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ADVANCES IN MAGNETIC RECORDING MATERIALS

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Résumé. — L'enregistrement magnétique est principalement effectué sur des couches minces constituées de particules magnétiques disposées dans un liant organique.

Ces particules sont des monodomaines, soit de $\gamma\text{-Fe}_2\text{O}_3$, soit de CrO_2 présentant une anisotropie magnétique provoquée par leur forme aciculaire.

Les performances des couches à base de $\gamma\text{-Fe}_2\text{O}_3$ ont été considérablement améliorées ces cinq dernières années. Le résultat a pu être obtenu grâce à un perfectionnement de la morphologie des particules. Les efforts déployés pour atteindre avec les oxydes de fer les mêmes performances à l'enregistrement qu'avec CrO_2 , et ce par augmentation de leur anisotropie magnétocristalline, par dopage à l'aide de cobalt, ont échoué jusqu'à présent du fait de leur stabilité physique insuffisante.

La morphologie de CrO_2 est bonne à l'heure actuelle, en conséquence il est peu probable qu'une meilleure mise en forme des oxydes permette d'atteindre des améliorations de performances.

Un progrès considérable — 6 dB comparé au CrO_2 — est pourtant possible, en utilisant des particules bien formées de fer métallique, grâce à leur saturation magnétique plus élevée.

Abstract. — Magnetic recording is mainly carried out on thin layers that consist of a dispersion of magnetic particles in an organic binder system.

These particles are single domains of either $\gamma\text{-Fe}_2\text{O}_3$ or CrO_2 , the magnetic anisotropy of which is due to their acicular shape.

The recording performance of $\gamma\text{-Fe}_2\text{O}_3$ coatings have been enhanced considerably in the past five years by improving the particle morphology. Attempts to make the recording quality of iron oxides equal to that of CrO_2 by increasing their magnetocrystalline anisotropy by Co-doping failed because of the resultant insufficient physical stability.

Taking into account the good morphology of the present CrO_2 a further significant increase of recording performance by the architecturing of oxidic materials is not to be expected.

Considerable progress, ~ 6 dB with respect to CrO_2 , is possible, however, by using well-shaped metallic iron or iron-alloy particles, owing to their much higher saturation magnetization.

1. Introduction. — In the recent literature there are excellent surveys concerning the knowledge acquired and the progress which has been achieved in the past decade in the domain of materials for sine wave as well as for digital recording [1-2-3-4].

There would be little sense in compiling another complete review. It seems more significant to emphasize the origins of the improvements attained in the past few years in the field of the materials for magnetic recording. On the basis of the knowledge of these origins, it is perhaps possible to indicate the trends for the near future, taking account of the physical constraints of the recording system.

A complete theoretical description of the recording-replay process is required to indicate the theoretical limits of the signal and noise imposed by the available magnetic materials and to predict the requirements these materials should meet in order that these limits can be attained.

There is indeed an adequate theory for the replay process ; for the write process, however, such a theory is lacking.

Much knowledge concerning magnetic recording is compiled in the well-known book of Mee [5], dating

from 1964. A more recent description of the state of the art is given in [6]. After 1964 various investigators have deepened the insights into the theory of the sine-wave writing process e. g. Tjaden with the aid of a large-scale model [7] and with the aid of computer simulation [8], however, without arriving at a complete description of the sine-wave write-process. A similar situation exists for digital recording on particulate media [9] while for recording on continuous layers several elucidating papers appeared [9-10]. A discussion about the sources that contribute to the noise has been given lately by Daniel [11].

In spite of the incompleteness of the theoretical knowledge, it is possible, on the grounds of the existing theoretical insight and experimental evidence to formulate the demands materials for magnetic recording should meet. These delineate the scope of further research.

2. Material parameters relevant for high-density recording. — In digital registration in order to obtain a sufficient signal output, it is required that the necessarily thin recording layer has a high remanence and as high a coercivity as possible. The upper level of the

coercivity is determined by the saturation of the write-head material.

