Flux and Flux-Frequency Measurements and Standardization in Magnetic Recording

By JOHN G. McKNIGHT

In order to have interchangeable tape recordings, standards are needed for flux-frequency response and for the absolute value of the recorded flux. It is shown that the recorded signal is best measured and specified as the "shortcircuit flux per unit track width"; measurements techniques are reviewed. The need for equalization and the division into recording and reproducing equalization are developed. Standard equalizations of many organizations are shown as flux-frequency responses. Standard reference fluxes and operating levels are tabulated and discussed. The terms necessary for response and level standardization are proposed and defined and, since terms are not defined in presently published standards, those defined here are compared with usages of the standards.

1. INTRODUCTION

A magnetic sound recording and reproducing system must fulfill a number of requirements; this paper is concerned with the requirements that the recording and reproducing system's overall frequency response[1] be flat over some specified bandwidth, and that the system's overall sensitivity[2] be known. When the recording and the reproducing systems are separated in time and/or place, independent measurements of the sensitivity and the frequency response of the recording system and of the reproducing system are necessary in order to have interchangeable recordings — that is, recordings which will give the required flat overall response and known sensitivity with any recorder and any reproducer.

The practical measurement and adjustment of the response and sensitivity of recorders and reproducers in the field is done by means of commercially available "Reproducer Test Tapes" (Morrison, 1967); these are secondary standards and they are a very satisfactory tool if sufficient care is taken in their use (McKnight, 1967a). Thus the practical secondary ("working") standardization is a satisfactorily accomplished fact.

Behind these secondary standards — the reproducer test tapes — there should be primary standardization which establishes the basic quantities to be standardized in units of the International System of Units (SI), and defines the various measuring methods, terms, frequency responses, etc., needed for producing this primary standardization. Similarly, measuring methods, terms, frequency responses, etc., are also needed for describing the performance of practical recorders and reproducers.

There are many industrial, national and international standards in existence: these are listed in a companion paper (McKnight, 1967b), which should be consulted for the complete titles, numbers, etc., for the standards referenced here by abbreviation as BS, DIN, NAB, etc. The author feels that no *one* of these existing standards satisfactorily fulfills the requirements for primary standardization as outlined in the preceding paragraph. Since most of the ingredients for a satisfactory standard can be found in the existing standards, the present paper reviews the literature and the existing standards, in order to draw together the best of the available knowledge on how a better standard could be written.

One must first be able to specify the recorded signal in terms of a quantity which can be measured practically and accurately, and expressed in SI units. Then one can discuss the various standard recording flux-frequency responses and reference fluxes.

Finally, one may write definitions for the terms needed to formulate standards (for instance, shortcircuit flux; voltage and flux levels; and frequency response) and compare these with the usages of present standards.

2. MEASURING THE SIGNALS

Figure 1 shows the most simplified representation of a system containing a recorder, a record and a reproducer, with the corresponding input signal, recorded signal and output signal. The input and output signals will be taken here as the input voltage and the output voltage.[3,4]

Most of the present magnetic recording standards are based on the concept of a "standard reproducer" consisting of an "ideal head" whose emf is modified by a standardized equalizing network. It is therefore necessary for every standard for a recorder, a reproducer or a test tape to describe carefully what is meant by the term "ideal head," and how one determines if a given head is in fact "ideal." A sufficiently careful description requires great detail and is just now being developed [e.g., in this paper, and those by Grimwood, Kolb and Carr (1969) and Lovick, Bartow and Scheg (1969)].

A far simpler procedure is to determine what *physical quantity* it is that we are trying to standardize. Then the recorder, reproducer and test tape standards may be written in terms of this quantity, and the techniques for the measurement of this quantity may be relegated to a separate detailed standard on measurements. This measurement standard would be applicable to *any* audio magnetic recording system.

The first step, then, is to determine the appropriate quantity for this mysterious "recorded signal" which most present standards decline to name.

2.1 Choosing the Quantity for the Recorded Signal

It is not possible to measure directly the magnetization,[5] M, that actually occurs inside a recorded tape — one can only measure the flux (Φ) at the surface of the tape. Although the relationship between the internal magnetization and surface flux may be calculated theoretically, it is preferable for standardization of the recorded signal to use a quantity which is directly measured by an idealized magnetic reproducing head of the same general type as practical reproducing heads — that is, a high-permeability "ring-core" (a magnetic "shortcircuit") contacting the surface of the tape on one side only.

Such an idealized head has been described by Wallace (1951): it is his idealized bar-type ferromagnetic reproducing head, shown in Fig. 2. "It consists of a bar of core material with a single turn of exceedingly fine wire around it.

1. The overall frequency response is defined as the ratio of the reproducer output voltage to the recorder input voltage, as a function of frequency.

2. The overall sensitivity is defined as the ratio of the reproducer output voltage to the recorder input voltage, at some specified reference frequency.

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3. The input and output signals could also be taken as acoustic signals; for simplification, this paper will not do so.

4. The input and output electrical signals are often most simply and meaningfully expressed as voltages, even though the common USA standards (developed from telephone transmission practices) are usually written in terms of power.

5. Magnetization is also symbolized by H_i. Many papers use the corresponding magnetic polarization, J or I, also called intrinsic magnetic flux density, B_i.

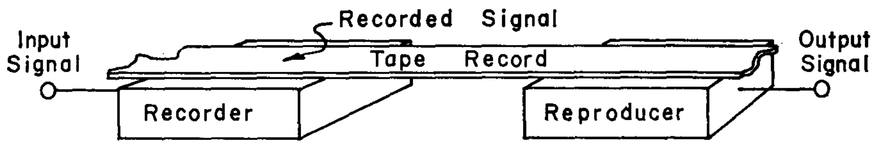


Fig. 1. Simplified recorder/record/reproducer system, showing the quantities needed for sensitivity and frequency-response specifications.

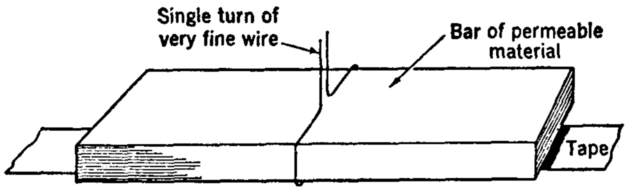


Fig. 2. Idealized bar-type ferromagnetic reproducing head.

If the dimensions of the bar are made large enough, the amount of flux through it will obviously be as great as could be made to pass through any sort of head which makes contact with only one side of the tape.... Calculations based on this bar type of head are applicable to ring type heads. If the bar...is now allowed to become infinite in length, width, and thickness, the . . . flux . . . can be evaluated." Thus, the practical quantity to be measured is logically this shortcircuit flux, Φ_{sc}, since this quantity can be defined in theory (Sec. 5.1), and directly measured in practice (Sec. 2.2).

Since most present tape recording standards are based on calibrated reproducers ("ideal" heads) and since we have shown that the "ideal" head does, in fact, simply measure the shortcircuit flux, we must conclude that the change from standardization based on a reproducer (or an "ideal" head) to standardization based on shortcircuit flux is only a conceptual change, in order to clarify and simplify the standards. *It is not in any way a change in practice.*

When full-track recording was the only track configuration, the *total* flux was specified. Now multiple smaller tracks are commonly used. Since, given a full-track recording, the amount of flux in the core of any multitrack reproducer is proportional to the individual track width, it is now more appropriate to specify the flux *per unit track width*, Φ_{sc}/w (also called Φ'), since this obviously remains constant as the track width changes. When there seems to be no chance of confusion, the full term "magnetic tape shortcircuit flux per unit track width" may be shortened to "tape flux" or just "flux."

The term "surface induction," B_y, (sometimes more appropriately called B_s) is frequently found in the standardizing literature. The Appendix presents conversion equations from one form to the other and the arguments for the use of "shortcircuit flux" rather than "surface induction."

2.2 Methods of Measuring the Recorded Signal

The measurement of flux is usually carried out in two steps: first, the absolute flux is measured at a medium-to-long wavelength (medium-to-low frequency); and second, the relative flux is measured as a function of wavelength (or in other words, the frequency response of the flux at a specified speed is determined). This division into two measurements is for practical measuring reasons: some of the measuring methods which can be absolutely calibrated in standard magnetic units are suitable only for medium-to-long wavelength measurements; other measuring methods which yield the relative response over a wide range of wavelengths (frequencies) may not be suitable for absolute calibration.

The recorded signal may be measured by techniques using any of the following apparatus: reference recordings, calibrated recorders and media, calibrated reproducers, and magnetometers.

2.2.1 Reference Recordings

Measurements of the recorded signal have been performed by adjusting a recorder/medium/reproducer system for satisfactory operation, then making a "reference recording" against which the flux and flux vs. frequency of all other recordings are measured by direct comparison. The arbitrary flux on this reference recording is itself the "standard measure" — it is not related to any internationally accepted standard unit. This method has been used in USA military standards (Comerci, Wilpon and Schwartz, 1954), and is used for the current NAB "reference level".

The accuracy of a measurement made with this reference recording depends on the amplitude stability of the medium — the tape — as a function of position (length) along the medium, storage conditions (length of time, quality of the tape winding, temperature and humidity, properties of the base and the coating, etc.), and the number of times the recording is reproduced.

The best commercial tapes in the USA have a signal level fluctuation at long wavelengths of about ±0.1 decibels (dB) over a length of several meters; some other tapes have a fluctuation of ±0.5 dB or even more. A magnetic tape recording at a long wavelength is relatively stable with storage and use: long-term repeatability of ±0.25 dB is practical. At short wavelengths, however, a tape recording is relatively fragile: storage and use will cause errors of 5 dB or more at 12 μm (0.5 mil) wavelengths (Morrison, 1967).

Therefore, measurements by comparison with a reference recording are not a satisfactory method of *primary* standardization, especially at short wavelengths. Nevertheless, this reference recording technique is very satisfactory for *secondary* standardization in the field. Such secondary reference recordings are called reproducer test tapes[6]; their manufacture and use were discussed by Morrison (1967), and McKnight (1967a).

2.2.2. Calibrated Recorders and Media

If the sensitivity of a recorder and medium (viz., the ratio of the tape flux to the magnetizing field) is known, one can produce recordings with known recorded tape flux, i.e., *standardized* reference recordings, as mentioned in the previous sections. One could make a new recording whenever the old one became damaged.

2.2.2.1 Sensitivity at Long Wavelengths: The theory of the sensitivity of a recording system (including tape) at very long wavelengths has been developed by Daniel and Levine (1960a and b). Unfortunately, this work has not been practically utilized, and sensitivity values for magnetic tapes are still not published by the manufacturers. It is therefore not possible to determine the absolute sensitivity of a recorder and medium by independently determining and specifying the sensitivity of each of them. (Even if sensitivity values were published, the recording gap length and tape coating thickness are involved, and a *simple* expression of recording sensitivity might not be possible.)

Because of these difficulties, attempts have been made to establish a reference for flux measurements by specifying the flux at which a certain amount of harmonic distortion occurs in the recording process (for example, 3% third harmonic distortion), or, alternately, by specifying a value relative to the saturation flux of the tape (for example, 14 dB below saturation output).

On the other hand, both the proper operating level and the maximum recording level depend on the tape, the recorder and its operating conditions. Therefore both the saturation and the distortion are valid criteria for determining the proper operating level for a given system, and the reference signal for a signal-to-noise measurement.

6. Reproducer test tapes are often referred to less specifically as "standard tapes," or "alignment tapes"; some other kinds of test tapes are also mentioned by Morrison (1967).

