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Boston Branch
25 August 1969

Frank S. Gardner

1969

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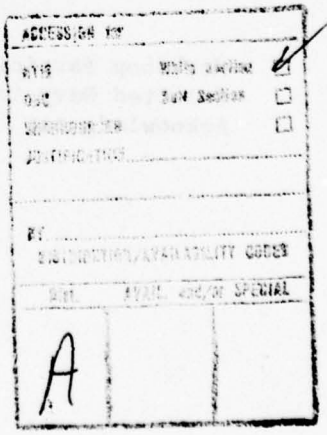

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FUNDAMENTALS OF MAGNETOSTRICTION

by

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INTRODUCTION:

This paper will deal with the elements of magnetostriction, particularly on the domain level, and with the means whereby it can be controlled. The discussion will be restricted to strongly magnetic substances; namely, ferromagnetics (like iron and nickel and their alloys), and ferrimagnetics (the ferrites). Both types show substantial magnetostriction, and the mechanism of magnetostriction is essentially the same for both.

The subject of this conference is the magnetostrictive transducer. This subject is of interest to at least two groups of people, and we must frankly face at the outset the uncomfortable fact that these groups speak quite different languages, a circumstance that makes it more than ordinarily difficult for one group to communicate with the other. These groups are: (1) those interested primarily in materials, who speak the language of magnetism, and (2) those concerned with transducer design, who speak the language of acoustics. Table 1, which is not complete, indicates some of the differences. A uniaxial stress is usually designated σ by the magnetician, but $\underline{P}$ (or $\underline{T}$) by the acoustician. Magnetic induction fortunately

TABLE 1. COMPARISON OF TERMINOLOGY

PROPERTY	MAGNETISM	ACOUSTICS
Stress	σ	P
Magnetic induction	B	B
Magnetostriction*	λ	S
Magnetostriction constant		$\lambda = \frac{dP}{dB}$ Strain

*Field-induced strain

has the same symbol B in both fields.

It is in the area of magnetostriction itself that confusion is most likely. By the word "magnetostriction" and the symbol λ the magnetician means a strain caused by the application of a magnetic field, or, more rarely, a strain which occurs spontaneously on cooling through the Curie point. The same symbol, however, has been used in acoustics to designate a quite different quantity, the "magnetostriction constant", defined as the derivative of stress with respect to induction at constant strain.

In this paper magnetostriction will be described in the language of magnetism.

KINDS OF MAGNETOSTRICTION

Although there is basically only one kind of magnetostriction, it is convenient to discuss this subject as though there were three kinds:

(1) Spontaneous magnetostriction,

(2) "Ordinary" magnetostriction,

(3) Forced magnetostriction.

These in turn correspond to three kinds of magnetization: spontaneous, "ordinary" and forced.

Spontaneous magnetization occurs when the material is cooled below its Curie point T_c, which is 770°C in iron, for example. Above T_c the material is paramagnetic, with the net magnetic moment (spin) per atom pointing randomly in all directions. Below T_c the material becomes ferromagnetic and breaks up into domains. Each domain is spontaneously magnetized, or self-saturated, with its spins more or less completely aligned, depending on the temperature. The force causing the spin alignment is called the "molecular field" (old-fashioned) or the "exchange force" (new-fashioned). The magnitude of the magnetization (magnetic moment per unit volume) of each domain is M_s. If the material has been cooled from above T_c to room temperature in the absence of a field, it will be demagnetized at room temperature; this means that the magnetizations M_s of all the domains must add vectorially to zero.

If a field H is now applied, the magnetization M of the specimen will change with field as indicated in Fig. 1. This curve is schematic, but the rough scale of H shown on the abscissa indicates the kinds of fields involved. By domain wall motion and domain rotation, the specimen is converted into one giant domain

magnetized almost parallel to the applied field. Its magnetization is then M_s, exactly equal in magnitude to the magnetization of each domain in the demagnetized state. When M equals M_s, the specimen is said to be saturated. (Sometimes the useful term "technical saturation" is applied to this state). The induction B is then $B_s = H + 4\pi M_s$. If the M,H curve is plotted on linear scales, the curve will become essentially flat when technical saturation is reached. This whole process of increasing the magnetization M of the specimen from zero to M_s may be called "ordinary" magnetization.

If the field is further increased, after technical saturation is reached, the spins will be turned still more closely to the field direction, and M will increase above M_s. This process is called forced magnetization and it requires very high fields. The value M_o marks the state of complete saturation, one in which all spins are parallel. It can be achieved at room temperature only by an infinite field or at 0°K by a finite field.

The effect of temperature is shown in Fig. 2. This curve can be regarded in two ways. If a material is cooled from above T_c to 0°K, then the curve shows how the spontaneous

magnetization M_s of each domain in the demagnetized specimen changes with temperature. Alternately, the curve shows how much magnetization can be produced in a specimen by an applied field when technical saturation is reached. If room temperature (300°K) is below T_c, then the dashed line shows field-induced "ordinary" magnetization. Any increase in M above the solid curve is forced magnetization. Corresponding to these three kinds of magnetization are three kinds of magnetostriction. When a material is cooled below T_c in zero field, it breaks up into domains which are spontaneously magnetized and spontaneously strained, each in a different direction. This is spontaneous magnetostriction.

If a field is now applied to the demagnetized specimen , say in the form of a rod, the length of the rod will change. If this field-induced strain λ is measured from the demagnetized state as zero, then the change of λ with H will resemble the curve of Fig. 3. The value of λ at technical saturation is called λ_s, and the change in length occuring between the demagnetized state and technical saturation is "ordinary" magnetostriction. Still further increase in field can cause a further "forced magnetostriction"; because of the very small slope of the λ, H curve in this region, forced magnetostriction is of no practical interst.

What is the physical origin of the spontaneous magnetostriction? This is a problem of great complexity and of great interest to the solid state physicist. It can be pictured very crudely in terms of the sketch of Fig. 4. Here the black dots represent atomic nuclei, lined up along some particular direction in the crystal. The arrows represent the net spin moment of each atom, and each ellipse encloses the electron cloud which is distributed non-spherically about each nucleus. The distortion of the cloud from sphericity is assumed to have some connection with the direction of the spin moment; here we assume the cloud to be elongated in the direction of the spin moment.

The upper row of atoms, of length L, represents the paramagnetic state, with spins oriented randomly in space. Below T_c the spins in adjacent atoms become more or less parallel (spontaneous magnetization) as shown in the lower row. If the turning of the spins drags the electron clouds with them, then a distortion ΔL would occur, causing a spontaneous magnetostriction of $\Delta L/L$. If the electron cloud rotates in unison with the spin, there must be a strong coupling between the electron spins and the electron orbits. However, this spin-orbit coupling is known to be rather weak. Figure 4 therefore exaggerates the extent to

which the electron clouds rotate with the spins and therefore exaggerates the magnetostrictive effect. (The strain $\Delta L/L$ indicated in Fig. 4 is about 0.15; observed magnetostrictive strains are of the order of 10^{-5}). Nevertheless, the sketch of Fig. 4, crude as it is, does provide a useful mental picture of the physical origin of magnetostriction.

To proceed further, from the level of a few atoms to the level of a large number of atoms making up a domain, it is convenient to consider a particular material, iron, for example. Figure 5 shows the ordinary, field-induced magnetostriction of iron single crystals; in each case λ is measured in the direction of $\underline{M}$ which is the direction of the applied field. We note that an iron crystal lengthens when magnetized to saturation (M_s = 1700 emu/cm^3) in the cube-edge direction [100], i.e., when the whole crystal is converted to a single domain saturated in [100]. Since [100] is the easy direction of magnetization in iron, we conclude that each domain in a crystal of demagnetized iron is already spontaneously elongated in the direction [100] of its M_s vector.

This means that the unit cell of iron, while cubic above T_c, is distorted into a tetragonal shape by spontaneous magnetostriction below T_c, as shown in Fig. 6. (Because this

distortion is too small to be detected by x-ray diffraction, the unit cell of iron appears to be cubic at room temperature.) Figure 6 also emphasizes the close connection between magnetostriction and the degree of spin order. If the spins are forced into complete parallelism by very high fields, then the further strain of forced magnetostriction occurs; the same thing can be accomplished in each domain by cooling the specimen to 0°K.

We are now in a position to understand ordinary magnetostriction. Figure 7(a) shows a possible arrangment of domains in a demagnetized crystal of iron. It contains only four domains, spontaneously magnetized in the direction of the arrows. The dashed lines indicate unit cells; their size, relative to the domain size, and the extent of their distortion are both enormously exaggerated. When a saturating field H is now applied in the direction [100], the crystal becomes converted, by the process of domain wall motion, into a single domain, shown in (b). This crystal must be distorted, relative to the demagnetized state, because it is now composed of distorted unit cells all oriented in the same way. The strain produced $\Delta L/L$ is just the ordinary saturation magnetostriction λ_s. We see therefore that ordinary magnetostriction is not involved with any fundamental change in the material, such as a change in the degree of spin order; it is caused merely by the field-

induced "rearrangement" of domains already distorted by spontaneous magnetostriction.

Magnetostriction of single crystals

The remainder of this paper is restricted to ordinary magnetostriction, because this is the only kind of any practical interest. Devices are normally made of polycrystalline materials, and an understanding of their behavior requires some knowledge of single-crystal magnetostriction.

Here we encounter a difficulty. Ordinary magnetostriction is defined as the strain produced in a specimen when it is brought from the demagnetized state to technical saturation by an applied field. But the demagnetized state is not unique. Any arrangement of domains whose M_s vectors, properly weighted by the domain volumes, add vectorially to zero is a demagnetized state. Inasmuch as the magnitude of the saturation magnetostriction depends sensitively on the domain arrangement in the demagnetized state, it is necessary to define a standard state, the ideal demagnetized state. It is one in which all possible domains are present in equal volumes. In an iron crystal, for example, all six kinds of domains -- [100], [$\bar{1}$00], [010], [0$\bar{1}$0], [001], and [00$\bar{1}$] -- would have to be present in equal volumes to

constitute the ideal state. The domain arrangement of Fig. 7(a), for example, is not ideal, because only four kinds of domains are present.

It is therefore necessary to distinguish between two kinds of saturation magnetostriction:

(1) λ_{si} = field-induced strain when a specimen is brought from the ideal demagnetized state to technical saturation. The value of λ_{si} is a constant of the material.

(2) λ_s = field-induced strain when a specimen is brought from any demagnetized state to technical saturation. The value of λ_s is structure-sensitive. It depends on the material and on its mechanical, thermal, and magnetic history.

(The reader should note that the symbol λ_{si} is an invention of the present writer and is not used by other authors. It is introduced here in an attempt to inject greater clarity into the discussion of magnetostriction).

Suppose we saturate a cubic crystal in a direction defined by the cosines α_1, α_2, α_3 with respect to the crystal axes

X, Y, Z, as in Fig. 8, and suppose we wish to know the strain in another direction, defined by the cosiness β_1, β_2, β_3. Then this strain, relative to the ideal demagnetized state is given by

$$\lambda_{si} = \frac{3}{2}\lambda_{100}\left(\alpha_1^2\beta_1^2 + \alpha_2^2\beta_2^2 + \alpha_3^2\beta_3^2 - \frac{1}{3}\right)$$

$$+ 3\lambda_{111}\left(\alpha_1\alpha_2\beta_1\beta_2 + \alpha_2\alpha_3\beta_2\beta_3 + \alpha_3\alpha_1\beta_3\beta_1\right) \quad (1)$$

where λ_{100} and λ_{111} are λ_{si} values when the crystal is saturated, and the strain measured, in the directions [100] and [111], respectively. It is important to note that λ_{si} is not simply an idealized concept; it can be exactly determined, with the aid of Eq. 1, from saturation magnetostriction measurements made in two different directions on the same crystal.

Often we wish to know the strain in the same direction as the field. Then $\alpha_1 = \beta_1$, $\alpha_2 = \beta_2$, $\alpha_3 = \beta_3$, and Eq. (1) simplifies to $\lambda_{si} = \lambda_{100} + 3(\lambda_{111} - \lambda_{100})\left(\alpha_1^2\alpha_2^2 + \alpha_2^2\alpha_3^2 + \alpha_3^2\alpha_1^2\right)$ (2)

Still further simplification results when the magnetostriction is isotropic, so that $\lambda_{100} = \lambda_{111} = \lambda_{si}$. Then Eq. (1) becomes

$$\lambda_\theta = \frac{3}{2}\lambda_{si}\left(\cos^2\theta - \frac{1}{3}\right) \qquad (3)$$

where λ_θ is the magnetostriction measured at an angle θ to the magnetization and the field. Figure 9 illustrates this situation, showing an originally spherical crystal distorted to an ellipsoid. The magnetostriction of nickel is approximately isotropic.

Magnetostriction of polycrystals

If a polycrystalline specimen has a strong preferred orientation of its grains, then a reasonably good estimate of its λ_{si} value can be directly inferred from single-crystal data. If its grains are oriented completely at random, then λ_{si} will be some sort of average over all crystal orientations. If the strain is assumed uniform from grain to grain of the polycrystal, this mean becomes

$$\lambda_{si} = \frac{2\lambda_{100} + 3\lambda_{111}}{5} \qquad (4)$$

By making an assumption intermediate between uniform strain and uniform stress, Callen and Goldberg[2] find that

$$\lambda_{si} = \lambda_{111} + \left(\frac{2}{5} - \frac{\ln c}{8}\right)\left(\lambda_{100} - \lambda_{111}\right) \qquad (5)$$

where $\underline{c} = 2c_{44}/(c_{11} - c_{12})$, the latter being the elastic constants of cubic crystals. If the crystals are elastically isotropic, then $\underline{c} = 1$ and Eqs. (4) and (5) become identical.

Control of Magnetostriction

The transducer designer wants materials with as large a magnetostriction as possible. Three kinds of approach to obtaining such a material are possible:

(1) Material selection. We search among the various metals and alloys for those with large values of λ_{si}.

(2) Grain control. For a given material, we try to devise a processing treatment that will yield a preferred grain orientation with a larger λ_{si} than a polycrystal with random grain orientation would exhibit. Dr. Chin will enlarge on this method in a later paper.

(3) Domain control. For a given material, we try to create a non-ideal domain arrangement in the demagnetized state, such that λ_s is larger than λ_{si}. This method is described below.

There are at least two ways of controlling the domain structure of the demagnetized state:

(1) By means of applied or residual stress.

(2) By magnetic annealing of certain alloys.

The effect of stress is illustrated in Fig. 10 for a material with positive magnetostriction. The sketches at the top show the domain arrangements in two demagnetized states (o and A) and in the saturated state S. The curves show how the strain varies with applied stress σ and magnetization $\underline{M}$. The sketch at top left shows the ideal demagnetized state, with all possible domain vectors represented. If this is now brought to saturation by an applied field, the strain will vary with $\underline{M}$ along the curve marked σ=o, and the total strain will be λ_{si}.

However, if a tensile (positive) stress is applied axially to the demagnetized specimen, domain vectors will rotate toward the axis. (We know this from the fact that, when

domain vectors are rotated toward the axis by an applied field in the absence of stress, the specimen elongated. Therefore, if we make the specimen elongate by applying a tensile stress, domain vectors must rotate toward the axis.) The mere fact that the domain vectors rotate itself causes a strain, the magnetoelastic strain e_{me}, entirely aside from the usual elastic strain (not shown) which occurs on application of the stress. The specimen is now in state A with a non-ideal domain orientation. When it is now magnetized to saturation, the field-induced strain varies from A to S along the curve marked $+\sigma$. The resulting magnetostriction under tension $\lambda_{s(t)}$ is smaller than λ_{si}. Conversely, if the demagnetized material is subjected to axial compression, domain vectors rotate away from the axis, e_{me} is negative, and the magnetostriction $\lambda_{s(c)}$ is larger than λ_{si}.

Figure 11 shows the effect of stress on nickel. Because the magnetostriction of nickel is negative, the effect of stress is just the opposite of that shown in Fig. 10. Thus, the effect of tension is to increase the magnitude of λ_s, while compression decreases it. Sufficient compressive stress (about 12 kg/mm^2 or 17,000 lb/in^2) eliminates the field-

induced strain entirely. The data of Fig. 11 are a vivid illustration of the fact that λ_s is a structure-sensitive property and not a constant of the material.

Figure 12 shows the effect of stress on polycrystalline Armco iron rods. Note the qualitative resemblance between the curve for zero stress and the curve for the [110] direction in an iron single crystal (Fig. 5); as $\underline{H}$ or $\underline{M}$ increases, both specimens increase in length, then contract to their original length, and finally become shorter. This is due to the fact that all iron wire or rod has a preferred orientation such that a [110] direction in each grain is more or less parallel to the wire or rod axis. The effect of stress on iron is similar to its effect on nickel, i.e., tension shifts λ in the negative direction and compression in the positive direction. The solid curves of Fig. 12 apply to an annealed specimen subjected to applied stresses within the elastic limit. The dashed curve refers to a specimen which had been prestrained plastically in tension by 3.2 percent; it was then unloaded and the $\lambda,\underline{H}$ curve measured without any applied stress. X-ray diffraction has shown that plastic prestrain in tension leaves many metals and alloys in a peculiar state of residual stress, with most of the specimen volume in residual compression parallel to the axis of prestrain[5]. The placement of the dashed line on the graph of Fig. 12 is independent evidence for this

residual stress state, because the magnetostrictive behavior of the pre-stretched specimen is just like that of an annealed specimen subject to compressive stress. We conclude that λ_s can be controlled by residual, as well as applied, stress.

Another example of domain control in the demagnetized state is afforded by the magnetic-annealing effect. Magnetic annealing means annealing in the presence of a magnetic field; certain alloys, particularly nickel-iron, develop an easy axis of magnetization during such a treatment, and this easy axis is "frozen in" on cooling to room temperature. The easy axis is parallel to the annealing field. The domain structure of the demagnetized state is then one in which the domain vectors are all near the annealing-field axis, just like the domain vectors in a material of positive magnetostriction under applied tension (sketch A of Fig. 10). The magnetostriction of such a specimen is expected to be small. In Fig. 13 the central curve labelled "slow cool" shows the magnetostriction of 68 Permalloy after cooling in the absence of a field; its demagnetized structure is then presumably ideal or nearly so. When the alloy is magnetically annealed, the magnetostriction measured in the direction of the annealing field is practically zero, as

shown by the lower curve. On the other hand, if the alloy is annealed in a field transverse to the direction in which magnetostriction is subsequently measured, that magnetostriction is unusually large, as shown by the upper curve, just like that of a material with positive magnetostriction under applied compression. Mixed ferrites containing cobalt are also responsive to magnetic annealing, but magnetostriction measurements after such treatment have apparently not been made.

These, then, are some examples of how λ_s in a given material can be controlled. The important point to note is that λ_s is not a constant of the material but a property subject to substantial alteration by proper control of the domain structure of the demagnetized state. In fact, the large differences in λ_s values sometimes reported by different investigators for the same material are almost certainly due to accidental differences in the domain structure of their demagnetized specimens.

Piezomagnetism

This paper will conclude with a brief digression on the subject of piezomagnetism. In the literature on magnetostrictive transducers, the word "piezomagnetic" often occurs, apparently as a synonym for "magnetostrictive".

The prefix "piezo-" comes from the Greek and means "to press". A piezoelectric crystal is one which, originally devoid of an electric moment, can nevertheless acquire a moment by the action of applied stress alone, in the absence of an electric field. Analogously, a piezomagnetic crystal is one which, initially demagnetized, can become magnetized by stress alone, in the absence of a magnetic field. Only a few examples of piezomagnetic materials are known. These are antiferromagnetics like CoF_2, in which a very small amount of magnetization (about 0.1 percent of that of iron at saturation) can be produced by the application of a very large shear stress[7]. No known ferro- or ferri-magnetic material is piezomagnetic.

It is true that a piece of iron, for example, <u>if already partially magnetized</u>, can have its magnetization <u>changed</u> by the action of stress alone. But this is not piezomagnetism. It is merely the effect of stress on magnetization, an effect due to magnetostriction and which

is called the "inverse magnetostrictive effect" by some writers, for example, Chikazumi.[8]

In the opinion of the writer the word "piezomagnetic" is incorrectly used in the transducer literature and should be abandoned, because none of the materials referred to there as piezomagnetic actually have that property.

References

1. W. L. Webster, "Magneto-Striction in Iron Crystals", Proc. Roy. Soc. A, 109, 570-584 (1925)

2. Herbert B. Callen and Norman Goldberg, "Magnetostriction of Polycrystalline Aggregates", J. Appl. Phys., 36, 976-977 (1965)

3. H. Kirchner, "Uber den Einfluss von Zug, Druck und Torsion auf die Langemagnetostriktion", Ann. Physik, {5}, 27, 49-69 (1936)

4. Michael E. Kuruzar. Unpublished research, University of Notre Dame.

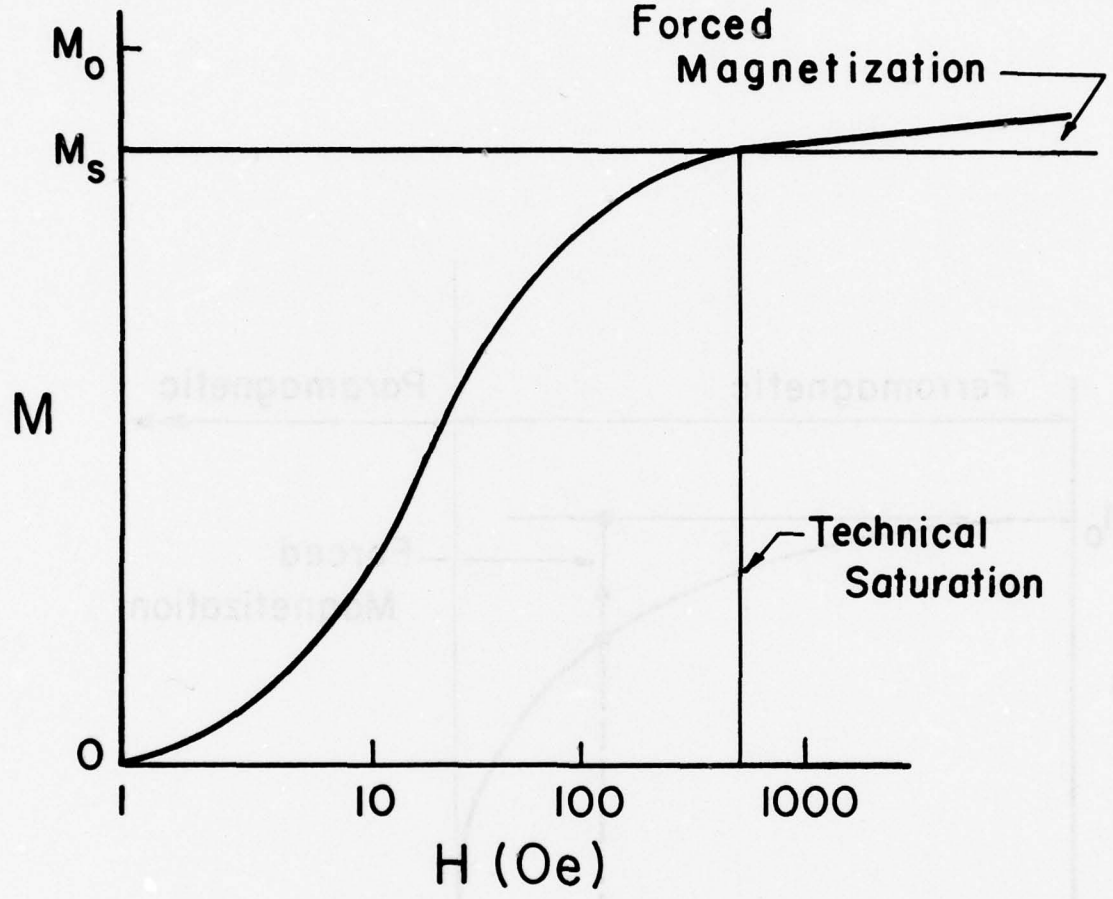
5. B. D. Cullity, "Sources of Error in X-Ray Measurements of Residual Stress", J. Appl. Phys., 35, 1915-1917 (1964)

6. H. J. Williams, R. M. Bozorth, and H. Christensen, "Magnetostriction, Young's Modulus and Damping of 68 Permalloy as Dependent on Magnetization and Heat Treatment", Phys. Rev., 59, 1005-1012 (1941)

References (Continued)

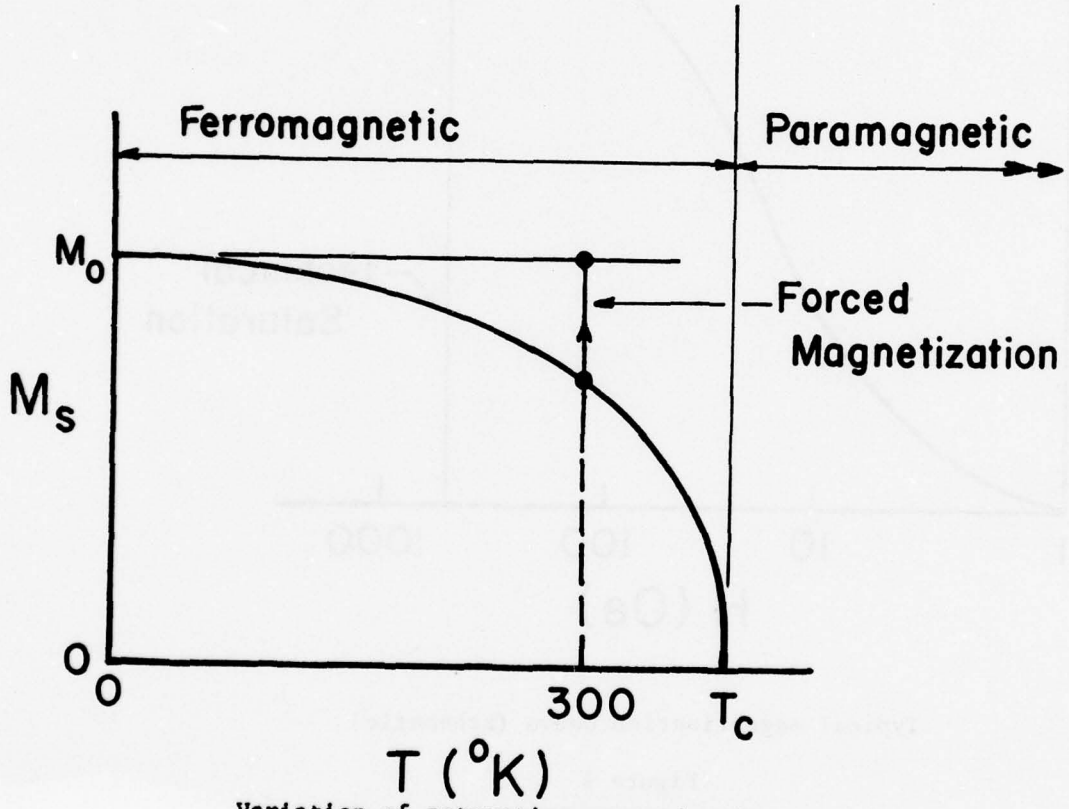
7. Michael M. Schieber, Experimental Magnetochemistry. p. 55 and 401. (John Wiley and Sons, New York, 1967).