These considerations suggest that continuous magnetically anisotropic metallic films could be ideal recording surfaces, especially for digital applications. In practice the highest recording densities can be achieved with Cobalt-Phosphorus layers and with a thickness far below $1\text{ }\mu\text{m}$. Despite considerable efforts these have not yet found a wide-spread application. No conclusive arguments can be given for it [2]. A possible explanation could be the insufficient resistance against mechanical and chemical attack leading to drop-outs.

For audio and video registration, likewise a recording surface with a high remanence and coercivity are preferable to obtain a high signal strength.

For audio the layer thickness is matched to the requirements of the recording of long-wave-length signals. In practice it varies between 3 and $10\text{ }\mu\text{m}$.

It must be emphasized, however, that for short wavelengths the remanent magnetization induced by the write field is only a small fraction of the remanent flux density of the recording medium (Fig. 1) and as a consequence the search for a better material not necessarily implies exclusively the use of materials with a high magnetic saturation. This low efficiency is caused by a combination of factors, i. e. the spread in interaction fields of the magnetic domains, the spread in the domain switching fields and the impact of the demagnetizing fields during the recording ⁽¹⁾.

FIG. 1. — Magnetization distribution of a signal with a wavelength of $4\text{ }\mu\text{m}$ written on a $\gamma\text{-Fe}_2\text{O}_3$ tape with a layer thickness of $10\text{ }\mu\text{m}$. Gap length $4\text{ }\mu\text{m}$. Surface to head distance $0.3\text{ }\mu\text{m}$. Bias and signal current are optimized for maximum output. The picture results from experiments with a large scale model by Tjaden [7].

The easy directions of magnetization of the domains have to be oriented parallel to the head surface. A high degree of orientation diminishes the influence of the vertical component of the writing-field. This vertical component has a less steep gradient than the horizontal one and thus gives rise to a smaller resolution [12].

The magnetization must be temperature independent. In this respect the magnetic hardness should preferably

be due to shape anisotropy instead of crystalline anisotropy, the latter being strongly temperature dependent for the materials of interest.

Magnetic recording is predominantly carried out on media consisting of either a rigid or a flexible substrate covered by a layer that consists of a dispersion of magnetic particles in an organic binder. It will be clear that, in order that in such a system the particles have large and uniform switching fields owing to their shape, they should preferably be needle shaped and contain only one magnetic domain. This limits the upper particle size for the available materials to about $1\text{ }\mu\text{m}$ and implies a length to diameter ratio larger than 5. It follows from theory that the signal to noise ratio is proportional to the square root of the number of domains and as a consequence the particles must be as small as possible at a given packing density. There is a lower size limit where superparamagnetic behaviour becomes manifest ; for the available materials about $0.02\text{ }\mu\text{m}$.

An additional condition that the particles have to fulfil is that they can be dispersed in the binder in such a way that smooth surfaces are obtained, thus avoiding a decrease in short wave-length output or a large contribution to the modulation noise due to surface roughness.

Taking the arguments above into account, the best choice for a magnetic material are Fe or Fe-Co alloys which have the highest attainable saturation. Attempts to prepare powders from these materials, suitable to give layers with a superior recording quality, did not succeed until recently.

On a technical scale exclusively oxides, i. e. mainly $\gamma\text{-Fe}_2\text{O}_3$ and in minor quantities also CrO_2 are applied. It has been tried to improve the recording performance of the oxides by improving the particle morphology and by increasing their magnetocrystalline anisotropy. How this has been done and which results this has yielded will be discussed below. The author will restrict himself to examples from sine wave recording. The material problems for digital recording are in principle the same.

3. Magnetic materials for recording surfaces. —

3.1 $\gamma\text{-Fe}_2\text{O}_3$. — 3.1.1 *Structure and magnetic behaviour.* — Until a few years ago, exclusively $\gamma\text{-Fe}_2\text{O}_3$ was used for digital as well as for sine wave recording.

