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# A FLEXIBLE SHEET MAGNETIC RECORDER

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# A FLEXIBLE SHEET MAGNETIC RECORDER

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This paper describes the design considerations and final performance specifications of the Cue-Matic Recorder*, a record/reproduce system which was developed to enable broadcasters to play short (3 minutes, 45 seconds), early generation program material directly on the air. The recording medium is a 3-mil-thick, circular magnetic sheet. The record/reproduce machine cues the sheet automatically and provides instant start and automatic stop.

A manufacturer must know the needs of the market he serves -- in the case of the broadcast industry, this market includes not only radio stations but recording studios and advertising agencies as well. At Ampex, design programs are started when the market indicates a strong need for a specific recording device. The Cue-Matic Recorder is the result of one such program.

The playing of commercial messages on the air is an important and profitable phase of broadcast station operation and the standard format for these commercials has been the electrical transcription (ET). The ET can be mailed from the advertising agency to the station and played on the air directly without being re-recorded. This, of course, gives the agency a reasonable control over the quality of the broadcast message. There are, however, disadvantages in using an ET. It must be handled a lot, be centered on the turntable, and be cued manually. This last process often causes wear, which leads to noise and distortion in the starting groove, and may also result in inconsistent program timing.

Many alternative media such as reel-to-reel tape and tape in different types of cartridges have been tried, but even the popular endless loop cartridge technique standardized by NAB has not been completely successful. A better tool was needed.

After studying the problems, the following properties were established as goals for the design of a machine that would satisfy this portion of the broadcasters' needs.

1. The recording medium should be inexpensive, be able to hold enough information, require a minimum of storage space, and be easy to mail.

2. The machine should be reliable and easy to maintain. It should be able to accept and locate the medium automatically, cue automatically, start instantly and stop automatically when the message is through.

Two types of machine would be desirable: a play-only machine for use in the control room, and a combined play-record unit for use in the production room.

3. The system should have consistently high sound quality as well as high reliability and low maintenance requirements. A minimum of effort should be necessary from the operator.

* TM Ampex Corporation

## THE RECORDING MEDIUM

The choice of a medium was severely limited by the requirement for ease of mailing, but this requirement was highly desirable; if the messages could be played directly on the air as received from the recording studios, no extra time, work, or equipment would be required by the broadcasting stations for re-recording, and there would be no risk of degrading the original quality of the recording. Most of the media considered -- reels, cartridges, belts, sleeves, sheets -- would result in too bulky a package or would require expensive containers. Only sheets had the double advantage of being easy to mail and easy to store.

The storage problem was solved by designing filing trays with identifying cardboard separators and sloping sides, so they will stay open when a mat has been removed. The daily needs of most stations are satisfied by 3 to 5 100-mat trays. Without separators, 300 mats per inch can be stored in a library with very little print-through as long as they all face the same way.

The 11 3/4-inch diameter of the mats was determined by the requirement for sufficient information storage, and this requirement involved factors such as quality of the oxide, desired playing time, signal-to-noise ratio, and frequency response. This size also fits nicely into standard 12-inch mailing envelopes.

Since the mats are punched out of a long web, the oxide in the coating must be randomly oriented. This reduces output variations due to orientation during mat rotation, but also reduces the output and thereby the signal-to-noise ratio.

After conferring with broadcasters, the desired length of playing time was determined to be 3 minutes and 45 seconds, long enough to permit storage on the mats of complete 45-rpm pop tunes or exerpts from LP's.

A signal-to-noise ratio of 50 db was considered the minimum acceptable. This was measured from peak recording level (3 percent third harmonic distortion at mid audio frequencies) to biased tape noise in the frequency band, 50 cps to 12kc. This signal-to-noise ratio can be expected from a 4-track, 1/4-inch, randomly oriented tape playing in the 3 3/4- to 7 1/2-ips speed range.

A frequency response of 50 cps to 12 kc would be desirable. Because handling the mats often results in greasy deposits along the outer edge, extremely short wavelengths should not be recorded there. A 1/2-mil wavelength was chosen as the shortest permissible in this area of possible hand contact, although shorter wave lengths can be tolerated at the innermost tracks.

The frequency response, the signal-to-noise ratio, and the playing time established the average linear velocity of the mat, the track width, and the necessary oxide properties. A 12-rpm angular velocity resulted from an inside-to-outside linear velocity ratio of 1 to 2. This speed is easy to check with a 600-bar strobe-disc, and the 1/16-inch centerline-to-centerline distance can be checked visually with a simple scale on a recorded track "developed" with small magnetic particles in liquid suspension.

The 3-mil thickness of the base material was a compromise between handling ease, cost, and the head wrap requirement for consistent minimum spacing loss. Our final mat, therefore, combined the familiar shape of a phonograph record with the familiar feel of office stationery.

The following are the data established for the mat.

| | |
|---|---|
| Rotational speed | 12 rpm |
| Linear speed | 7 to 3 1/2 ips, approximately |
| Track width | 45 mils |
| Centerline-to-centerline | 62.5 mils ( 1/16 inch) |
| Playing time | 3 minutes, 45 seconds |
| Signal-to-noise ratio | 50 db |
| Shortest recorded wavelength | .35 mil (inside) (10kc at 3 1/2 ips) |
| Thickness of base material | 3 mils |
| Sheet diameter | 11 3/4 inches |

The frequency response of the final unit measured at operating level is shown in Figure 2. To illustrate the frequency response available for short messages, the high frequencies were recorded first near the outside edge where the linear speed is highest. A response up to 15 kc is demonstrated.

The measured track-to-track crosstalk versus frequency from one track to the next is shown in Figure 3. If crosstalk from the tracks on both sides is considered, 3 db may be added to the crosstalk figure in the case of non-correlated signals of equal amplitude.

One problem was to maintain tracking on such a large sheet. Since it is guided only by its center hole, there is a large chance of mis-tracking near the edge. This problem was alleviated in two ways. First, by choosing a very stable material and, second, by using the following cancellation scheme. Some polyesters have a coefficient of thermal expansion of $1.5 \times 10^{-5}$ inch/inch/°F and a coefficient of humidity expansion of $1.1 \times 10^{-5}$ inch/inch/percent RH. If, for example, a temperature variation of 50°F and a change in relative humidity of 70 percent exist between the locations of recording and playback, the outside track, which is approximately 5.6 inches from the center, may have moved $1.5 \times 10^{-5} \times 5.6$ in. $\times 50 \times 1000 + 1.1 \times 10^{-5} \times 5.6$ in. $\times 1000 \times 70 = 4.2 + 4.3 = 8.5$ mils away from the center. Even though most machines will probably be used at fairly constant temperatures, we felt it advisable to reduce this figure. When the mat contracts or expands, the head motion should follow it. Therefore, cancellation was obtained by using a belt made from the same polyester material as the mat to pull the head; any temperature and humidity changes will affect the mat and the head position in the same direction and by approximately the same amount.

