beyond track 400. Each head assembly consists of a 10 mil wide erase head mounted in front of a combination write/read head that is 8.5 mils wide. Therefore, a 1.5 mil guard band exists between tracks. The actuator has a 2.5 inch travel so that Head No. 1 covers tracks 1 through 250 and Head No. 2 covers tracks 150 through 400. Track registration on the moving head system is ±0.5 mil. Indication of track position will be supplied by a counter. A 25 mil wide fixed head assembly is centered over tracks 200 and 201. This fixed head assembly can be manually moved to other mounting positions centered over tracks 1 and 2, and 399 and 400. Head-to-disc spacing is maintained at 10 micro inches with 3 grams of pressure supplied by a canti levered spring. Gap length on Read/Write head to 60 micro inches. Head inductance is nominally 20 μh.

4.2.4.3 Servo Controlled Drive - A model 2202 double loop servo is included in the system. Information in the form of a once around clock and a sector clock where 100 $\leq$ number of sectors $\geq$ 1000 are used to control the speed variation to within ± 50 nanoseconds. This corresponds to less than 3 parts per million in speed variation. A dc printed circuit motor provides the drive power.

4.2.4.4 Extra Clock Track - A 25 mil wide head located at the outside radius provides a 10 mega bit per sec NRZ clock rate at 3600 rpm. The clock signal is recorded directly and is TTL compatible Interchannel Time Base Error (ICTBE) is ± 20 nanoseconds.

4.2.4.5 Modulation/Demodulation - Data Disc has developed a proprietary period modem that provides linear amplitude to period conversion with minimum intermodulation distortion. It also allows the use of maximally flat time delay filter design (linear phase). Thus, overshoot and undershoot characteristics that cause intersymbol interference and is especially objectionable in multilevel transmission system can be minimized. Linearity is within ±1 percent.

4.2.4.6 Performance Characteristics - The performance characteristics for 1800 rpm operation are summarized below along with the summary of disc parameters which directly affect these characteristics:

1)	Erase head width	10.0 mils
2)	Moving R/W head width	8.5 mils
3)	Fixed R/W head width	25.0 mils
4)	Guard band for moving head	1.5 mil
5)	Guard band for fixed head	5.0 mil
6)	Disc recording zone	16" to 10" diameter
7)	Response (with modem)	dc to 4 MHz (6 dB down)
8)	Carrier Frequency	7.5 MHz
9)	Signal to noise ratio	> 40 dB p.p. signal/r/min noise
10)	Intermodulation distortion	< 5%
11)	Linearity	< 1%
12)	Saturating write current	60 to 90 ma
13)	Crosstalk (Write/Write)	> 50 dB
14)	Head output	2.5 to 5 mV
15)	Interchannel time base error	< ± 20 ns

5.0 CONCLUSIONS

Development of the disc recorder test model is proceeding according to schedule. There are no anticipated problems which might prevent laboratory test demonstrations of performance as stated in the contract.

* Evaluation of various encodings and the UNIDAR technology shows that the UNIDAR code is most applicable to the disc recording requirement of high packing density at the low error rates. Evaluation of the disc system has determined that the 'in-contact' disc system is necessary to accomplish this high data density requirement.

Initial design has addressed the maximum capabilities of the system. The design objectives have been to meet all present disc requirements and those anticipated for the near future. Some compromises have been made to allow the cost effective utilization of existing hardware. For example, access time of the initial system has been sacrified to accommodate hardware whose present design is frequency limited and would require additional redesign.

Three channels of UNIDAR encode/decode logic have been redesigned, built and tested for 4 Megabit/second operation. These will be used for disc operation at 1200 rpm at a bandwidth of 2 MHz. The disc has capability for speeds up to 3600 rpm and 6 MHz bandwidth with minimum changes. A precision servo control holds time base error to within ± 50 ns. Several track widths, both moving and fixed head configurations, and redundant recording capabilities are available. Error performance criteria has been investigated and a technique for error detection/correction identified.

6.0 PROGRAM FOR NEXT INTERVAL

The custom wideband instrumentation disc recorder will be received by General Dynamics Electronics division on May 15 without the controller. The design and fabrication of a condensed version of the controller will be completed before receipt of the disc. Disc characterization will begin after brief equipment checkout. Head response, interchannel time base error, signal-to-noise, cross talk, erasure characteristics, and equalization requirements will be measured and identified for each track. Response measurements for both 25 mil and 10 mil wide heads will be conducted. Variations in performance due to inaccuracies in track registration will be measured. Noise characteristics will be identified for different biasing techniques. A computer program has been written to aid in the equalization network design. The impulse response will be photographed and the data points will be used to generate a transversal filter equalization network. Eye patterns will be used to indicate the performance of the networks. The UNIDAR spectrum will be compared with other code spectrums for various encoding sequences.