This material has a cubic symmetry with a spinel lattice with $a_0 = 8.34\text{ }\text{\AA}$ and with an X-ray density of $4.9 \times 10^3\text{ kg/m}^3$. It has some crystalline anisotropy, $K_1 = -4.64 \times 10^3\text{ J/m}^3$ [13] and [111] as the preferred direction. This small anisotropy means that the desired magnetic hardness must be derived from shape anisotropy ; as a consequence it has been tried to give the particles an acicular shape.

The available $\gamma\text{-Fe}_2\text{O}_3$ powders consist of needles the majority of which has [110] as the long axis [14-15].

The mechanism of magnetization reversal is not known. If the magnetic vector rotates coherently, then

(1) TJADEN, D. L. A., Private Communication.

the coercivity of a random powder should be in the order of 10^5 A/m. In reality this is lower by a factor of 3 to 5. This means that flux reversal occurs by an incoherent mechanism [16].

3.1.2 Preparation. — Due to the cubic symmetry a direct formation of elongated γ -Fe₂O₃ particles in a crystal growth process is not possible. The desired acicular shape, with a length to diameter ratio above five, must be attained in a roundabout way. This is done, as initially proposed by Camras [17], by a pseudomorphosis in which first acicular FeOOH is prepared, reduced to Fe₃O₄ and then converted to γ -Fe₂O₃ according to :

The morphology of the γ -oxide thus depends considerably on that of the starting FeOOH. This may be either γ or α -FeOOH. One can only guess at the way in which the FeOOH is prepared from which the commercially available γ -Fe₂O₃ is obtained. The α -FeOOH (goethite) is probably prepared according to a procedure invented by Penniman and Zoph [18] where iron scrap, in a weakly acid solution, is oxidized by bubbling air through it. The γ -FeOOH (lepidocrocite) can be prepared by blowing air in an aqueous solution of a ferrous salt which is kept at a pH of about 3 [19].

The pseudomorphic conversion of the FeOOH yields γ -Fe₂O₃ particles with a morphology that only more or less resembles that of the starting material. During the conversion the formation of agglomerates occurs. The resultant agglomerates in the recording surface increase the noise level and decrease the signal strength due to a larger spread in the switching fields, a diminished orientability and in some cases a worsened surface roughness. The formation of agglomerates is stimulated as the conversion temperature is higher. On the other hand, already during the dehydration step holes and fissures are formed, which may partly disappear at higher temperatures [20]. The influence which these defects might have on the magnetic anisotropy of the γ -Fe₂O₃ is not known. In any case it is certain that, due to a lower material density of the recording layer a proportionally lower remanence results.

It can be concluded that the art of the preparation of γ -Fe₂O₃ comprises to a large extent the control of the reaction parameters that govern the conversion of FeOOH into γ -Fe₂O₃.

In figures 2 and 3 examples are given of an α -FeOOH powder and the γ -Fe₂O₃ prepared from it. Apparently the degree of aggregation is reasonable. A close inspection shows that the magnetic material contains cavities.

3.1.3 Progress. — The improvements in recording performance which have been achieved in the past years are largely attributable to a better shaping of the starting FeOOH. Recently investigators from Japanese as well as American [21-22] industries introduced better powders with a particle length below 0.5 μm and a length to diameter ratio up to 10. With these powders

FIG. 2. — Electronmicrograph of a α -FeOOH powder.

FIG. 3. — Electronmicrograph of a modern γ -Fe₂O₃ powder prepared from the α -FeOOH depicted in figure 2.

recording surfaces can be obtained with a high degree of orientation and a good squareness. The coercivity can be as high as 38×10^3 A/m ; usually it is between 25 and 30×10^3 A/m, tables I and II.