8. Soshin Chikazumi, Physics of Magnetism. p. 182 and 433. (John Wiley and Sons, New York. 1964).



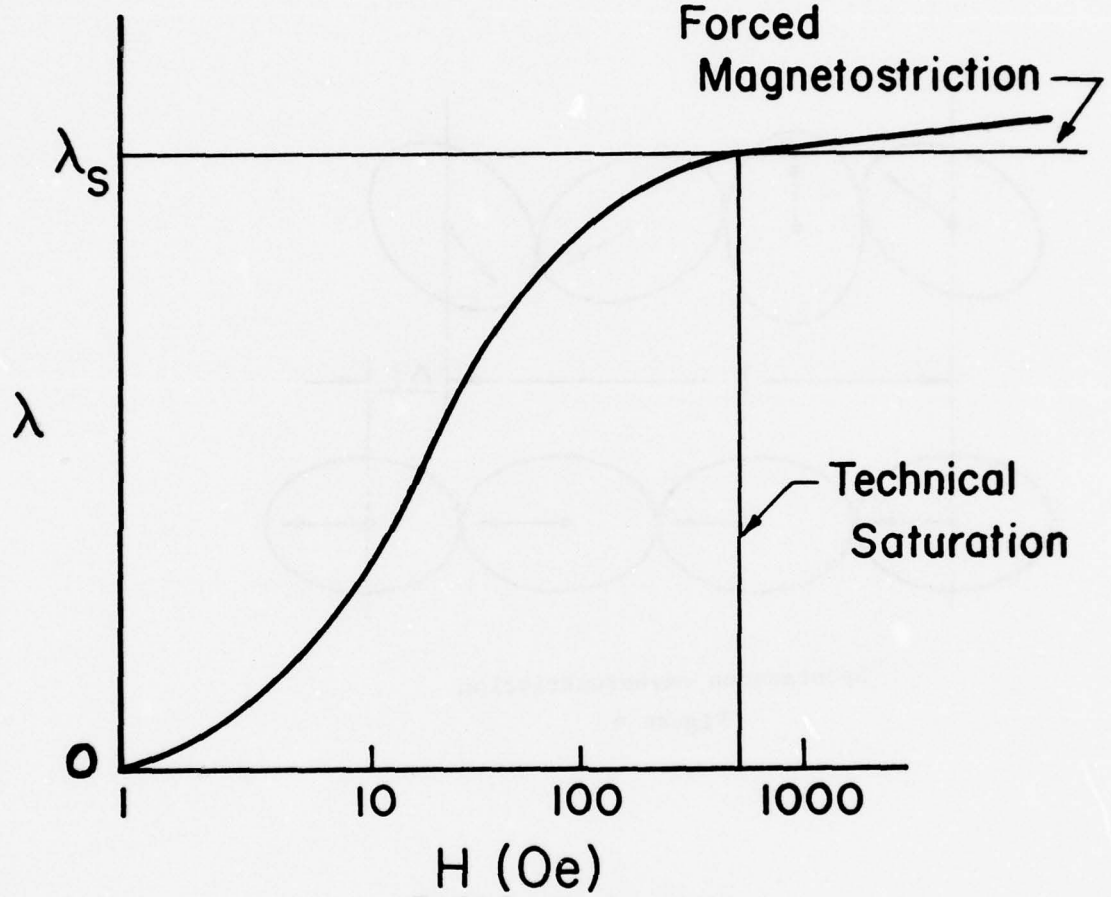
Typical magnetization curve (schematic)

Figure 1

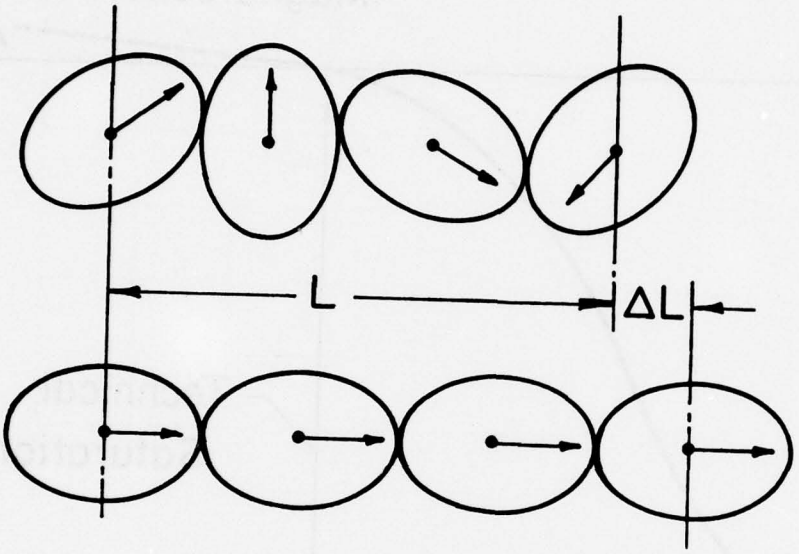


Variation of saturation magnetization $\underline{M_s}$ with temperature

Figure 2

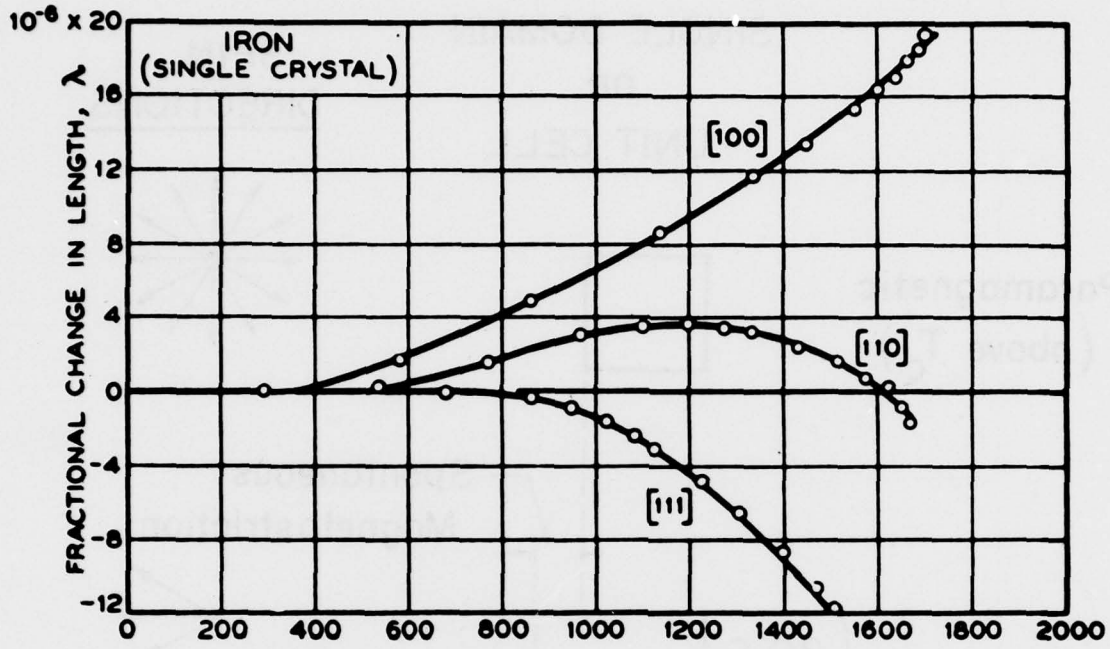


Typical magnetostriction curve (schematic)
Figure 3



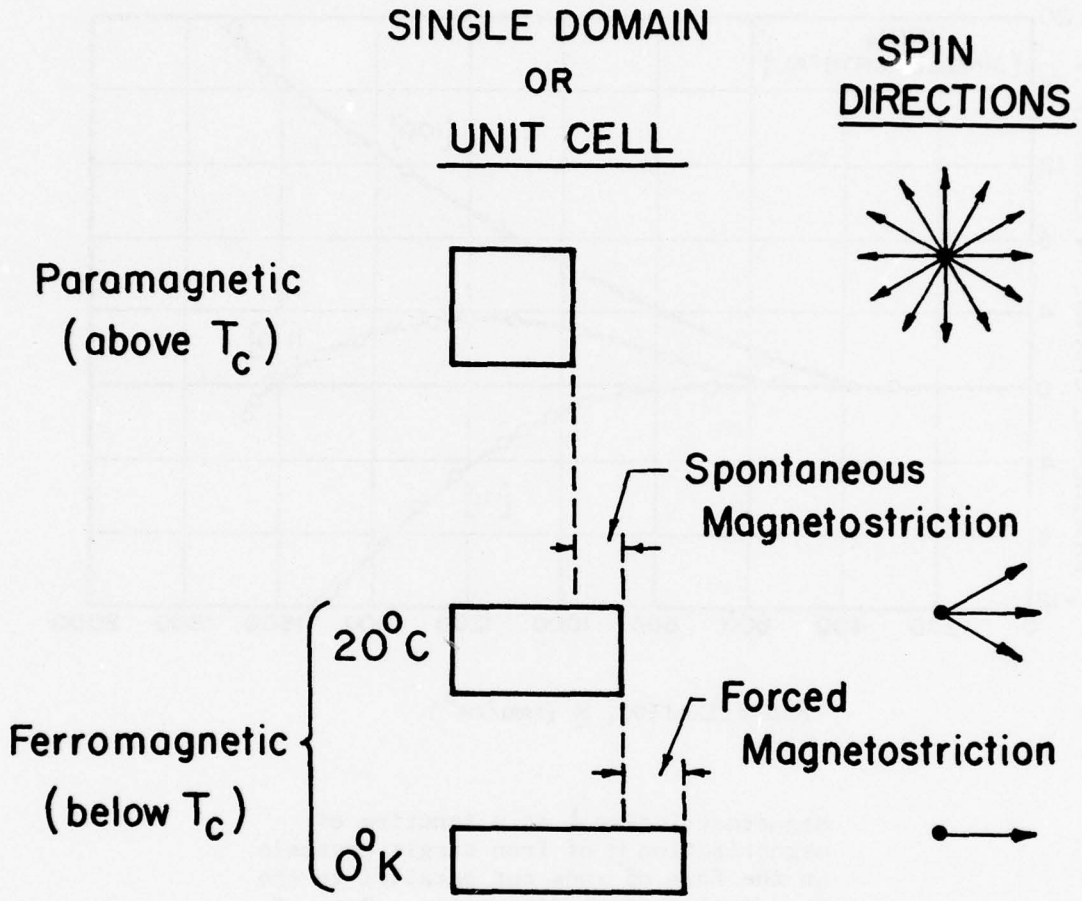
Spontaneous magnetostriction

Figure 4



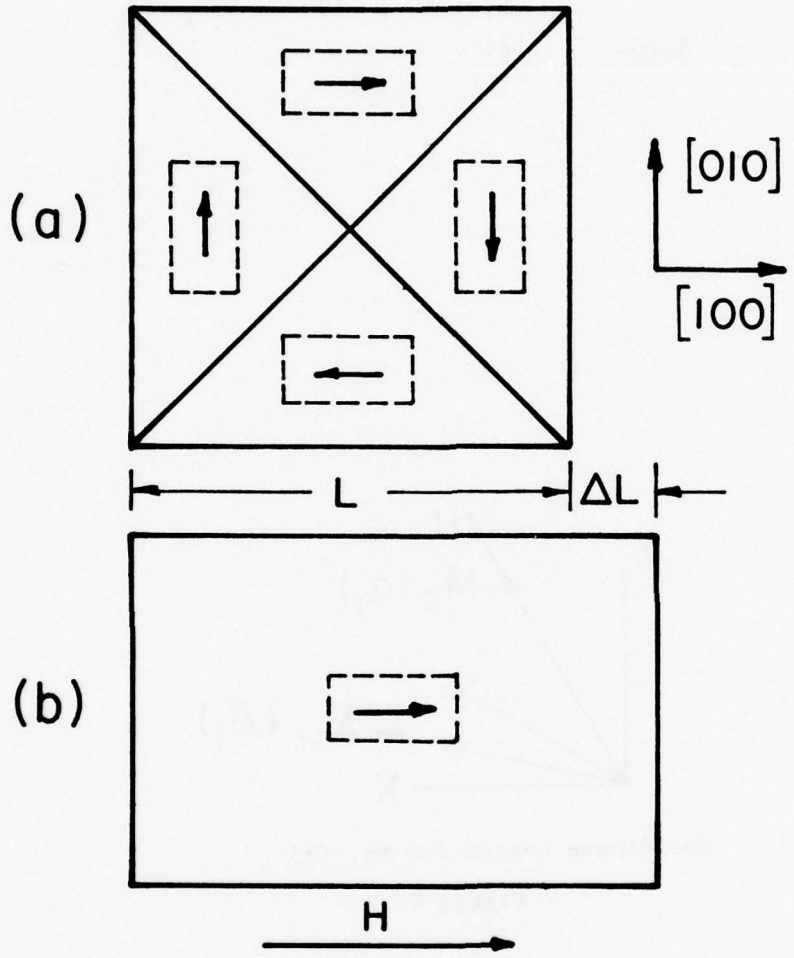
Magnetostriction λ as a function of magnetization $\underline{M}$ of iron single crystals in the form of rods cut parallel to the principal crystal directions. Data of Webster[1].

Figure 5



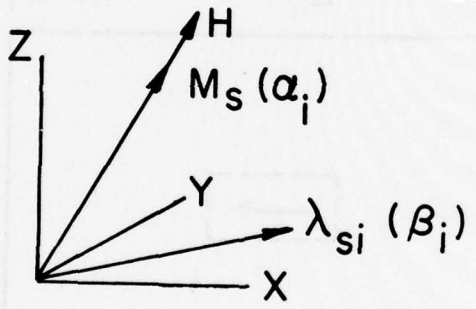
Distortion of the unit cell by magnetostriction

Figure 6



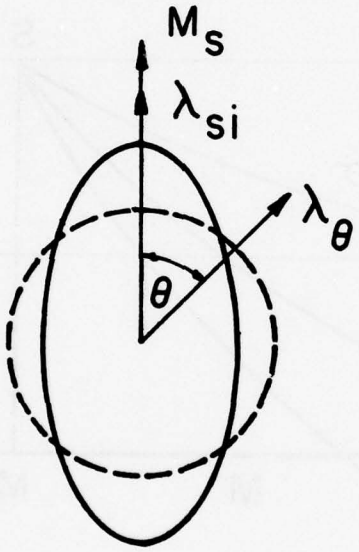
Distortion of a crystal by ordinary, field-induced magnetostriction

Figure 7



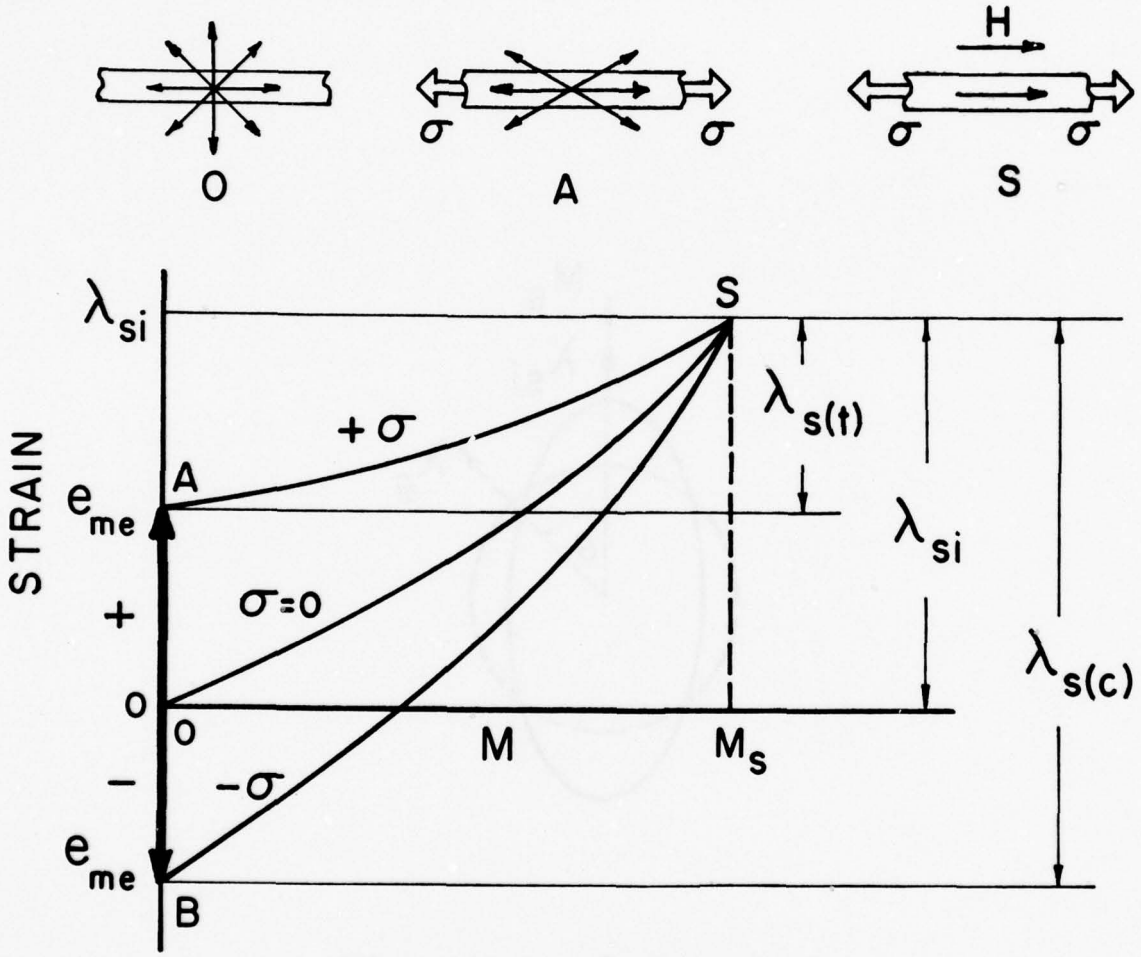
Coordinate system for Eq. (1)

Figure 8



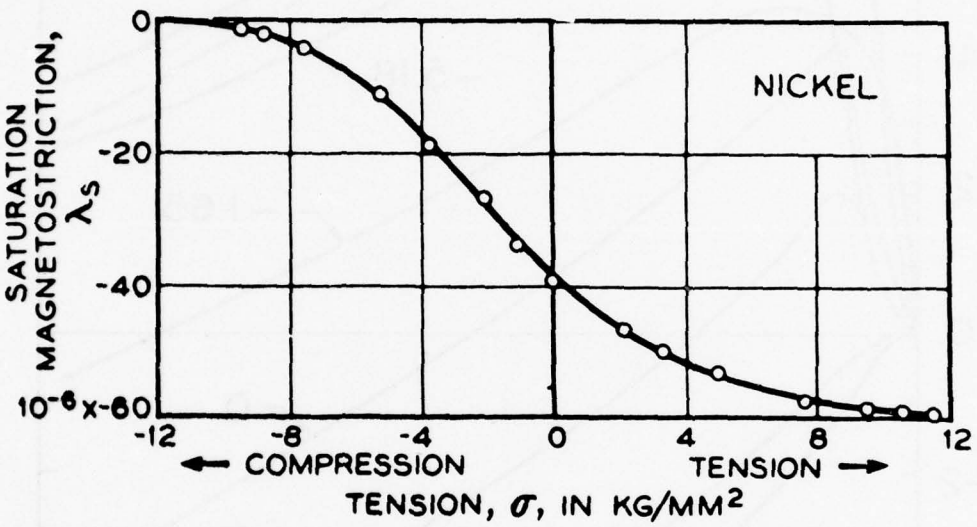
Isotropic magnetostriction

Figure 9



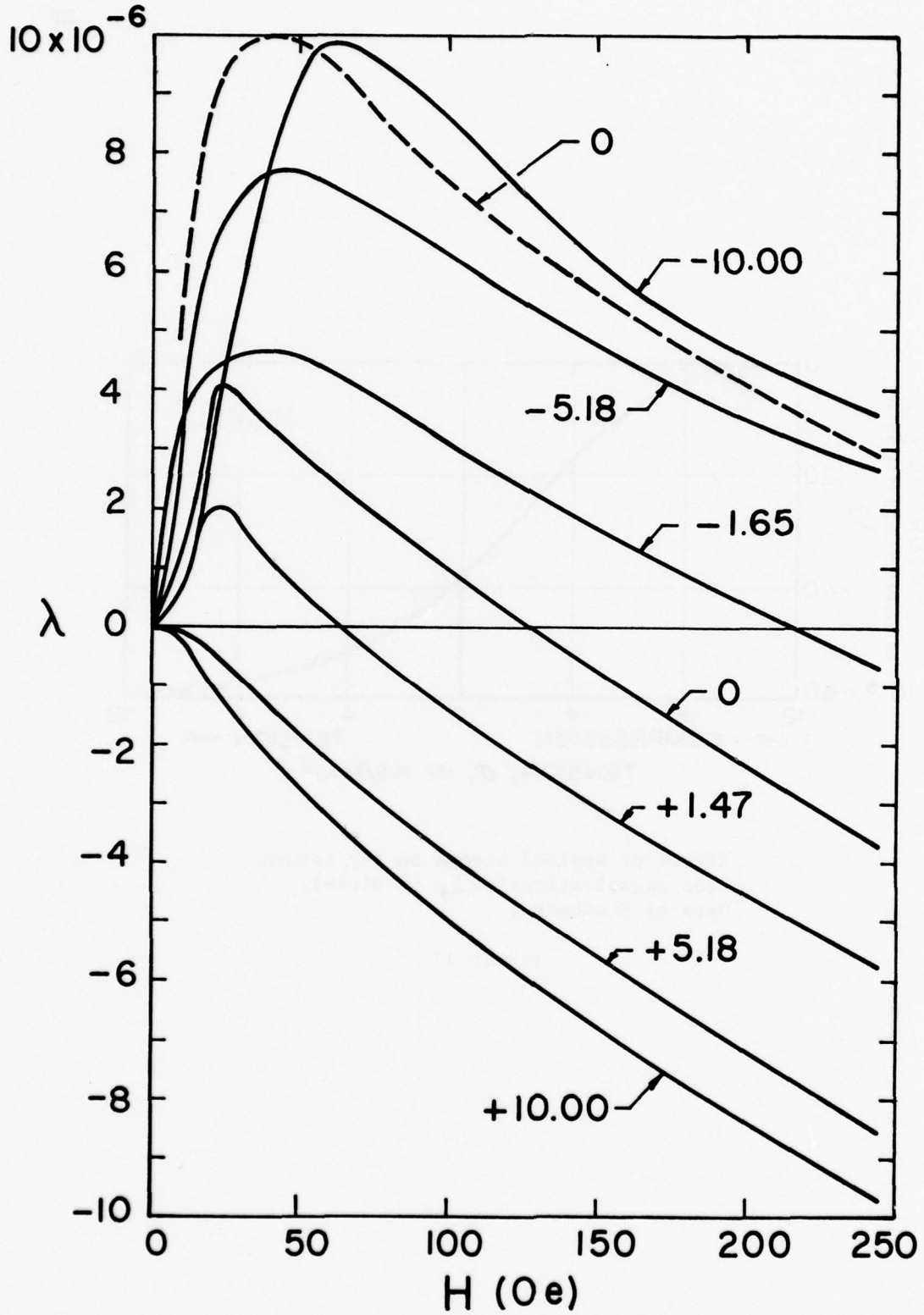
Effects of stress σ and changes in magnetization $\underline{M}$ on strains of magnetic origin