On the other hand, precisely because saturation and distortion are dependent on the tape and the recorder, and these are not controlled factors, distortion and saturation are not satisfactory references for absolute flux measurements[7] (Radocy, 1954). For example, both the distortion and the "saturation output" are determined in large part by the coating thickness, and are therefore different for thin-coated (double length), regular, and thick-coated (high output) tapes. The tape formulation, the recording gap length and the bias current adjustment also influence the distortion for a given flux. And finally, certain commercially available recording systems using complementary pre-distortion for amplitude nonlinearity (for instance the Scully Linearity Circuit and the Gauss Electrophysics Focused-Gap Recording System) have distortion vs level functions which are very different from those of ordinary recorders.

2.2.2.2 Response at Long Wavelengths; Wavelength response, and therefore the frequency response, of an ac-biased recording system at long wavelengths is flat: constant magnetizing field vs. frequency produces constant tape flux vs. wavelength. The qualification of long wavelengths is fulfilled when the tape coating is very thin compared to the wavelength (to eliminate the thickness loss described by Wallace (1951), and customarily charged to the recording process); and when the recording field is essentially constant while an element of tape passes across the recording gap. (It is also assumed that the bias frequency is high compared to the signal frequency.) These criteria are met in the usual audio-recording system for wavelengths greater than 1 mm (40 mil), which corresponds to frequencies below 400 Hz at 38 cm/s (15 in/s).

Experimental verification of this long-wavelength response is given by Schmidbauer (1957b): he made a recording with varying frequency and constant magnetizing field (i.e., a "constant current" recording); when this was reproduced with a ring-core reproducing head (see Sec. 2.2.3, below) having a diameter of 6.4 cm (2.5 in), the flux response was found to be flat over a wavelength range of 1 to 30 mm (40 mil to 1.2 in). (At longer wavelengths, the reproducing head response was not flat.)

Another experimental verification is given unwillingly by Henocq and Houlgate (1964): their Fig. 2a shows the reproduction, by one head, of recordings made by four different heads. If the data are normalized at 100, 200 or 500 Hz (rather than the 1000 Hz which they chose), the response of the four recording heads is seen to fall within a spread of 0.5 dB ($\pm$ 0.25 dB) over the wavelength range considered (1 to 10 mm, or 40 to 400 mil).

Thus it is seen that the long-wavelength (low-frequency) response of a recording system (including the medium) is easily calibrated: if the recording head current is constant, the recorded tape flux is constant at wavelengths much greater than the tape thickness. This is fortunate, because the calibration of a reproducing head at long wavelengths may be somewhat difficult. The requirement of "very long wavelengths" holds even at slow speeds: for a 10 cm/s (4 in/s) system, the reference frequency must not exceed 100 Hz for an 0.25-dB error with a 10-μm (0.4-mil) coating.

2.2.2.3 Response at Short Wavelengths: At short wavelengths, on the other hand, the response of the recording system is dependent on the properties of the tape coating, the bias field (McKnight, 1961), and a number of other factors (Daniel, Axon and Frost, 1957). The theoretical analysis is so complicated that it has never been undertaken in detail; therefore the high-frequency response of a recording system cannot be directly calibrated (Radocy, 1954). Fortunately, as we will see below, it is possible to calibrate the reproducer at short wavelengths.

2.2.3 Calibrated Reproducers

A recorded signal may be measured directly by means of a calibrated reproducer. Usually this must be a head specially built for measurement purposes — ordinary heads seldom have the required characteristics. The calibration of reproducers will be considered first at medium wavelengths; then at long and short wavelengths. Finally, frequency response effects will be considered.

A "medium" wavelength is a hypothetical wavelength which is so long that the short-wavelength response factors are unity, and so short that the long-wavelength factors are unity. (These factors are given in Tables I and II.) Several kinds of heads can be built for which 0.5- to 1-mm (20- to 40-mils) wavelengths are "medium" wavelengths. At longer and shorter wavelengths, each of the various reproducing head configurations has its own particular wavelength response; when this response is calculated and experimentally verified, the head response has been calibrated, and may be used to measure the recorded tape flux vs. wavelength.

Measurements of the tape flux over a wide range of wavelengths (frequencies) are usually performed with calibrated short-gap ferromagnetic ring-core heads. In the standards literature (CCIR, NAB, DIN, etc.), these are called "ideal" heads; but the means given in the existing standards for determining deviations from "ideal" are inadequate, leaving far too much to the user's imagination and individual judgment. A standard procedure is needed giving the detailed means for calibrating a magnetic reproducing head. The description of such a procedure is the subject of a future paper; the known theory and measuring methods will be discussed here.

2.2.3.1 Sensitivity at Medium Wavelengths: The magnetic reproducer is a transducer for converting the flux from the tape into an electrical voltage proportional to that flux. (Note that shortcircuit flux is defined as the *total* tape flux of the recording; therefore the reproducing head used for measurements must be at least as wide as the recorded track.) If it is possible to determine the sensitivity of a reproducing system (viz., the ratio of the output voltage of the transducer to the flux on the tape at medium wavelengths) then this reproducer may be used in conjunction with an accurately calibrated voltmeter to measure the absolute magnitude of the medium-wavelength flux.

Although there are flux-to-voltage transducers whose output is independent of the frequency (Kornei, 1954), the most commonly used principle of transduction is that based on Faraday's law of induction, which states that the magnitude of the electromotive force in each turn of a conductor is given by $E = d\Phi/dt$ where E is the emf in volts, Φ is the flux in webers, and t is the time in seconds. The addition of an integrating amplifier will make even this reproducing system frequency-independent: $\int E dt \propto \Phi$.

When a tape is sinusoidally magnetized along its length, the flux varies with position as one moves along the length of the surface of the tape; the flux also varies in space going away from any given point on the surface of the tape. When the tape is moved by a point just at the surface of the tape, the flux at that point varies in time according to $\Phi = \Phi_m \sin\omega t$, where ω is the angular frequency in radians per second and $\omega = 2\pi f$, where f is the reproduced frequency in Hz, and Φ_m is the maximum flux. (Tape speed per se does not appear in the equation.)

One needs only a transducing "single conductor" placed next to a tape moving in free space, as shown in Fig. 3 (from Daniel & Axon, 1953), a voltmeter, and a frequency meter, to measure the absolute magnitude of the open-circuit flux on that one side of the tape: $E_{oc} = d\Phi/dt = 2\pi f\Phi_{oc}$, or $\Phi_{oc} = E_{oc}/(2\pi f)$, where Φ_{oc} is the open-circuit (free-space)

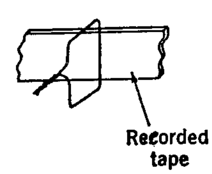


Fig. 3. Single conductor non-ferromagnetic reproducing head.

7. Reference to the saturation flux presents two further difficulties: (1) not all recording amplifiers are able to saturate all tapes — special equipment is sometimes required; and (2) the saturation flux is a square wave; therefore both the frequency and phase responses of the reproducer, and the rectifier law of the meter (peak, rms or average) will affect the readings.

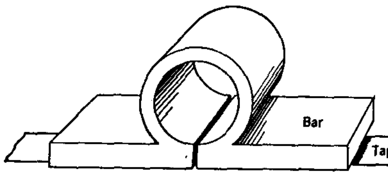


Fig. 4. Ring-core head: the ferromagnetic reproducing head of Fig. 2, modified to accept many turns of wire on a ring core, in order to increase the output voltage.

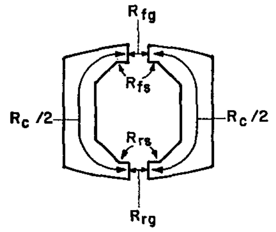
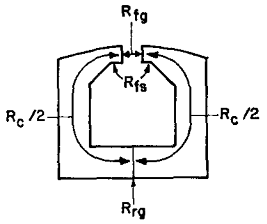


Fig. 5. Head-constructions for medium-wavelength measurement showing the flux paths and their reluctances: (a, left) the symmetrical head. (b, right) the high-efficiency head.



flux on one side of the tape in rms webers, E_{oc} is the emf measured for the magnetic open-circuit condition, in rms volts, and f is the reproduced frequency in Hz. In the shortcircuit condition specified in Sec. 2.1, the flux from both sides of the coating is collected by the head; this total flux is twice that available on only one side of the tape. Using this relationship, that $\Phi_{sc} = 2\Phi_{oc}$, and dividing both sides by the track width w one obtains the shortcircuit flux per unit track width, $\Phi_{sc}/w = E_{oc}/(\pi f w)$.

The shortcircuit flux can be measured directly by making a head similar to the idealized head shown in Fig. 2: when E_{sc} (the emf measured for the magnetic shortcircuit condition) is measured, one obtains directly $\Phi_{sc}/w = E_{sc}/(2\pi f w)$.

In order to increase the very small output voltage from this idealized bar-type magnetic head, a short gap may be cut in the core shown in Fig. 2, and the magnetic circuit completed by using a ring of core material. This is shown in Fig. 4 (from Wallace, 1951). Many turns can then be wound on this core. The tape flux divides in this head: part flows around the core, and part of it is lost directly across the front gap. The ratio of flux in the core (Φ_c) to shortcircuit tape flux (Φ_{sc}) may be called the flux efficiency (η_Φ) of the head:

$$\eta_\Phi = \Phi_c/\Phi_{sc} = R_g/(R_g + R_c + R_r)$$

where R_g is the front-gap reluctance, R_c the core reluctance, and R_r the rear-gap reluctance. (The gap reluctances are the parallel values of the reluctance across the gap itself, and the stray reluctance outside of the gap. The stray reluctance is often appreciable, and cannot be neglected.)

The shortcircuit tape flux per unit track width is therefore

$$\Phi_{sc}/w = E_{sc}/(2\pi f w N \eta_\Phi)$$

where N is the number of turns on the coil. Thus the ring head may be used for the absolute measurement of the flux at medium wavelengths if η_Φ is accurately known. (The wavelength response of the core is ignored here, but will be treated in Secs. 2.2.3.2. and 2.2.3.3.).

The calibration of the efficiency of a general-purpose head presents several difficulties: first, it is quite difficult to calculate all of the important reluctances with sufficient accuracy; second, playing tape on such a head causes wear which changes the head's sensitivity by unknown amounts, and frequent recalibration is therefore necessary. Two particular configurations are attractive for the design and construction of calibrated heads: these are the "symmetrical head" and the "high-efficiency head."

The symmetrical head uses cores which are symmetrical front-to-back, and front- and rear-gaps which are identical (see Fig. 5a). By using rather long front and rear gaps (about 25-μm, or 1-mil) and high-permeability pole pieces, we can assure that the gap reluctance is quite large compared to the core reluctance. We need only perform the simple calculations of the core reluctance and the reluctance of the long air-gaps in front and rear; the difficult determination of the reluctance of a "closed" (but unknown) rear gap is completely avoided. Efficiency of 0.495, or 1% (0.09 dB) less than exactly 0.50 is practical. Once we have calculated the core, gap, and approximate stray reluctances, the only "calibration" required is verification that the sensitivity is the same for the "front" gap and the "rear" gap. Simply reproduce any medium-wavelength recording from the front gap, and then from the rear gap, and see that the output voltage is the same. If so, one is assured that the design and construction of a new head is truly symmetrical, or that a used head is still properly calibrated. It is, in effect, "self calibrating."