The mats have a long lifetime if given reasonable care -- mats used in life tests and in our extensive field tests have played 20,000 to 30,000 times with negligible degradation of quality. The high frequency response actually improves because of the polishing effect of the head. The mats can therefore be bulk-erased and reused many times.

## THE MACHINE

The requirement for high reliability of the machine was met by conservative dimensioning of both the transport and the electronics.

The transport base is a 3/8-inch-thick aluminum jig plate on which heavy castings carry the basic mechanism. The flywheel bearing and the turntable bearing are of the oil pump type with a spiral cut in the shaft to recirculate the oil.

The all-solid-state electronics use mostly silicon transistors and diodes. The mean time between failures for the electronics, as determined by an independent test laboratory, was 25,000 hours.

The requirement for easy maintenance and service was met by designing the transport for easy disassembly -- all electrical components (solenoids, switches, lights, etc.) are individually plugged into a "control box". Both the components and the control box are easily exchangeable. Transistors are mounted in sockets for easy exchange and trouble shooting, and only three different types are used. Generous holes in the electronics chassis provide easy access to printed circuit boards and the play/record switch.

All controls are located behind a door in front of the machine, so that routine maintenance is easy -- the built-in VU meter can be used for most adjustments such as playback level, bias level, pilot record level, record calibrate, and bias trap adjustment. The electronics move out of the front of the transport on slides for easy access and the transport moves out of its case, whether the machine is rack mounted (with accessory rack mounting brackets) or standing on a table.

## BASIC TRANSPORT FUNCTIONS

The transport is somewhat similar to a disc cutting lathe; it has a rotating turntable and a head which moves radially from the outside toward the inside of the turntable. Figure 4 shows the drive system. The turntable has a pliable rim which is driven by a capstan protruding through and fastened to a heavy flywheel. This flywheel is belt driven from a hysteresis synchronous motor. A polyurethane pad is ground smooth after being attached to the surface of the turntable. The compliance of the foam permits enough head penetration to ensure sufficient "tape" wrap around the head surface for negligible spacing loss.

### Capstan-Turntable Coupling

One major problem in the transport design was to obtain low wow and flutter without resorting to an extremely heavy turntable. If a high moment of inertia of the turntable could be obtained indirectly by coupling to it a secondary flywheel with high kinetic energy , then the coupling between them would have to be very tight for maximum transfer of energy.

The turntable weighs approximately 7 1/2 pounds and the flywheel approximately 3 3/8 pounds ( about 2 to 1), and the mass distributions are very similar. The speed of the turntable is 12 rpm and that of the flywheel 480 rpm. If the kinetic energy of flywheel f were transformed to a flywheel F rotating 480/12 = 40 times more slowly and with the same mass distribution, then

$$\tfrac{1}{2} I_f \omega_f^2 = \tfrac{1}{2} I_F \omega_F^2$$

where $I_f$ and $\omega_f$ are moment of inertia and angular velocity of the flywheel, $I_F$ and $\omega_F$ are moment of inertia and angular velocity of the transformed flywheel, and $I_t$ is the moment of inertia of the turntable.

We then have:

$$I_F \cong I_f \left(\frac{\omega_f}{\omega_F}\right)^2 = I_f \ (40)^2 = 1600 I_f$$

to which must be added the moment of inertia of the turntable itself, $I_t \cong 2I_f$, which is negligible, or $I_F \cong 1602\ I_f$.

The ratio of $(1600\ I_f)/(2\ I_f)$ underlines the need for a very tight coupling between the flywheel and the turntable if we are to benefit enough from the size of the flywheel to obtain a low flutter reading. The closest coupling would be perfectly smooth metal surfaces against each other under high pressure. However, this is impractical due to the cleanliness required. One standard coupling method in sound recording equipment is to utilize a rubber rim drive. We tried this method using different types, hardnesses, and thicknesses of rubber, and found that it is very difficult, if not impossible, to get a completely homogenous rubber rim. Hard and soft spots added to the wow and flutter. One particular problem aggravated the situation; as the pressure between the capstan and the turntable rim determines to a large degree the speed of the turntable, a very well-defined pressure must be maintained to keep the timing accuracy.

All of these problems were solved by stretching a seamless polyester belt around the rubber rim. This belt has very little compliance in the longitudinal direction and a reasonably tight coupling is achieved without excessive pressure between hard surfaces. Figure 4 shows a section of the turntable and Figure 5 shows turntable speed variation versus capstan-turntable pressure with and without the belt, and with and without the head load. The considerable improvement in timing accuracy shown in the figure was accompanied by a comparable improvement in wow and flutter. Values as high as 0.2 to 0.3 percent without the belt were reduced to 0.03 to 0.06 percent with the belt.

Vibrations from the motor are attenuated by the low pass filter comprised of the elastic drive belt and the mass of the flywheel.

## Insertion and Positioning of the Mat

The requirement for automatic acceptance and positioning of the mat by the machine was met in two stages: a coarse positioning first and a fine one next. We shaped a chute around the mat for easy insertion and proper vertical positioning. Figure 6 shows the mat fully inserted and playing. Figure 7 shows how the mat first hits two end stops (only one shown) and also actuates a microswitch (not shown) when the center hole is right above the turntable center. A slight time delay is introduced in the microswitch circuit to cope with operators who may throw the mat so violently into the machine that it bounces back from the guides before it positions itself properly. A clamping disc is then lowered, and centers the mat accurately; friction between the turntable surface and the mat will make the latter rotate. A white light above the insertion chute will indicate this mode of operation. Figure 6 also shows that a considerable portion of the mat is lifted off the turntable in play mode and stays inside the chute for easy removal.

## Automatic Cueing

Several cueing methods were comtemplated but we found a simple, mechanical one to be most reliable, accurate, and time saving in actual use.

The rectangular hole in the mat is used for cueing (see Figure 1). As the mat rotates, a teflon pin slides on the mat surface and eventually falls through the cue slot. The mat is then locked in cued position and a yellow light will indicate this. Although the mat is stationary now, the turntable continues to rotate. Since the pin is located in the left side of the machine (9 o'clock position), the mat can be inserted so that the hole is just short of 9 o'clock for minimum cueing time. The maximum cueing time is one revolution of the turntable (5 seconds).

An "Automatic Re-cue" switch will make the machine cue up again automatically after termination of a message to be ready for instantaneous repeated playback.

## Start and Stop

The requirement of an instantaneous start into stable "tape" motion is met because very little kinetic has to be transferred from the turntable to the mat during start, since the inertia of the mat is negligible compared with that of the turntable.

When the Start button is pushed, the pin is pulled out of the cue slot and the mat is clamped to the turntable with a reasonable pressure. This process is limited in time only by the inertia of the clamping assembly -- starting time is less than 0.1 seconds. A green light will indicate this mode of operation.

The clamping disc is mounted on a rail assembly, the lapped surfaces of which serve as guides for the head. This whole assembly is actuated by two solenoids: a rotary type for the long stroke bringing the clamping disc down to cue position, and a standard linear type for the short powerful clamping stroke. The clamping pressure is adjusted so it is entirely practical to stop the mat manually any time during playback and release it again if, for example, a live message should be inserted.