Figure 10



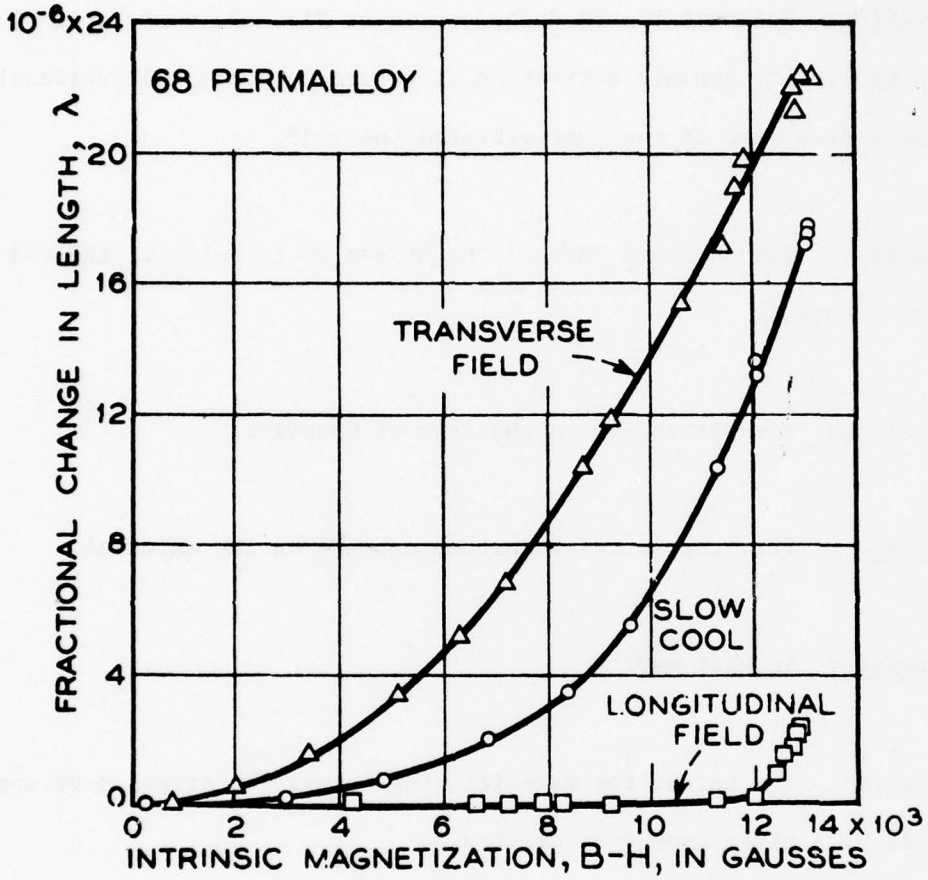
Effect of applied stress on the saturation magnetostirction λ_s of nickel. Data of Kirchner .

Figure 11



Magnetostriction as a function of field $\underline{H}$ for iron under applied tensile and compressive stress. The number on each curve is the stress in units of 1000 lb/in . The dashed curve is for a pre-stretched specimen. Data of Kuruzar .

Figure 12



Magnetostriction λ as a function of (B-H) ($=4\pi M$) for an alloy of 68 pct Ni, 32 pct Fe after various treatments. Data of Williams et al .

Figure 13

Discussion

Question: Relative to the dashed curve of Fig. 12, would that be neutralized by dynamic activation of the rod? Would that residual stress disappear if you just vibrated the rod?

Answer: Only a small part of the stress would relax if the rod were vibrated.

Question: Does it depend on the type of material?

Answer: Yes, the stress magnitude depends on the material.

Question: In what way?

Answer: The harder the material, the larger the stress developed in it by a given amount of prestrain.

Question: Has anyone looked at weak magnetic materials, like canted antiferromagnetics?

Answer: I am sure Prof. Callen can answer that better than I. Such materials can show real piezomagnetism, because a shear stress can upset the balance between the two sublattices.

Question: I raise the question because I think there is a tendency for us to ignore the small magnetic terms and the weak magnetic materials as being too small for us to do anything with them. But maybe they are not too small, and here would be a case, (canted antiferromagnetism) where I was curious as to whether anybody thought about it along these lines.

Answer: (by Prof. Callen): I will talk about it.

Question: My question concerns your Fig. 10, where you show a magnetoelastic strain at point A in the demagnetized specimen, independent of the ordinary elastic strain. Does this mean that you get an enhancement of the usual strain, when a stress is applied, because of the domains present in the magnetic bar?

Answer: Right. This leads to the so-called ΔE effect. When a stress is applied to a magnetic material, two kinds of strain are produced, elastic and magnetoelastic. This means that Young's modulus is smaller than if the material were non-magnetic.

Question: How large is this effect?

Answer: The value of $\Delta E/E$ is about 6 percent for nickel and less than 1 percent for iron.

Question: In regard to the sign convention for σ, does a positive sign mean that the material is under tension?

Answer: Yes.

Question: In regard to the quantity P in your Table 1, does P stand for pressure, and, if so, is P positive or negative when you have pressure?

Answer: I think that that P stands for a normal stress (tensile or compressive) and not for something like hydrostatic pressure, if that is what you mean.

Question: I do not believe you touched on this, but if you put a rod under tensile stress and then magnetize it, and then remove both the stress and the field, is there not a residual magnetostriction? Does not the bar remain elongated?

Answer: Right. As long as there is some remanent magnetization, there must be some remanent magnetostriction.

Question: I would like to comment briefly on the term piezomagnetism. In the transducer field it is used for polycrystalline materials operated at remanence; under these conditions pressure will change the magnetization. That is the way we use the term.

Answer: I agree that a partially magnetized body, for example, at remanence, will change its magnetization under the action of stress alone, but I submit that that is extending the word piezomagnetic further than it should be. At least, it confuses a person who thinks of the analog to piezoelectric.

Question: The point is that it is an extension, but the extension has already been made in piezoelectricity. When the ferroelectric ceramics are poled, they are then called piezoelectric.

Answer: Can I take it, when I run into the word piezomagnetic in transducer technology, that I am to understand that it refers to a partially magnetized material to which stress has been applied? Is that correct?

Question: Yes, a polycrystalline material with either a maintained bias (D.C. field bias) or one with a permanent magnetization.

Answer: I see.

Question: I would like to comment a little further. If you use the term piezomagnetic material, you mean one like the cobalt fluoride mentioned earlier, whereas, if you use the word piezomagnetic, you may mean a piezomagnetically polarized (biased) material. There is a slight distinction there, and you have to be careful when you use the word.

Answer: Yes.

TECHNOLOGY OF MAGNETOSTRICTIVE TRANSDUCERS RELATED TO MATERIAL REQUIREMENTS

B. A. Wise
General Dynamics
Rochester, New York

presented to

SCIENTIFIC OPPORTUNITIES IN MAGNETOMECHANICAL SYSTEMS

Metallic Magnetoacoustic Materials

A REGIONAL WORKSHOP (UNCLASSIFIED)

Navy Building
495 Summer Street
South Boston, Massachusetts

Sponsored by ONR Boston

25 August 1969

ABSTRACT

Technology of Magnetostrictive Transducers
Related to Material Requirements

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General Dynamics
Rochester, New York

A review of the literature, particularly the conference held in October 1966 under Navy sponsorship* shows that there is current interest in using magnetostrictive transducers in underwater sound transducers. Free-flooding scroll transducers have shown a ruggedness, shock resistance and reliability that would be desirable in other transducers, particularly those used in scanning sonars.

The author discusses the relationship between material properties and the requirements of sonar devices. The contrast is drawn between a scroll transducer and a scanning sonar. The required strain level, power level and effective coupling are stated for "competitive" scanning sonar elements and for state-of-the-art elements. Essential features of a scanning sonar element are illustrated. Finally, magnetostrictive strain and coupling are related to the required power level and effective coupling coefficient, and the hope is expressed that materials research may provide the needed materials.

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*See JUA 17-2, 1967

INTRODUCTION

A review of the literature, particularly of the conference on Magnetostrictive Materials and Their Application to Underwater Sound Transducers* held in October of 1966 under Navy sponsorship, shows the following:

1. Success has been reported with test and research scroll transducers.
2. A desire has been expressed for ruggedness, shock resistance and reliable operation of Navy transducers for the period of time between dry dockings or other extended maintenance periods.
3. Several authors have assured us that magnetostrictive transducers can generate the required power for typical sonar use.
4. The hope has been expressed that scanning sonars may again use magnetostrictive transducers, with the assistance of material development and good transducer design. One of the more specific suggestions has come from Leon Camp, who tells us that if we can achieve an effective coupling of 40 per cent in an element that still possesses all the requisite virtues, then the competition will be real indeed between magnetostrictive transducers and other types.

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*Reported fully in JUA 17-2, 1967

In reviewing the technology of magnetostrictive transducers, it is the author's objective to put into clear focus the relation between material properties and the requirements of sonar devices, particularly the scanning sonar element. To this end, comment will be made upon

1. The essential nature of a scroll transducer in its typical use in a transmit array.

2. The multiple uses of an element in a scanning sonar, leading to impedance variations.

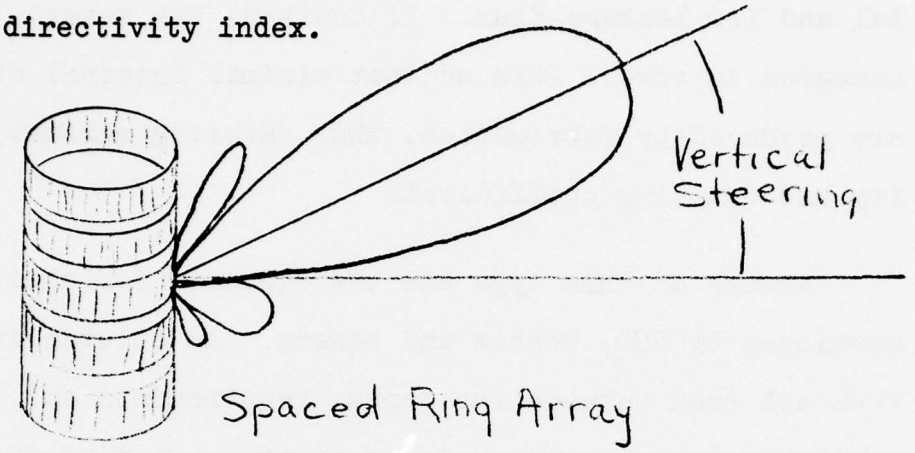
3. Characteristics of a scanning sonar element, including the in-phase strain level, the power density and the effective coupling, as well as mechanical and magnetic features.

Having set forth the goals in terms of driving strain level and coupling coefficient, the author suggests values of maximum coupling coefficient and saturation magnetostrictive strain for magnetostrictive materials that would meet these goals.

SCROLL TRANSDUCERS

A scroll transducer consists of a vertical array of ring elements, usually about 1 to 5 wavelengths high. One

wavelength is enough to obtain good loading; a 5 wavelength height is enough to permit vertical steering and an appreciable directivity index.



If beam forming is used at all, it is of a simple type to tilt the beam upward or to reduce side lobes, and is usually fixed (not scanned). The spaced-ring array used with many scroll transducers actually makes good use of radiation loading on the inside of the ring as well as the outside, and accordingly, should be free-flooding. This situation does not prevail in scanning sonars, as commented on later.

An individual ring element has a nearly ideal construction from the standpoint of ruggedness and simplicity. It is free-flooding, nearly all metal and may be highly corrosion resistant.

Magnetically, the element may be used at its best. The toriod is an ideal shape, with uniform use of the material and low leakage flux. If desired, the material can be annealed in scroll form so that minimal internal strains are produced by fabrication, thus favoring maximal permeability and coupling coefficient.

Arrays of this type and the elements for them have been developed by USL, Bendix and others. An outstanding fit has been achieved between the design requirements and the means available to meet them. As an example, we find from Bulmer, et al*, of USL, that a nickel scroll transducer has achieved an effective coupling of .28 and a mechanical Q of 8. Again, this is an excellent match between material properties and performance.

We are left wondering, "Should we not go and do likewise with scanning sonar". May we have increased ruggedness and reliability, along with satisfactory performance?

Perhaps this can be done. If so, it will be the more likely if the requirements are clear to all working to meet them. This is the purpose of this presentation.

---

*Bulmer, R. J., et al "Free-flooding Magnetostrictive Scroll Transducers", JUA 17-2, 1967

SCANNING SONAR

A cylindrical array used with a scanning sonar typically has about 50 vertical lines, called "staves", disposed to form a cylinder. Each stave has about 10 individual elements, leading to a total number of about 500 elements, Groups of elements are used in sub arrays to form beams. The arrays overlap in such a way that a given element may be used in 30 or more different array positions. When frequency diversity is added as a requirement, the total number of distinct element uses may be 100 or more.

Each use of an element involves its own value of radiation impedance determined by array position, steering angle and frequency.

Both the resistive and reactive components of radiation impedance may change over a ratio of 4:1 or greater from their nominal values. In a typical array, the impedance normalized to ρc of water will vary over the range

$$.4 < \frac{R}{\rho c} < 1.5$$

$$-.1 < \frac{X}{\rho c} < 1.5$$

Except in special cases, one element must cover all combinations of resistive and reactive loading. Ideally,

it will do so with little change in its tuning, its velocity or its efficiency, and certainly will do so without being damaged.

On account of the difficulty of meeting such requirements, efforts have been made to decrease the complexity of the arrays by divorcing receive and transmit functions. This helps, but not much. It is still required that the elements in a scanning sonar have tight coupling so that they can do with considerable accuracy whichever of the many things they are supposed to do at a given time.

The comments above refer particularly to a surface ship sonar of current vitange. For submarine arrays and for surface ship arrays of the future, the requirements will be more severe, not less.

All of these requirements add up to a need for a low mechanical "Q" or ratio of stored to dissipated energy

$$Q_M = 2\pi \frac{\text{Stored Energy}}{\text{Energy Dissipated Per Cycle}}$$

In a most commonly used system of design, the slopes of the positive and negative reactances of a tuned element are made equal at the geometric mean frequency of the operating frequency range. When this system is used, there is a

definite relationship between the value of Q_M and the effective coupling coefficient of the material, k_{eff}. The value of k_{eff} should be determined from the dynamic device:

$$k^2_{eff} = \frac{\text{Mechanical Stored Energy}}{\text{Total Stored Energy}}$$

The value of mechanical Q_M for matched tuning over a broad band is

$$Q_M = \frac{1 - k^2_{eff}}{k^2_{eff}}$$

Table I lists values of Q_M that correspond to various values of k_{eff}. To assist in assessing the significance of coupling, three statements are made:

1. Higher values of coupling are better, approximately as they affect Q_M, if other factors remain the same.

2. An effective coupling of .45 is probably high enough to make a satisfactory scanning sonar, especially if other advantages exist compared with elements that have higher coupling.

3. An effective coupling of .707 is "state-of-the-art" and by present standards does not need to be exceeded for a transmit element in a scanning sonar.

TABLE I

MECHANICAL Q AS A FUNCTION OF COUPLING COEFFICIENT

K	Q_M	Comment
.15	44	Ni "Hairpin" element
.30	10	Ni Scroll
.45	4	Barium Titanate, Co-Ni*
.58	2.0	Current PZT Designs
.65	1.4	Ideal PZT Designs
.707	1.0	Hydroacoustic and (?)

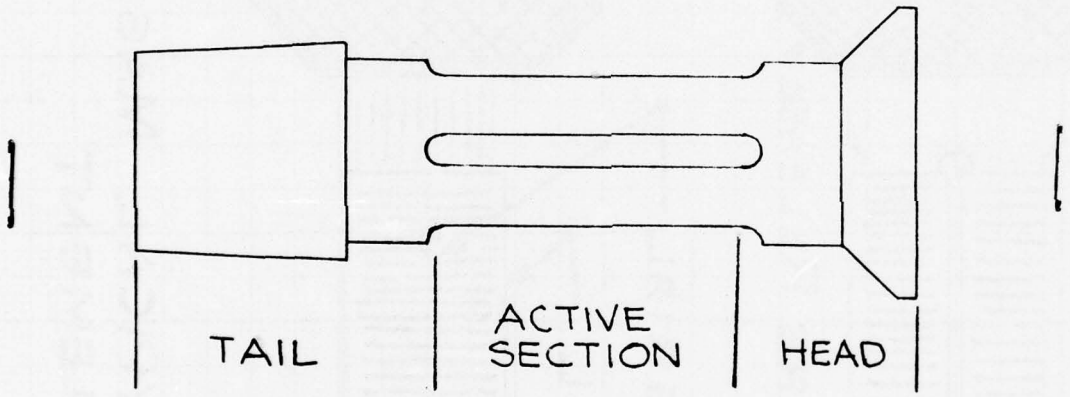
*A Co-Ni alloy probably would have a slightly lower effective coupling, about .40, at useful strain values, but should approximately compare with barium titanate, as used in Navy transducers.

THE SCANNING SONAR MAGNETOSTRICTIVE ELEMENT

To sketch in the broadest of terms what a magnetostrictive element must be like to be used in a scanning sonar, let us consider the element illustrated in Figure 1.

Mechanical

Referring to Figure 1, the element will tend to have three separate sections:



a head, an active section and a tail. In olden times, all three were made of one material, i.e., stamped laminations of the magnetostrictive material. This lead to advantages in element reproducibility, ruggedness and reliability. Unfortunately, the same construction cannot be used for the low-Q_M elements now under discussion. Instead, they require a broad, lightweight head coupled to a slender active section, terminated by a massive tail. The construction tends to become like that of a ceramic composite element -

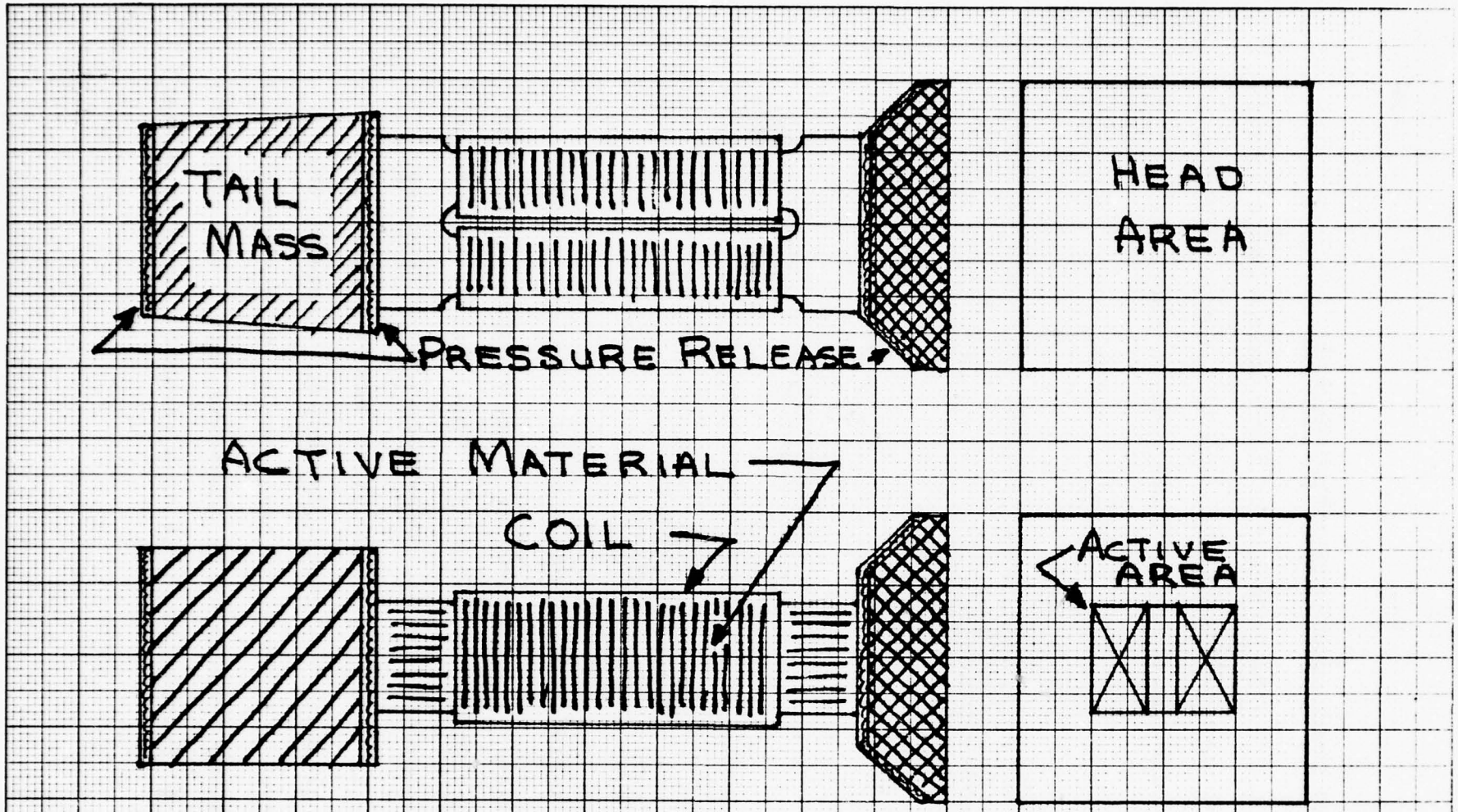


FIGURE 1 TYPICAL MAGNETOSTRICTIVE ELEMENT

and with the construction go the physical characteristics.

The head will be square or round and will have an area of about .9 $\lambda^2/4$. This size is relatively fixed because of beam-forming, which requires closely spaced elements, and impedance-averaging, which requires a "large" element. The material may be a light metal or ceramic, or may use a webbed structure of a heavier material.

The active section will be a stack of metallic laminations, thin enough to limit eddy currents, insulated from one another and with a high enough "packing factor" to permit close coupling of the winding. While it is assumed here that the material will be a magnetostrictive metal, any "active" material having adequate properties could be used.

The typical tail will be a truncated wedge made of cast bronze or some other dense material having suitable properties.

Figure 1 indicates that "pressure-release" material covers the back of the element head and the front and back of the tail. This is needed to suppress coupling to the medium of any surface except the front side of the radially-vibrating head. With the pressure-release material present

the array may be free-flooding. Unfortunately, pressure-release materials or constructions introduce problems of their own and are not so nice as the bare-element free-flooding described for the scroll transducer.