The high-efficiency head uses cores which have a deep rear gap (see Fig. 5b). By using a rather long front gap (again about 25-μm) and high-permeability pole-pieces, we can assure that the gap reluctance is quite large compared to the core and rear gap reluctance. A 50:1 ratio is practical, resulting in an efficiency of 0.98; this may be confirmed by reluctance calculations and measurements, and may be experimentally verified by using the symmetrical head. Although this head is not "self calibrating" as is the symmetrical head, it does have the advantage that, once calibrated, the gap wear caused by tape does not appreciably change its sensitivity. Thus it is a better "production tool."

A means of calibrating the flux efficiency of any ring core reproducer is described by Horak (1966): an electromagnet may be made and calibrated by the use of a special "keeper"; then, by a technique for controlling the circuit reluctance, this electromagnet may be used to introduce a known flux into any head core. Knowing the number of turns on the core, the flux efficiency is easily calculated. The accuracy of this method is not fully verified; it appears that, in some cases, stray reluctances may cause errors.

Several symmetrical heads and many high-efficiency heads have been constructed for the author; the efficiencies have been calculated and experimentally measured; and tape flux measurements have been made with a magnetometer (Sec. 2.2.4, below). The correlation between the several measurements is quite good; the construction details of the heads, and the calculations and measurements of sensitivity are given by McKnight (1969b).

The construction, calibration and use of both symmetrical and high-efficiency ring-core reproducing heads is much simpler and more reliable than the alternative techniques utilizing either the single-conductor head, or the magnetometer (to be discussed below).

2.2.3.2 Wavelength Response at Long Wavelengths: The factors in the calibration of the long-wavelength response of a ring-core reproducing system are well documented in the literature and are outlined in Table I. In practice, the long-wavelength response of a head is usually calibrated by a recording made on a calibrated recorder and medium as described in Sec. 2.2.2.2.

The single-conductor reproducing head of Fig. 3, mentioned in the previous section, may also be used for measurement of the long-wavelength response. If a single *round* conductor is used, its response is shown by Daniel and Levine (1960b) to be the same as that of a filament of infinitesimal cross-section spaced one wire-radius away from the tape. If the conductor is of rectangular cross-section, the response formula is more complicated (Daniel and Axon, 1953; Schwartz, Wilpon and Comerci, 1955). The calculated responses assume that the tape passes by the conductor in a straight line (no wrap): this condition must be observed in practice (Henocq and Houlgate, 1964).

Descriptions of measuring techniques and experimental results of measurements

Table I. Factors in the Calibration of the Long-Wavelength Response of a Ferromagnetic Core Reproducing Head System.

Effect	Theory	Experimental measurement
Head-length response (contour effect), including effect of wrap angle of tape around head	Strip and plate heads: Westmijze (1953) Round head, and plate head with round corners: Duinker & Geurst (1964) Semi-infinite head with face tapering away from tape: Fritzsch (1966)*	Long-wavelength response of a reproducer can be measured by reproducing a constant-flux recording made by a calibrated recorder: Schmidbauer (1957b)† and McKnight (1967a)
Long wavelength rise due to secondary gap effect (due to finite core permeability)	Fan (1961) Fritzsch (1966)*	
Response changed by presence of shields	Fritzsch (1966)*	
Response changes when wavelength comparable to track width	Geurst (1965)	
Response depends on *location* of winding on core	Schmidbauer (1960)	
Fringing (recorded track wider than reproducer core)	Grimwood, Kolb & Carr (1969)	Data shown by McKnight (1967b)

† Schmidbauer shows wavelength response for a "constant current recording" over the 1- to 80-mm wavelength region (40 mil to 3.2 in.). His results agree with the calculations of Duinker & Geurst (1964).

* Fritzsch compares calculated and measured responses.

with single-conductor reproducing heads are given by Daniel and Axon (1953) and Henocq and Houlgate (1964).

2.2.3.3 Wavelength Response at Short Wavelengths: Factors in calibrating the wavelength response of a short-gap ferromagnetic core reproducing system are well documented in the literature, and are outlined in Table II. Intercomparisons of short-wavelength measurements by several laboratories using the short-gap magnetic head method indicate a repeatability of measurements at 12 μm (0.5 mil) of about 5%; considering all of the factors involved, this is very satisfactory.

In early standards work, Daniel and Axon (1953) calculated the short-wavelength response of the ring-core reproducing head, using the well-known "(sin x)/x" formula for the gap loss. They also compared the measured response with the calculated response, and they found a systematic discrepancy which they could not explain. They hypothesized that the core affected the flux distribution from the tape, and that serious errors might occur when the gap length and recorded wavelength were comparable. They avoided this unsolved problem by using the single-conductor non-ferromagnetic head to make all of their basic measurements.

Westmijze (1953) subsequently found that the error which Daniel and Axon had observed was due entirely to the fact that the "(sin x)/x" gap-loss formula is only approximately valid: the *exact* gap-loss formula (which is very complicated) is in fact completely in agreement with Daniel and Axon's experimentally measured responses. (A graph from Westmijze of the exact formula is shown in McKnight, 1967a, Fig. 3.)

The obvious conclusion is that there is no longer any reason to use single-conductor heads in preference to ring-core heads for basic measurements. Despite this, there has been a lingering (and, in this author's opinion, mistaken) reverence for the single-conductor head as a standard. Since all of the factors of Table II (except for "low-density core") apply equally to single-conductor heads and short-gap ring-core heads, there is no fundamental advantage of one type of head over the other, for standardizing purposes.

The choice of reproducer is therefore mainly determined by the ease and quality of fabrication and the accuracy of calibration. Both fabrication and calibration of short-gap ring-core reproducers seem to be less complicated than for the single-conductor reproducers (Schwartz, Wilpon and Comerci, 1955; Schwartz, 1957): large correction factors are necessary for the single-conductor reproducer, but very small correction factors are needed for the short-gap ring-core reproducer.

The last item in Table II, "head-to-tape spacing," may be viewed in two ways: From a fundamental point of view, anything which spaces the magnetized particles of the coating from the reproducing head is a "spacing." This would include tape surface roughness, uneven dispersion of the magnetic material in the binder such that a nonmagnetic surface layer exists, etc. In practice, however, these effects are a part of the *particular sample* of medium itself and for standardizing purposes, are conveniently considered to be a part of the recording system. Thus the only "spacing" of concern in the measurement of tape flux is *additional* spacing, such as that caused by "dirt" on the head face, inadequate head-to-tape pressure, inadequate wrap angle, incorrect vertex adjustment, and head wear (grooving). These factors are discussed in more detail elsewhere (McKnight, 1967a; Grimwood, Kolb and Carr, 1969.)

2.2.3.4 Frequency Response: In addition to wavelength effects of reproducers already discussed, there are effects which are solely a function of the reproduced frequency.

Different head designs (viz., bar-type ferromagnetic, single-conductor non-ferromagnetic, and ring-core type) will have their own particular responses; similarly, each of the methods mentioned in Sec. 2.2.3.1 for transduction from core flux in a ring-core head to output voltage will have its own particular frequency response. In this section we shall consider only the commonly used ring-core head with a "Faraday's law of induction" winding for the flux-to-voltage transducer, working into an amplifier which senses the output voltage of the winding.

The most obvious frequency response is the frequency-proportional (6-dB/octave) rise in coil emf, when constant flux is in the core. This is normally compensated by the use of an integrating amplifier — one whose response is inversely proportional to the frequency, making system output proportional to tape flux only (i.e., independent of recorded frequency, tape speed, etc.).

In the ring-core reproducer, the permeability of the core determines the flux efficiency of the head, as discussed above in Sec. 2.2.3.1. At higher frequencies the core permeability decreases due to eddy-current losses; therefore, as frequency increases the flux efficiency of the head drops, and the frequency response falls with increasing frequency (Daniel, Axon and Frost, 1957). This response is a function of both the core itself (core material resistivity and lamination thickness) and the relative reluctances of the core path and the air-gap path — the core alone does *not* determine this response factor.

Finally, there is a response due to the self-inductance, self-capacitance and self-resistance of the head winding, not only acting with themselves but also in conjunction with the input impedance (usually a capacitance shunted by a resistance) of the following amplifier. Note that the response of this electrical circuit may be a resonant *amplification* of the head emf, and that this will often conceal the loss of response due to eddy currents that was mentioned in the previous paragraph.

Several practical methods are available for measuring the total effect of these frequency responses. Bick (1953) describes techniques and compares measured results for four methods: variable-speed tape, flux induced by conductor, flux induced by iron-cored electromagnet, and constant current input in shunt with head; one could also insert constant voltage input in series with the head. McKnight (1960) also compares results of the variable-speed and the flux-induced-by-conductor methods; these two methods are usually subject to the least error of calibration.

In order to separate the eddy current losses, it is necessary to wind the coil in such a manner as to have the resonant frequency three to five times the highest frequency of interest; then the response measurement would indicate only the eddy-current effect.

This and the previous three sections have thus shown that theory and measuring methods do exist for calibrating the sensitivity, long- and short-wavelength responses, and frequency response of single-conductor and ring-core heads.

2.2.4 Magnetometers

As shown in Sec. 2.2.2.2, it is possible to produce a dc recording on tape with the same flux as that from a given long-wavelength ac recording; then, by measuring the dc flux, the ac flux is indirectly determined. The dc flux measurement can be made by means of traditional magnetometer techniques: a search coil, the torque developed in a uniform magnetic field, a vibrating sample magnetometer, etc. Such a technique was described by Schmidbauer (1957a), and later by Daniel and Levine (1960a and b) and by Comerci (1962). Some comparisons have been made between the flux measured by the single-conductor head and the magnetometer method: Daniel and Levine (1960b) state: "The two methods of measuring tape flux gave results in very good agreement," but give no experimental data. Comerci (1962) does present experimental data: of six comparisons, five show disagreement between the two methods of 2% or less; one shows 5%. One would therefore conclude that both measurement techniques are capable of providing accurate measurement of long-wavelength flux.

2.2.5 Summary of Measuring Methods

Shortcircuit flux per unit track width, in standard units, may be measured accurately at long wavelengths by means of a single-conductor reproducer, a bar-type ferromagnetic head, or a short-gap ring-core head. Alternately, the long wavelength flux may be transferred to an equivalent unidirectional flux which can be measured by a magnetometer. Any arbitrary "reference recording," can be used as the basis for *relative* flux measurements at medium-to-long wavelengths, but it is then not related to standard units.

With the present state of knowledge, the recorder and medium cannot be calibrated for accurate flux determinations at medium wavelengths.

The relative response at long wavelengths is most easily determined by means of a calibrated recorder; the ring-core head and the single-conductor head can also be calibrated for long-wavelength response measurements, but with more difficulty.

The relative response at short wavelengths is most easily determined by means of the calibrated short-gap ring-core head; the single-conductor head can also be used. The recorder and medium cannot (at the present state of knowledge and technique) be calibrated for short-wavelength response measurements. Neither is the "reference recording" suitable for this purpose.

Confidence in the calibration of the sensitivity and response of a reproducing system is gained by:

(1) the ability to calculate theoretical response and compare it with at least one experimental measurement;

(2) the ability to make practical reproducers which require only very small correction factors; and

(3) the ability to achieve repeatability: several "identical" reproducers should in fact have identical performance characteristics.

All of these requirements are well met by the short-gap ring-core head, especially when separate heads are designed and made for measurement of absolute flux, long-wavelength response, and short-wavelength response.

2.3 Magnetic Units

Measurements of absolute shortcircuit flux per unit track width may be ex-

Table II. Factors in the Calibration of the Short-Wavelength Response of a Short-Gap Ferromagnetic Core Reproducing Head System.