A trade-off analysis will be conducted to study packing density vs. error performance for the UNIDAR recordings in both the direct technique and the modulation technique. Tests will also be made to separate and identify errors caused by timing, intersymbol interference, electronic noise, and variations in head/disc characteristics.

Redundant recording techniques will be demonstrated to determine just what advantage exists over single track recordings for equivalent data packing densities.

7.0 REFERENCE

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APPENDIX I

DISC EVALUATION MATRIX

PARAMETER	Weight	
NUMBER OF TRACKS AND TRACK DENSITY	8	Number inch Head W Guard Extend Disc r Record
FREQUENCY RESPONSE AND LINEAR PACKING DENSITY	10	Head t Induct Gap le Modula Signal Bandwi Harmon Interm dist Satura Wavele Wavele
TRACK ACCESS	7	Feed r Regris Compat with Method

1

Weight	VARIABLES	Weights	RAW SCORE		WEIGHTED SCORE		NORMALIZED TOTALS	
			Data Disc	DMI	Data Disc	DMI	Data Disc	DMI
	Number of tracks per inch	10	5	10	50	100		
	Head Width	10	5	10	50	100		
	Guard band	10	8	8	80	80		
	Extended radius range	7	8	7	56	49		
	Disc radius	5	8	6	40	30		
	Recording zone range	8	8	8	64	64		
8					340	423	3.57	4.43
	Head to disc spacing	10	8	8	80	80		
	Inductance	5	8	5	40	25		
	Gap length	8	6	8	48	64		
	Modulation method	10	8	6	80	60		
	Signal/Noise ratio	10	10	7	100	70		
	Bandwidth	10	10	5	100	50		
	Harmonic Distortion	8	6	7	48	56		
	Intermodulation distortion	5	5	5	25	25		
	Saturation Write Current	7	6	8	42	56		
	Wavelength of signal	10	5	4	50	40		
	Wavelength of carrier	10	6	7	60	70		
10					673	596	5.30	4.70
	Feed rate	8	8	2	64	16		
	Regristation/Indication	10	8	8	80	80		
	Compatibility of feed with speed change	7	10	3	70	21		
	Method of feed/reset	5	6	6	30	30		
7					244	147	3.70	3.30

PARAMETER	Weight	VA
ERROR PERFORMANCE	10	Disc coat Thickness of radi Roughness Flatness Head to d stabili Head pres Time base Head effi Crosstalk Variation speed
CLOCK	7	Accuracy Resolutio Availabil Complexit
SUPPORT	10	Warranty Reliabili Credibili Engineeri Productio Maintenan Service Responsiv Documenta

Weight	VARIABLES	Weights	RAW SCORE Data Disc	RAW SCORE DMI	WEIGHTED SCORE Data Disc	WEIGHTED SCORE DMI	NORMALIZED TOTALS Data Disc	NORMALIZED TOTALS DMI
	Disc coating material	7	6	8	42	56		
	Thickness as function of radius	8	7	3	56	24		
	Roughness	5	5	5	25	25		
	Flatness and runout	5	5	5	25	25		
	Head to disc spacing stability	10	6	4	60	40		
	Head pressure	8	3	8	24	64		
	Time base error	10	6	2	60	20		
	Head efficiency/Output	7	5	5	35	35		
	Crosstalk	5	5	5	25	25		
	Variation of basic disc speed	8	7	5	56	40		
10					408	354	5.35	4.65
	Accuracy	8	6	6	48	48		
	Resolution	10	6	6	60	60		
	Availability	5	8	0	40	0		
	Complexity	7	8	2	56	14		
7					204	122	4.38	2.62
	Warranty	10	5	8	50	80		
	Reliability	8	5	5	40	40		
	Credibility	5	5	5	25	25		
	Engineering Capability	7	8	4	56	28		
	Production Capability	5	8	5	40	25		
	Maintenance/Factory Service	6	9	2	54	12		
	Responsiveness to RFQ	7	8	6	56	42		
	Documentation	8	9	3	72	24		
10					393	276	5.83	4.17

2

PARAMETER	Weight	
GENERAL		Syst Disc Sens En Esth
	3	
		De li
	10	
		Cost
	10	
ERASE PROCESS		Comp Eras Fe Head Co Capa du
	6	
SYSTEM VERSATILITY CAPABILITY AND EXPANDABILITY		Spee ab Serv Expa fi ap Vari ha