A 30-cycle pilot tone is automatically recorded on the mat when the Stop button is pushed in record mode. In playback mode, this 30-cycle burst will release the mat at the end of a message and provide means for automatic start of the next machine.

Both start and stop can be performed via remote control.

## 30-cycle Pilot Tone System

The 30-cycle generator is a simple sheet metal strip with 22 turns of wire, and is located near the shaft of the hysteresis synchronous drive motor. The shaft carries a two-pole, ferrite ring magnet; therefore, the frequency of the 30-cycle pilot tone is as stable as the power line. A 30-cycle selective filter is coupled to the generator and serves a dual purpose. It eliminates the higher harmonics of 30 cycles and its long "attack time" provides an inaudible and click-free introduction of the pilot tone.

The VU meter automatically displays the pilot tone level when the Stop button is pushed in record mode.

In playback, the 80-microsecond equalized preamplifier brings the signal from the head to the playback level control. An isolating and amplifying stage brings the signal to a double clipper. A 30-cycle selective amplifier picks the 30 cycles out of the clipped program material and feeds it to two saturated transistors, the last of which holds a latching relay. This relay provides power to the transport solenoids and, because it is a latching type, it also prevents the 30-cycle signal from turning the saturated transistors on and off at a 30-cycle rate. Instead, the relay will open and stay open when the saturated transistors are fed 30 cycles at sufficient amplitude. The sensitivity curve in Figure 8 shows how efficient the circuit is.

Head Motion

The requirement for consistent high sound quality makes the head motion critical. In order to maintain optimum azimuth throughout the mat, the gap must travel on a line through the center of the mat. A displacement error in the track direction will make this impossible. The following example will show the order of magnitude involved. Figure 9 shows the geometry.

d is the displacement error in the track direction.
r is the minimum recording radius of 2.8 inches.
V is the error angle caused by d at distance r from the center of the mat.

A 10-kc tone recorded at the inside track (at 3 1/2 ips) has a wavelength of

$$\lambda = \frac{3500}{10{,}000} = 0.35 \text{ mil}$$

The error angle $$\lambda \cong \frac{360 \times d}{2\pi r} = \frac{360 \times \delta}{2\pi 43} \quad \text{or} \quad \delta = \frac{d \times 43}{r}$$

where $\delta$ is the displacement causing an azimuth error on the 43-mil-wide track. The loss in db is then,

$$20 \log \frac{\sin \pi \frac{\delta}{\lambda}}{\pi \frac{\delta}{\lambda}}$$

Figure 10 shows the loss in db as a function of d, disregarding the gap loss which amounts to approximately 1 db at 0.35-mil wavelength.

The required accuracy was easily achieved by mounting a "fixed base" head (with no azimuth error) in a head carrier, the lapped surfaces of which slide on the hardened lapped surfaces of a solid rail. The head carrierhas adjusting screws for azimuth and displacement in the track direction, and both are factory set to at least one order of magnitude higher accuracy than required for a high frequency loss of 1 db, thus leaving room for small production variations. Since the heads are of the fixed base type, they can be replaced without any adjustments.

The head carrier moves in a vertical direction only and its motion is slightly damped with silicone grease. The final pressure between head and mat is set to 20 grams, which was found to be a good compromise between head life and head-to-tape contact.

The average head life is approximately 1,000 hours,depending to a large degree upon the type of mats used. If only virgin mats are used (such as the case would be in a record-only facility), the life will be shorter; if mats which have been played several times are used (such as is the case in playback facilities), the lifetime will be longer.

## The Head

Narrow gap record heads require high bias currents due to the pole tips being close together; therefore, a 100-microinch gap was considered the smallest gap that would not give pole tip saturation if we used a mat coated with 0.4-mil-thick oxide having a coercive force in the 250 to 300 oersted region. A gap depth of 10 mils was chosen as a compromise between head life and bias power.

The pole pieces protrude through the head shield by approximately 10 mils, so the distance between the shield and the oxide is small enough to sufficiently reduce the long wavelength track-to-track crosstalk. The pole tips are shaped for minimum low frequency bumps.

The magnetic head structure is symmetrical to balance out stray (homogeneous) hum fields, and a mu metal shield further reduces the hum sensitivity.

# ELECTRONIC CIRCUITRY

The basic electronic circuit will be described to illustrate the extent of the electronic contribution to the high sound quality. Block diagrams are shown in Figures 10 and 11.

## Record

Plug-in cans provide input facilities for microphone level and balanced and unbalanced line. A sharp 30-cycle filter removes (attenuation approximately 50 db) any 30 cycle component in the program material before it is recorded. The signal then enters the record amplifier, which is also the line output amplifier in playback mode, and a VU meter amplifier. The record amplifier clip level is at least 20 db above operating level, leaving adequate room for transient peaks -- and the VU meter amplifier approximately 15 db above for the same reason. The VU meter amplifier output also presents the proper source impedance for correct ballistics of the VU meter. We have defined operating level as the level which is 14 db below tape saturation at mid audio frequencies in order to have a reasonable margin for transient peaks -- third harmonic distortion at this level is slightly less than one percent.

A red warning light next to the Start button is lit in record mode and to avoid recording by mistake, a "record interlock" lever must be pushed down to initiate the cueing process in record mode. The VU meter will then automatically display the bias current through the head. Only the power to the bias oscillator is regulated, resulting in a bias current variation of less than 0.1 db from 80 to 130 vac power line voltage. The record amplifier has sufficient feedback to hold the record current change within 0.2 db in the same line voltage range.

Due to the decreasing linear velocity on the mat versus time, a variable record equalization is required. The playback equalization is fixed at 80 microseconds; the record equalization is passive, and directly in series with the head. Several schemes were tried: both continuously varying equalization and different types of variation in steps. The simplest was found to be a leaf switch with five leaves and crossbar contacts with good wiping action. Successive closings of the contacts vary the time constant of the equalizer.

The polyester belt mentioned earlier, which pulls the head across the mat, is wound on a drum which in turn is driven with a worm gear by the clamping disc. There is, therefore, a digital connection between the positions of the head and th clamping disc (another reason why it is feasible to stop the mat manually without any mis-tracking problems). The cam that actuates the equalization switch is located at the end of the drum.

The average record equalization step is 3 db at 10 kc and much less at lower and more audible frequencies. Figure 12 shows 3 kc and 10 kc recorded throughout a mat. At the frequency of maximum ear sensitivity, 3 kc, very little change is noticeable. This explains why the switching is practically inaudible when program material is recorded. Even a recording of white noise does not reveal much audible change.

Since the machine has only one head, monitoring in the record mode is done off the record amplifier. When the program material comes to an end, the Stop button may be manually depressed. A relay then interrupts the signal path and connects the 30-cycle pilot tone to the record amplifier, the level of which automatically is displayed on the VU meter, and the mat is released.