Magnetic Circuit

Commenting now on the magnetic circuit of the element shown in Figure 1, each leg of active material carries a coil configured for low leakage flux. A long, close-fitting winding, while not easy to install, probably would be needed to maximize coupling. A high-permeability path at each end of the active length is also a practical necessity if coupling coefficients of .45 and above are to be achieved.

Both remanent operation and permanent magnet bias detract from available coupling coefficient and probably should not be used, until such time as there is performance to spare.

Remanent bias is most unlikely to provide the best coupling available, simply on the basis that a hard, or half-hard condition is needed to get high remanence, and this is in opposition to both high permeability and low core loss.

Permanent-magnet bias implies a large gap of low-permeability material and has resulted in sacrifices of as much as 50 per cent in coupling, in elements such as the Ni hairpin element. The benefit of an air gap in linearizing the core could be of interest in some cases. If so, the air gap specifically needed for this purpose should be used.

TYPICAL ELEMENTS

Twelve illustrative element designs* are described below. All of them are for use at 3.5 kc with half-wavelength element spacing in the array and a square head that occupies .9 of the total area. Thus,

$$\text{Head Area} = .9 \left(\frac{\lambda}{2}\right)^2$$

$$= 413 \text{ cm}^2, \; f = 3.5 \text{ kc}$$

All elements are designed on an approximate basis in which head and tail masses are "lumped", rather than calculated as distributed elements. This makes little difference in the comparisons to be made here. A distributed

---

*These designs are illustrative of design requirements. There has been no occasion to build these or similar elements, although test elements undoubtedly would be built as part of a transducer development program.

calculation must refer to a particular material and shape, neither of which is specified.

All elements are alike in the following respects:

Head area = 413 cm^2

Power Output (far-field radiation) = 413 watts

Mechanical Efficiency = 2/3

Head Velocity/Tail Velocity = 3.0

Resonant Frequency = 3.5 kc

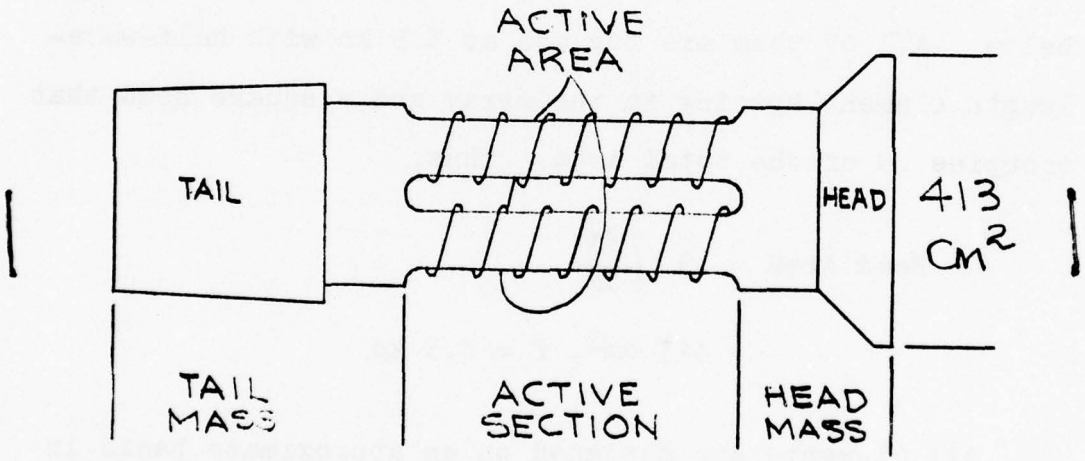


Table II shows the element weights and total weights for each of twelve elements.

The three values of Q_M can be identified as follows:

TABLE II. LONGITUDINAL ELEMENTS FOR 3.5 KC; Q_M VALUES OF 4.0, 2.0 AND 1.0 ARE SHOWN; THREE ELEMENT LENGTHS ARE SHOWN

Active Length* Degrees	Active Area CM^2	Head Mass K_g	Tail Mass K_g	Active Mass K_g	Q_M	Total Mass K_g	Power Density Watts/ cm^2	Strain Total Peak 10^6	Strain MS., Peak 10^6
45+13.5	60	10.9	37.8	12.0	4	60.7	10.3	40.3	9.75
"	30	5.45	18.9	6.00	2	30.3	20.6	"	18.0
"	15	2.72	9.4	3.00	1	15.2	41.2	"	28.5
40+12.5	52	11.3	35.5	9.34	4	56.1	11.9	44.3	10.7
"	26	5.65	17.7	4.67	2	28.0	23.8	"	19.8
"	13	2.82	8.8	2.33	1	14.0	47.7	"	31.3
35+11.0	46	11.9	34.9	7.24	4	54.0	13.5	49.6	12.0
"	23	5.95	17.4	3.62	2	27.0	27.0	"	22.1
"	12	2.97	8.7	1.81	1	13.5	54.0	"	35.1
30+9.5	39	12.2	34.2	5.27	4	51.7	15.9	57.0	13.8
"	19	6.10	17.1	2.63	2	25.8	32.6	"	25.4
"	10	3.05	8.5	1.32	1	12.9	62.0	"	40.1

*Total length is sum of length from head to node and length from node to tail: for Elements 1, 2 and 3, the length of the active element is 58.5 degrees. For nickel, this is about 23 cm.

A Q_M of 4.0 is sufficient for a reasonably good scanning sonar element. Historically, it was the best achieved in sonar elements employing barium titanate as the active material and was about the same as the value in sonar elements using PZT-4 in the d_{31} mode (inside-outside electroding of a cylinder).

A Q_M of 2.0 has been approached in a number of recent scanning sonars. It represents reasonably good use of PZT-4 ceramic, but has been compromised repeatedly for supposed (economic) advantages of using less ceramic material in an element.

A Q_M of 1.0 has not yet been used in a shipboard scanning sonar element but could be approached by a well-designed element using PZT-4 in the d_{33} mode (stacked rings) and could be achieved in a hydroacoustic element. This is considered state-of-the-art at present and probably will remain so for the next few years, unless new materials or design concepts are introduced. It may also be commented that a Q_M of 1.0 provides a one-octave bandwidth, which is enough for most of the schemes that involve transmit elements. This is not to say that still lower Q_M and still wider bandwidth would not be attractive if available. The limit is unity coupling, no circuit tuning and a bandwidth from d.c. to light.

The dimensions of one element from Table II are illustrated in Figure 2. This is the element having a Q_M of 4.0 and an active length of 58 degrees.

Still referring to Table II, four element lengths are shown for each Q_M value. It can be seen that the elements with longer lengths of active material have a lower power density and lower magnetostrictive strain. These relationships are shown in Figure 3 and Figure 4. No attempt is made here to indicate an absolute lower limit of strain or power density, but heroic measures would be required to lower the values shown for the 58.5-degree elements by an additional 20 per cent.

It can be seen that the minimum magnetostrictive strain value in Table II is $\pm$ 10 microinches per inch, corresponding to the highest Q_M and to the greatest volume of active material. Note that the k_{eff} of .45 for this condition is not a peak value of coupling attainable over a narrow range of magnetostrictive driving strain; it is the effective value over a 20 microinch per inch total strain excursion.

The situation becomes progressively more severe for higher k_{33} values and lower Q_M values, or for higher power levels. For state-of-the-art performance in a sonar limited

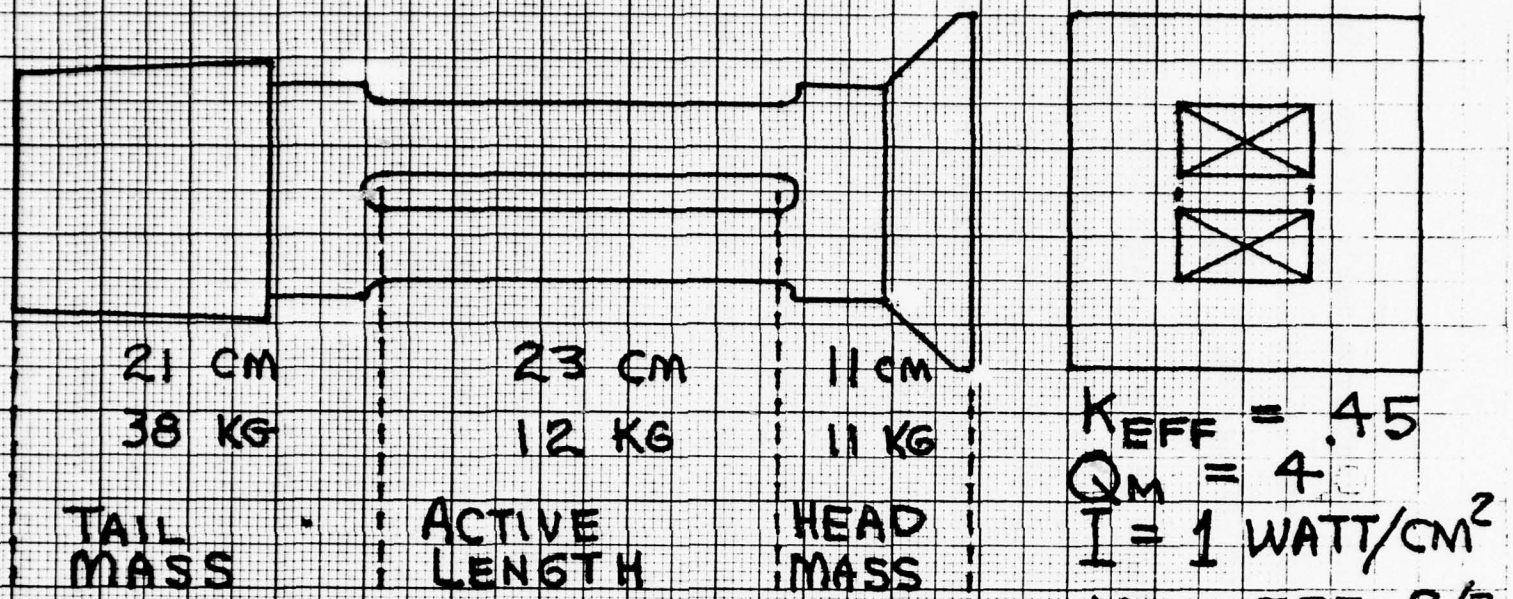


FIGURE 2 TYPICAL 3.5 Kg ELEMENT

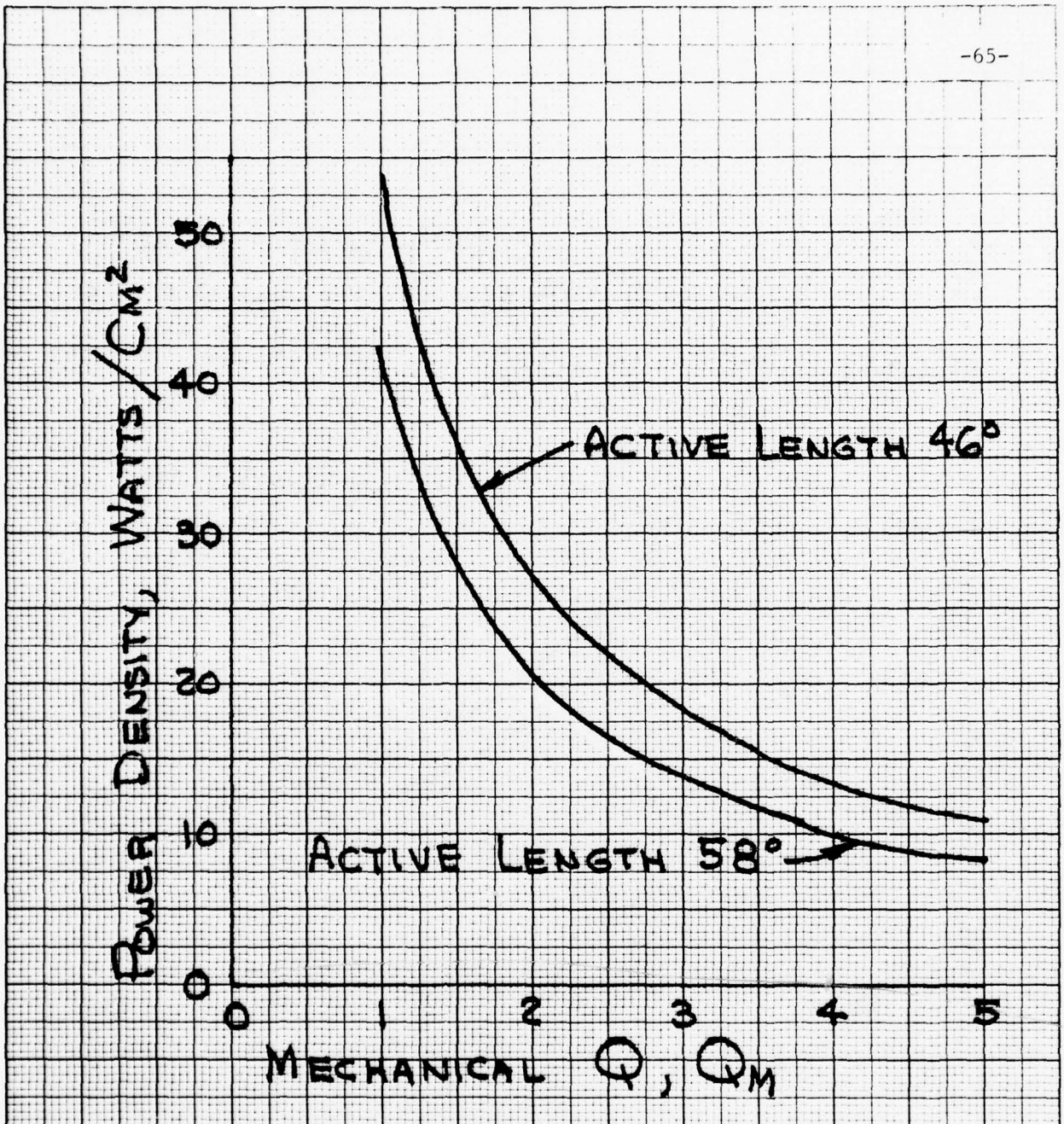


FIG 3 POWER DENSITY FOR A LONGITUDINAL SONAR ELEMENT AT 1 WATT/CM² RADIATION INTO SEAWATER

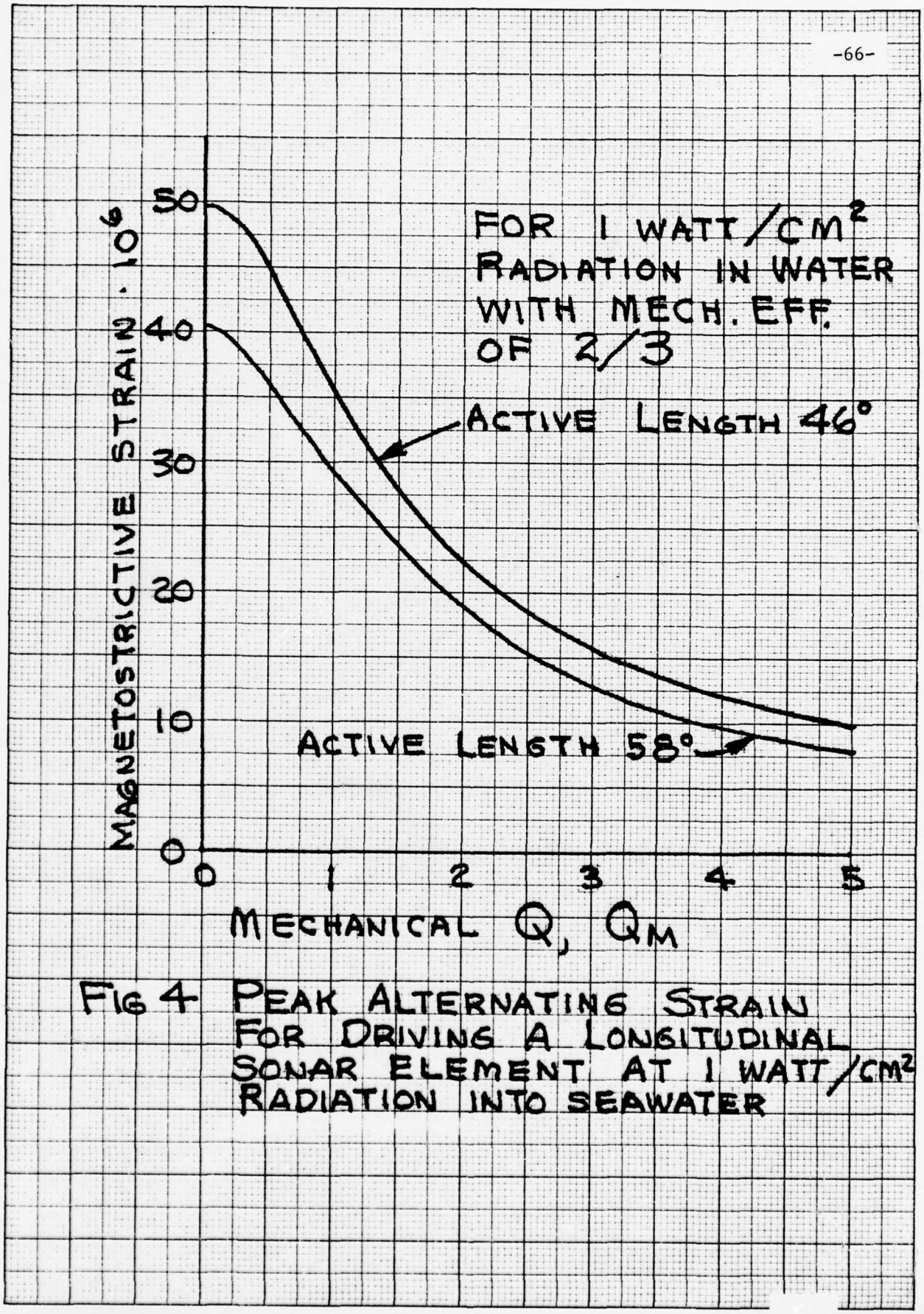


FIG 4 PEAK ALTERNATING STRAIN FOR DRIVING A LONGITUDINAL SONAR ELEMENT AT 1 WATT/CM² RADIATION INTO SEAWATER

by cavitation at shallow depths, required values would be a magnetostrictive driving strain of ± 30 microinches per inch at an effective k_{33} coupling of .707.

AVAILABLE MATERIALS

The data needed to examine the suitability of various materials at given strain levels and mechanical Q values are not at hand, but an illustrative approximation may be made using the materials data given by Edson*.

Figure 5 shows a selected operating region for a 4.5 Co-Ni alloy. It is recognized that these are static or quasi-static curves. Since low magnetic and mechanical hysteresis apply to this material (and would necessarily apply to any useful material), the static curves alone should provide a reasonable sorting tool.

The operating region in Figure 5 is selected on the basis of the coupling coefficient. Bearing in mind that little scarifice can be made if coupling values of .45 and higher are ever to be attained, the minimum value is set so that the average over the range is about 90 per cent of maximum, or in this case about .40.

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*Edson, A. P., "Alloys for Magnetostriction Transducers", JUA 17-2, 1967.

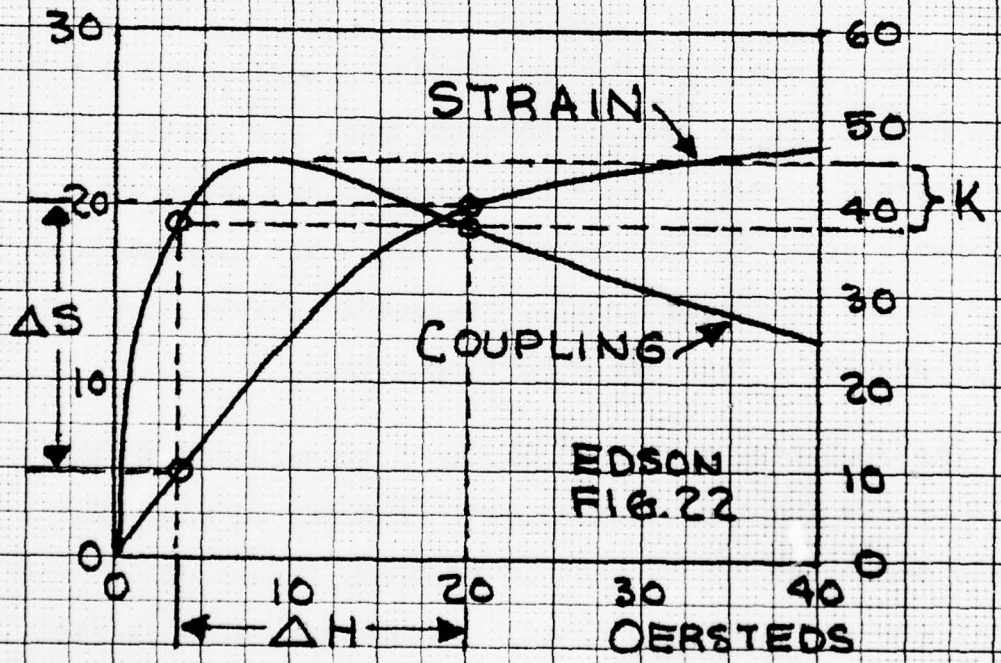

FIG. 5 STRAIN AND COUPLING FOR 4.5 CO-NI

It can be seen that the corresponding strain is about 15 microinches per inch. With the bias set at 12 oersteds, an alternating strain of $\pm$ 7.5 microinches per inch would result.

According to the criteria established earlier, it would appear that this material would qualify for use at a Q_M of about 5.3.

Other materials might be examined in a similar manner. Dynamic measurements would be needed for any material determined to be of interest because of its static characteristics.

PROJECTED MATERIAL PROPERTIES

Indulging in a bit of approximation, one might project the following requirements for a magnetostrictive material:

1. The maximum coupling must be at least 10 per cent higher than the effective coupling over the dynamic range to be used.

2. The saturation strain must be at least twice as high as the dynamic range to be employed, and four times as high as the peak strain values given in Figure 4.

These two criteria are satisfied by the operating values in Figure 5.

Based on these two criteria, materials that would be

suitable for use in scanning sonars would have the properties shown in Table III.

It should be reemphasized that the values for 1 watt/cm^2 apply to materials used in a surface ship scanning sonar. For other devices not so limited by cavitation, the intensity levels could be 10 times as high, or possibly higher. For such devices, k_{eff} values would be the same, but the λ_{max} values would be higher by a factor equal to the square root of the intensity. Values for 10 watts/cm^2 are also shown in Table III.

Questions regarding the ability of metallic magnetostrictive materials to meet the criteria outlined are left to those engaged in materials research, with hope for their success.

CONCLUSIONS

The elements needed for scanning sonars have mechanical, acoustic and magnetic requirements that tend to make them more complex than scroll transducer elements and that tend to decrease the possibility that characteristics obtained with scroll transducers can be duplicated in scanning sonar transducers. Chief elements of contrast are the composite construction, more complex magnetic circuit and pressure-release requirements of the scanning sonar element.

TABLE III

MINIMUM VALUES OF COUPLING AND STRAIN FOR MAGNETOSTRICTIVE MATERIALS USED IN SONAR*

Q_M	k_{eff}	k_{max}	λ_{max}^* 10^6	
			1 watt/cm^2	10 watts/cm^2
4	.45	.50	40	130
2	.58	.64	72	230
1	.707	.78	112	350

*Strain values are proportional to the square root of intensity.

The required effective coupling coefficient is estimated to be a minimum of .45 for an element that can perform all of the essential functions of existing scanning sonar elements. Lower coupling values would imply limited or specialized applications. An effective coupling of .58 would be competitive with current ceramic transducer materials, specifically PZT-4. An effective coupling coefficient of .707 would be "state-of-the-art", and should be adequate for a number of years to come.

The peak dynamic strain levels required for radiation of 1 watt/cm^2 are illustrated, with Q_M as a parameter. A peak strain value of 10 microinches per inch corresponds to a Q_M of 4, at 1 watt per square centimeter. Values can easily be translated to lower or higher power levels by using the relationship that strain is proportional to the square root of power.

Using static characteristics of 4.5 Co-Ni, a method is illustrated for estimating the effective coupling and dynamic strain. For this material, adequate characteristics appear to be available at a Q_M of about 5.3, for a radiated power of 1 watt/cm^2.