TABLE I

Magnetic properties of γ -Fe₂O₃, CrO₂ and metal powders for magnetic recording purposes

POWDER	$H_C \times 10^{-3}$ (A/m)	$\sigma_S \times 10^6$ (Wbm/kg)	σ_R / σ_S
γ -Fe ₂ O ₃	28	90	0.45
CrO ₂	38	100	0.40
Fe-metal	81	190	0.46

The improved morphology may be illustrated by comparing a modern γ -Fe₂O₃, figure 3, with that of a powder that, about five years ago was considered to be an advanced one, figure 4. Perhaps even more convin-

TABLE II
*Characteristic data of oxide tapes
γ-Fe₂O₃ (ref.), CrO₂ and experimental Fe-metal tape*

TAPE	coating thickness (μm)	vol packing %	H _c × 10 ⁻³ (A/m)	B _s (Wb/m ²)	Br/B _s
γ-Fe ₂ O ₃ (ref.)	4.6	33	29	0.15	0.79
CrO ₂	4.0	38	39	0.18	0.73
Fe-metal	3.1	28	77	0.37	0.72

FIG. 4. — High-quality 1969 commercial γ-Fe₂O₃ powder.

TABLE III
Record performance of top quality commercial oxide tapes and of an experimental metal tape (). Record head : μ metal, gap length 2.5 μm. Repro. head : ferroxcube, gap length 0.7 μm ; track width 2 mm. Tape speed : 4.75 cm/s.*

	γ-Fe ₂ O ₃ (1969)	γ-Fe ₂ O ₃ (1974)	γ-Fe ₂ O ₃ (ref.)	CrO ₂	Fe-metal
Playback equalization (μ sec)	120	120	120	70	70
Bias noise (weighted)	- 51.5	- 52	- 52.5	- 54	- 54
MOL 333 Hz (5% thd)	- 2	+ 1.5	+ 0.5	0	+ 4.5
MOL 8 kHz (15 dB compr)	- 12	- 8	- 9	- 8	- 2
SAT 10 kHz	-	-	- 13	- 10	- 4
SAT 12.5 kHz	-	-	- 18	- 14	- 8

cingly the progress can be demonstrated with table III, where the recording properties of 1969 and 1974 top quality audio cassette tapes are given together with the present reference, BASF P. E. S. 12 D. I. N. standard.

3.2 Co-DOPED γ-Fe₂O₃. — 3.2.1 *Structure and magnetic behaviour.* — Another approach to increase the coercivity is to introduce crystalline anisotropy by building Co(II) ions in the spinel lattice. This does not change the crystal structure. The anisotropy constant,

however, changes from the negative value of $-4.64 \times 10^3 \text{ J/m}^3$ characteristic of γ-Fe₂O₃ to a positive value that depends upon the quantity of Co(II) ions in the lattice. The anisotropy is already large at small Co(II) concentrations : at 4 % Co, K_1 amounts to 10^5 J/m^3 [23-16]. The easy axis thus shifts from the [111] to the [100] direction. Hence the homogeneity of the distribution of the Co in the lattice is important for the magnetic behaviour. This requirement for homogeneity imposes severe demands on the preparation methods.

The coercivities of Co-doped materials, being due to crystal anisotropy, exhibit a strong temperature dependency. Moreover the material shows instabilities as a result of magnetostrictive effects. An additional source of instability is probably the diffusion of the Co(II) ion over the cation vacancies of the spinel lattice toward ordered positions which are determined by the direction of the magnetization.

Such effects result in a strong temperature/time dependency of the recording replay properties.

3.2.2 *Preparation.* — The preparation of Co-doped iron oxides is carried out according to the patent literature, by soaking an iron oxide with a solution of a Co(II) salt before the subsequent conversion to γ-Fe₂O₃ [24, 25] or by carrying out the oxidation of Fe(II) to FeOOH in the presence of Co(II) ions [26, 27, 28, 29].