1

	Weight	VARIABLES	Weights	RAW SCORE		WEIGHTED SCORE		NORMALIZED TOTALS	
				Data Disc	DMI	Data Disc	DMI	Data Disc	DMI
		System Complexity	6	6	8	36	48		
		Disc Containment	3	8	7	24	21		
		Sensitivity to Environment	7	5	5	35	35		
		Esthetic Appearance	2	5	6	10	12		
	3					105	116	1.42	1.58
		Delivery	10	5	5	50	50		
	10					50	50	5.00	5.00
		Cost	10	8	5	80	50		
	10					80	50	6.16	3.84
		Complexity	6	5	5	30	30		
		Erase before Write Feature	8	6	7	48	56		
		Head position and Configuration	8	8	5	64	40		
		Capability of AC Erase during turn off	7	6	4	42	28		
	6					184	154	3.26	2.74
		Speed change adaptability	10	10	1	100	10		
ITY		Servo Control	8	8	3	64	24		
		Expandability/Modifications for future applications	7	10	1	70	7		
		Variety of modular hardware	5	7	4	35	20		

PARAMETER	Weight	
SYSTEM VERSATILITY CAPABILITY AND EXPANDABILITY (Continued)	10	Disc He costs Compati Signa Accessi elect Locatio elect Variety posit Head co start Coolin Self t
PROJECT NO. 4926101		DISC E MA

Weight	VARIABLES	Weights	RAW SCORE Data Disc	RAW SCORE DMI	WEIGHTED SCORE Data Disc	WEIGHTED SCORE DMI	NORMALIZED TOTALS Data Disc	NORMALIZED TOTALS DMI
	Disc Head replacement costs	8	4	8	32	64		
	Compatibility of I/O Signal levels	6	5	5	30	30		
	Accessibility of electronics	7	5	5	35	35		
	Location of head electronics	7	5	5	35	35		
	Variety of fixed head positions	6	8	4	48	24		
	Head contact during start up/turn off	5	7	5	35	25		
	Cooling and power	5	5	5	25	25		
	Self test features	5	4	8	20	40		
					529	339	6.09	3.91
10								
							50.06	40.94
	DISC EVALUATION MATRIX							

DESCRIPTION AND SPECIFICATION

FOR AN

INSTRUMENTATION DISC RECORDER

for

Project No. 4926101

Prepared by: J. E. Kress

R. W. Freytag

Approved by: D. L. Lassell

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Electronics Division
1400 North Goodman Street
Rochester, New York 14601 · 716-342-8000

CONTENTS

1.0 INTRODUCTION

1.1 Scope

This specification describes a special purpose instrumentation disc recorder.

1.2 Purpose

The recorder is to be used as a laboratory test bed during a study which evaluates the recording efficiency of some binary modulation forms. The study requires system performance trade off analysis as parameters (track density, data density, error rate, medium S/N ratio, etc.) are varied. Because of this, a skeletonized disc system having versatile and adaptable features is desired.

2.0 PERFORMANCE REQUIREMENTS

These requirements are suggested; disc manufacturers are encouraged to offer parameter trade-off features or substitutes which maintain the intent of the study.

3.0 GENERAL REQUIREMENTS

3.1 Environmental Conditions

		Operating	Non-Operating
3.1.1	Temperature	0°C to 50 °C	*
3.1.2	Humidity	20 to 80% relative humidity with no condensation	*
3.1.3	Room	Air Conditioned Lab	*
3.1.4	Disc Protection	Air tight or sealed, a transparent cover is preferred	*
3.1.5	Vibration	Less than 0.10g in 10 to 65 cps range	Less than 0.15g in 10 to 65 cps range
3.1.6	Shock	No mechanical damage shall result from shocks up to 5g. Temporary signal failure is permissible; recovery shall be within 30 sec.	
3.1.7	Power	115V ±10%, 20 amps (maximum) @ nominal 60 cps	
3.1.8	Cooling	Suitable provision for cooling with air intake and exhaust at rear of the module shall be provided.	

* Manufacturer should specify his tolerance or requirements.

3.2 Hardware

3.2.1 Interconnecting Cabling - Cabling from back panel to slide mounted module(s) shall be fully supported when module is extended from rack.

3.2.2 Controls - Shall be made from the front panel during normal operation, without need for sliding the module out of the rack.

3.2.3 Adjustments - Manufacturer shall indicate necessity and extent of screwdriver adjustments, either mechanical or electrical, for normal and calibration modes.