Effect	Theory	Experimental measurement
Gap length	Basic: Westmijze (1953) Effect of tape permeability on the gap-length response: Fan (1961) Effect of rounding of gap edge on the gap-length response: Duinker (1961)	Optical measurement of gap: Response measurement to locate null wavelength and sharpness of null: Daniel & Axon (1953)
Gap defects	Wedge-shaped gap: Daniel & Axon (1953) Arc-shaped gap: Schmidbauer (1960)	A "perfect recording" at a short wavelength is reproduced; measurement of output *vs* azimuth angle should show a symmetrical curve with sharp nulls and secondary peaks at −13 dB: Daniel & Axon (1953, Fig. 12) A given head is used to make a short-wavelength recording; the same head is used as reproducer, and the output measured. The tape is reversed end-for-end, and the same recording again reproduced. Output should be the same. (Does not detect symmetrical defects, which are, however, unlikely.) Schmidbauer (1957b)
Non-magnetic bonding material between laminations of the core (a "low-density core") causes reduction of response at short wavelengths		Optical measurements of intra-lamination spacing: Morrison (1967)
Misalignment of recording and reproducing-head gaps (azimuth adjustment)	Daniel & Axon (1953)	Daniel & Axon (1953); McKnight (1967a)
Head-to-tape spacing	Wallace (1951)	Causes discussed by McKnight (1967a), and Grimwood, Kolb & Carr (1969). Daniel & Axon (1953) conclude: "No test, other than that of inconsistency, can be established for imperfect contact. . . ."

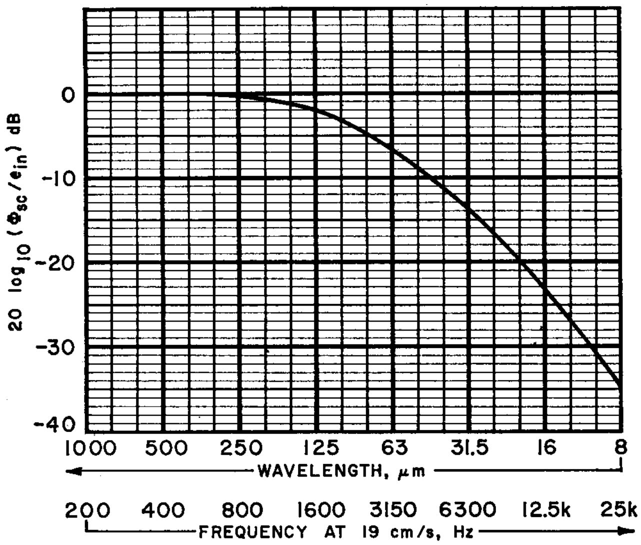


Fig. 6. An example of an unequalized recording flux-frequency response (the ratio of shortcircuit flux to the recorder input voltage vs. recorded wavelength).

pressed in the SI units, webers per meter of track width. Previous literature and standards have usually used the cgs electromagnetic unit, the maxwell; the conversion is 10^8 Mx = 1 Wb.

Measurements of surface induction (flux density, discussed in the Appendix) may be expressed in the SI unit, the tesla; again, the previous work has been in the cgs unit, the gauss; 10^4 G = 1 T. Actually, a knowledge of the flux density alone (without also knowing the recorded wavelength) is completely useless; or, to put it the other way, given a recorded tape, one cannot determine the flux density without knowing the recorded wavelength. Flux density times wavelength ($B_s . \lambda$) in tesla-meters would be a useful quantity; it would, in fact, be dimensionally identical to flux per unit width, in webers/meter: $B_s\lambda/\pi = \Phi_{sc}/w$.

Two other conversions may also be of some practical value: 1 millimaxwell = 10 picowebers, and 1 picoweber per millimeter of track width = 1 nanoweber per meter of track width.

There has been considerable hesitancy on the part of the international and USA standardizing organizations to call the recorded signal the shortcircuit flux per unit track width, and to express it in the SI units. Instead, even the primary standards have usually been "nonstandard" measures — the description of a calibrated reproducing system for frequency response, and reference to an arbitrary reference recording for the flux reference. This has occurred largely because of a lack of confidence in the accuracy of the absolute measurements. The author believes that the proof of accuracy has been established sufficiently well that the absolute measurements should now be adopted into primary standardization.

Since the standardization of other measurements is performed in the USA by the National Bureau of Standards, it would be very helpful if the basic measurements used in magnetic recording could also be standardized by the NBS. Preliminary inquiries have not been very encouraging.

3. FREQUENCY RESPONSE AND EQUALIZATION

Once flux has been chosen as the quantity for the recorded signal, we can define the recording flux-frequency response of a recorder *and medium* as the flux from the tape when the input signal to the recorder is a constant voltage vs. frequency. Similar, the reproducing flux-frequency response is the output voltage of a reproducer when the input signal is a constant-flux recording vs. frequency.

We may use the term "unequalized recording flux-frequency response" when the recording field of the recording head itself is constant vs. frequency. The unequalized recording flux-frequency response of an idealized recording system (which includes the wavelength response of the medium) is flat at long wavelengths (low frequencies), but falls at shorter wavelengths (higher frequencies) in a fashion determined by the particular medium (the make and type of tape), and by the recorder and the setting of the recording bias (McKnight, 1961). The unequalized recording flux-frequency response for one particular present-day system is shown, for example, in Fig. 6 (see McKnight, 1960, for a discussion of these recording losses). On the other hand, the unequalized *reproducing* flux-frequency response of an idealized reproducing system is a flat curve; (that is, by definition an "idealized" reproducer is one which measures the tape flux); therefore the unequalized overall response of such an idealized system will be the same as the recording flux-frequency response shown in Fig. 6.

In order to make the overall frequency response of the system flat, an equalization of the frequency response is necessary. The minimum amount of equalization is the inverse of the unequalized recording flux-frequency response shown in Fig. 6.[8] This equalization may be applied in recording, in reproducing, or partly in each. The division is controlled by the desire to achieve two ends: first, to maximize the ratio of the undistorted signal to the audible noise of the system, and second to simplify the equalization circuitry.

Recording and reproducing equalization may be defined as the process of modifying the frequency response of the recorder and/or reproducer in such a manner as to provide the maximum signal-to-noise ratio, while producing flat overall response. (Recording equalization is often called pre-equalization or pre-emphasis, and reproducing equalization post-equalization, or post-emphasis.)

3.1 Division of the Equalization

Cramer (1966) has discussed the theory of optimizing the division of the equalization for maximum signal-to-noise ratio. His theory requires: (1) knowledge of the system noise spectrum, which is easily measured in practice; (2) knowledge of the ear's response to the noise spectrum, which is not so easily known in practice, because it varies with the system gain (i.e., the "playback volume"), and with the room noise spectrum, and the consequent aural masking; (3) knowledge of the signal spectrum, which is not usually available in practice because the spectrum varies from one program to another, and from one moment to the next in a given program; and (4) control of the equalized signal level so as to maintain constant power at the program level maxima; this could be achieved in practice by using an equalized peak level indicator, but it is not even approached by the flat (unequalized) vu meter which is commonly used.

In the past the division of equalization has always been done empirically by "cut and try" methods based on the total losses involved for the particular types of tape and biasing fields to be used, the tape speed, the types of program material to be used most commonly, the operating level (see Sec. 4), the performance of the level-indicating system (short averaging time, called a

8. Additional complementary equalization — i.e., an equal rise of response in recording, and droop in response in reproducing — may be applied at high and/or low frequencies; for example, additional high-frequency equalization is discussed in Academy Research Council (1944), McKnight (1959), Goldberg and Torrick (1960), and Pipelow (1962). Low-frequency equalization is discussed by McKnight (1962) and Pieplow (1963).

"quasi-peak level indicator," or "peak program meter"; or long averaging time, such as the vu meter), the compromise desired between noise and distortion, and frequently a large dose of personal preference, commercial practice, and politics. Considering the practical difficulties in applying Cramer's theory, it seems unlikely that the situation will soon change.

This discussion assumes a fixed equalization. The Audio Noise Reduction System manufactured by Dolby Laboratories (London) circumvents these problems by having in essence a system whose recording equalization automatically varies continuously to suit the level and power spectrum of the program itself; the reproducing equalization is automatically controlled to complement the recording equalization (Dolby, 1967). Thus one is able to achieve maximum signal-to-noise ratio for each instant of each program — a condition not possible with simple fixed equalization.

3.2 Equalizer Response Shapes

The equalizer response shape simplest to design and to fabricate commercially is the frequency-proportional resistance-capacitance equalizer. Fortunately, the total required equalization, which is the inverse of the unequalized response shown in Fig. 6, can be very closely approximated by two such frequency-proportional equalizers, with the transition frequencies in the ratio of about 4:1.[9] If this pair of curves is translated along the frequency axis, it can very closely approximate the practical response required for the different speeds and for tapes with different loss characteristics.

The range of responses which this pair of simple frequency-proportional R-C equalizers can approximate is actually very flexible. Consider the total equalization required at 38 cm/s (15 in/s), as shown in the solid curve of Fig. 7. Making the practical assumption that the reproducing equalizer has its transition frequency at $f_{rep} = 3150$ Hz,[10] as shown by the single-dot curve, the recording equalizer (double-dot curve) would have its transition frequency $f_{rec} = 12.5$ kHz in order to make the sum of recording and reproducing equalizations equal the total required. This sum, the dashed curve, falls very closely on the desired response, the solid curve.

One might suppose that if the tape speed were changed by 2:1, resulting in the response of Fig. 8, it would be necessary to move f_{rep} to 1600 Hz; in fact, f_{rep} may be left at 3150 Hz, and f_{rec} readjusted to 2800 Hz, and the sum will still be within ±1 dB of the total required amount. This is a considerable economic convenience in designing equalizers: one reproducing equalization can be used for two speeds. This also shows

9. The transition frequency may be defined as that frequency in an R-C equalizer where $X_C = R$, and $f = 1/(2\pi RC)$; at this frequency the level has risen or fallen 3 dB.

10. The transition frequencies have all been rounded to the nearest "preferred frequency", according to USA Standard S1.6-1967. Where "time constants" are given, these are the exact values given in standards.

Table III. Flux-Frequency Response Currently Specified by Various Standardizing Organizations: Summary of Transition Frequencies and Time Constants.

Speed		Transition frequencies[10]		Equivalent time constants[10]		
cm/s	in/s	f_l, Hz	f_h, Hz	t_l, μs	t_h, μs	Standardizing organization
76	30	0	9000	∞	18	Ampex professional equipment
		0	4500	∞	35	CCIR (1953 or earlier to 1966); IEC (1968); DIN (1962)
38	15	50	3150	3180	50	NAB (1953 and 1965); EIA (1963)
		0	4500	∞	35	CCIR (1953 or earlier through 1966); IEC (1968); DIN (1962)
19	7.5	50	3150	3180	50	Ampex professional equipment; NAB (1965); RIAA (1968); EIA (1963); DIN home (1966)
		0	3150	∞	50	EIA Standards Proposal 1015; Ampex Stereo Tapes & Consumer Equipment (1967 to present)
		0	2240	∞	70	CCIR (1966); IEC (1968); DIN Studio (1966)[a]
9.5	3.75	50	1250	3180	120	EIA (1959); Ampex professional equipment (1959 to present)[b]; DIN (1962)
		0	1600	∞	100	EIA Standards Proposal 1015; Ampex Stereo Tapes & Consumer Equipment (1967 to present)
		50	1800	3180	90	NAB (1965); RIAA (1968); IEC (1968)[c]
4.76	1.87	50	800	3180	200	Ampex Consumer Products
		100	1250	1590	120	DIN (1966); IEC (1968); RIAA (1968); Philips Compact Cassette system

[a] ∞- and 100-μs were formerly used by CCIR, IEC and DIN.
[b] 3180- and 200-μs formerly used by Ampex (1953–1958).
[c] 3180- and 140-μs formerly used by IEC (1964).