3.2.3 *Progress.* — The idea to increase the anisotropy of recording oxides with Co is already more than 20 years old [30]. Due to the strong temperature/time instability of the — at that time spherical — materials these had only a temporary commercial success.

In the past years this theme has been reconsidered, now by doping acicular oxides in order to fall back on shape anisotropy at elevated temperature. The American 3M company introduced the so-called High-Energy tape. In Japan a similar tape is fabricated by T. D. K. Such tapes have a coercivity of $40 \times 10^3 \text{ A/m}$ which make them compatible with present CrO₂ tapes which are increasingly used for audio and more particularly for video recording. Their signal strength is indeed markedly higher than for γ-Fe₂O₃ tape [31]. However the instabilities make it not probable that recording surfaces on the basis of Co doped oxides will find a wide-spread application. Yet a tremendous effort is still going on as is apparent from the patent literature [32].

3.3 CrO₂. — 3.3.1 *Structure and magnetic properties.* — CrO₂ has a tetragonal crystal structure with $a_0 = 4.41 \text{ Å}$ and $c_0 = 2.91 \text{ Å}$; the X-ray density is $4.9 \times 10^3 \text{ kg/m}^3$. The magnetic saturation is higher than that of γ-Fe₂O₃, cf. Table I.

The CrO₂ used for recording purposes consists of elongated, submicroscopic, particles (Fig. 5) with the [001] direction parallel to the long axis. The crystal anisotropy is relatively large,

$$K = + 2.5 \times 10^4 \text{ J/m}^3 \text{ [33, 34].}$$

(*) DATA : dB with reference to a level of 250 pWb/mm.

FIG. 5. — CrO₂ powder used for magnetic recording purposes.

The observed coercivity, H_c , is 4×10^4 A/m. Experiments indicate that the shape anisotropy is dominant.

According to Rodbell [34] the preferred direction is [001] and thus coincides with the long particle axis. This is in contrast to conclusions from earlier work from which it was thought that the easy axis made an angle of 30 or 40° with the needle axis. Switching of the magnetization occurs notwithstanding the good crystallinity, by an incoherent mechanism [35].

3.3.2 Preparation. — CrO₂ is made on a technical scale by the decomposition of CrO₃ under hydrothermal conditions, schematically represented by [36] :

CrO₂ is metastable at room temperature and atmospheric pressure [37]. At 300 °C the equilibrium pressure equals 10 kb. For a good reaction kinetics and a good morphology of the end product a controlled nucleation is essential. In the patent literature numerous proposals are to be found for appropriate dopes. An excellent dope is Sb₂O₃, with the aid of which the reaction can proceed at 300 °C and at 50 at., while needles are obtained with a good acicularity and, corresponding high coercivity.

An alternative method has been put forward lately ; instead of CrO₃ a mixture of metallic Cr and CrO₃ is used [38].

The pressure procedure is expensive and it is logical that much work has been done to find methods that yield CrO₂ at one atmosphere. This has been tried by heating a mixture of Cr(OH)₃ and CrO₃ [39], by heating CrO₃ in an atmosphere of NO₂ + O₂ [40] and by crystallization from a melt [41, 42].

As far as may be concluded from this patent literature these methods all lead to inferior products and probably the commercially available CrO₂ is only made by the hydrothermal method.

3.3.3 Progress and prospects. — Although the ferromagnetic properties of CrO₂ are known for long [43], it were in the fifties scientist of Du Pont who realized that the material has a great recording potential [44]. In

the past two decades they have done a lot of work to arrive at useful preparation methods. This work has resulted in a number of publications, and patents — the oldest dating from 1958 [45] and it culminated into a magnetic tape that especially in the short wave-length region has a high signal to noise ratio, see for instance [46]. Some relevant data are given in table II and III.

The reason of this high short wave-length output is not known with certainty ; it must probably be ascribed to a good orientability as well as a high magnetic moment and coercivity.