Reproduce

The flux from the recorded mat is picked up by the head and the resulting voltage is stepped up in an input transformer, the losses of which (series copper loss and parallel eddy current losses in the laminations) are low compared with those of the head so that the majority of the thermal noise originates in the head. A preamplifier with an 80-microsecond equalization then brings the signal to the playback level control and to a 30-cycle dip filter which greatly reduces the audibility of the final pilot tone. The line amplifier brings the level to line level: +4 dbm out for standard operating level on the tape and no amplifier clipping until 2 db above tape saturation. The VU meter is now connected directly across the output terminals.

A muting switch opens both sides of the line and prevents switching transients from reaching the line output. It also prevents accidental stop in the playback cueing mode if the mat has a residual curl and touches the playback head during cueing of messages of less than five seconds duration.

A final contribution to the sound quality is low modulation noise. Modulation noise is caused by mechanical AM and FM modulation of the signal being recorded, and it results in the creation of sidebands. The amplitude modulation is to a large degree a function of the properties of the tape medium and the frequency modulation consists mainly of scrape flutter. Scrape flutter is caused by friction between the head and the tape medium. Contrary to reel-to-reel recorders where long unsupported pieces of tape under tension may resonate longitudinally, mats with their heavy base material further damped by the supporting foam pad will produce very little of this type of modulation.

A method of measuring modulation noise proposed by Robert Z. Langevin(1) was used to get a comparative figure. A standard reel-to-reel machine, such as the Ampex 354 or F-44 with 43-mil track width and 7 1/2-ips tape speed, measured modulation noise to be -40 db below the carrier level. The Ampex AG-100 Cue-Matic sheet recorder with 43-mil track width and 7-ips tape speed measured -51 db below the carrier level. This 11-db improvement indicates not only that the scrape flutter is low but also that the oxide on the tape medium is of high quality.

## CONCLUSIONS

This new magnetic recording system fulfills a definite need for the broadcast industry. It simplifies the handling and storage of short duration program material; and it permits early generation program material to be played directly on the air.


## ACKNOWLEDGEMENTS

I wish to thank Charles A. Vogel, who designed the transport, for his contribution to this paper and the Ampex engineering staff for their contributions to the design of the system.


(1) R. Z. Langevin, "Modulation Noise in Tape Recording", 1965 AES Convention

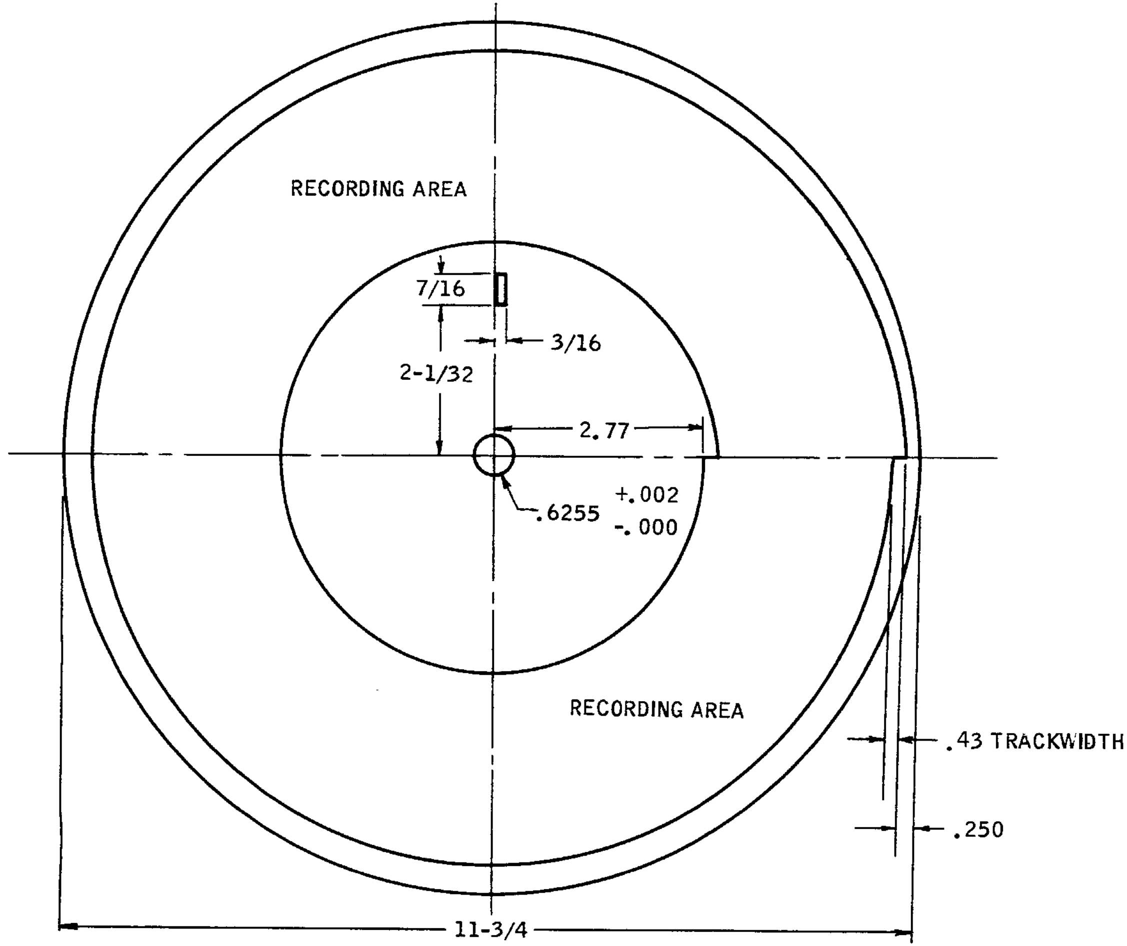



Fig. 1 AMPEX CUE MAT. THICKNESS 3 MILS.