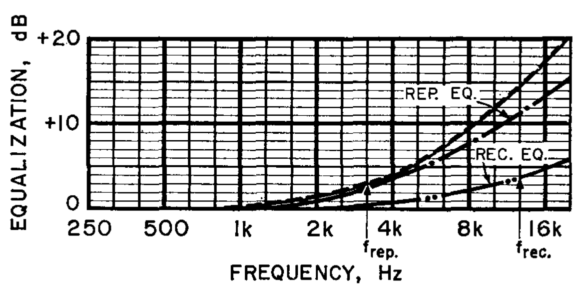


Fig. 7. Equalization at 38 cm/s (15 in/s): ——— total equalization required: — — — reproducer equalization, with transition frequency f_{rep} = 3150 Hz; — — — — recorder equalization, with transition frequency f_{rec} = 12.5 kHz; - - - - total equalization from recorder and reproducer.

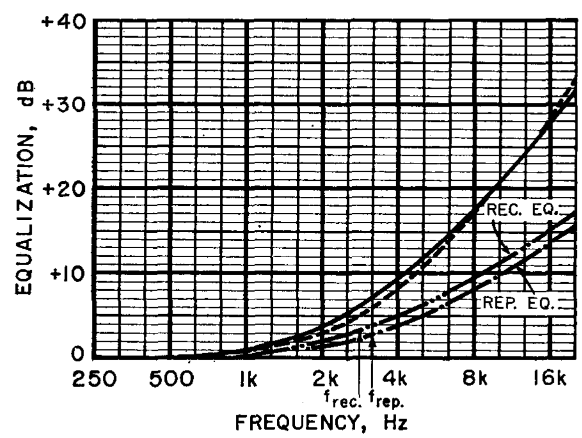
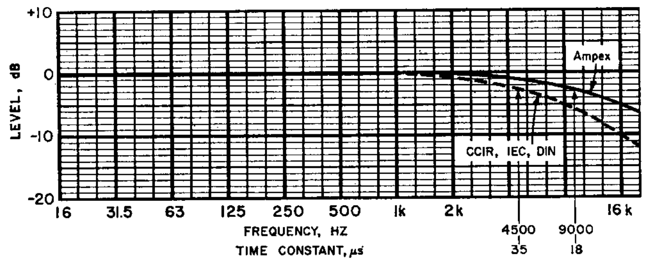
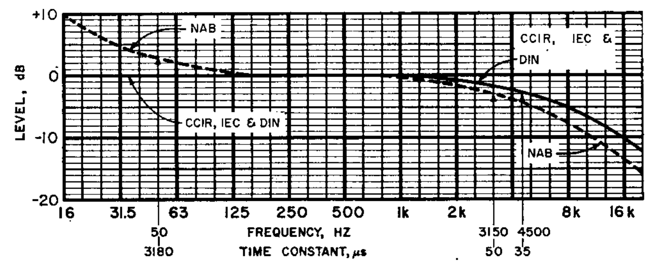


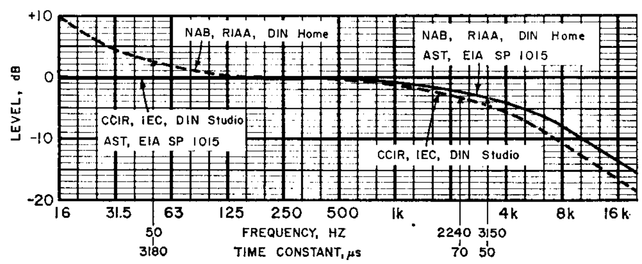
Fig. 8. Equalization at 19 cm/s (7.5 in/s): ——— total equalization required; — — — reproducer equalization, with transition frequency f_{rep} = 3150 Hz; — — — — recorder equalization, with transition frequency f_{rec} = 2800 Hz; - - - - total equalization from recorder and reproducer.



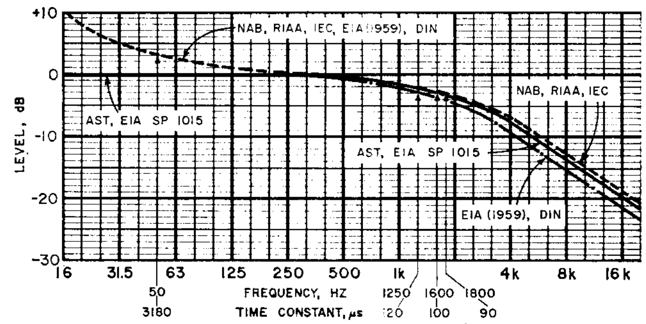
(a) **standards for 76 cm/s (30 in/s)**



(b) **standards for 38 cm/s (15 in/s)**

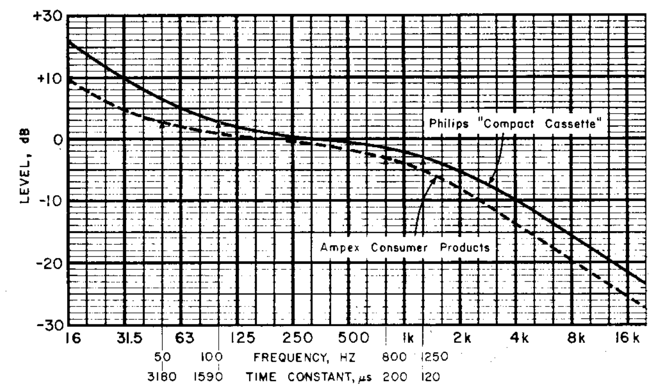


(c) **standards for 19 cm/s (7.5 in/s)**



(d) **standards for 9.5 cm/s (3.75 in/s)**

Fig. 9 (a-e). Standard flux-frequency responses as specified by several standardizing organizations for magnetic tape recording. Each of the curves represents three quantities: the standard recording flux-frequency response, $20 \log_{10} \Phi_{sc}/e_{in}$; the standard reproducer test tape flux vs. frequency, $20 \log_{10} \Phi_{sc}$; and the inverse of the standard reproducing flux-frequency response, $-20 \log_{10} e_{out}/\Phi_{sc}$.



(e) **standards for 4.8 cm/s (1.87 in/s)**

that a considerable range of unequalized recording flux-frequency response (e.g., due to tape changes) may be accommodated by simply changing the recording equalizer, keeping a constant reproducing equalization.

There is a limitation to the range of adjustment: when the wavelength at which the "standard" reproducing flux-frequency response produces a 3-dB rise in reproducer response is greater than the wavelength at which the unequalized *recording* flux-frequency response has fallen 3 dB, then the reproducing equalization alone exceeds the total required equalization at middle frequencies! For instance, Fig. 6 shows a 3-dB loss at 110 μm (4 mil). Some tapes now available have the 3-dB loss at even shorter wavelengths. Old standard equalizations (see Table III) for 9.5 cm/s (3.75 in/s) used a 1250-Hz transition frequency; present standard equalizations for 38 cm/s (15 in/s) use a 3150-Hz transition frequency curve. Both of these reproducing equalizations work out to be +3 dB at 120-μm wavelengths. Thus, to achieve a flat overall response, it is actually necessary to use a recording equalization (i.e., recording head current vs. frequency) that produces a 1-dB negative shelf in response, rather than the usual boost in response! Even worse, the CCIR standard for 76 cm/s (30 in/s) calls for 4500-Hz transition frequency, which is a 3-dB wavelength of 174 μm; this would require a 4-dB negative shelf in the recording equalization. When this condition of "too much reproducing equalization" occurs, one may take one of the following courses: (1) redesign the recording equalizer to provide the needed negative shelf response; (2) use another tape, having the 3-dB loss at a longer wavelength (more "wavelength loss"), e.g., use a tape with a thicker coating, which is usually identified as a high-output tape, and usually has more short-wavelength loss; or (3) change the "standard" equalization.

Because of the convenience and simplicity of the simple R-C equalizer, it is almost universally used. Ampex Mastering Equalization (McKnight, 1959) is one of the few exceptions, and has pretty well substantiated the convenience of the simple R-C equalizer.

The response of the R-C equalizer may be described as follows:

The recording flux-frequency response is uniform with frequency except where modified by the following equalizations:

(1) the inverse of the voltage attenuation of a single resistance-capacitance high-pass filter having a transition frequency[9] of f_l; and

(2) the voltage attenuation of a single resistance-capacitance low-pass filter having a transition frequency of f_h.

This response may be given as a logarithmic ratio as a function of frequency by the following equation:

$$\frac{\Phi_{sc}}{e_{in}}(f), \text{ in dB} = 10 \log_{10}\left[\frac{1 + (f_l/f)^2}{1 + (f/f_h)^2}\right]$$

where f is the frequency at which the response is being computed, f_l is the low-frequency transition frequency, and f_h the high-frequency transition frequency, all in Hz.

When no low-frequency equalization is used, $f_l = 0$, and the equation reduces to:

$$\frac{\Phi_{sc}}{e_{in}}(f), \text{ in dB} = 10 \log_{10}\left[\frac{1}{1 + (f/f_h)^2}\right]$$

It has become standard audio practice over the years to express these responses

Table IV. Summary of Magnetic Reference Fluxes.

Organization	Terminology in Standard	Speed cm/s	Speed in/s	Rms flux as specified	Rms flux/unit track width nWb/m
Ampex Corp.*	Ampex Operating Level	9.5–76	3.75–30	185 nWb/m†	185
BS	None			None	
				1955 issue mMx/6.3 mm — 1962 issue mMx/mm = pWb/mm	
DIN 45513	*Bezugspegel*	4.8	1.87	— 25 = 250	250
	(literally, Reference Level)	9.5	3.75	160 ≅ 25 = 250	250
		19	7.5	160 ≉ 32 = 320	320
		38	15	200 = 32 = 320	320
		76	30	100 = 16 = 160	160
EIA	Considering "Reference Flux"			100 nWb/m	100
IEC	None			None	
CCIR	Suggests consideration of "Standard Reference Level"			100 pWb/mm	100
NAB Reel-to-Reel (1965)	Standard Reference Level	4.8–38	1.87–15	Value not given in standard units, and proposed test tapes not available, therefore value not yet known	
RIAA	None			None	
SMPTE, 8 mm film PH22.130–1962	Signal Level	9.15	18 ft/min	10 gauss at 400 Hz	**73**
—, 16 mm film PH22.132–1963		18.29	36 ft/min	10 gauss at 400 Hz	**146**

* Company practice for audio recorders.
† Previously shown as 210 nWb/m. The change reflects a new and more accurate *measurement;* the tape flux on the test tape has *not* changed.

not by the obvious means of the transition frequency, but in terms of the time constant τ (or t) of the R-C circuit which is used to achieve this response. The time constant is simply the reciprocal of the angular frequency: $t = 1/(2\pi f)$, or, more simply, t (in μs) $= 160/f$ (in kHz).