The morphology of CrO₂ has a high degree of perfection as a result of which the dispersability in the binder is also adequate. Any further improvements in the future are likely to be obtained by synthesizing smaller particles with a narrower size distribution. It may be assumed, however, that CrO₂ indicates the limits of recording possibilities on the basis of well-architected oxides.

3.4 Fe-Co-ALLOYS. — 3.4.1 Some historical notes.

— Of all materials metallic iron and alloys of iron and cobalt have the highest magnetic saturation values. Yet they have not found an application in magnetic recording. The principal reasons are :

- difficulties with the preparation of homogeneous powders with the desired morphology,
- chemical instability (pyrophoricity),
- bad dispersability leading to an inhomogeneous particle distribution in the binder and to rough surfaces,
- the required high coercivity which makes the system incompatible and which, moreover, can cause difficulties in writing and erasing.

Nevertheless research on these alloy systems has continued. The many investigations for a suitable preparation method that were done about a decade ago yielded poor results, after which the interest in them decreased. In the past five years, probably also stimulated by the success of CrO₂, the work is resumed on a world-wide scale, and seemingly, with some success.

3.4.2 Structure and magnetic behaviour. — Below 960 °C iron crystallizes in the cubic bcc structure with $a_0 = 2.866$ Å at room temperature. The magnetic saturation is 275×10^{-6} Wbm/kg, the density 7.9×10^3 kg/m³, table I. The crystal anisotropy $K_1 = 4.8 \times 10^4$ J/m³ although being large compared with that of γ -oxides, is insufficiently high to attain the required coercivities. Hence also for this material the main factor contributing to the magnetic anisotropy must be the shape.

Luborsky *et al.* studied the magnetic reversal in what they called « almost perfect whiskers » with the long axis in the [100] direction. For whiskers with a diameter below 1 000 Å the mechanism is incoherent, probably curling [47]. In less perfect elongated Fe particles the reversal is believed to occur by a chain of spheres mechanism [48, 49].

3.4.3 Preparation. — In the literature numerous methods are described for the preparation of elongated iron particles. These will not be discussed here except one, a method based on the decomposition of oxalates. In this way, Fe-Co powders have been prepared in the past, which yielded tapes with a significantly higher output than the iron oxide tapes of that time [50]. Noise data, resistance against mechanical load and chemical attack were not given. It can only be guessed whether these aspects hampered the application of these tapes.

The search for materials on the base of Fe has been intensified again, as proved by the number of conference papers and patent applications now being produced. Apparently two lines are followed :

1) Reduction of a solution of a Fe(II) salt with the aid of NaBH_4 and 2) pseudomorphic reduction of iron oxides with H_2 .

Reduction of Fe(II) salts solution with NaBH_4 . — When aqueous solutions of NaBH_4 and FeSO_4 are mixed a precipitate of metallic iron is formed, containing some B and consisting of strings of more or less spherical beads. Under optimum conditions one kg of NaBH_4 is needed for one kg of iron, which implies that the process is expensive.

A search for the preparation of iron powders with this method was done in the early sixties [49]. This method still is the subject of research [51, 52, 53]. There are no reports known from the literature about the properties of recording layers containing these powders.

Pseudomorphic reduction of iron oxides. — It is obvious to prepare iron powders in just the same way as $\gamma\text{-Fe}_2\text{O}_3$ i. e. by a pseudomorphic reduction of FeOOH with H_2 . This has been tried already nearly twenty years ago [54]. The conversion is difficult to carry out and leads to sintered products. An important advance was the finding that with certain dopes the pseudomorphosis can be improved considerably [55, 56]. Also through adsorption of relatively large quantities of $\text{Co}(\text{OH})_2$, on the particle surface of the starting FeOOH , powders are obtained having a reasonable morphology. With these powders tapes can be made with a short wave-length output which is twice as high as that of a CrO_2 tape [57]. No data are given about the noise and the chemical stability.