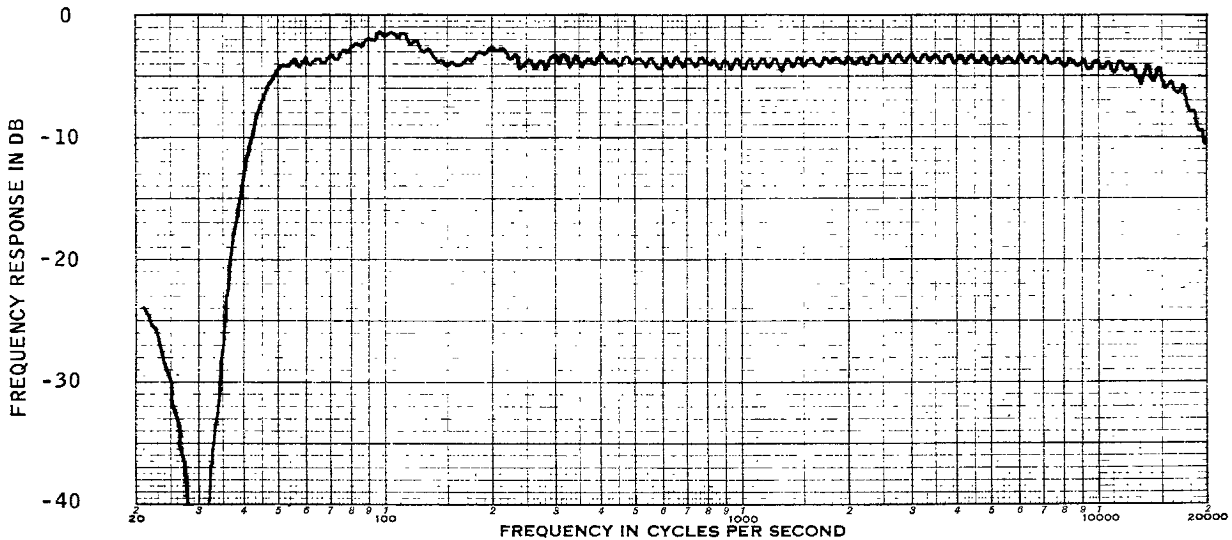



Fig. 2 FREQUENCY RESPONSE AT OPERATING LEVEL

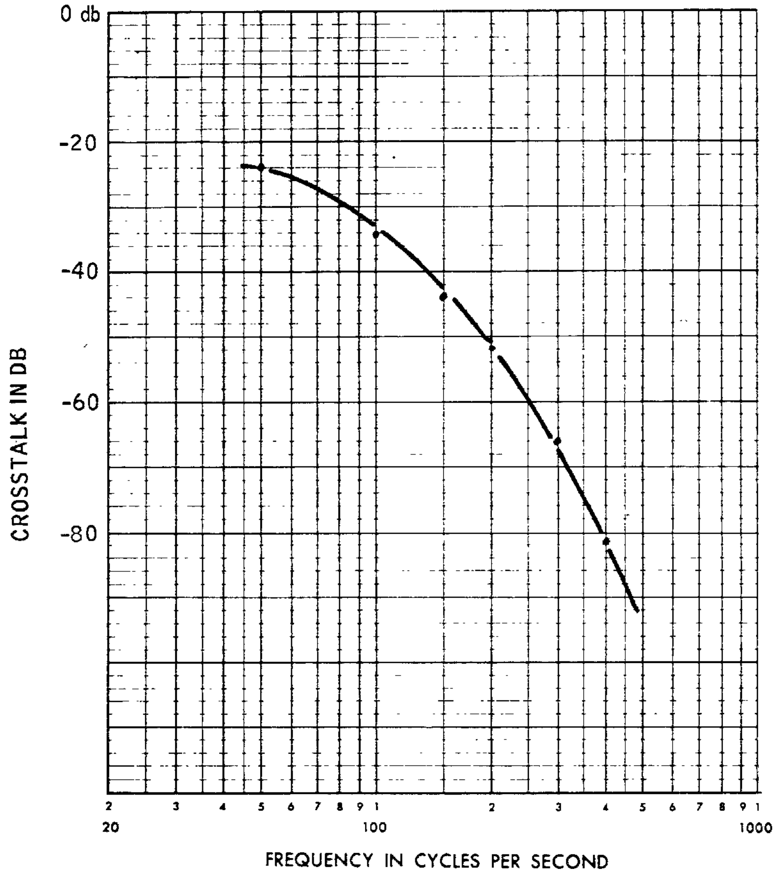



Fig. 3 TRACK-TO-TRACK CROSSTALK VERSUS FREQUENCY

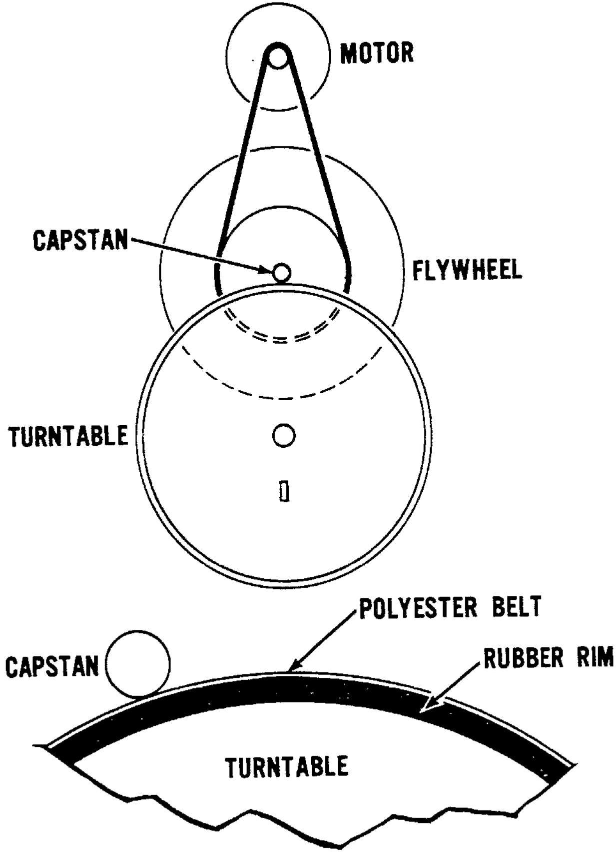



Fig. 4 BASIC DRIVE SYSTEM