The advantage of the time constant concept is that it enables quick calculation of the R-C equalizer components directly from $t = RC$. The disadvantage is that it obscures the idea that this is an equalizer with a frequency-proportional response which one locates on a graph by knowing the *transition frequency*. Also, the author has heard the statement made (seriously!) that "this tape recorder has a 50 μs transient response." The point is of course that the "50 μs" has nothing at all to do with the system transient response — it is just a backwards way of indicating the frequency at which the equalizer changes its response by 3 dB.

That the description of simple R-C equalizers in terms of time constants can be made very complicated is well shown in an article by V. Rettinger (1964).

3.3 Standard Flux-Frequency Response

In order to standardize the frequency response of a magnetic recording and reproducing system, one must specify both the response of the recorder (the recording flux-frequency response Φ_{sc}/e_{in} vs. frequency), and the response of the reproducer (the reproducing flux-frequency response e_{out}/Φ_{sc} vs. frequency). For practical measurements, one also needs to have a reproducer test tape with a known tape flux vs frequency (Φ_{sc} vs. frequency).

For a flat overall system response, the recording and the reproducing flux-frequency responses must be the inverse of each other. The shape of the reproducer test tape flux vs frequency must be the same as that of the recording flux-frequency response.

Table III summarizes the standard flux-frequency responses specified by several standardizing organizations for magnetic tape recording; the corresponding graphs are given in Fig. 9. A similar table for motion-picture systems is given by Grimwood, Kolb and Carr (1969). The differences in the various flux-frequency responses which have been standardized reflect the factors mentioned in Sec. 3.1, above.

The "EIA SP 1015" is for a *single* test tape which is usable for *both* 19- and 9.5-cm/s (7.5- and 3.75-in/s) tape speeds. Advantage is taken of the fact that the NAB and RIAA responses for both speeds are nearly identical on a wavelength basis. The time constant for 9.5 cm/s has been rounded from 90- to 100-μs (0.9-dB error), and the low-frequency pre-emphasis eliminated. The latter is both for convenience in allowing only one test tape for two speeds, and also because some manufacturers of recorder/reproducers (including Ampex Consumer Products) and of tape records (including Ampex Stereo Tapes) are now manufacturing equipment and tape records in this manner, because they believe the pre-emphasis to be both technically and economically undesirable.

It is curious to note that the "change of equalization" in Fig. 9E for 4.76 cm/s (1.87 in/s) systems, from the old (Ampex) curve with 50 Hz and 800 Hz transition frequencies, to the new (Philips) curve with 100 Hz and 1250 Hz is essentially equivalent to retaining the old transition frequencies and simply raising the flux level at all frequencies by 2 dB!

The specification of all three flux-frequency responses — recording, reproducing and reproducer test tape — is not "double dimensioning" because these are in fact the specifications for three *different* pieces of apparatus. The fact that the curves have the same (or inverse) shapes is a result of the specification that the overall system be flat in response.

4. FLUX AND FLUX LEVEL SPECIFICATIONS

The tape flux per unit track width may of course be expressed in the basic units: so many webers per meter. In most audio transmission work, however, a logarithmic ratio to a reference quantity, denoted by "level L re/——, in dB" is used. Common reference quantities in electrical transmission systems are, for instance, one milli-watt, giving "power level, L_P re/1 mW, in dB"; and one volt, giving "voltage level, L_V re/1V, in dB." (The reference quantity needs to be specified only once in any given context.) Note that these are not "recommended operating levels" for transmission over a particular system; they are *arbitrary* but *fixed* reference points for measurement; they are usually basic units of the International System of Units (SI) (e.g., the volt) or decimal multiples thereof (e.g., the milliwatt).

A reference flux per width for magnetic recording levels would be useful. Table IV shows that practical recording tape fluxes fall in the region around 100 nWb/m, and this value is therefore suggested as the reference, giving "flux per width level, $L_{\Phi/w}$ re/100 nWb/m, in dB." (This proposal is being considered by both CCIR and EIA.)

In a practical recording and reproducing system, the levels are indicated on some sort of level indicator, e.g., a vu meter,[11] a quasi-peak-reading meter, etc. The choice of flux level for the operating level — i.e., the flux level when the meter points to its "0-dB" mark — depends on the same factors enumerated in Sec. 3.1; it is an operating quantity determined by experience with a recording system. When recordings are to be interchanged, as in broadcasting applications and with master tapes for phonograph disc manufacturing, it is very desirable that a uniform operating level be adhered to. Surprisingly enough, most of the existing standards — BS, EIA, IEC, CCIR, RIAA and SMPTE — make absolutely no mention of an operating level. Those who do consider an operating level — Ampex Corp., DIN, and NAB — do not employ uniform terminology and practices.

The Ampex reproducer test tapes contain an "Ampex Operating Level" section in the sense defined above. The NAB "standard reference level" is identical to the NAB "standard recorded level," and is, in fact, also an operating level as defined above. The DIN Standards call for setting the operating level of a recorder by means of a distortion measurement; the *Bezugspegel* (reference level) on the DIN Test Tapes is not referred to in the other DIN Standards. On the other hand, the *Bezugspegel* is used as the operating level in Geraman broadcasting practice.

The SMPTE has standardized a "signal level," which is "for use in controlling magnetic sound recording levels and standardizing methods of signal-to-noise measurements. . . ." Since no description is given of operating practices, this signal level is really an arbitrary reference quantity similar to the "100 nWb/m" mentioned above; it is not a true operating level.

The clear separation of the reference quantity and the operating level is very desirable: the reference quantity is only a measurement unit, and, once chosen, needs never be changed. On the other hand, the operating level is variable, as shown in Table V, because it is influenced by the tape, the equalization, the level indicator, and the other factors of Sec. 3.1.

5. DEFINITIONS FOR MAGNETIC RECORDING

In this section the terminology used in the previous sections of this paper is reviewed and given precise definitions. This is done in order to crystallize the previously developed concepts, and also as a basis for a comparison (in Sec. 6) of these terms with similar terms used in the various published standards.

5.1 The first quantity to be defined is that for the recorded signal, the "*magnetic tape shortcircuit flux*," Φ_{sc}, which is usually shortened to *tape flux*, or just *flux*. At an intuitive level, we may say that the shortcircuit flux is that flux from a magnetic tape record which flows thru a magnetic shortcircuit placed in intimate contact with the record. More precisely, the tape flux is the total flux of a recorded track which passes through a half-plane normal to both the plane of the tape, and to the direction of the tape flux (see Fig. 10). This half-plane is contained within a semi-infinite block of infinite permeability (a mag-

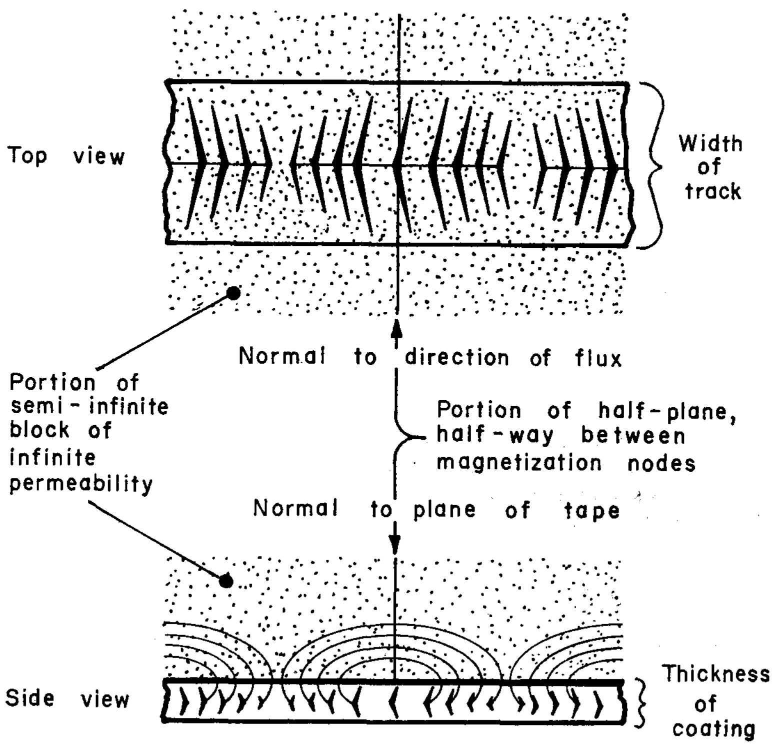


Fig. 10. Simplified illustration for the definition of "shortcircuit flux," showing the sinusoidal magnetization of the coating, the resulting flux, the relationship of the coating to the semi-infinite block, and the relationship of the flux to the half-plane of measurement. ("Half-plane" and "semi-infinite block" refer to the fact that they are bounded by the plane of the tape.)

Table V. Magnetic Operating Levels.

Organization	Speed cm/s	Speed in/s	Operating flux level, $L_{\Phi/w}$ re/ 100 nWb/m, dB
Ampex Corp.*	9.5—76	3.75—30	+ 5.4
DIN 45513, 1962†	4.8	1.87	+ 8.0
	9.5	3.75	+ 8.0
	19	7.5	+10
	38	15	+10
	76	30	+ 4
NAB	4.8—38	1.87—15	to be determined

* Company practice for audio recorders.

† See text for further discussion: the DIN *Bezugspegel* is used as an operating level in German broadcasting practice only

11. One often sees reference to a level on a magnetic recording as a certain number of "vu." This practice is deprecated because the vu is presently defined *only* for electrical transmission systems, being referred to a power measurement in milliwatts (USAS C16.5-1954). To add to the confusion, the vu level of an electrical transmission system is defined as the reading of the *associated vu meter variable attenuator* (or fixed pad) when this attenuator is adjusted to make the meter pointer deflect to the "reference deflection" (0 vu mark on the scale). Since most magnetic recorders do not have a variable meter attenuator to be read, it is not apparent that the line level is, for instance, often + 4 vu or + 8 vu, *not* 0 vu, when the meter pointer deflects to "0 vu." These problems occur because the vu meter was originally designed only for telephone-system transmission measurements, and the standard did not foresee its use in recording systems. The standard requires revision to make it relevant to present audio system practices.

netic shortcircuit) which is in intimate contact with the tape surface. This half-plane is located halfway between magnetization nodes on the tape; in the case of a recorded sine-wave, the rms value is the total flux divided by the square-root of two. The SI unit for flux is the weber.

As mentioned in Sec. 2.1, the short-circuit flux is the quantity which is measured by the "ideal" heads which are mentioned in many standards. The definition given here precludes all of the known errors in making and using an "ideal" head: "flux which passes through a half-plane" means a measurement without gap-length loss, gap defects, or non-magnetic spacing between the laminations; "normal to the direction of the flux" means adjustment for zero azimuth error; "semi-infinite block" means a head which is wider than the track (no fringing effect), and very long compared to the longest wavelength (no head-length effect, which also means no effect from wavelength comparable to track width); "infinitely permeable" means that all of the flux is collected, and also precludes "secondary-gap effect"; "intimate contact" precludes additional spacing over that inherent in the medium itself. Any system which meets these criteria directly or by calibration and correction can therefore be used to measure the tape flux.

5.2 For some purposes, we may be more interested in the *magnetic tape shortcircuit flux per unit of recorded track width*, Φ_{sc}/w, which is usually shortened to *flux per width*. It is simply the tape flux divided by the width of the recorded track. The SI unit is the weber per meter.