3.2.4 Meters and Test Points - Signal output level and meter(s) shall be provided on front panel.

3.2.5 Warning, Control and Operational Lights - Color coded, front panel mounted are preferred indicating when illuminated (that servo is not synchronized, that heads are not in contact with disc, etc.).

3.2.6 Self Test Mode - The system shall pass signals through the signal electronics without recording on the disc. This feature allows operator to set up system calibration without need for recording.

3.2.7 Elapse Time Meter - Provided to indicate total power on time.

3.2.8 Power On Switch - An alternate action push button back lighted switch shall be provided on the front panel.

4.0 DISC PARAMETERS (MECHANICAL)

4.1 Shape Configuration

Sectionalized standard 19 inch chassis mountable packages are preferred with mounting on full suspension roller bearing slides.

4.2 Weight

Each package shall be less than 200 pounds; total weight shall be less than 1,000 pounds.

4.3 Drive

A printed circuit bearing-less dc motor is preferred. Motor should be compatible for servo speed control.

4.4 Disc Speed

Manufacturer should advise on availability of multi-speed system.

4.5 Servo Control

Double loop servo control is preferred. It should provide the following specifications:

4.5.1	Jitter	±50 n sec
4.5.2	Start up Acquisition Time	< 1 minute
4.5.3	Re-Synch Acquisition Time	< 30 seconds

4.6 Disc Surface

Disc should consist of thin metallic magnetic film coated with hard, long wearing protective coating for contact recording purposes.

4.6.1 Film Tolerance - Variations in magnetic coating thickness should not exceed 10%.

4.6.2 Surface Roughness - Surface roughness of protective film/heads should not exceed 0.4 microinches peak-to-peak.

4.6.3 Head/Disc Interface - System should consist of write/read heads in contact with disc surface. Contact of erase head is optional.

4.7 Number of Data Recording Surfaces

One is preferred: two are permitted.

4.8 Head Configuration

Three identical radially in-line track channels each consisting of an assembly of one erase head and one write/read head. Track channel separation and separation between erase and write/read heads should be minimized for minimum track access time within signal-to-noise specification described in Section 5.1.3 and 5.1.4.

4.8.1 Head Width - All heads shall be nominally 7.5 mils wide.

4.8.2 Head and Head Electronics Location - Mounting of clock heads and associated electronics on the bottom surface of disc is preferred. Location of clock tracks shall be at extreme outside diameter of recording zone. Data heads shall be mounted on top surface of disc. Applicable head electronics shall be located as near write/read head as feasible.

4.8.3 Replacement of Head Assembly - Manufacturer shall indicate applicability of changing separate head assemblies regarding downtime (field or factory operation) cost, and compatibility. Manufacturer shall identify the tolerance of the clean room requirement for this operation.

4.9 Track Access

The head stacks (consisting of three head assemblies) may be moved manually under micrometer control in a radial direction, and/or alternative semi-automatic track accessing systems using linear or incremental feed are appropriate. Track accessing must be accomplished with transparent protective cover installed. The manual head positioner shall be automatically disengaged when the disc drive is in the automatic drive mode.

4.9.1 Track Registration - Radial track registration shall be within ± 0.1 mil. Circumferential track registration (arc sec.) shall be identified by disc manufacturer.

4.9.2 Track Density - A radial recording density of 100 tracks/inch is desired.

4.9.3 Head Stack Throw - Recording shall be made over a disc radius whose ratio is greater than two; as a minimum. A greater recording range is preferred.

4.9.4 Track Access Time - Average and worst case time required to move and register a head assembly from one track location to any other shall be identified by disc manufacturer

4.9.5 Track Counter - A digital means of controlling and indicating the head to track position shall be provided.

4.10 Input/Output Connectors

All data and clock signal input and output shall be brought out via connectors of the quick disconnect BNC type.

5.0 DISC CHARACTERISTICS (ELECTRICAL)

5.1 System Response at Operating Speed

5.1.1 Disc Speed 1800 rpm

5.1.2 Disc Dia 12"

5.1.3 Frequency Response Outer Zone - Equalized head response on outer 1.5" wide recording zones shall be ±1.5 dB within the bandwidth of 400 Hz to 4 MHz with 6 MHz FM carrier and down 3.0 dB ±1.0 dB at band edges.

5.1.4 Frequency Response Inner Zone - Equalized head response on inner 1.5" wide recording zone shall be ±1.5 dB within the bandwidth of 400 Hz to 2 MHz with 4 MHz FM carrier and down 3.0 dB ±1.0 dB at the band edges. The outer and inner zones shall not overlap.