Required material properties are estimated for several values of mechanical Q. Estimates are based on the assumptions that the maximum coupling must be at least 10 per cent

higher than the effective coupling, and that the saturation strain must be at least four times as high as the peak dynamic strain corresponding to the mechanical Q and intensity. The lowest coupling and strain values shown slightly exceed those available with Ni or Co-Ni. The highest values of coupling and strain would require a great advance in the properties of magnetostrictive materials.

SINGLE CRYSTAL SATURATION MAGNETOSTRICTION

by

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SINGLE CRYSTAL SATURATION MAGNETOSTRICTION

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My task is to display for you the fundamentals of magnetostriction -- the saturation magnetostriction of single crystal materials. In actual device operation, as you well know, the material is polycrystalline, and one ordinarily operates very far from technical saturation, but the behavior under these circumstances is, to some extent, a manifestation of the underlying "fundamental" behavior, and the connection between these has already been developed by Dr. Cullity.

To begin then, consider the temperature and magnetic field dependence of magnetostriction in the simplest of circumstances, a localized spin ferromagnet whose magnetostriction, say λ_{100} or λ_{111} (or any of the second degree magnetostriction coefficients of a non-cubic material) is of a single-ion, additive character. The theory[1] gives then, and I shall not derive the theory[2],

$$\lambda(T,H) = \lambda_0 \hat{I}_{5/2} (m(T,H)). \qquad (1)$$

Equation (1) says that the temperature and field dependence of this second degree coefficient (it is of degree $\ell=2$ in that it is the coefficient of a polynomial which is quadratic in direction cosines of the magnetization) is equal to a constant λ_0 times a known function, $\hat{I}_{\ell+1/2}$, whose argument is the reduced magnetization

$$m(T,H) = \frac{M(T,H)}{M(0)} \qquad (2)$$

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1. C. Kittel and J. H. Van Vleek, Phys. Rev. 118, 1231 (1960).
2. A rather current review, with a number of references is given by E. Callen, J. Appl. Phys. 39, 519 (1968).

The temperature and field dependence of $\lambda(T,H)$ arise through the T and H dependence of M itself. The reduced hyperbolic Bessel function $\hat{I}_{5/2}$ is shown in Figure 1, as a function of its argument m. (Higher degree ℓ=4,6 functions are also shown. These relate to magnetostriction coefficients of terms with 4 and 6 magnetic field direction cosines.) For each T and H one must know the appropriate reduced magnetization m from experiment. Figure 1 then shows how much the magnetostriction is reduced from its T = 0 value, λ_0 .

How well this theory fares is shown in Figure 2, depicting a basal plane magnetostriction of a rare-earth metal, dysprosium, as measured by Clark, De Savage and Bozorth[3] at the Naval Ordnance Laboratory. Below 85°K dysprosium is ferromagnetic. In the absence of a magnetic field, the material develops a complex spin structure between 85° and 178°K, above which it is paramagnetic. In the measurements shown, a field of 13.5Koe was applied in the basal plane to supress the antiferromagnetic phase. It will be seen that as the temperature is varied through the disordered and ordered phases, the magnetostriction varies by four orders of magnitude. Nonetheless, within a single adjustable constant, the value of λ at 0°K, theory agrees with experiment everywhere.

The next complication to contemplate is that of a Néel ferrimagnet, a material with two or more colinear but antiparallel magnetic sublattices of unequal magnitude, so that there is a net moment. The extension of eq. (1) is evident -- each sublattice n has its own 0°K magnetostriction coefficient $\lambda^n(0)$ and its own T and H dependent reduced magnetization $m^n(T,H)$ The net (ℓ=2) magnetostriction is simply

$$\lambda(T,H) = \sum_n \lambda^n(0)\ \hat{I}_{5/2}\ m^n(T,H) \qquad (3)$$

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3. A. E. Clark, B. F. De Savage and R. Bozorth, Phys. Rev. 138, A216 (1965).

Knowing the sublattice magnetizations, one adjusts the $\lambda^n(0)$ by fitting eq. (3) to the experimental curve at as many points as there are sublattices. Figure 3 shows the first application of this theory[4], in this case to yttrium iron garnet, which has two magnetic sublattices. There are now two adjustable constants for each curve. Because these two constants sometimes have opposite signs, and because of the different temperature dependence of the two sublattice magnetizations, in the case of λ_{111} a maximum in magnetostriction results. The same competition can even produce a "magnetostriction compensation point", a temperature, or field strength, or composition at fixed T and H, at which some λ passes through zero. This is something distinct from a magnetization compensation point, a temperature, or compostition at fixed T at which the net moment of the ferrimagnet passes through zero. Yet, a first-glance strange thing happens to the magnetostriction at a magnetization compensation point[5]. One sees this illustrated in Figure 4, showing the behavior of gadolinium iron garnet. The explanation of the spike in magnetostriction at 10°C is not far to seek. Magnetostriction is determined by measuring the change in strain as the magnetization is rotated by a magnetic field from one direction to another. But at the magnetization compensation point, since there is no net moment, rotation of an external field fails to rotate the sublattice magnetizations, and no change in strain is produced. Because of its tunability (the compensation temperature depends upon the composition) and sharpness, this experimental artifact might perhaps be useful in application.

The next figure, Figure 5, shows the temperature dependence of λ_{100} of iron, with and without added silicon. The course of the curve in no way suggests the monotonic behavior of Figures 1 or 2. In fact, it may occasion some chagrin here that, in the one class of materials whose magnetostriction many of you care about, the 3d transition metals, we do not know why they behave as they do[6]. Nor do we understand the effect of alloying on magnetostriction of 3d metals. Figure 6 shows data of Hall[7] on room temperature λ_{100} of iron alloys. Studying Figure 6, it is the considered

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4. E. R. Callen, A. E. Clark, B. F. De Savage, W. Coleman and H. B. Callen, Phys. Rev. 130, 1735 (1963).
5. A. E. Clark, J. J. Rhyne and E. R. Callen, J. Appl. Phys. 39, 573 (1968).
6. H. B. Callen and E. Callen, J. Phys. Chem. Solids 27, 1271 (1966).

judgement of this theoretician that some curves go up and some go down. But although there may not yet be apparent order in this behavior, for the empiricist there is distinctly hope.

Table 1 shows the room temperature anisotropy and magnetostriction constants of a number of iron alloys. It will be seen that some alloys of lowest anisotropy constant, such a 14.7 Cr Fe, have the largest magnetostriction. In transducer applications a figure of merit is the ratio of magnetostriction to anisotropy constants[8]. By proper alloying, it seems that improved materials could be developed. Such a suggestion has already been made at the 1966 Navy Conference on Magnetostrictive Transducers.

I want to end by returning us to near where we began. Figure 2 illustrates the single-ion one-sublattice theory with a rare earth, dysprosium. Figure 7 shows[9] a number of magnetostriction coefficients for this material. It will be seen that magnetostrictive strains approaching 1% can be attained at essentially the demagnetization field. In other crystallographic directions and magnetic phases the fields required can be huge. Unlike in the transition metals, here we understand where these large strains come from. The rare earth 4f charge cloud is not spherical; it is oblate, like a pancake, for rare earths to the left of holmium, and prolate, like a banana, for those to the right of erbium. (Substitute "frisbee" and "football" for those dieting.) Consider the banana. Spin-orbit coupling links the direction of the banana axis to that of the spin magnetic moment. Rotating an external field rotates the spin, which drags around the charge cloud. As the banana rotates, the surrounding ions distort to accomodate. This distortion accompanying spin rotation is the magnetostrictive strain. (In actuality, the largest part of the effect comes from conduction electron readjustment to maintain local charge neutrality.) Dysprosium and terbium have the largest positive magnetostriction, while the banana-pancake theory suggests that thulium should have the largest negative value. The anisotropy and magnetostriction constants properly change sign between holmium and erbium, where the shape of the charge cloud changes from oblate to prolate.

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7. R. C. Hall, J. Appl. Phys. 31, 1037 (1960).
8. Dr. Chin discusses this much more thoroughly in his accompanying paper.
9. S. Legvold, J. Alstad and J. Rhyne, Phys. Rev. Letters 10, 509 (1963).

Now is is not suggested here that pure dysprosium metal will be useful transducer material. Not only are impractically large fields required, but the Néel temperature is below room temperature. I am suggesting that mixtures of dysprosium and other rare earths in 3d metals do hold promise. Since the magnetostriction is additive, 1% of rare earth will do a lot for the magnetostriction of the 3d host without much affecting its Curie temperature. I think there is useful work to be done there.

Wt. % in iron	At. % in iron	Anisotropy const, K_1 (ergs/cm^3)	Magneto-striction $\lambda_{100} \times 10^6$	Magneto-striction $\lambda_{111} \times 10^6$
2.79 V	3.05 V	435 000	28.3	−12.4
6.07 V	6.62 V	410 000	28.4	−12.6
11.4 V	12.4 V	355 000	38.7	− 8.4
14.4 V	15.6 V	330 000	42.8	− 9.7
3.69 Mo	2.18 Mo	450 000	31.9	−13.2
5.72 Mo	3.41 Mo	440 000	32.5	−10.3
7.24 Mo	4.35 Mo	420 000	39.3	− 8.3
5.08 Ge	3.95 Ge	400 000	32.2	− 0.8
7.32 Ge	5.73 Ge	330 000	37.1	− 3.5
14.7 Cr	15.6 Cr	265 000	51.3	− 6.3
19.9 Cr	21.1 Cr	200 000	51.7	− 2.7
1.39 Ti	1.61 Ti	395 000	17.7	−15.7
2.09 Ti	2.43 Ti	450 000	14.5	−13.1
2.47 Sn	1.18 Sn	475 000	13.3	−15.3
3.76 Sn	1.80 Sn	495 000	12.1	−13.9

Table 1. Room temperature anisotropy and magnetostriction coefficients of a number of iron alloys. R. C. Hall, J. Appl. Phys. 31, 1037 (1960).

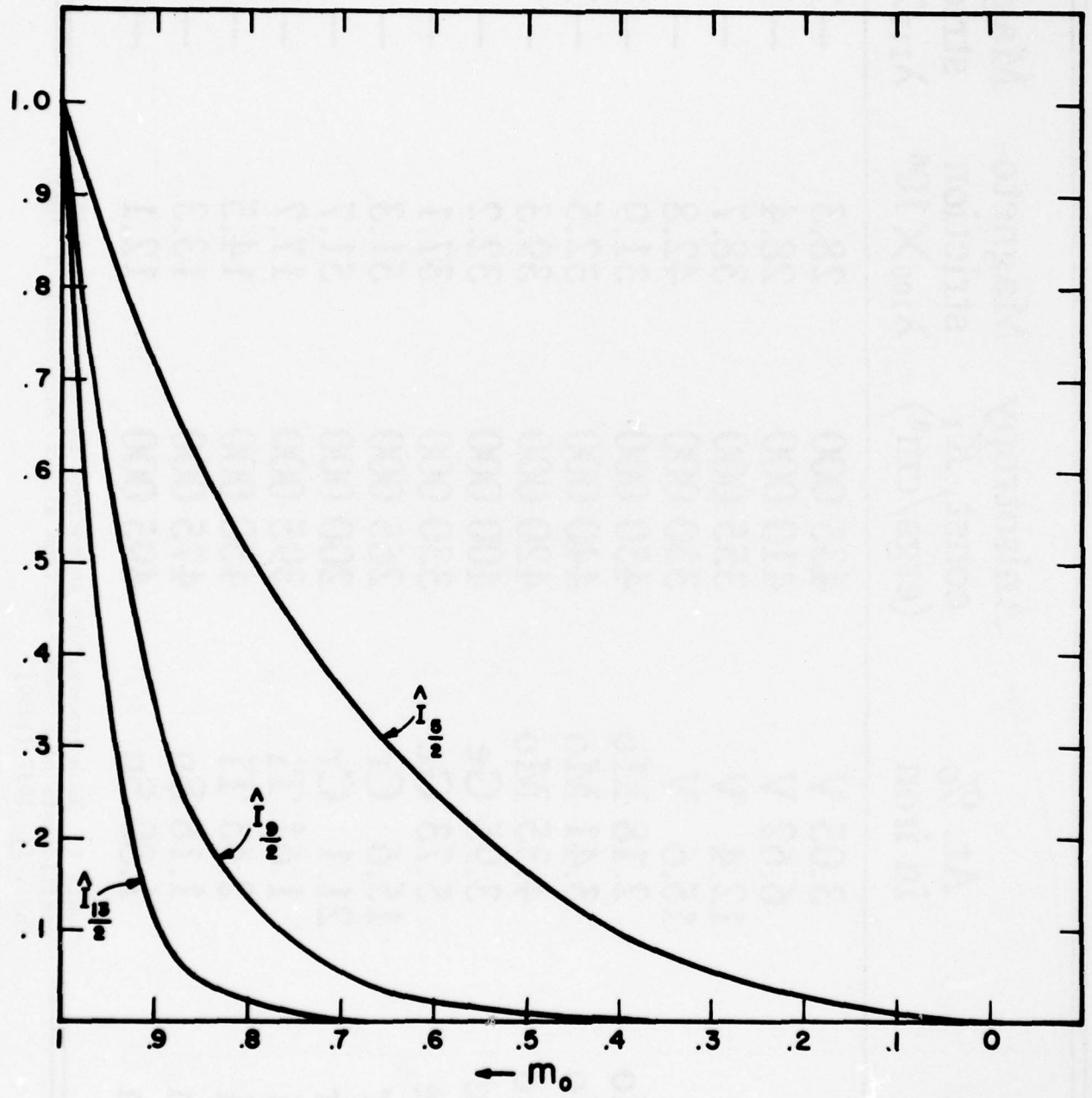

Fig. 1. The reduced hyperbolic Bessel functions.

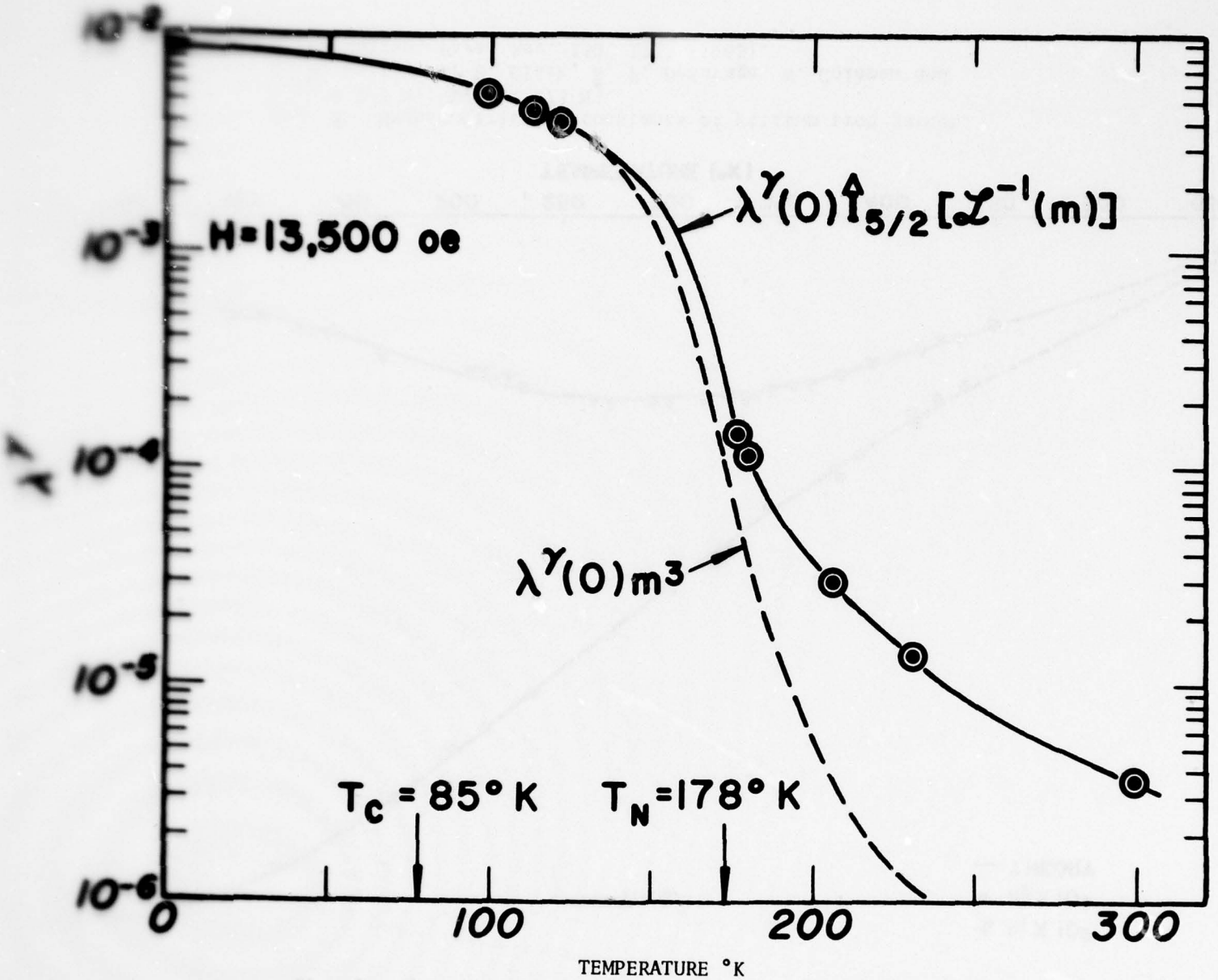

Fig. 2. The temperature dependence of one of the magnetostriction coefficients of dysprosium.
A. E. Clark, B. F. DeSavage and R. Bozorth, Phys. Rev. 138, A216 (1965).

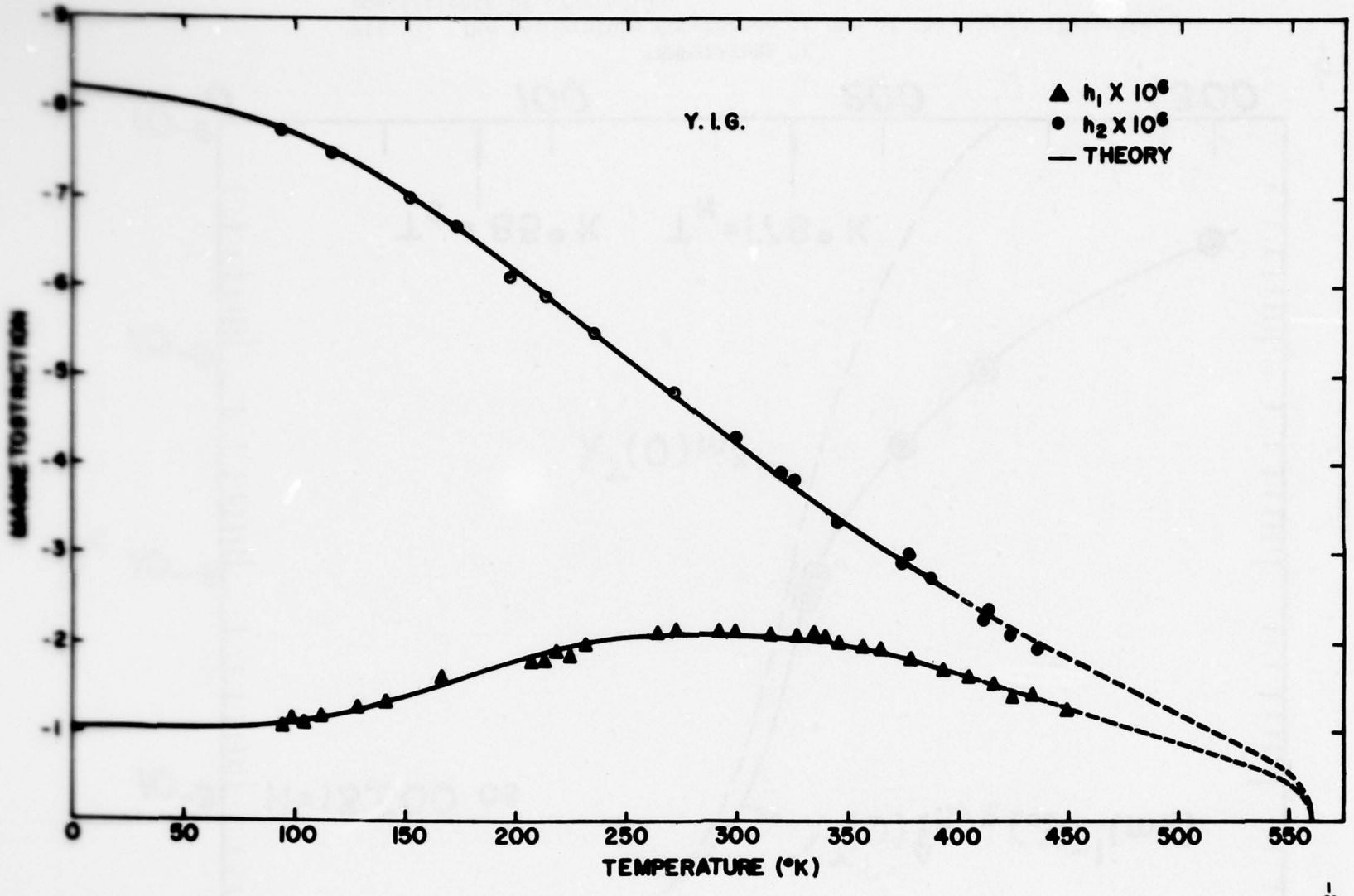

Fig. 3. Magnetostriction constants of yttrium iron garnet. $\lambda_{100} = 2/3\ h_1$; $\lambda_{111} = 2/3\ h_2$.
E. R. Callen, A. E. Clark, B. F. DeSavage, W. Coleman and H. B. Callen, Phys. Rev. 130, 1735 (1963).

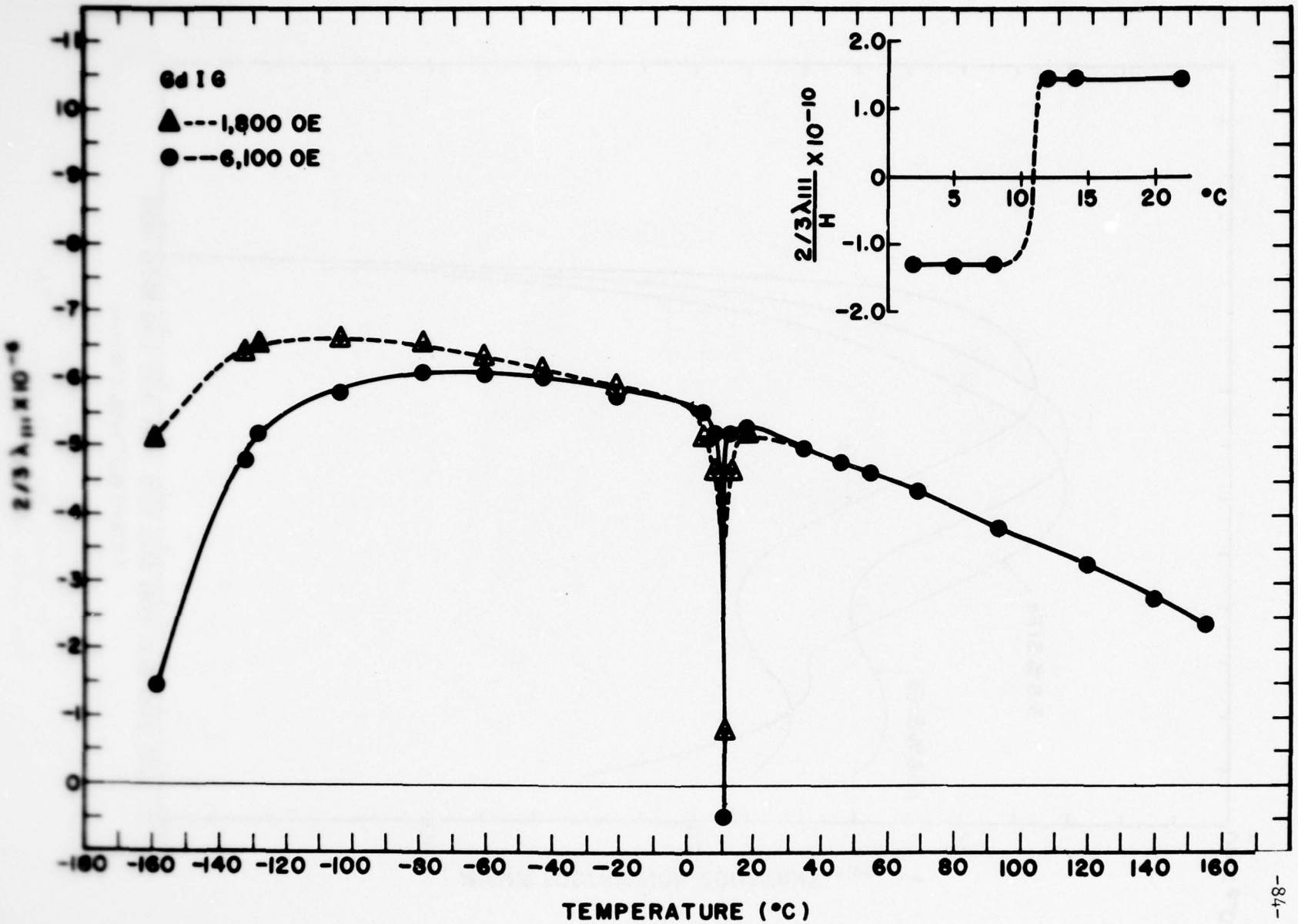

Fig. 4. Magnetostriction of gadolinium iron garnet.
A. E. Clark, J. J. Rhyne and E. R. Callen, J. Appl. Phys. 39, 573 (1968).