5.3 Signal magnitudes in audio transmission systems — including magnetic recorders — are often expressed in terms of a logarithmic measure called a *level*, and designated by the term *decibel*. A modern interpretation of these terms (McKnight, 1969) proposes that, although present definitions appear to restrict the terms "level" and "decibel" to use with power-proportional quantities, common engineering practice does not fully conform to these definitions. Instead, these terms are used for both powers and amplitudes, interchangeably. Since this usage is firmly established, and is satisfactory if done carefully, the *definitions* should be revised and clarified to conform to the actual present usage. According to this proposal, the author has used the terms "level" and "decibel" in this paper when speaking of tape flux level, voltage level, etc.

5.4 A *reference quantity for flux levels* is desirable. Numerous "reference fluxes" have been used; the author proposes 100 nWb/m as the reference flux per width, designating levels to this reference as "flux per width level, $L_{\Phi/w}$ re/100 nWb/m. in dB." (It should be noted that this reference flux does not imply an "operating level" as defined in Sec. 5.5.)

5.5 With the above definition of flux level, *the operating flux level of a magnetic record*, shortened to *operating level*, may be defined as that flux level which results on the magnetic record when the volume indicator of the recording system deflects to its reference (0 dB) scale mark. Concomitantly, this is also the flux level on a magnetic record which causes the reproducing system volume indicator to deflect to its reference (0 dB) scale mark.

The "operating level" is, in effect, a "recommended recording level." Its choice depends upon the particular magnetic recording medium, the level indicating system, the organizational operating practices, the tape speed, the division of equalization between recording and reproducing, the type of program material most often encountered, and the compromise chosen between noise and distortion. Several different operating levels are presently used.

5.6 The frequency response of a recorder and medium is described in terms of its *magnetic recording system equalized flux response vs. frequency*, shortened to *recording flux-frequency response*, which is the frequency response of a magnetic recording system, where the input is the voltage level at the input terminals of the recording system, and the output is the flux level on the magnetic record.

5.7 The frequency response of a reproducer is described in terms of the *magnetic reproducing system equalized flux response vs. frequency*, shortened to *reproducing flux-frequency response*, which is the frequency response of a magnetic reproducing system, where the input is the flux level on the magnetic record, and the output is the voltage level at the output terminals of the reproducing system.

5.8 When the "standard" flux-frequency responses are established by a standardizing organization, the difference between the standard response and the actual response of a practical recorder becomes important. This is called the *recording flux-frequency response deviation*, and defined as the difference between the recording flux-frequency response of a recorder and a specified standard recording flux-frequency response. The practical measurement of the recording flux-frequency response deviation of a recorder/reproducer is most conveniently made by measuring the recorder/reproducer overall frequency response, Sec. 5.10, and subtracting from it the measured reproducing flux-frequency response deviation, Sec. 5.9.

5.9 For a reproducer there is, similarly, the *reproducing flux-frequency response deviation* which is the difference between the reproducing flux-frequency response of a reproducer and a specified standard reproducing flux-frequency response. The practical measurement of the reproducer flux-frequency response deviation is made by reproducing a Reproducer Test Tape conforming to the appropriate standard and speed. The output voltage level vs. frequency is measured; a reproducer with no reproducing flux-frequency response deviation will have a constant output voltage level vs. frequency.

5.10 The sum of the frequency responses for a recording and reproducing system is the *magnetic recording and reproducing system overall response vs. frequency*, shortened to the *overall frequency response*, which is the frequency response of a magnetic recording and reproducing system, where the input is the voltage level at the input terminals of the recording system, and the output is the voltage level at the output terminals of the reproducing system. The overall response is the sum of the levels shown in the recording flux-frequency response deviation and the reproducing flux-frequency response deviation.

5.11 In order to test recording and reproducing frequency responses in the field, one uses a *reproducer test tape*, which is a magnetic tape record containing recordings having known characteristics. It is used to calibrate a reproducer directly, and the recorder indirectly by means of the calibrated reproducer. A reproducer test tape usually contains three sections:

(1) The *azimuth adjusting section:* A recording of a short wavelength sinusoidal flux exactly parallel to the edge of the tape, used for adjusting the azimuth of the reproducing head.

(2) The *reference flux section:* A recording of a medium-frequency sinusoidal signal with an rms short-circuit flux of 100 nWb/m, used to calibrate the sensitivity of the reproducing system. Alternatively, *an operating level section* is often used, to calibrate the recommended recording level (see Sec. 5.5, above).

(3) The *frequency response section:* A recording of sinusoidal signals[12] over the audio-frequency range, used for calibrating the reproducing flux-frequency response of the reproducer.

5.12 The *reproducer test tape flux level vs. frequency* is the flux level from a reproducer test tape as a function of frequency. The

12. The recorded signals usually consist of numerous single frequencies, suitable for manual measurement methods; a continuously-swept frequency may also be used, especially when automatic measuring equipment such as a graphic level recorder is available. Noise "signals" of known spectrum—e.g. "white noise" or "pink noise"—may also be used.

Table VI. Comparison of the Terms Defined in Sec. 5, and Usages in Standards.

Standard	*Term Used in This Paper and Section Where Defined* — Recording flux-frequency response (Sec. 5.6)	Recording flux-frequency response deviation (Sec. 5.8)	Reproducing flux-frequency response (Sec. 5.7)	Reproducing flux-frequency response deviation (Sec. 5.9)	Overall response (Sec. 5.10
	Equivalent Term Used in Standards				
BS	Recording characteristic (but in terms of surface induction)	Implied under "tolerances on recorded level"	Reproducing characteristic (but in terms of surface induction; mentioned only in a note)	Implied under "reproducing equipment response"	None
DIN	None	None	None	Reproducer response from a test tape	Overall response
EIA	None	None	None	None	None
IEC (1968)	Recording characteristic (but in terms of surface induction*)	None†	Reproducing characteristic (but in terms of surface induction*)	None†	None
CCIR (1966)	None	By reference to IEC, which has since deleted the section on tolerances	None	None	None
NAB	None	Recorded response	Reproducing characteristic (in graph and table; not used in text)	Standard reproducing system response	None
RIAA (1968)	None	None	Reproducing characteristic	None	None
SMPTE	None	None	None	Reproducing characteristic	None

* IEC is now considering a change to shortcircuit flux.

† Under study at present.

shape of any standard reproducer test tape flux level vs. frequency curve will be the same as that of the corresponding standard recording flux-frequency response curve.

6. DISCUSSION OF EXISTING STANDARDS

6.1 The Use of the Term "Characteristic"

Practically all of the English-language standards use the terms "recording characteristic" and "reproducing characteristic," yet nowhere in any of these standards can one find a definition of these characteristics. The definitions used in Sec. 5.6 and 5.7 above are based on those found in the IEC International Electrotechnical Vocabulary (1960) which defines: "08-25-035 Recording Characteristic: Graph displaying the relation, with respect to frequency, of the variations (created by the recording signal) in the state or configuration of the recording medium when a signal of a constant value and variable frequency is applied to a specific point of the recording system." And "08-25-040 Reproducing Characteristic: Graph displaying the relation, with respect to frequency, of the variations of the output voltage when a signal of constant value and variable frequency is recorded on a recording medium."

Table VI compares the usages of these terms in the various standards, since definitions are not given in the standards themselves. This table shows that the terms defined in Sec. 5 involve no new concepts, but merely define and differentiate between the present conflicting usages of the terms "recording characteristic" and "reproducing characteristic." In the present standards, a given concept may be known by several names, and a given term may stand for two different concepts.

The term "characteristic" has been abandoned in this paper (despite its long-standing use in sound recording) because it means simply "the graph," and this restricts one to considering and defining graphs. The more general term "frequency response" has been substituted.

6.2 Standard Measurements

Table VII summarizes the techniques given in the standards for measuring the recorded signal, the methods of describing the equalizer response, and the techniques for measuring the absolute flux. Again, inconsistency is the keynote of the standards.

6.3 Ambiguous Statements

Present standards contain a number of ambiguous statements which are open to misinterpretation. Grimwood, Kolb and Carr (1969) have pointed out several such ambiguities in the NAB and RIAA Standards.

6.3.1 Track Width

The NAB Standard (1965) calls for a full-track test tape to be used for both full-track and multitrack reproducers. Footnote 7 says "Since NAB Standard Test Tapes are recorded across the full width of the tape, . . . a low-frequency boost may be expected when the test tape is reproduced on a head of less than full-track width. Refer to the instructions supplied with the test tape for further details." Since the "further instructions" are not yet available, the user must decide for himself whether this boost is to be considered as a *measuring* error, or whether one is to compensate the multitrack reproducer response so that it will give a constant output from the full-track test tape. The actual intent (known only to the NAB Standards Committee members) was that the *measurement data* with the full-track tape must be corrected so as to give results equivalent to the use of a multitrack test tape, as explained by McKnight (1967a), in the section "Test Tape Track Format."

In some systems, the recorded track width is intentionally greater than the width of the reproducing head core: this occurs, for instance, in the RIAA Bulletin E-5 (1968), Sec. 8.3.3 for 8-track cartridges on 6.3-mm tape, and in the proposed standards for "super-8" motion-picture film. For "8-track," the recording width is 0.56 mm (22 mils) and the reproducing core is 0.51 mm (20 mils); a response error of 1 dB is inherent in this system, due to the fringing effect at low frequencies. It is not stated in the standard whether the compensation is to be applied in the recording or the reproduction. The author recommends that the shortcircuit flux be standardized — that is, the measuring reproducer for standardizing recordings should be at least as wide as the recorded track. Any compensation required due to the reproducer core width would then be applied in the reproducer. This suggestion is based on these reasons:

(1) The intra-track shielding affects

Table VII. Measuring Techniques and Description of Response as Specified in Various Standards.

Organization	Technique described for measuring response of the recorded signal	Description of response	Technique described for measuring absolute flux
BS	None	Admittance of a series R-C network; table of surface induction	None
DIN	Short-gap ferromagnetic head	Response of an R-C circuit; graph of shortcircuit flux	ac to dc flux transfer, and measurement with magnetometer
EIA (1959 & 1963)	Short-gap "ideal" ferromagnetic head and specified amplifier response	Admittance of series and parallel R-C networks (no graph)	None
IEC (1968)	None	Admittance and impedance of series R-C networks; tables and graphs of surface induction*	None
CCIR (1966)	"Ideal" ferromagnetic head and specified amplifier response. By reference to IEC, which has since deleted the sections on measurements	Impedance of a series R-C network	None
NAB & RIAA (1968)	Short-gap "ideal" ferromagnetic head and specified output voltage response for constant flux input to the head core	Response of an R-C network, plus its equation; graph of amplifier output voltage for constant flux input to the head core	None
SMPTE	Short-gap "ideal" ferromagnetic head	Table of surface induction vs. frequency (no graph)	Non-ferromagnetic head (inductive loop)

* IEC is now considering a change to shortcircuit flux.

the amount of response error due to fringing — even a very narrow reproducing core with a close shield has no fringing effect — but one with no shield has a large amount of fringing effect; therefore there is no "standard" reproducer correction.

(2) If an unshielded reproducing head of width different from the "recommended" width is used, a different correction is needed.

(3) The shortcircuit flux definition is more simple and has less chance for confusion.

(4) There is less chance for error if the calibrating head is full width, than if a correction factor is applied to a narrow head.

6.3.2 *Thickness Effect*

Another problem of the NAB Standard is that the section on calibrating long-wavelength response of the reproducer (Annex C) allows the "calibrated recording system" concept described in Sec. 2.2.2.2 to be used up to 750 Hz at 19 cm/s. The corresponding wavelength is 0.25 mm; with a 10-μm (0.4-mil) coating, a "thickness effect" error of 1 dB occurs. There is no specific prohibition, for that matter, from using this reference frequency at even slower speeds; for 750 Hz at 4.8 cm/s (1.87 in/s), the measurement error would be 4 dB! The actual intention was to limit the use of this technique to wavelengths long enough to have negligible thickness effect. These several problems should be eliminated by revision of the NAB Standard.