5.2 Signal Characteristics

5.2.1 Harmonic Distortion - Less than 3% for any harmonic of a single frequency.

5.2.2 Intermodulation Distortion and Spurious Products - Less than 3% worst case for any IM component (two equal level mixed signals at 0.5v p-p).

5.2.3 Amplitude Linearity - ±5%

5.2.4 Amplitude Stability - ±0.5 dB

5.2.5 Signal-to-Noise Ratio - Peak-to-Peak Signal/Peak-to-Peak noise greater than 32 dB on center channel during simultaneous write on adjacent channels.

5.2.6 Residual Noise - Noise resulting after dc erase shall be less than 10% of nominal head output at FM carrier frequency.

5.2.7 Input/Output Logic Level - +4.5 v ±0.5 v True
+0.25v ±0.25v False

5.2.8 Input Signal Level 1 v p-p adjustable over range 1.5v p-p to 0.25v p-p.

5.2.9 Input/Output Impedance - Either 50, 75 or 100 ohm system.

5.2.10 Output Signal Level - 100 mv p-p minimum; 1.0v p-p preferred.

5.2.11 Magnetic Film Characteristics - It is desired that the minimum 50% pulse width due solely to self-demagnetization shall be at least 30 μ inches where the 50% pulse width is defined as

$$P.W._{50-s.d.} = \frac{B_r \delta}{\pi H_c} \quad \text{and}$$

B_r = Remanent Induction

H_c = Coercive Force

δ = Film Thickness

Manufacturer should advise on compatibility with other system requirements and cost.

5.3 Clocks

5.3.1 Clock, Origin - An origin clock shall be provided on the underside of the disc. This may be permanently inscribed. Manufacturer should advise on necessity of spare origin clock track.

5.3.2 Clock, Sector - A sector clock shall be provided on the underside of the disc. Means for writing and reading N/revolution clock pulses shall be provided; where $100 < N < 1000$. Manufacturer should advise on necessity of spare sector clock track.

5.3.3 Clock Signal Output Levels - The clock signals of Section 5.3.1 and 5.3.2 shall be provided as separate outputs isolated from servo loop and compatible with TTL logic levels as described in Section 5.2.7.

5.4 Heads

5.4.1 Write/Read Heads - Inductance of windings should not exceed 10 μ hy $\pm 10\%$ per leg. Leg-to-leg unbalance of 10% is acceptable. Self resonant frequency with associated electronic loading should peak at frequency no lower than 12 MHz. Head shall be suitable for dc bias mode.

5.4.2 <u>Erase Head</u> - A means for both AC and DC erasure of a track and DC erasure of a sector shall be provided within a single revolution. Erase head shall magnetically degauss the track just prior to recording. Adequate protection from erasing or degrading adjacent tracks should be included.

5.5 Circuits

Manufacturer shall provide complete circuits for writing/reading and earsing including pre/post equalization circuits, drive amplifiers, read amplifiers, FM modulation/demodulation circuits, logic for write/read enable and clock control, etc.

6.0 HEAD AND DISC LIFE

A minimum head and disc life of 1000 hours is desired. Manufacturer should identify his ability to comply.

6.1 Fail Safe Mechanisms

Manufacturer shall provide head retractors and/or head protectors as required to guard against the perils which are encountered during normal operation.

7.0 OPTIONAL EQUIPMENT

A redundant read-only head is desired on center track spaced a minimum fixed distance from preceding write/read head. Support electronics for read-only mode should be provided. Manufacturer should advise on ability to comply.

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13. ABSTRACT

This interim report is the first of two technical reports required by contract. It covers the prgoress made during the first six months of the program.

The program objective is to apply the technology which has been employed in the General Dynamics UNIversal DAta Recorder, UNIDAR, system utilizing magnetic tape to the disc-type magnetic recorders. The recording technology applicable to magnetic tape and discs is similar, however, the techniques of one cannot be directly applied to the other without considerable investigation. The technology is a method of coding binary information into a format which greatly increases the equivalent packing density of data on tape. The program goal is to increase the disc recording track data density above that which is currently achieved with standard systems while maintaining an error rate of approximately one in 10''.

The report compares various encodings, identifies the UNIDAR technology code as being the best approach, and specifies the in-contract disc requirements for high density data recording. Described are three channels of UNIDAR hardware and the versatile disc test bed which have been procured. A novel error detector which has potential error correction is also described.

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14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Data Recorder						
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