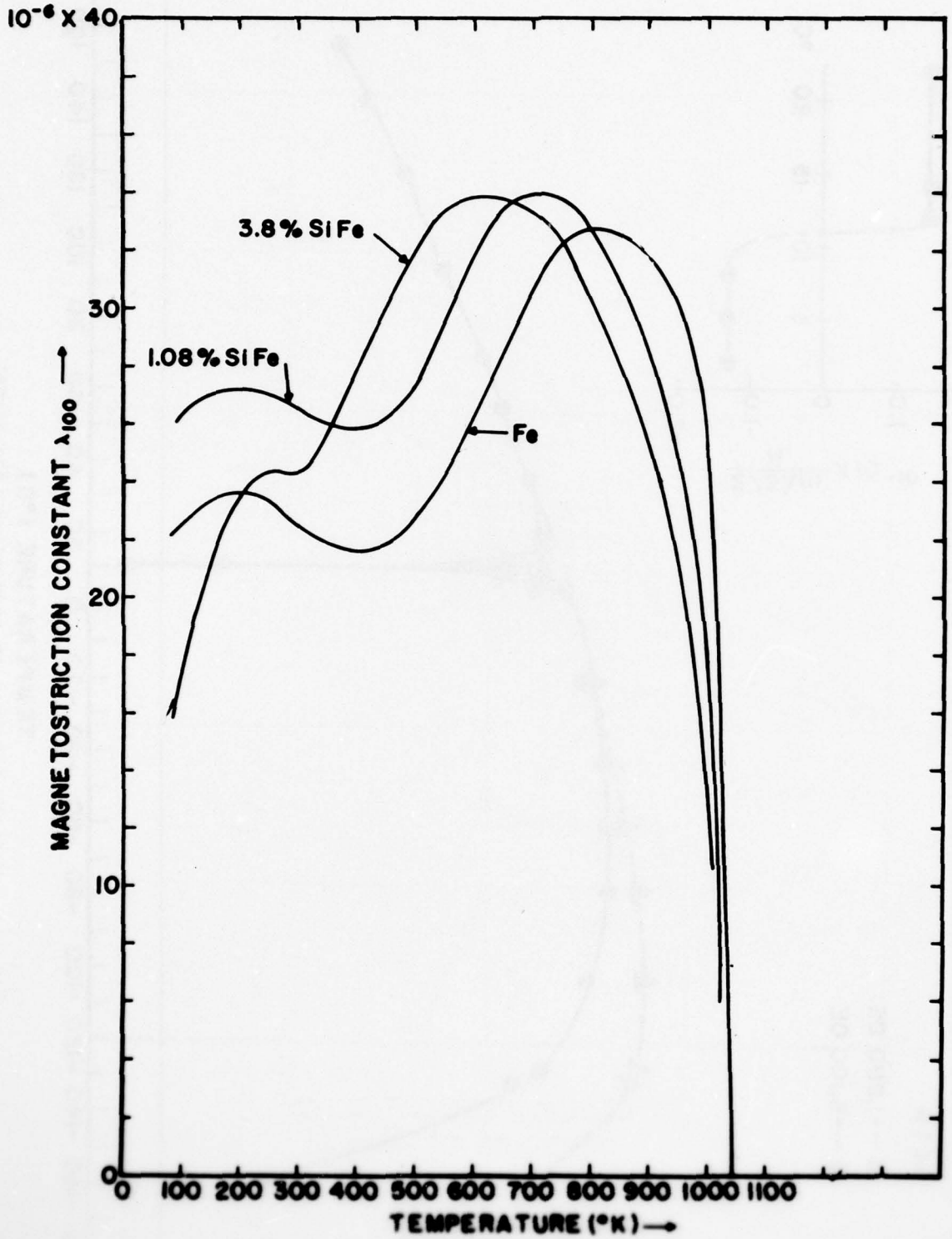

Fig. 5. Magnetostriction of Iron
E. Tatsumoto and T. Okamoto, J. Phys. Soc. Japan 14, 1588 (1959).

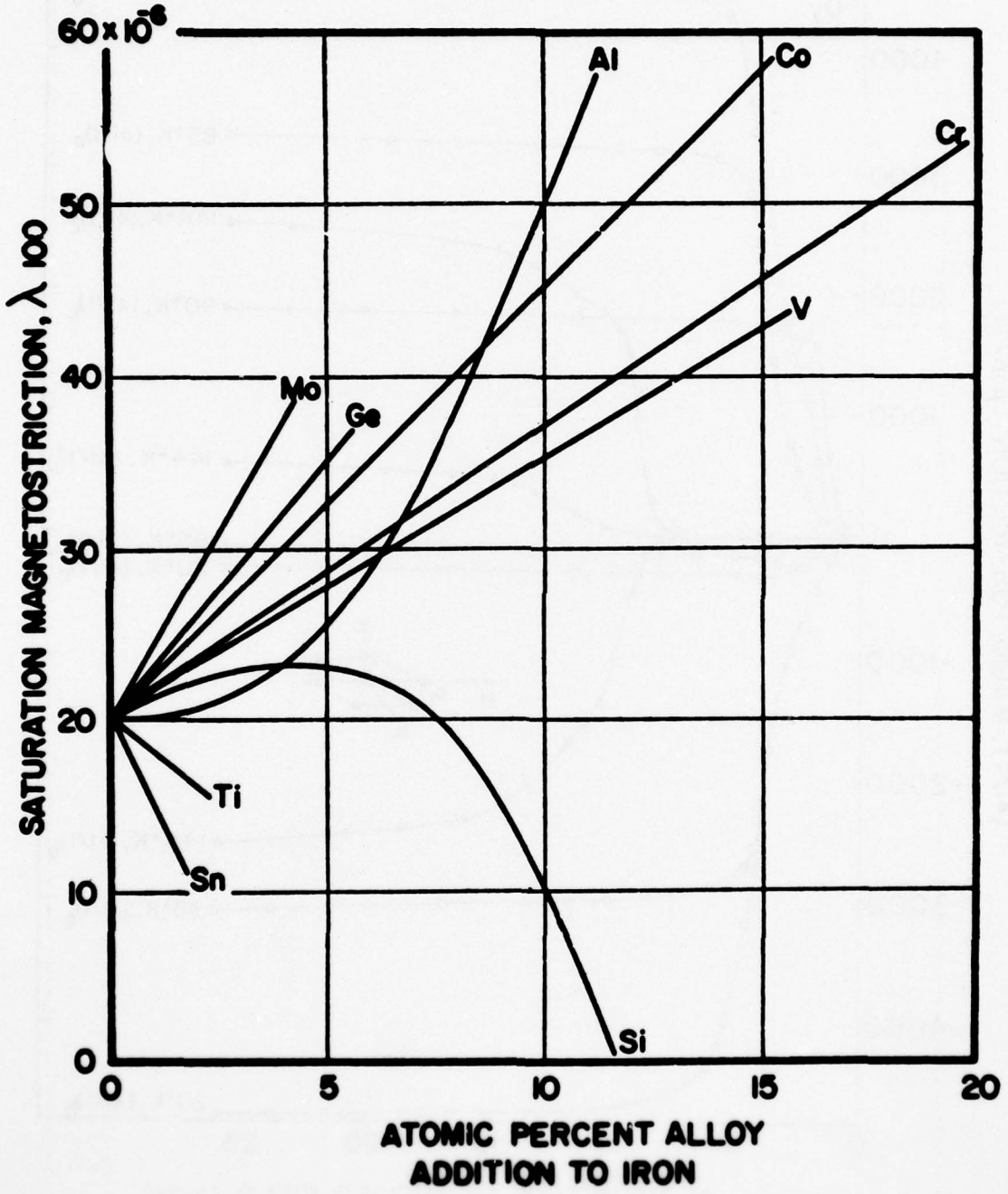

Fig. 6. Effect of alloying on the room temperature magnetostriction of iron. R. C. Hall, J. Appl. Phys. 31, 1037 (1960).

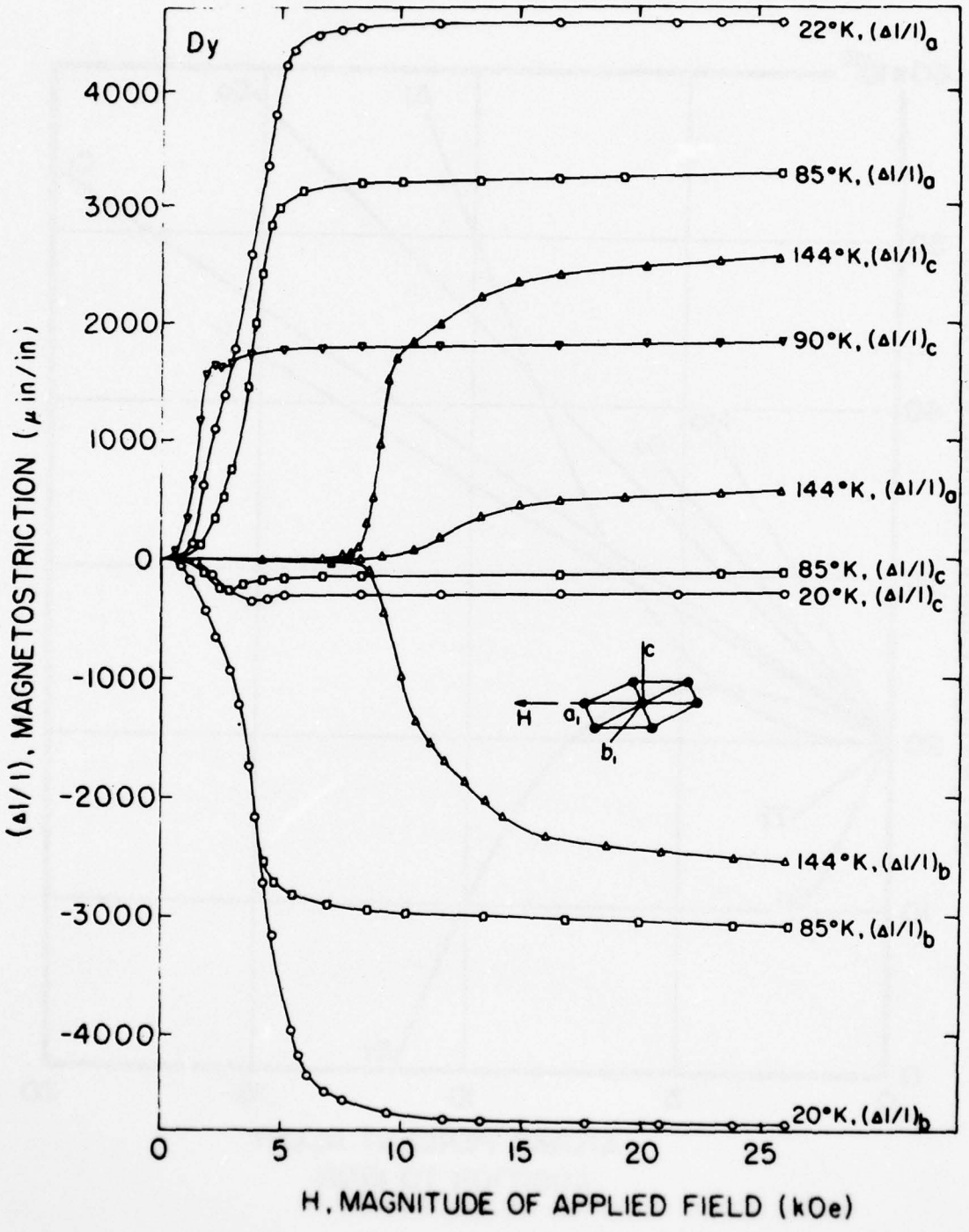

Fig. 7. Field dependence of the magnetostriction of dysprosium. S. Legrold, J. Alstad and J. Rhyne, Phys. Rev. Letters 10, 509 (1963).

MAGNETOSTRICTIVE MATERIAL REQUIREMENTS FOR SONAR TRANSDUCERS

by

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INTRODUCTION

Before we discuss magnetostrictive materials for sonar transducers, it probably would be a good idea to illustrate some of these transducers for those who have not worked with them.

Figure 1 shows a magnetostrictive radially vibrating ring transducer. The rings are made of nickel sheet metal wound in scroll fashion and consolidated with an epoxy cement. The ring vibrates with a uniform breathing motion and radiates sound from both its inside and outside surfaces. Other ring transducers are built with end caps so that only their outside surfaces are exposed to the water and radiate. The free-flooding type shown, however, has the advantages of simplicity, reliability, and the capability of operating at great depths. There is no waterproofing problem other than that of providing wire with good insulation.

Figure 2 shows a much larger ring transducer, which is used for radiating low-frequency sound. It was manufactured by Bendix for the Navy. The ring, which is made of a cobalt-

nickel alloy, weighs six tons and is capable of an acoustic output of 100 kW.

The magnetostrictive metals are constantly in competition with the piezoelectric ceramics for adoption in transducer design. For example, ring transducers may be made of piezoelectric ceramic by cementing a great number of ceramic segments together to form the ring. The metal rings are, of course, much more rugged than the ceramic rings. The ceramic rings suffer the disadvantage of requiring elaborate waterproofing enclosures. On the other hand, the piezoelectric ceramics promise greater power output per pound of active material and other advantages that will be discussed later.

Figure 3 is a schematic illustration of a longitudinally vibrating composite transducer. The resonator consists of two laminated magnetostrictive bars joined at the front to a radiating head and at the rear to a counterbalancing tail mass. Permanent magnets are sometimes incorporated in the structure to provide the dc magnetic bias that is usually desired. However, the reluctance of the magnets seriously degrades the performance of the transducer so that their use is not recommended. Instead a dc current should be provided in the winding. In recent years most transducer designers have chosen piezoelectric ceramics rather than magnetostrictive metals for the active material in longitudinally vibrating transducers.

Figure 4 shows a flexurally vibrating magnetostrictive bar assembly.[1] There are two bars in this assembly, and they flex inwardly and outwardly together, forming a balanced vibrator. Flexural vibrators are advantageous for low-frequency use since they are more compact than extensionally vibrating types. To generate flexural motion it is necessary for the magnetostrictive strains in the opposite sides of a bar to be of opposite polarity. In the arrangement shown, each bar is slotted, and separate windings are put on the two halves of each bar. Then an attempt is made to restore the integrity of the bars by filling the slots with aluminum and epoxy. A simpler method of making a magnetostrictive bender is to use two dissimilar metals, one with positive magnetostriction and one with negative magnetostriction. A composite bar of such materials does not require a winding slot but rather can be excited by a common winding.

Figure 5 shows the competitor of the previous vibrator, namely a piezoelectric ceramic flexurally vibrating bar. Bar transducers of this type, developed by Honeywell, dominate the field, and the magnetostrictive bar has not found any applications. The main reason for this probably is the higher power capability of the ceramic. The piezoelectric bar is composed of two layers in order that opposing stresses may be generated, and each layer is made of many small pieces cemented together. A very important feature is the

steel tie rods that run along each side of the bar. These rods are used to prestress the ceramic in compression. Prestressing in one form or other is used in all modern ceramic transducers, and this technique has gone a long way toward overcoming the low-strength liability of the ceramics.

Ceramic flexural disks, which vibrate like a drumhead, also make good low-frequency transducers. No direct magnetic analog of the piezoelectric flexural disk exists (because of the solenoidal nature of the magnetic field); so the ceramics have this field to themselves.

The magnetostrictive transducers that have been illustrated normally are operated with a bias magnetization, and in this condition they are useful as sound receivers. However, their design is directed toward the production of high-power acoustic output rather than the receiving function. Transducers that are intended only for detecting sound (i. e., hydrophones) are small and easily designed. Magnetostrictive hydrophones are satisfactory, but sonar system designers normally prefer piezoelectric hydrophones because of their flat voltage receiving response below resonance. In this same frequency region, the voltage receiving response of a magnetostrictive hydrophone has a slope of 6 dB/octave.

Only metal magnetostrictors have been considered in the previous discussion. Their ruggedness and shock resistance are

their main selling points. These qualities are lacking in magnetostrictive ferrites. While the ferrites may be somewhat stronger than the piezoelectric ceramics, they bear the same general stigma of fragility and do not seem to have any advantages over the piezoelectrics in other properties.

Low electrical impedance is readily achieved in magnetostrictive transducers, whereas in piezoelectric transducers this is not always easy. High voltages have proved troublesome in some piezoelectric ceramic transducers, and in such cases the lower electrical impedance of a magnetostrictive design is attractive as a way of escaping the voltage difficulties. Of course the current is raised as the voltage is reduced, and this could also prove to be a problem if the cable runs are long.

SMALL-SIGNAL PIEZOMAGNETIC PROPERTIES

The design requirements for sonar transducers usually call for high power at good efficiency over a broad bandwidth about resonance. A fair degree of linearity of the transmission characteristics is also commonly required. Moreover, the transducers must maintain their specified properties over a wide range of hydrostatic pressures and for long times while operating in the hostile environment of the sea.

Although occasional applications arise for magnetostrictors operating in the unbiased frequency-doubling mode, usually the

design requirements make necessary operation with a dc bias magnetization. The transducers then behave as linear transmission systems for small signals, and it is appropriate to call them piezomagnetic transducers, in the same sense that prepoled electrostrictive ceramic transducers are called piezoelectric.

Use of small signal analysis for the design of high-power magnetostrictors is obviously unrealistic; nevertheless, it is useful in the preliminary stages of design. Hence, the small-signal linear piezomagnetic equations will be discussed first, before consideration is given to nonlinear effects. It is also convenient initially to ignore dissipation. Figure 6 shows the piezomagnetic equations of state (or constitutive equations)[2] for a polycrystalline material, which apply when the ac magnetic field is colinear with the dc bias field. If the ac field had a component normal to the dc field, shear strains would be produced piezomagnetically and additional terms would appear in the equations, but this type of exciting field is not used in sonar transducers. In the equations in Fig. 6, S_4-S_6 are shear strains and T_4-T_6 are shear stresses. By convention the x_3 coordinate axis coincides with the direction of the bias magnetization. However, the bias magnetization and the resulting static strain do not appear in the equations; the variables that are shown are the small-signal incremental

values of stress, strain, and field.

The lower-case s-coefficients in the equations of state are elastic moduli measured at constant field intensity, the d-coefficients are piezomagnetic moduli, and μ_{33}^{T} is the incremental permeability measured at constant (or zero) stress. The values of all the coefficients depend on the particular value of the bias magnetization that is chosen for the operating point. There are nine independent coefficients in this set, but in engineering applications they are not all used or measured.

Figure 7 shows the equations of state reduced to the simple form that is adequate for most transducer applications. These equations apply to slender bars or thin rings, in which lateral stress can be neglected. Shearing stresses are also presumed to be absent. We are left with three coefficients that are of practical interest in small-signal transducer design. In addition, we are interested in the density of the material and its resistivity.

The designer is often asked what properties he would prefer in a magnetostrictive material. If we consider only small-signal properties, we can not go very far toward answering this question. Nevertheless, these properties are worth discussing before we go on to the large-signal case. The elastic compliance modulus S_{33}^{H}, together with the

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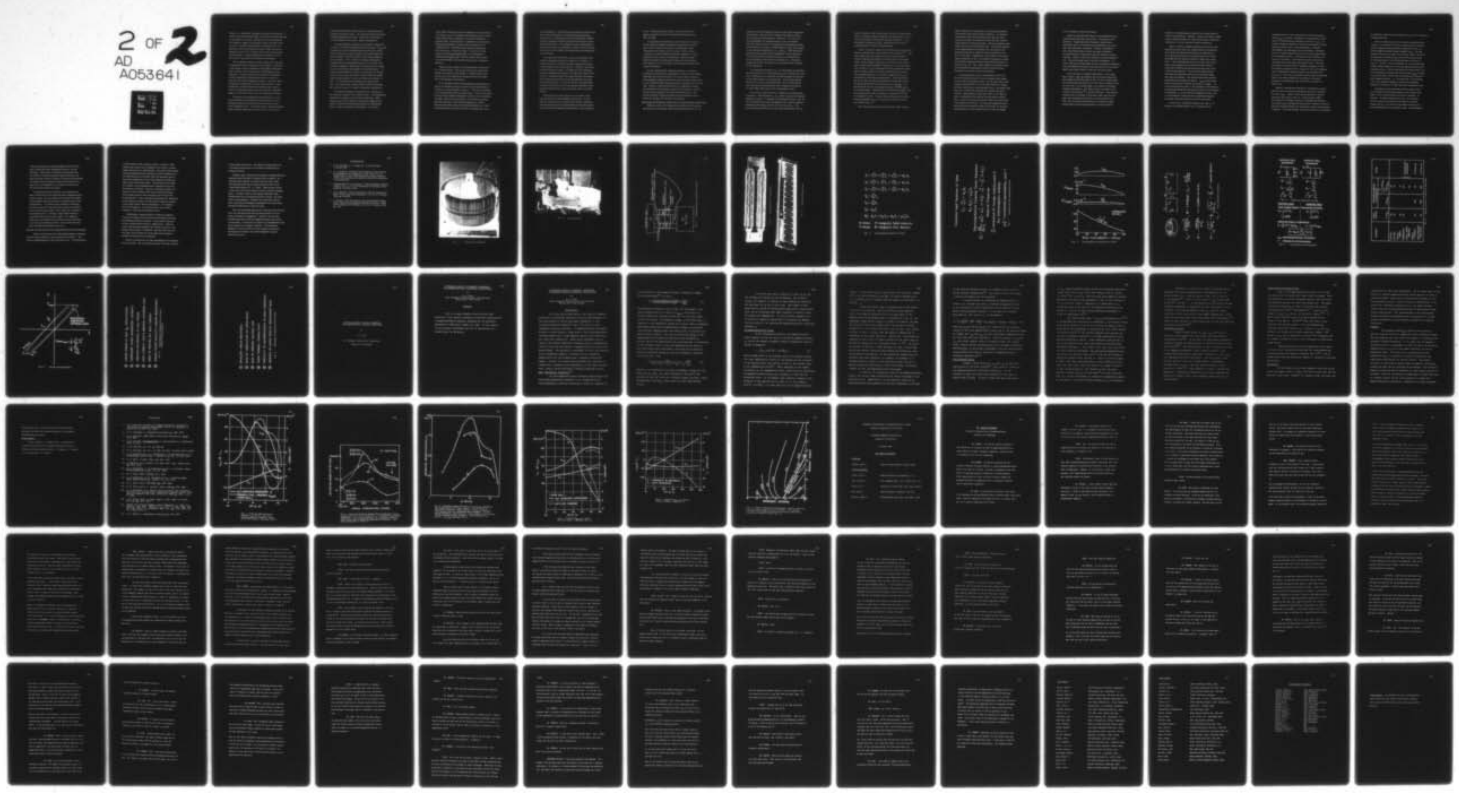

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density ρ, determines the speed of sound in the material. A small sound velocity (large S_{33}^{H}) is sometimes desired because it can result in a compact resonator for a given frequency. For example, suppose one wanted a ring to resonate at 500 Hz in air. A nickel ring would have a diameter of 9.7 ft, whereas a PZT-4 piezoelectric ceramic ring would have a diameter of only 6.1 ft, because of the lower sound velocity of the ceramic. In most applications the smaller size of the ceramic ring would be considered an advantage.