6.3.3 *Separation Effect*

The RIAA Bulletin E-5 (1968), in Sec. 9, Note 2, mentions correcting for "separation losses." If these were to include *all* separation loss, the RIAA standard would be basically different from all other audio standards, since they consider the separation due to the medium itself to be a part of the recording system, whereas this RIAA Standard seems to consider some of the separation to be a part of the reproducer. It would make the RIAA flux-frequency responses about 6 dB different from those apparently specified. Actually, the RIAA committee merely meant to indicate — as is implied in other standards — that no *additional* separation loss should occur. Thus the RIAA Standard is identical to the others. This defect has been corrected in the Feb. 1969 revision.

6.3.4 *"Ideal" Heads*

The many standards which refer to "ideal heads" are ambiguous to the extent that the description of what "ideal" is, and how it is measured, is usually lacking or inadequate. Therefore many equipment designers have assumed that "all heads are nearly ideal"; this has resulted in systems which have had design errors of about 3 dB in high- and low-frequency responses.

6.4 *Reference Fluxes*

Most of the standards make no mention at all of level standardization, or of a flux reference quantity. German Standards (DIN) have three *different* flux reference quantities, because these "reference levels" are also sometimes used as "recommended recording levels." This makes these standards unnecessarily complicated to interpret. A single flux reference quantity of 100 nWb/m is proposed here; the recommended recording levels ("operating levels") can then be specified as a given flux per width level, $L_{\Phi/w}$, in dB. Then when tapes, speeds and other factors change, the recommended level can be changed without adding a new "reference level."

7. CONCLUSIONS

Present standards on the "frequency response" of magnetic recording and reproducing systems are written in terms of intuitive quantities such as "ideal heads," "standard reproducers" and "reproducing characteristics." These are unsatisfactory because of the lack of precise definitions and descriptions of measuring techniques.

This paper shows that the physical quantity for the "recorded signal" is the "shortcircuit tape flux" (shortened to "tape flux"); this quantity is precisely and concisely defined in Sec. 5.1. The tape flux is the quantity which "ideal heads" and "standard reproducers" measure; therefore this change from "ideal head" to "tape flux" is a *conceptual* change which clarifies and simplifies the standards; it does *not* change the intent of present practices.

Put another way, the "ideal head" should be abandoned as a *standardizing concept*, although, of course, calibrated ferromagnetic ring-core heads will still be the major *apparatus* for the measurement of shortcircuit tape flux.

The standards for the "frequency response" of recorders, reproducers and test tapes should be written in terms of the "recording flux-frequency response," "reproducing flux-frequency response" and the "test tape flux vs. frequency," respectively, (definitions: Sec. 5.6, 5.7, 5.11).

The recorded flux level should be specified as "tape flux per width level, $L_{\Phi/w}$ re/100 nWb/m, in dB." The "Operating Levels" (that is, the recommended recording levels) should be expressed as $L_{\Phi/w}$, in dB, according to the best judgment of the designers and users of each particular recording system.

These concepts should be used in future magnetic recording standards. The measurement techniques reviewed here in Sec. 2.2 are being prepared as a standard to be entitled "Methods of Calibration of Magnetically Recorded Multi-frequency Records."

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APPENDIX

Choice of Shortcircuit Flux Rather Than Opencircuit Flux Density

In the standards literature, "flux" and "magnetic shortcircuit condition" are invariably associated; likewise, "flux density" (also called "surface induction") and the "magnetic opencircuit condition." Here these points will be treated separately, since they are in no way physically related to each other; we will first consider the question of flux vs. flux density, and second consider the shortcircuit vs. the opencircuit condition.

Flux vs. Flux Density: "Flux" is used in the body of this paper; the use of flux density is of interest because most existing standards are in terms of surface induction (= opencircuit flux density): British Standards, CCIR, IEC and SMPTE use surface induction.† Only the German Standards (DIN) and the Philips Compact Cassette system standard use shortcircuit flux.

The two quantities are related by the equation: $\Phi_{sc}/w = B_s\lambda/\pi = sB_s/\pi f$, where Φ_{sc} is the shortcircuit flux in webers, w is the tape width in meters, B_s is the opencircuit flux density ("surface induction") in teslas, λ the recorded wavelength in meters, s the recording speed in meters/second, and f the recording frequency in Hz. Thus, for constant flux, the surface induction at a given recording speed must increase directly with frequency.

The reason for the choice of surface induction in the CCIR standard is apparently that "The opencircuit voltage developed in a ferromagnetic reproducing head depends on the surface induction on the tape while it is in contact with the head."*

Choosing a quantity which is proportional to the head output voltage is of doubtful value, because head voltage and flux density are both conceptually more difficult to handle than flux, which is intuitively correct and simple. Consider these examples:

(a) In the long-wavelength region, a constant recording field vs. frequency (constant-current recording) produces constant magnetization of the tape vs. wavelength. Such a recording has constant flux with changing wavelength (and therefore with frequency at a given speed). The surface induction, on the other hand, is rising proportionally to the frequency; this goes against the

* This statement itself is a partial truth. The voltage depends on the product of the surface induction and the tape speed in reproduction; when the tape is stopped, the surface induction does not change but the output voltage drops to zero.

† Several of these standards committees are considering changing to shortcircuit flux.

intuitive feel for the performance of a constant-current recording.

(b) Similarly, a recording at constant distortion, or a recording at tape saturation (in this long-wavelength region) will have constant flux; surface induction will rise proportionally to the frequency.

(c) Put another way, a constant-flux recording will have constant distortion vs. wavelength (in this region); but, since the flux of a constant-surface-induction recording is inversely proportional to frequency, and since the distortion due to the tape is proportional to the *square* of the flux, a constant-surface-induction recording we have a distortion that is inversely proportional to the square of the frequency; (i.e., falling 12 dB/octave).

Another factor cited for using flux density is the "fact" that the single-conductor head measures flux density. This is not true: both the single conductor head and the ring-core head measure the rate of change of tape flux. Daniel and Axon (1953) state that "it has been found convenient to define . . . reproducing characteristics in terms of B_y, the surface induction." With this, they arranged their calculations and formulae for the single-conductor head to be in terms of flux density; this is a mathematical transformation, not a physical principle. Given a piece of recorded tape, one could measure the flux directly with a calibrated head: $\Phi/w \propto E/(\pi f w)$, where f is the reproduced frequency. On the other hand, to find the surface induction, one must also know the wavelength of the recording: $B_s \propto E/(wf\lambda)$. B_s by itself has a very limited value in tape recording.

As an example of practical confusion due to the use of surface induction, SMPTE standards PH 22.130 and PH 22.132 (*Signal Level Test Films*) both call for a level of "10 gauss" flux density at 400 Hz; the casual reader would assume that he would measure the same output level if both of these recordings were reproduced on the same reproducer. The fact is that, since the film speeds are different by the ratio of one-to-two (9.15 cm/s vs. 18.3 cm/s), the outputs would be 6 dB different. (There is even considerable question as to the actual intention of the standardizing organization!)

As another example of confusion, Bick (1953) refers to "surface induction" in his Fig. 1, and the text referring to Figs. 2, 3 and 8. But the curves given are actually for shortcircuit flux. Similarly, Henocq and Houlgate (1964) speak of "surface induction" in their text, but present graphs of *flux*. Thus the arguments presented here against surface induction as the standard quantity for the recorded signal are not of purely academic interest.

Finally, Table AI lists the magnetic recording references cited in this paper, and their authors' usage of "flux" or "surface induction." Of the 19 articles cited, all 13 articles on the physics of magnetic recording calculate the tape flux; only the four "standards" articles have used surface induction. (Note that Daniel's early papers on standards similarly used surface induction, but the later "physics" papers all use tape flux.) This certainly demonstrates that most workers in magnetic recording consider the tape flux — not the flux density — to be the ultimate quantity of interest.

Opencircuit Condition vs. Shortcircuit Condition: When a tape is in "free space"† a demagnetizing field exists which may reduce the surface flux of the tape. When this tape is brought into contact with a ring-core ferromagnetic head, the demagnetizing field is eliminated.

Table AI. Usage of "Flux" and "Surface Induction" in the Magnetic Recording Literature.

Author	Uses flux	Uses surface induction
Bick (1953)	+	+
Comerci (1962)		×
Daniel & Axon (1953)		×
Daniel, Axon & Frost (1957)		×
Daniel & Levine (1960a)	×	
Daniel & Levine (1960b)	×	*
Duinker (1961)	×	
Duinker & Geurst (1964)	×	
Fan (1961)	×	
Fritzsch (1966)	×	
Geurst (1965)	×	
Henocq & Houlgate (1964)	+	+
Horak (1966)	×	*
Kornei (1954)	×	
Mallinson (1966)	×	*
Schmidbauer (all)	×	*
Schwartz, Wilpon & Comerci (1955); Schwartz (1957)		×
Wallace (1951)	×	*
Westmijze (1953)	×	*
	13 ×	4 ×

Key:
× = used exclusively or nearly so; results expressed this way.
* = mentioned in passing, or in process of calculation.
\+ = uses flux density in text, but data (response curves) are plotted as flux.

† "Free space" is sometimes called "a medium of unit permeability." This is true only in the cgs electromagnetic system of units (emu) where μ_0 = 1 gauss per oersted. In the SI units, μ_0 = $4 \cdot 10^{-7}$ henrys per meter (= teslas per ampere meter).

In the early standards work (Daniel and Axon, 1953) there was a concern that different tapes and different heads would behave differently in this respect, and that measurements should therefore be made in the "more fundamental" condition, namely in free space.

Whether this concern is now of importance depends largely on the actual amount of demagnetization: if the total demagnetization were negligible, then there would be no fundamental reason to prefer one condition over the other.

In a theoretical study, Mallinson (1966) gives the equations from which the maximum demagnetization occurring at the highest possible fluxes may be calculated for the magnetic opencircuit and shortcircuit conditions. At 19 cm/s (7.5 in/s) this would amount to 1 dB at 500 Hz, 2 dB at 1250 Hz, 3 dB at 3150 Hz, decreasing back to 2 dB at 20 kHz. In an experimental study, Mallinson (1967) finds that the measured difference in demagnetization with the highest recorded fluxes is about 1.5 dB, which would occur at about 8000 Hz at 19 cm/s. Mallinson (unpublished reports, 1966) has stated that "At practical recording levels (approximately 15 dB below saturation), theoretically *no* demagnetization can occur . . . ."

Further experimental verification of the amount of demagnetization may be derived from the data of Daniel and Axon (1953), who show comparative responses of opencircuit and shortcircuit measurements: for recordings up to 50 μm (2 mil) wavelength, or 4000 Hz at 19 cm/s, the maximum difference is less than 1 dB.

Since it appears that the responses are essentially identical in the opencircuit and shortcircuit cases, measurements may be made in either condition, providing only that the reproducer is properly calibrated. Since practical reproduction always involves the shortcircuit condition, it seems logical to specify the shortcircuit case as the standard.

Inasmuch as we have found several obvious disadvantages and no apparent advantages to the use of opencircuit flux density (surface induction) as a measure of the recorded signal, the shortcircuit flux is used in this paper, and the author feels it should be used in all magnetic recording standards.