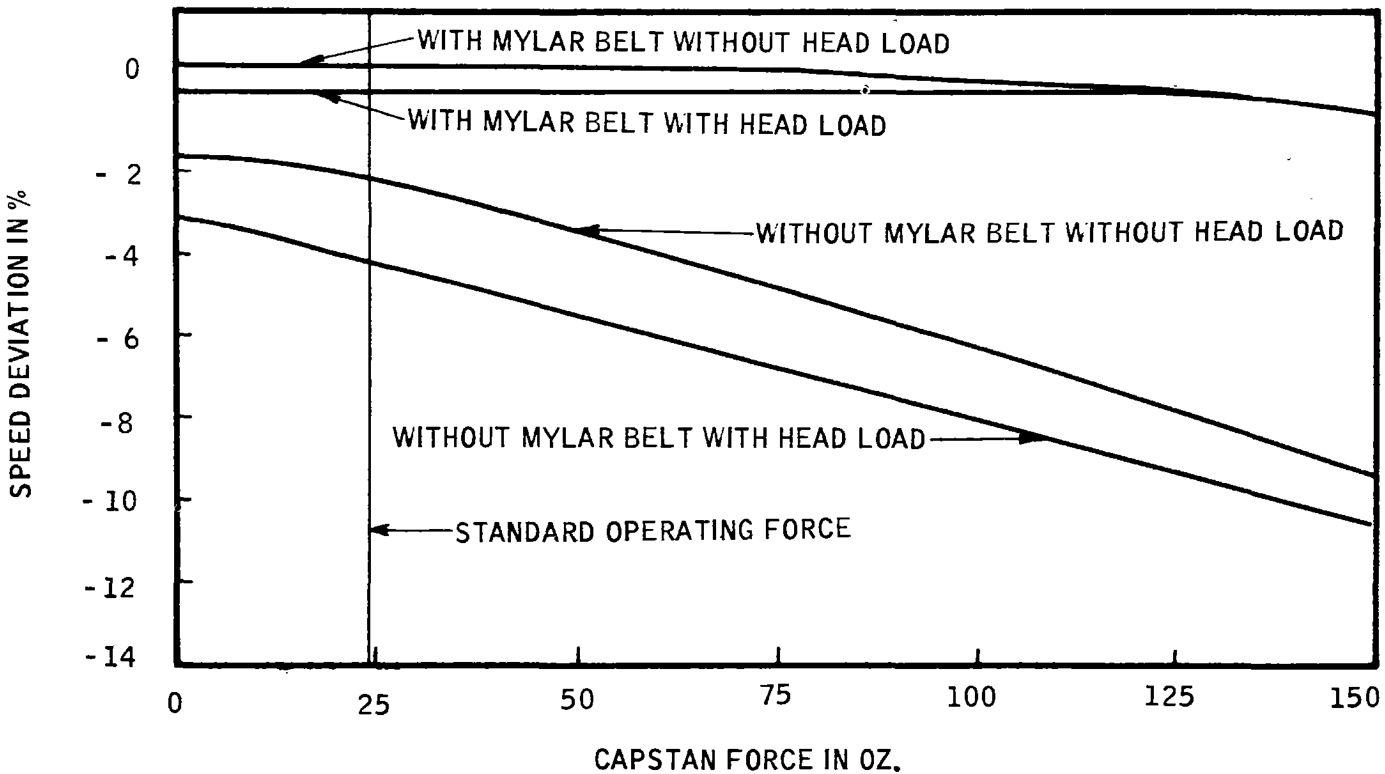



Fig. 5 TURNTABLE SPEED VARIATION VERSUS CAPSTAN FORCE

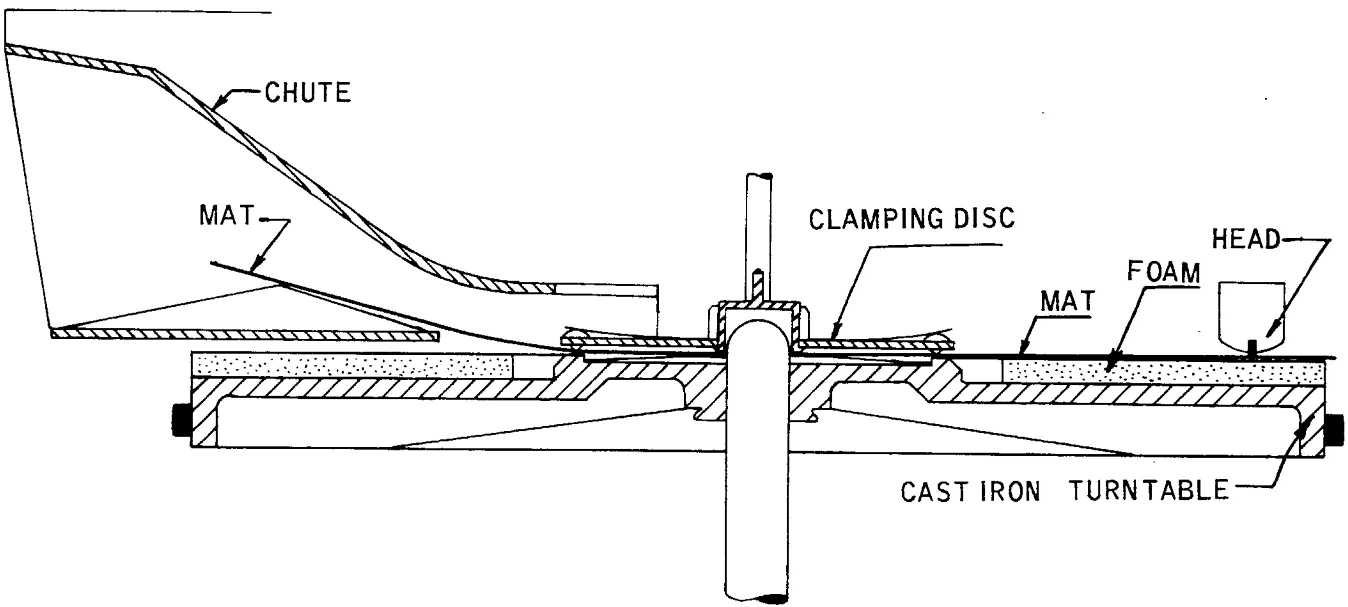



Fig. 6 SECTIONAL VIEW SHOWING POSITION OF MAT AND HEAD IN PLAY MODE

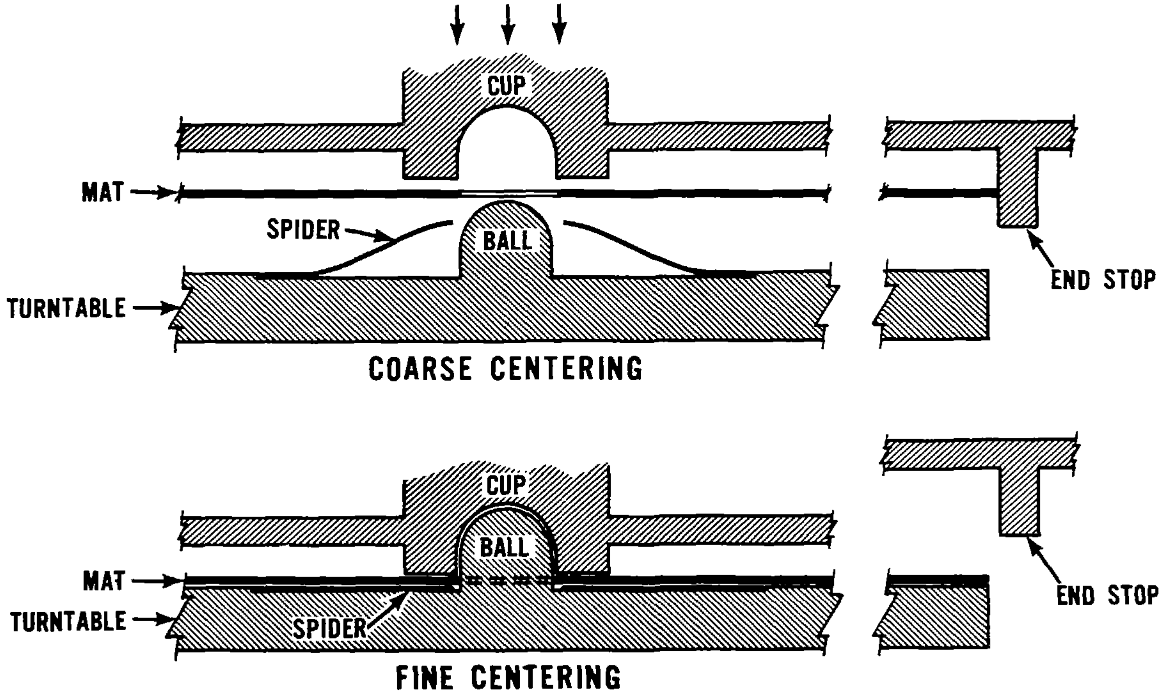



Fig. 7 POSITIONING OF THE MAT