The compliance modulus and the density also determine the specific acoustic impedance of the material. Generally a low specific acoustic impedance (large S_{33}^{H}) is desired because it leads to low mechanical Q, which implies broad bandwidth. It seems that both sound velocity and specific acoustic impedance considerations lead one to prefer a material with a high compliance modulus. However, many exceptions could probably be found to this dictum. In the development of magnetostrictive materials the matter is mostly of academic interest since the molecular engineers appear to have little control over the compliance modulus.

Turning to the incremental permeability μ_{33}^{T}, we note that a high value of permeability would enable us to use a winding with few turns and still achieve the normal electrical impedance level. On the other hand, high permeability tends to produce high eddy current loss; so we would not

want the permeability raised unless the resistivity of the material were also raised. As a practical matter the incremental permeability of nickel, which lies in the range of 30-100 relative to free space, appears satisfactory.

The piezomagnetic modulus d_{33} obviously is desired to be high. In the older magnetostriction literature,[3] d_{33} was considered to be an important figure of merit for a hydrophone, because for a given number of turns the higher the d_{33} the higher would be the open-circuit output voltage of the hydrophone. This concept is no longer emphasized; magnetostrictive hydrophones have gone out of style, and the idea of judging a hydrophone by its open-circuit voltage is now considered an unacceptable oversimplification. To judge the piezomagnetic activity of a material, one should not look at d_{33} alone, but rather combine the three coefficients of the equations of state, as shown in the center of Fig. 7, to yield the electromechanical coupling factor k_{33}. The values of the coupling factor always lie between zero and one; hence, it is easy to judge their significance.

The electromechanical coupling factor is analogous to the coupling coefficient of a mutual inductor. Its fundamental character is brought out by its energy definition: When energy is put into a transducer electrically, k_{33}^2 gives the fraction of the input energy which appears in mechanical form, stored in the elastic displacement. It is thus a

basic index of energy-conversion capability of the transducer. For nickel, $k_{33} \simeq .3$ at optimum bias whereas for the cobalt-nickel alloys values exceeding .5 have been obtained at optimum bias. Most aspects of a transducer's performance (especially bandwidth) improve with an increase in the coupling factor. Relations among material parameters also involve k_{33}, as shown in Fig. 7: the factor $(1-k_{33}^2)$ relates the free permeability μ_{33}^T to the longitudinally clamped permeability $\mu_{33}^{S_3}$, and the constant-field compliance modulus S_{33}^H to the constant-flux-density compliance modulus.

Figure 8 gives values of the piezomagnetic parameters for annealed nickel. The curves show the way these parameters vary with bias flux density. Evidently these parameters can not be treated as constants unless the swing of the ac flux density is kept small.

As an example of how the piezomagnetic parameters are used in a transducer design, we show an electromechanical circuit for a ring transducer in Fig. 9. The ring is assumed to be vibrating with uniform radial motion. The circuit relates the electrical variables voltage and current to the mechanical variables radial velocity and force. The classical analogy has been used here, with velocity analogous to current. Starting at the left we have the blocked inductance L_b, which is determined by the number of turns, the dimensions, and

the permeability. The electrical and mechanical portions of the circuit are coupled by an electromechanical gyrator, whose ratio a is determined by the piezomagnetic modulus and the compliance modulus along with the number of turns and the dimensions. The compliance C_M is determined by the dimensions and the compliance modulus of the material. The mass M of the vibrator is determined by the dimensions and the density.

The right-hand side of the circuit is terminated in the radiation impedance when the transducer is in water. It is then possible to calculate the small-signal performance of the transducer by circuit analysis. However, the circuit as shown omits all losses. A mechanical loss resistance should be estimated and added to the right-hand mesh of the circuit. The eddy-current loss angle should be calculated from lamination thickness and the permeability and resistivity of the material. To account for this calculated eddy-current loss in the circuit, one would add resistance to the left-hand mesh and also make the gyrator ratio a complex number.

The equivalent circuit analysis is also useful in the measurement of the piezomagnetic parameters. In this case one would construct a small ring resonator and determine the equivalent circuit parameters from measurements of the electrical impedance characteristics of the resonator

in air. Then the formulas in Fig. 9 could be used in an inverse manner to solve for the material parameters d_{33}, S_{33}^{H}, and $\mu_{33}^{S_3}$.

An important consideration in sonar transducer design is the fact that the radiation impedance terminating the transducer circuit usually varies over a considerable range. Transducers are usually used in arrays, and the acoustic interactions cause the effective radiation impedance of each transducer in the array to be different. Optimum design therefore implies maximizing the transducer performance with respect to a set of acoustic load impedances rather than a single impedance.

For the longitudinally vibrating transducer, an electromechanical circuit may be obtained also, but it is more complicated than the one shown here for the ring in that it contains transcendental impedance functions in the mechanical part of the circuit rather than the lumped-parameter elements shown for the ring. However, approximations for the longitudinal vibrator are possible for the frequency region about resonance, and the circuit is then reduced to the same form shown here. The relations between material properties and transducer performance are similar for both types of vibrators.

MATERIAL PROPERTIES RELEVANT TO HIGH-POWER OPERATION

Although a study of the high-power operation of transducers will take us into the realm of the nonlinear phenomenon, we can

initially use linear transducer theory to gain some insight into the problem. Figure 10 shows standard equivalent circuits for a transducer operating near resonance. The circuit on the right applies to a magnetostrictor, and it is obtained from the circuit of Fig. 9 by subjecting the mechanical impedance elements to a gyrator transformation so that they emerge as the electrical elements L_z, C_z, and R_z. These electrical elements make up the motional impedance of the transducer. The objective of the present discussion is to maximize the power dissipated in the motional resistance R_z. Except for mechanical losses, this power is the acoustic power radiated by the transducer.

To maximize the power in R_z, it is necessary to maximize the energy stored in the inductances L_b and L_z during the course of the vibration cycle, and these storable energies are limited by the characteristics of the material. The motional energy storable in L_z has a mechanical limit, due to metal fatigue, but it also has an electrical limit due to magnetic saturation. It is this latter limit that we will concentrate on first.

The circuit on the left in Fig. 10 applies to a piezoelectric transducer. The elements C_y, L_y, and R_y make up the motional admittance branch. By analogy to the magnetostrictive case, we wish to maximize the power dissipated in R_y, and this requires maximizing the energy cyclicly stored in C_b and C_y. The motional energy storable in C_y has a mechanical limit, due to

ceramic fracture, and an electrical limit due to voltage breakdown or excessive dielectric heating. The equations in Fig. 10 show the relations of the angular resonant frequency ω_r, the mechanical storage factor Q_m, and the electromechanical coupling factor k to the circuit parameters.

Figure 11 shows an equation for electrically limited power, which is obtained from the equivalent circuit analysis[4]. This limit applies when the vibrators are so heavily damped by acoustic radiation that fatigue or fracture does not manifest itself. Heavy loading of this type is common in sonar transducers when broad bandwidth is specified. In the power equation, the factor η_{ma} is determined by the mechanical losses, and it is kept as high as possible by minimizing the losses. The resonant frequency ω_r and the storage factor Q_m are determined by the design specifications. The properties of the active material that are of primary importance in determining the power show up in the factors U_e and $\frac{k^2}{1-k^2}$. U_e is the maximum electric (or magnetic) energy storable in the blocked reactance. Multiplication of this energy by $\frac{k^2}{1-k^2}$ gives the energy that has been converted to mechanical form and is available for work. Values of this mechanically available energy (designated U_{em}) for materials of current interest are shown in Fig. 12.

If we look in the second column from the right, we find

figures which give a comparison of the power potentiality of materials under field-limited conditions. According to these figures the common piezoelectric material (lead titanate zirconate) is enormously better than the common magnetostrictive material (nickel). Several qualifying statements must be made about these data. The energy densities of the magnetostrictive materials are calculated on the assumption that the ac signal drives the material all the way to saturation. Dependence of the results on the small-signal parameters k and μ is avoided by employing instead the saturation magnetostriction (and using the formula included in Fig. 13). Thus, these values are ultimate values, and considerable nonlinearity would be observed if the materials were driven as hard as indicated.

In the piezoelectric case a driving field of 4 kV/cm for lead titanate zirconate is not an ultimate value; higher values could conceivably be used. On the other hand, some designers feel that 4kV/cm is too high a field for reliable operation under many circumstances; hence, one might argue that the 650 joules/m^2 listed for this material should be reduced. Specifically if a high duty cycle or CW signal is used, the heating of the ceramic would probably necessitate a reduction in field (and a power reduction proportional to the square of the field). Of course the magnetostrictive materials will also heat up under CW driving, but the good heat conductivity of the metals will be to their advantage

in any comparison with the ceramics.

Figure 12 indicates that there are two magnetostrictive materials that are better than nickel. On the basis of its saturation magnetostriction Permendur should have a high power limit, but little has been published on its actual use under high power conditions. Russian investigators have reported that Alfer can have as high a saturation magnetostriction as Permendur when the material is grain oriented. Again, no data are available on actual transducer use. These materials deserve further investigation. Of course they have disadvantages as well as potential advantages. They are difficult to prepare, and they lack the noncorrosive quality that makes nickel so ideal for use in sea water.

If the transducer is lightly loaded (that is, has a high Q_M in water), then the material may be stress-limited and the ranking of materials given in Fig. 12 will no longer apply. The mechanically limited power for the various materials does not vary over a very great range, on the basis of presently available information. The fatigue limit of annealed nickel is reported by Kikuchi [5] to be about 6000 psi. Piezoelectric ceramics have a strength in this same range when they are used with compressive prestress, as they normally are. Thus, the two classes of materials are on about an equal footing when stress-limiting prevails, and the ceramics

might be at a disadvantage because of the complications involved in prestressing. However, whereas the lightly loaded (stress-limited) condition is often encountered in industrial ultrasonics, it is not common in sonar transducers.

Figure 13 shows a diagram devised by Kikuchi for displaying the power limits of a magnetostrictive transducer. The results obtained from this figure are equivalent to those already presented, but the graph helps one to gain an insight into the operating mode of a high-power transducer. The closed figures show loci in the stress-strain plane of the magnetostrictive material which could be traversed in withdrawing mechanical energy from a unit volume of the material. The area of the quadrilateral represents the maximum amount of mechanical energy that could be obtained. The symbols associated with the quadrilateral are defined as follows. T_{max} is the stress limit of the material imposed by fracture or fatigue. T_b is the blocked stress, that is, the maximum stress that can be generated magnetostrictively when motion of the material is prevented. λ_s is the saturation magnetostriction, that is, the maximum strain that can be generated magnetostrictively when the material is free of constraints.

To carry out a maximum-energy cycle, that is, to operate on the quadrilateral locus, switching of the

magnetization from zero to saturation would be necessary when T_{max} is reached. Similarly, the magnetization would have to be switched from saturation to zero at $-T_{max}$. In actual transducer operation it would not be feasible to follow this quasi-static locus. If the transducer is vibrating sinusoidally, the operating locus is an ellipse. Maximum power is obtained when the ellipse fills out the quadrilateral to the maximum extent. To bring about this condition, two steps are necessary. The frequency must be adjusted to resonance to give the ellipse the proper slope. Then, with the transducer being driven to magnetic saturation so that the ellipse is tangent to the $B = B_{sat}$ line, the load resistance must be adjusted so that the ellipse is also tangent to the T_{max} line. The locus in the stress-strain plane at maximum power is the same whether the transducer is operated polarized or unpolarized; thus, the power is the same in either case.

Figure 13 includes the formula for computing the energy that has been converted to mechanical form and is available for work, U_{em}. Values of this energy density for various materials were given in Fig. 12. In the formula, S_{33}^{H} is the reciprocal of Young's modulus at constant field intensity. The energy U_{em} is defined for quasi-static conditions, whereas Kikuchi's diagram displays the mechanical energy under dynamic conditions. The latter energy, found from the area of the ellipse,

is obtainable analytically by multiplying U_{em} by the mechanical storage factor Q_M.

Since for maximum power we want the largest possible ellipse, it is clear that we want a magnetostrictive material with the highest possible saturation magnetostriction λ_s and the highest possible fatigue strength T_{max}. Once the material has been provided, the next step, ideally, would be to design for the optimum Q_M such that the ellipse would fill the quadrilateral to the maximum extent as shown in Fig. 13. However, other considerations, such as bandwidth, usually dictate design for a lower Q_M than that which would maximize power. Then the transducer is field-limited, and in the diagram the ellipse does not reach the T_{max} boundary. The limit on power in this case is determined by the saturation magnetostriction λ_s. It follows that, at the present time, the transducer designer's plea to the molecular engineer is primarily for high saturation magnetostriction.

Although the most important material requirements are revealed by the Kikuchi diagram in the stress-strain plane, the B-H characteristics are also, naturally, of interest. To keep hysteresis loss low, we would like the B-H loop to be as narrow as possible; to keep the copper loss low, we would like the slope of the loop (i.e., the permeability) to be reasonably large. The importance

of these considerations becomes apparent when we scan tables listing saturation magnetostriction for various materials. High values of saturation magnetostriction are listed for certain permanent magnet materials, but these materials would be useless in transducer applications. The field intensity required to approach saturation is so large and is accompanied by such large coercive force, that the losses would be enormous.

In specifying an ideal material, the transducer designer would like not only high-saturation magnetostriction and low losses, but also linearity of the input and transfer characteristics when the material is operated with a bias magnetization. A nonlinear input impedance (reflecting curvature in the B-H characteristics) presents a difficult load to the driving amplifier, often requiring a derating of the amplifier power. Nonlinear input/output relations cause distortion in the acoustic signal. In a high-Q_M transducer such effects are not serious because the transducer acts as a mechanical filter, but in broad band operation objectionable distortion can occur.

REVIEW OF THE STATUS OF MAGNETOSTRICTIVE MATERIALS

Figure 14 summarizes the main disadvantages of magnetostrictive metals relative to the piezoelectric ceramics. The first two disadvantages are the most basic ones. The significance

of the distortion level is hard to assess. However, high fidelity may receive more emphasis in the future, if sonar signals become more sophisticated. The eddy current losses endowed magnetostrictive transducers with a reputation for low efficiency back in the days when the emphasis was on ultrasonic frequencies, but in audio frequency transducers these losses can be kept small. The hysteresis loss tends to be higher in the magnetostrictive materials than in the ferroelectric ceramics. However, the balance tends to be restored if one includes in the loss reckoning the losses of the tuning reactors which normally must be used with the transducers. Thus, although the piezoelectric transducer avoids copper loss and core loss, these losses are present in the tuning inductor that accompanies it. The magnetostrictive transducer, on the other hand, uses a tuning condenser, which has low dielectric loss.

Traditionally, requests that dc currents be supplied to bias the transducers are looked on with disfavor by those providing the electronic systems. The dc power required is only a small fraction of the ac signal power. However, chokes and blocking condensers are usually necessary, and perhaps extra wiring. In addition, when the cable runs are very long, the dc power lost in the cable may be large if straight dc transmission is employed.

Figure 15 summarizes the main advantages of the magnetostrictive metals. All, except the last item, have been covered

in the earlier discussion. The absence of aging effects is a dividend accruing from our reluctant investment in dc biasing circuitry.

Finally, some comments on progress in magnetostrictive materials from the user's viewpoint will be offered. My feeling is that progress in recent years has been small. The principal event was the announcement in 1956 of the cobalt-nickel alloys by C. A. Clark. These alloys seemed to have a lot of promise because of their increased coupling factor. However, when it was realized that their field-limited power was no greater than that of nickel, our enthusiasm was diminished. Whether the cobalt-nickel alloys have a pronounced advantage in bandwidth over nickel when operated at high power is still not clear.

The most promising approach for securing improvements from the presently known alloy systems appears to lie in grain orientation investigations. However, for any real breakthroughs that would put magnetostriction in a position of supremacy, we must pin our hopes on the fundamental work that is going on in magnetic research. The transducer designer is not in a position to know whether such breakthroughs are imminent, but will be delighted to exploit them if they occur.

REFERENCES

1. R. S. Woollett, U. S. Patent No. 3,174,130 issued 16 March 1965.

2. S. L. Ehrlich, "Proposal of Piezomagnetic Nomenclature for Magnetostrictive Materials," Proc. IRE, vol. 40, August 1952, p. 992. IEEE Standards including equations of the form used here (introduced by Ehrlich) are expected to be issued soon.

3. "Magnetostriction Transducers," National Defense Research Council, Div. 6, vol. 13, Department of Commerce Clearinghouse, PB 77669, 1946.

4. R. S. Woollett, "Power Limitations of Sonic Transducers," IEEE Trans. Sonics and Ultrasonics, vol. SU-15, October 1968, pp. 218-229.

5. Y. Kikuchi, "The Theoretical Limit of Mechanical Output Power Available from Magnetostriction Vibrators," IEEE Trans. Sonics and Ultrasonics, vol. SU-15, January 1968, pp. 1-12.