4: Acicular iron particles the magnetic recording material of the future ? — The first detailed set of data concerning a recording medium based upon metallic particles was published in the proceedings of the 1973 Intermag conference, where the author reported the recording performance of experimental tapes obtained from powders that were prepared by the pseudomorphic conversion of acicular iron oxides [58]. Some relevant data will be presented here.

Tapes have been made with a metal powder of which an electronmicrograph is given in figure 6 and of which the magnetostatic properties are collected in

FIG. 6. — Iron powder used for the preparation of the tape, the data of which is given in the tables.

table I. The high coercivity, $H_c \approx 80 \times 10^3$ A/m is mainly due to the particle shape.

The iron powder particles can be stabilized against air oxidation by coating them with an oxide layer. Even in humid air such powders oxidize only slowly, at elevated temperatures, figure 7. Tapes made with such a stabilized powder have an excellent chemical stability. When kept in an atmosphere saturated with water vapour at 50°C for a period of nine months, only a small and, in comparison with CrO_2 , insignificant decrease in output level of a prerecorded signal with a wavelength of $24\text{ }\mu\text{m}$ is observed. It should be remarked here that all recording materials, $\gamma\text{-Fe}_2\text{O}_3$, CrO_2 and Fe are used under conditions in which they are thermodynamically unstable.

FIG. 7. — Oxidation velocity of an iron powder at 50°C in air of a relative humidity of 90 %.

Agglomerate formation, initially during the chemical conversion of $\alpha\text{-FeOOH}$ into Fe, as well as afterwards due to the strong magnetic attraction between the particles, might result into badly dispersable powders. Yet by carefully avoiding sintering, powders were obtained with which tapes could be made in which the particles are homogeneously distributed, figure 8 and

which have a high orientation ratio ⁽²⁾. This together with the high magnetization of the metal powder leads to a high Br despite the relatively low packing density, table II.

FIG. 8. — Electronmicrograph of a microtome slice of an iron tape.

The high output observed at long wavelengths is thus by no means surprising. Less predictable and of special interest is the high output at short wavelengths in combination with the low noise level. This means, that, for instance by application in audio-cassette recording,

FIG. 9. — Output versus bias of $\gamma\text{-Fe}_2\text{O}_3$, CrO_2 and Fe-metal tapes. Output levels at 5 % distortion (333 Hz) or 1.5 dB compression (8 kHz). Other conditions as specified in table III.

(2) The orientation ratio is the ratio of the value of the remanent magnetization in the longitudinal direction to that in the cross direction.

with respect to CrO_2 a significantly (6 dB) higher signal to noise ratio is achieved.

This higher output is probably also simply a result of the higher B_r in combination with the proportionally higher H_c . The reduced static remanence curves, which are an indication of the distribution of the switching fields over the particles in the recording surface, of the $\gamma\text{-Fe}_2\text{O}_3$ and Fe tape coincide although there is a difference in signal strength of more than 10 dB, figure 10.

The advances in recording performance achieved in the past five years and the potential progress, can be seen from table III and are illustrated by figure 9. At

FIG. 10. — Reduced static remanence curves of $\gamma\text{-Fe}_2\text{O}_3$ $\square$, CrO_2 $\triangle$ and Fe-metal $\circ$ tapes. Vertical scale : Relative remanent magnetization (I_R/I_∞). Horizontal scale : Relative field strength, H , with respect to the field at a remanence of half the maximum value, H_0 .

a medium wavelength the $\gamma\text{-Fe}_2\text{O}_3$ gained 3-5 dB in signal to noise ratio, there is an additional contribution for short wavelengths of the, however, non compatible CrO_2 of 3-4 dB while with iron powders a potential gain of another 6 dB may be reached.

For slow speed audio recording the iron tape could give a quality very close to that of gramophone records. Whether this will really be achieved on a technical scale depends on a number of factors of which the most important are :

- the mechanical performance of the recorder-tape system,
- the availability of appropriate write- and erase-heads.

The latter theme could be the subject of another discussion.

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