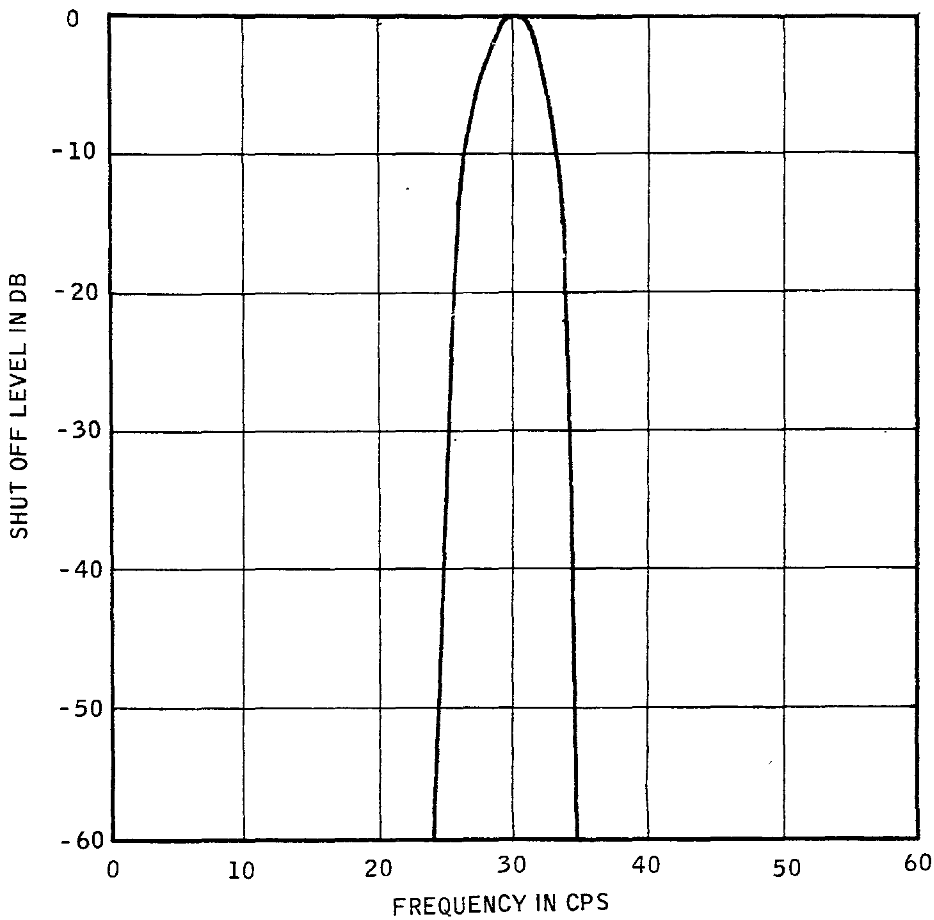



Fig. 8. PILOTTONE SHUT OFF SENSITIVITY VERSUS FREQUENCY

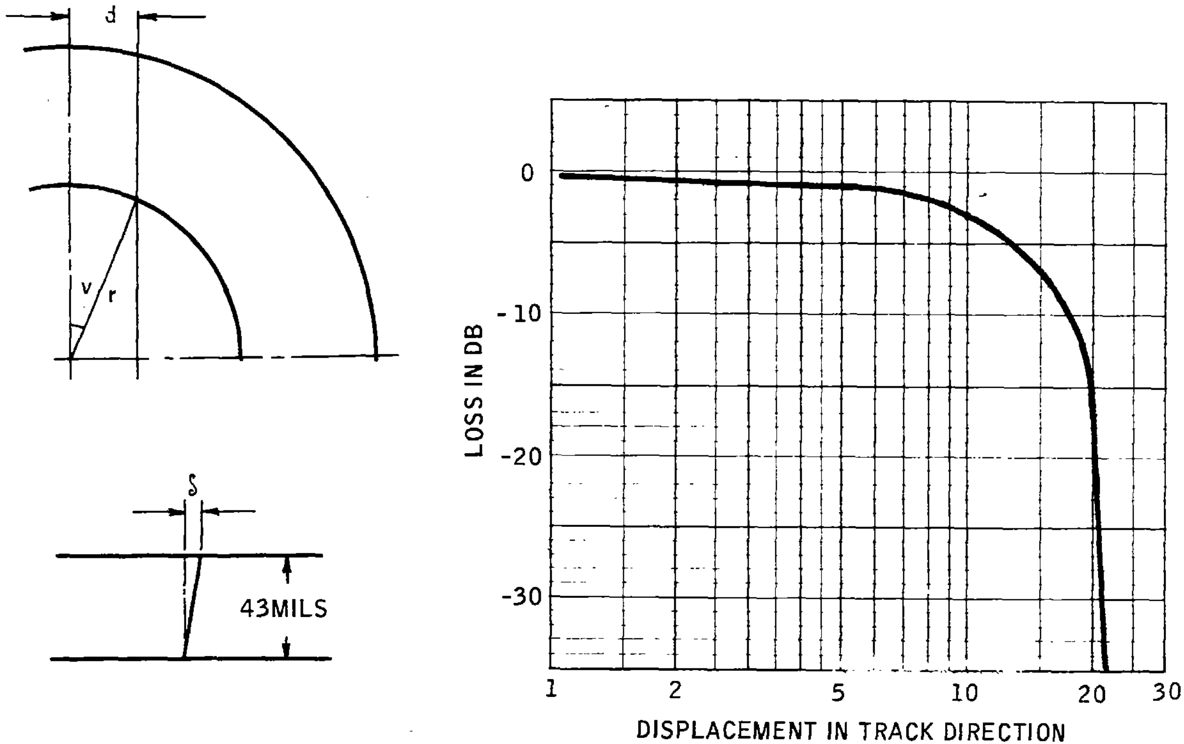



Fig. 9. GEOMETRY OF HEAD MOTION AND 10KC INSIDE TRACK LOSS VERSUS HEAD DISPLACEMENT IN TRACK DIRECTION.

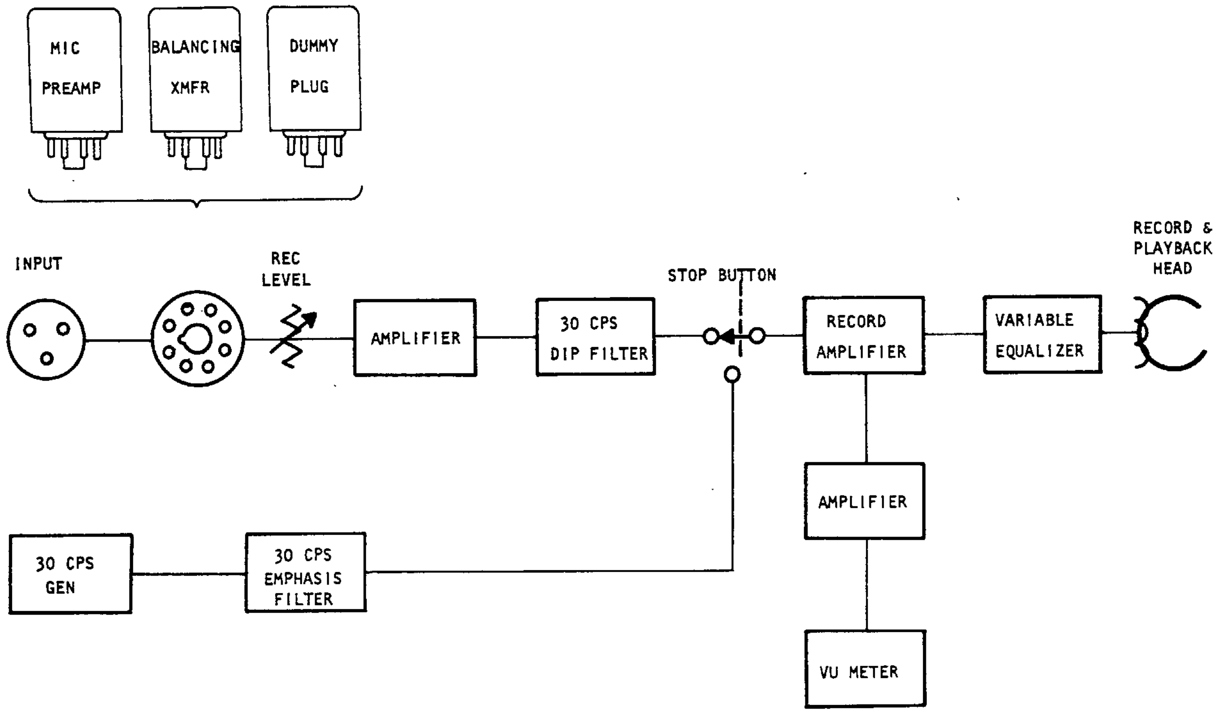



Fig. 10 RECORD CIRCUIT BLOCK DIAGRAM

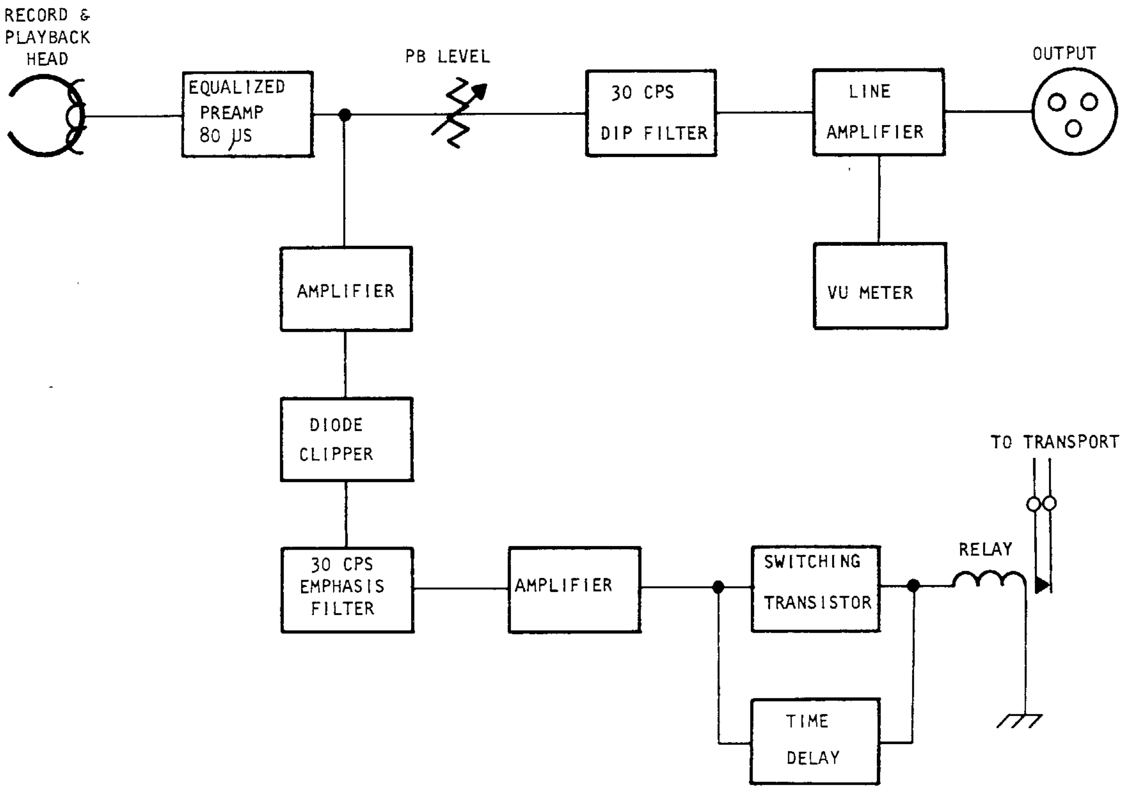
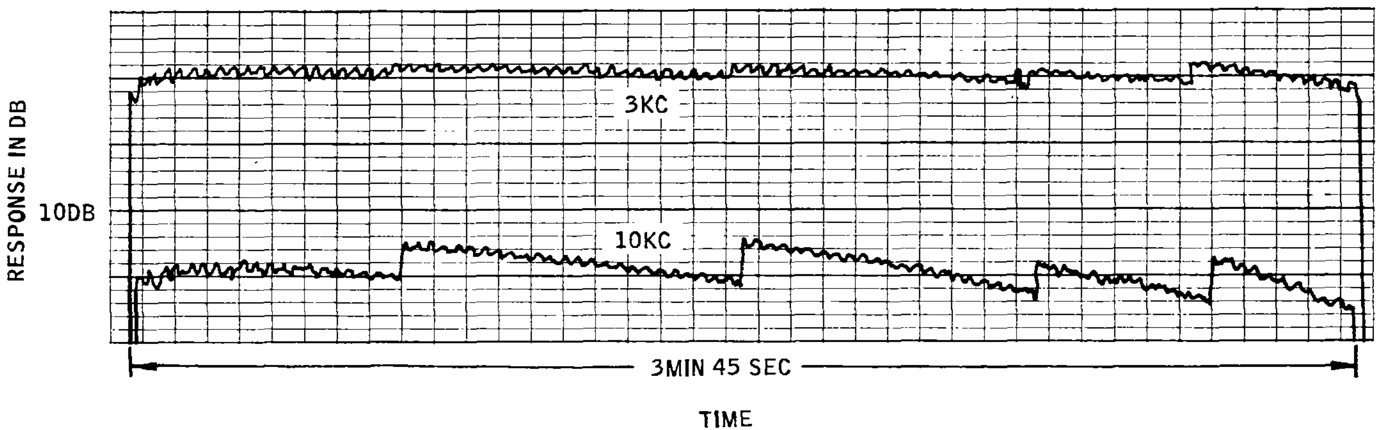



Fig. 11 REPRODUCE CIRCUIT BLOCK DIAGRAM




F 2 3KC AND 10KC RESPONSE VERSUS T