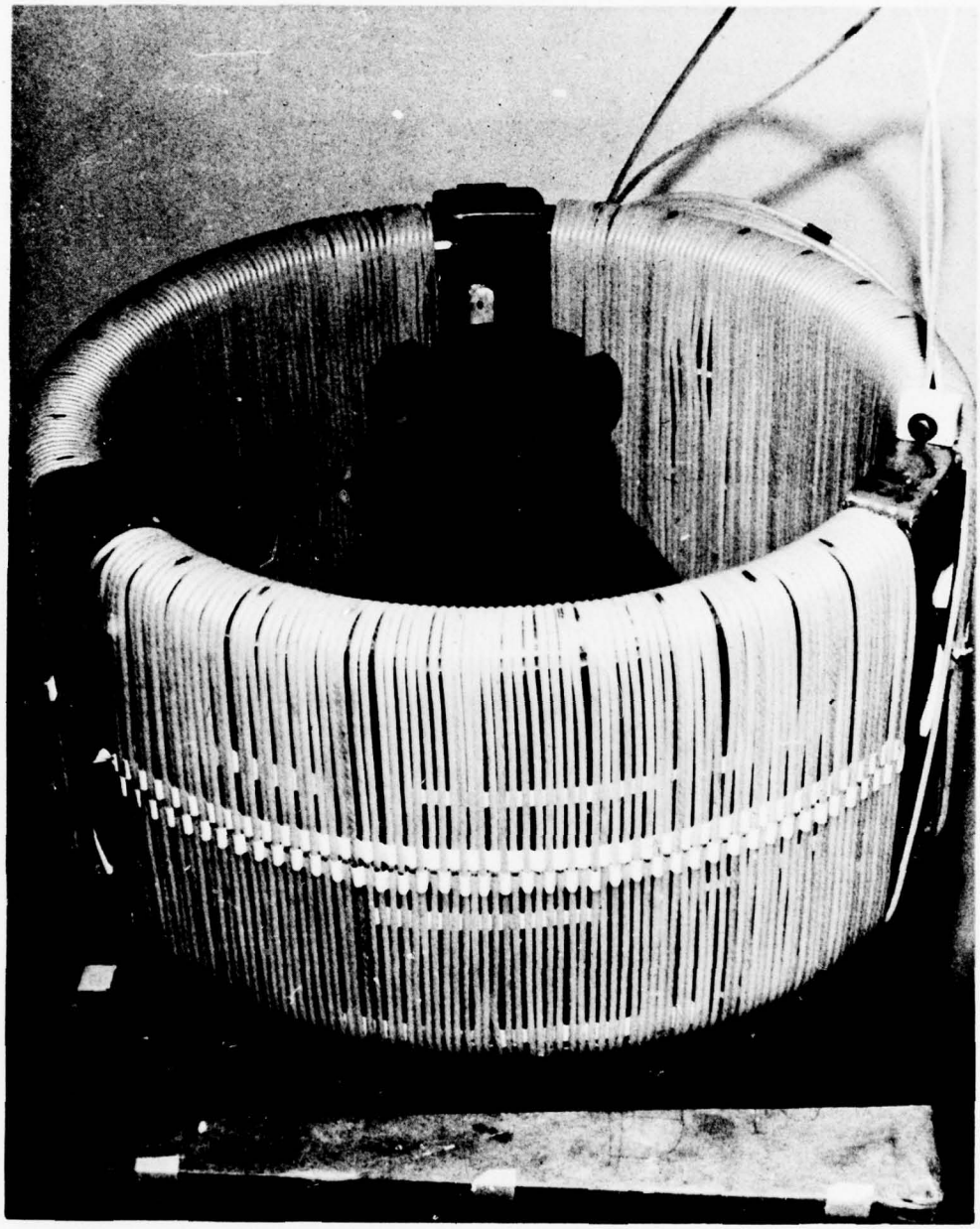


Fig. 1 Twin Scroll Transducer

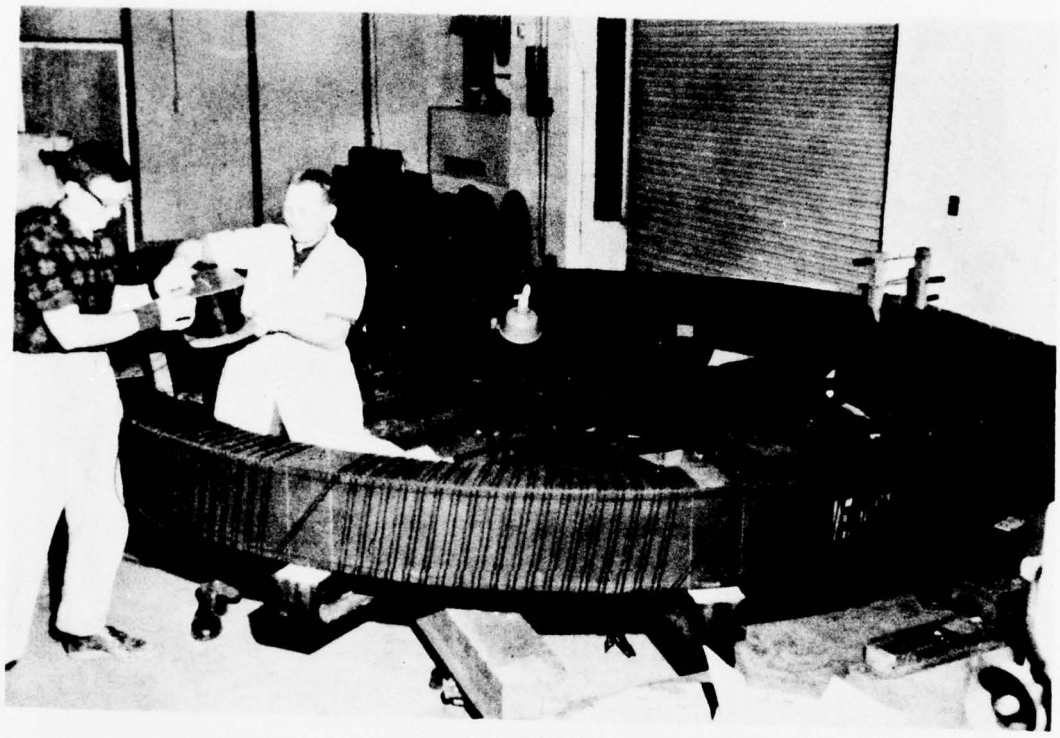


Fig. 2 Six-ton Scroll

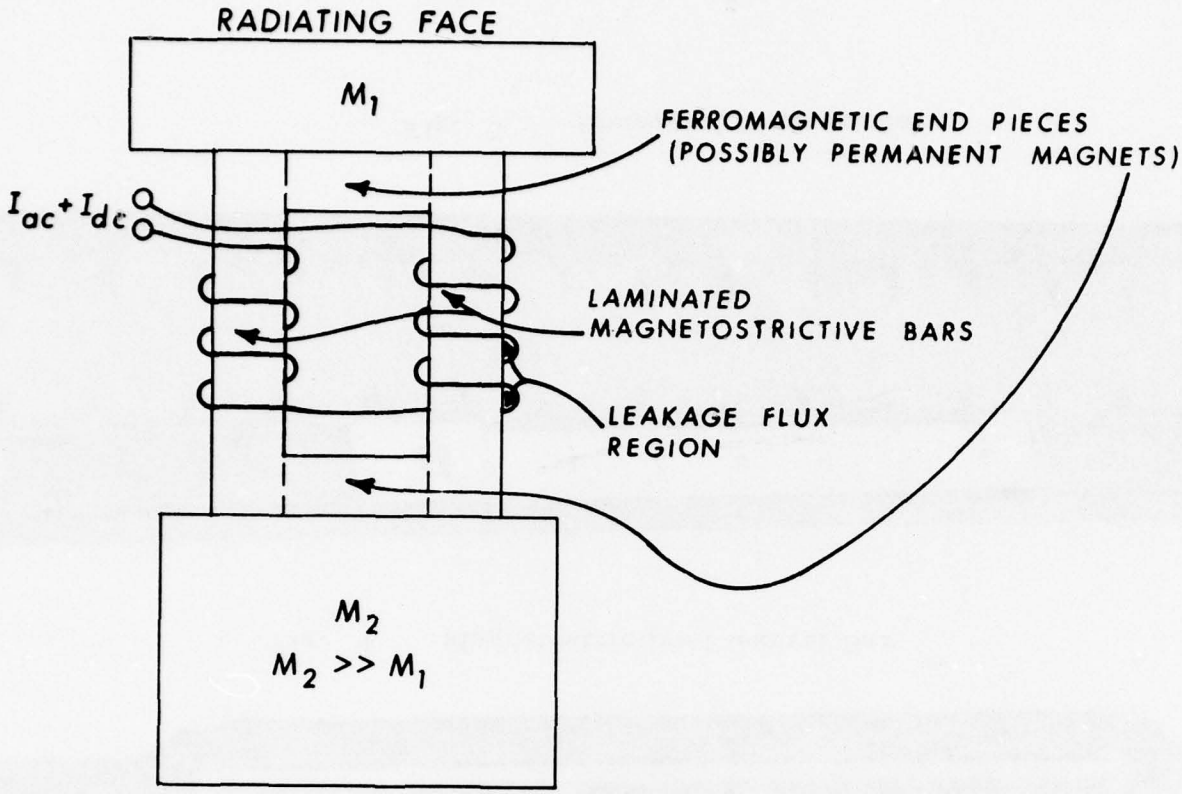


Fig. 3 Magnetostrictive Longitudinal Vibrator

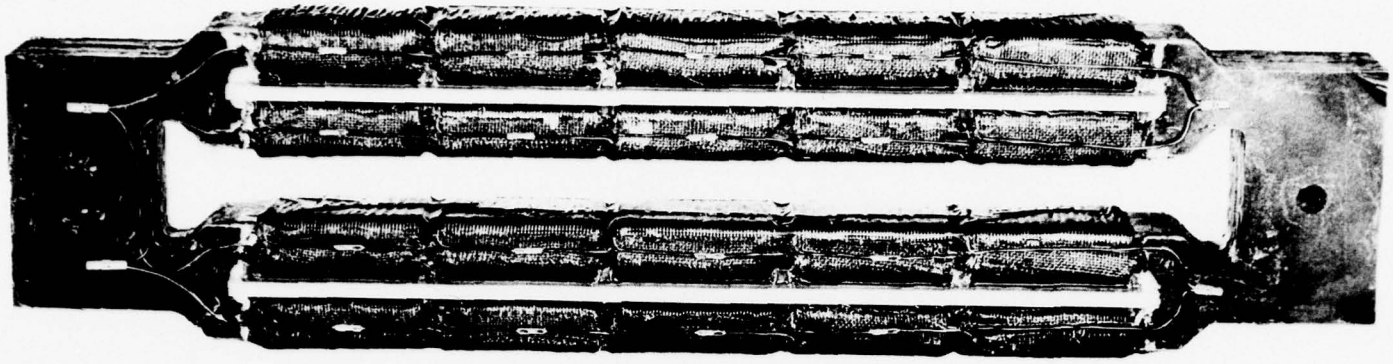


Fig. 4 Magnetostrictive Flexural Bar

Fig. 5 Honeywell Flexural Bar

$$S_1 = s_{11}^H T_1 + s_{12}^H T_2 + s_{13}^H T_3 + d_{31} H_3$$

$$S_2 = s_{12}^H T_1 + s_{11}^H T_2 + s_{13}^H T_3 + d_{31} H_3$$

$$S_3 = s_{13}^H T_1 + s_{13}^H T_2 + s_{33}^H T_3 + d_{33} H_3$$

$$S_4 = s_{44}^H T_4$$

$$S_5 = s_{44}^H T_5$$

$$S_6 = s_{66} T_6$$

$$B_3 = d_{31} T_1 + d_{31} T_2 + d_{33} T_3 + \mu_{33}^T H_3$$

S = strain H = magnetic field intensity

T = stress B = magnetic flux density

Fig. 6 Piezomagnetic Equations of State

Commonly Used Equations of State

$$S_3 = s_{33}^H T_3 + d_{33} H_3$$

$$B_3 = d_{33} T_3 + \mu_{33}^T H_3$$

Electromechanical Coupling Factor Equations

$$k_{33}^2 = \frac{d_{33}^2}{s_{33}^H \mu_{33}^T}, \quad \mu_{33}^{S_3} = \mu_{33}^T (1 - k_{33}^2), \quad s_{33}^B = s_{33}^H (1 - k_{33}^2)$$

Material Properties

s_{33}^H = reciprocal of Young's modulus, const H

d_{33} = piezomagnetic modulus

μ_{33}^T = incremental permeability, const T

Fig. 7 Equations for One-Dimensional Stress

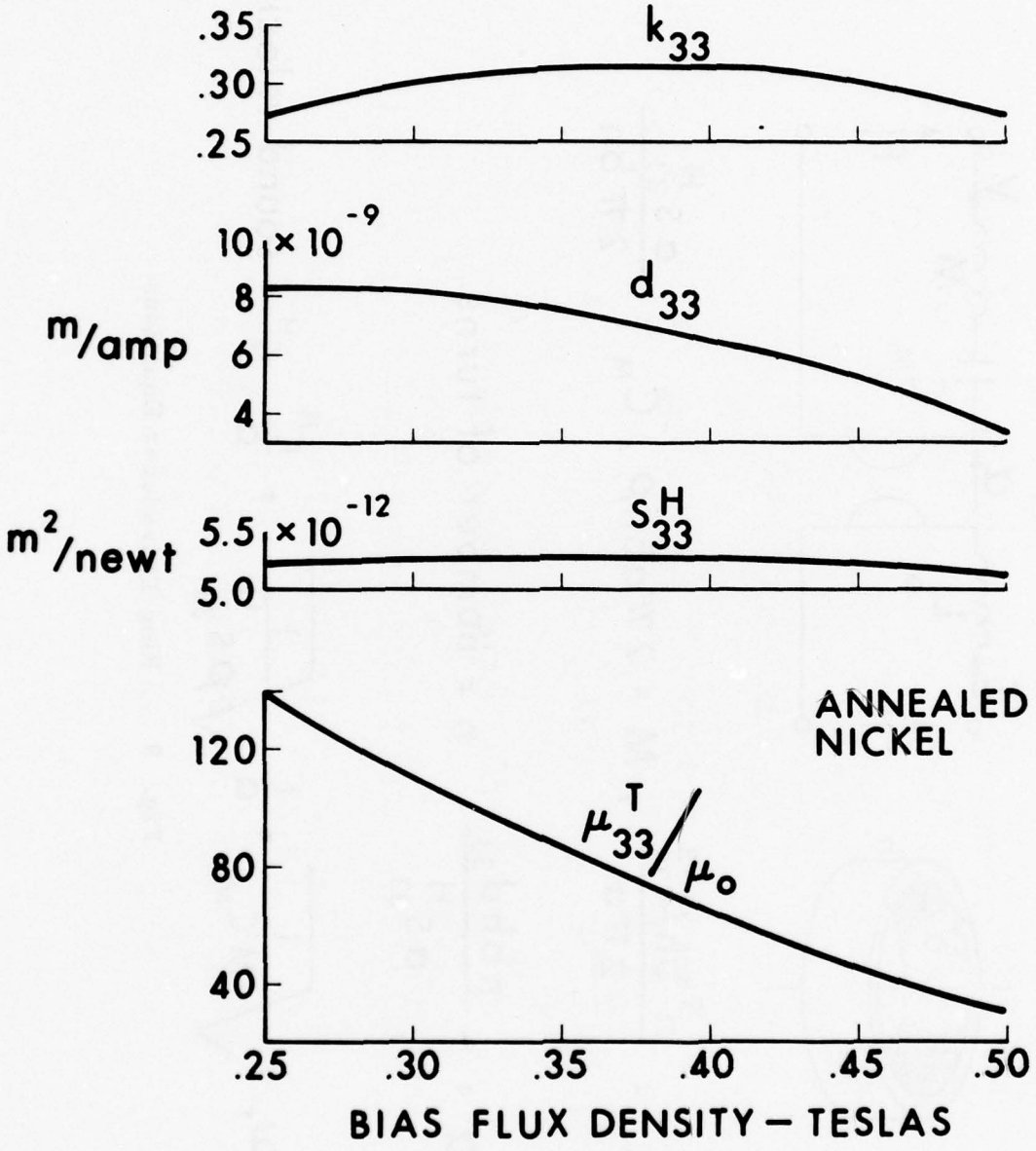
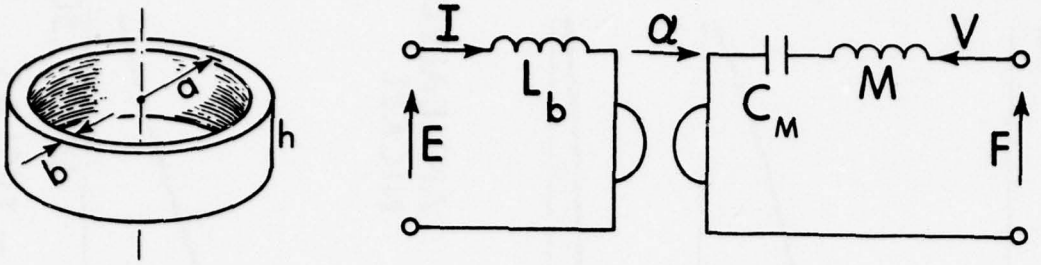


Fig. 8 Piezomagnetic Parameters for Nickel



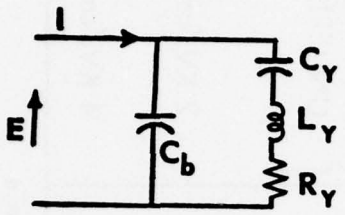
$$L_b = \frac{n^2 bh\mu_{33}^{S_3}}{2\pi a}, \quad M = 2\pi abh\rho, \quad C_M = \frac{a\, S_{33}^{H}}{2\pi bh}$$

$$\alpha = -\frac{nbhd_{33}}{a\, S_{33}^{H}} \qquad n = \text{number of turns}$$

$$\omega_r = \sqrt{\frac{1}{MC_M}} = \frac{1}{a}\sqrt{\frac{1}{\rho S_{33}^{H}}} = \frac{C^H}{a}, \quad C^H = \text{sound velocity}$$

Fig. 9 Ring Transducer Equations

ELECTRIC FIELD TRANSDUCER

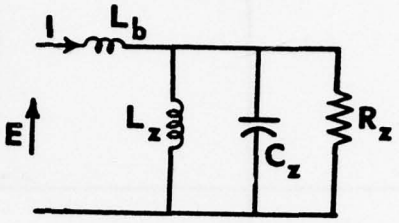


$$\omega_r^2 = \frac{1}{L_Y C_Y}$$

$$Q_M = \frac{1}{\omega_r C_Y R_Y}$$

$$\frac{k^2}{1-k^2} = \frac{C_Y}{C_b}$$

MAGNETIC FIELD TRANSDUCER



$$\omega_r^2 = \frac{1}{C_z L_z}$$

$$Q_M = \frac{R_z}{\omega_r L_z}$$

$$\frac{k^2}{1-k^2} = \frac{L_z}{L_b}$$

Fig. 10 Electrical Equivalent Circuits

ELECTRIC FIELD	**MAGNETIC FIELD**
PEAK STORED ENERGY, TRANSDUCER BLOCKED:	
$U_e = \frac{1}{2} \lvert E \rvert^2 C_b$	$U_e = \frac{1}{2} \lvert I \rvert^2 L_b$
$= \frac{1}{2} \epsilon_b \mathcal{E}_p^2 V$	$= \frac{1}{2} \mu_b H_p^2 V$
RADIATED POWER AT RESONANCE:	
$P_r = \left(\frac{1}{2} \lvert E \rvert^2 / R_Y\right) \eta_{ma}$	$P_r = \frac{1}{2} \lvert I \rvert^2 R_z \eta_{ma}$

$$\boxed{P_r = \eta_{ma} \omega_r \frac{k^2}{1-k^2} Q_M U_e}$$

η_{ma} = MECHANOACOUSTICAL EFFICIENCY

V = VOLUME OF ACTIVE MATERIAL

Fig. 11 The Electrical Limit Equation

MATERIAL	COUP. FACTOR	ESTIMATED ENERGIES IN JOULES/m^3		NOTES
	$k = k_{33}$	$(Ue)_{max}$	$\frac{k^2}{1-k^2}(Ue)_{max} = (Uem)_{max}$	
NICKEL	.30		27	
4% CoNi	.40		23	
NICKEL FERRITE	.40		17	
PERMENDUR	.29		110	PRACTICALITY UNVERIFIED
ALFER, GRAIN ORIENTED			110	PRACTICALITY UNVERIFIED
BARIUM TITANATE	.45	340	86	2 KV/cm rms
LEAD TITANATE ZIRCONATE	.62	1000	650	4 KV/cm rms

Fig. 12 Energy Limits of Transducer Materials

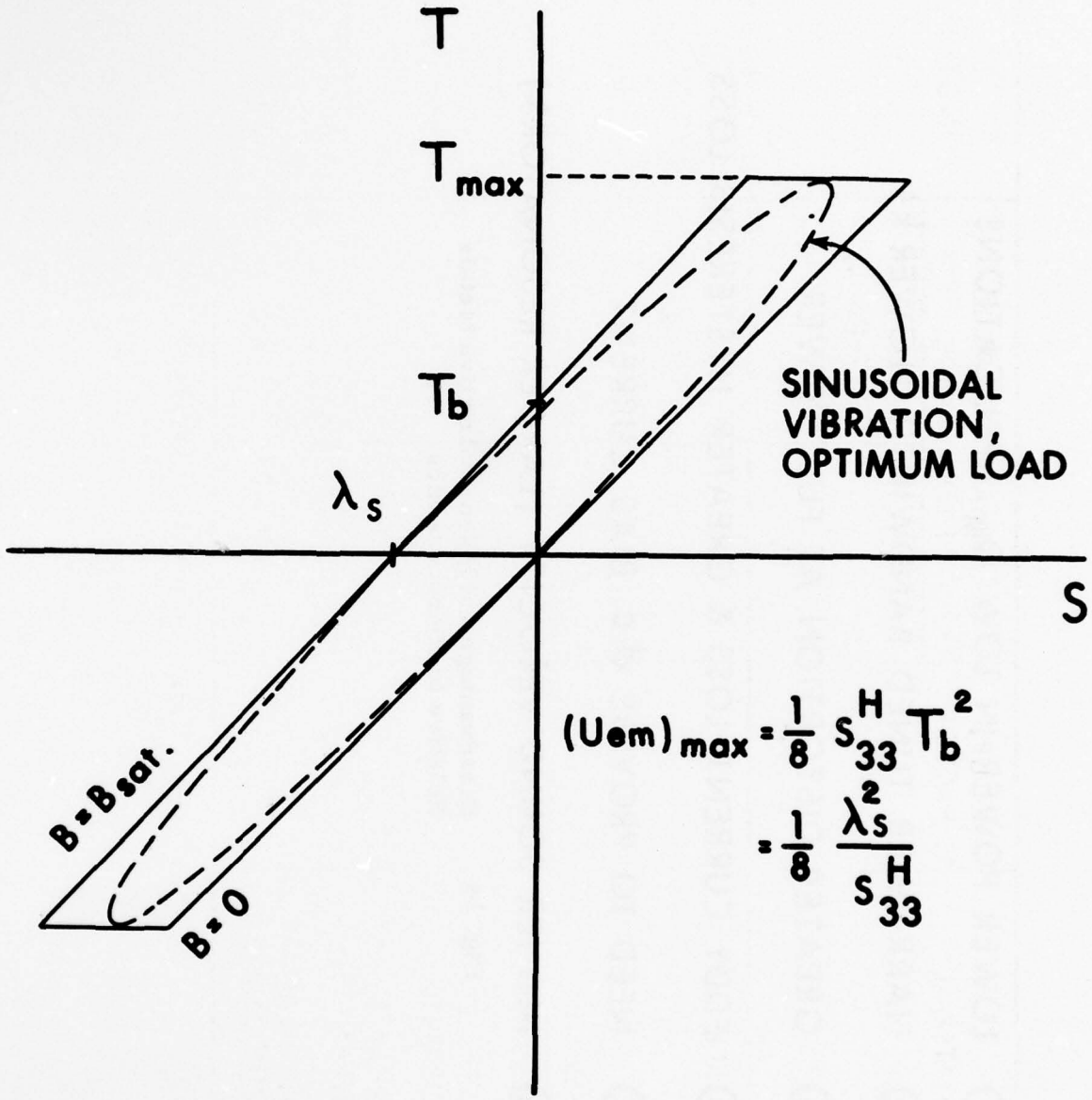


Fig. 13 Kikuchi Energy Diagram

① LOWER POWER IN LOW Q_M APPLICATIONS

② NARROWER TUNED BANDWIDTH (LOWER k)

③ GREATER DISTORTION AT FULL POWER

④ EDDY CURRENT LOSS & GREATER HYSTERESIS LOSS

⑤ NEED TO PROVIDE d.c. BIAS CURRENT

⑥ HIGHER SOUND VELOCITY (LARGER RESONATORS)

Fig. 14 Disadvantages of Magnetostrictive Metals Relative to Piezoceramics

① EXCELLENT SHOCK RESISTANCE

② EASE OF FABRICATION OF LARGE RINGS

③ EASE OF KEEPING VOLTAGE LOW

④ GOOD THERMAL CONDUCTIVITY

⑤ SIMPLICITY OF WATERPROOFING (IF NON-CORROSIVE)

⑥ ABSENCE OF AGING EFFECTS (MAINTAINED BIAS)

Fig. 15 Advantages of Magnetostrictive Metals

PROCESSING CONTROL OF MAGNETIC PROPERTIES FOR MAGNETOSTRICTIVE TRANSDUCER APPLICATIONS

by

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Bell Telephone Laboratories, Incorporated

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ABSTRACT

This is a paper adapted from an invited talk delivered at the regional workshop on Scientific Opportunities in Magnetomechanical Systems, sponsored by the Scientific Department of ONR Boston, August 25, 1969. It will appear in the workshop proceedings and will be distributed on a limited basis by ONR Boston.

PROCESSING CONTROL OF MAGNETIC PROPERTIES FOR MAGNETOSTRICTIVE TRANSDUCER APPLICATIONS

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INTRODUCTION

As in any device application, the control of material properties by processing requires a detailed understanding of the relationship of device performance parameters to the structure-sensitive properties, and of the latter to the fundamental material constants. In magnetostrictive transducer devices, we often desire a large value of the electromechanical coupling coefficient, a high magnetic quality, good efficiency, and large power capability. These device parameters are related to the dynamic hysteresis properties such as permeability, coercive force and the response of magnetostrictive strain to an applied field. The hysteresis properties, in turn, are governed by the fundamental magnetic constants such as saturation magnetization and the various types of magnetic anisotropy energy. Finally, by knowing these constants as a function of composition, orientation and temperature, we can then, and only then, optimize device performance through processing control.

Magnetomechanical Parameters[1]

For most magnetostrictive transducer applications, the chief magnetomechanical parameter to be considered is the electromechanical coupling coefficient k, which is a measure of

the conversion of the magnetic energy to mechanical energy. Following Brockman[2], we write

$$k^2 \propto \frac{\text{stored mechanical energy}}{\text{stored magnetic energy}} \equiv \frac{w_{mech}}{w_{mag}} \qquad (1)$$

The mechanical energy per unit volume, for the example of an axially magnetized rod, is equal to $w_{mech} = E\lambda^2$ where E is Young's modulus (at constant field) and λ is the axial magnetostrictive strain. The magnetic energy, on the other hand, is comprised of the mechanical energy plus various types of magnetic anisotropy energy and the magnetostatic energy e_p associated with internal demagnetizing poles around voids, inclusions and grain boundary regions. One type of anisotropy energy is the magnetocrystalline anisotropy denoted by the constant K_1. Another type is the magnetostrictive anisotropy due to interaction of the internal stress σ_i with the magnetostrictive strain λ. For some alloys such as Permindur, there may be an additional uniaxial anisotropy energy K_u obtained by magnetic annealing or by cold work. Thus

$$k^2 \propto \frac{E\lambda^2}{E\lambda^2 + |K_1| + |\sigma_i\lambda| + |K_u| + e_p} \equiv \frac{E\lambda^2}{K_{eff}} \qquad (2)$$

Equation 2 is essentially the same as Brockman's except for the additional K_u term. For power transducers, Wollett[3] has pointed out that $E\lambda^2$ would be a suitable design criterion. Hence maximization of $E_\lambda{}^2/K_{eff}$ would serve for power applications as well.

It will be seen that virtually all terms in eq. (2) are affected by composition and processing. The internal stress, for example, is reduced by high temperature annealing. The same goes for K_u due to cold work. The energy of free poles may be lowered by starting with high-purity alloying materials and by following sound ingot practice to minimize voids, inclusions, and segregation. In the following, examples will be cited with regard to maximizing k^2 by raising the magnetostrictive strain λ and lowering the magnetocrystalline anisotropy constant K_1.

The Magnetostrictive Strain

In the unsaturated condition, the magnetostrictive strain depends on both the value of saturation magnetostriction, λ_s, and on the change in magnetic domain configuration from its initial arrangement:

$$\lambda = \frac{3}{2} \lambda_s \left(\langle \cos^2\theta \rangle - \langle \cos^2\theta \rangle_0\right) \qquad (3)$$

where $\langle \cos^2\theta \rangle$ refers to the average value of the angles between the local magnetization vector of the domains and the direction of the applied field, and $\langle \cos^2\theta \rangle_0$ refers to the average value in the demagnetized state[4]. Thus, depending on the domain orientation in the demagnetized state, controllable by processing, the magnetostrictive strain can be greater or less than the saturation value. If the domains were initially aligned in the direction of the applied field or 180° to it, for example, $\langle \cos^2\theta \rangle = \langle \cos^2\theta \rangle_0 = 1$; hence there will be no magnetostrictive

strain. On the other hand, if the domains were initially aligned 90° to the field direction, $\langle \cos^2\theta \rangle_0 = 0$; hence a maximum value of $\lambda = (3/2)\lambda_s$ will be reached when the sample is saturated, i.e., $\langle \cos^2\theta \rangle = 1$.

There are various ways of aligning the initial domain structure by processing. One must develop an easy magnetic axis in the desired direction via one or more types of the magnetic anisotropy energy (terms in denominator of eq. 2). By applying a large tensile stress to nickel, for example, the magnetostrictive anisotropy energy forces the domains to become aligned 90° to the stress axis (since $\lambda_s<0$ for Ni). As a result, $\langle \cos\theta \rangle_0 = 0$ and $\lambda = (3/2)\lambda_s$ when the sample is magnetized to saturation in the stress direction. Bozorth has cited additional examples of the control of domain orientation via other types of anisotropy energy, and its subsequent effect on λ[5]. It should be pointed out that for a given material one type of anisotropy may be more easily controlled than another as dictated by other requirements of processing. If the fabrication design calls for annealed thin sheet material, for example, the presence of a recrystallization texture in the sheet may dictate the use of magnetocrystalline anisotropy to control the domain orientation instead of, say, the magnetostrictive anisotropy.

In addition to changing the value of the magnetostrictive strain, the initial domain structure also alters the shape of the hysteresis loop. Magnetization in the easy axis direction is characterized by high permeability and large remanence, while that

in the hard axis direction shows low remanence and a low but fairly constant permeability[6]. The effect of such loop shape on device performance must be evaluated.

A second method of increasing the magnetostrictive strain is to increase the value of saturation magnetostriction λ_s by selecting the proper composition and processing for the proper crystallographic texture. In the usual two-constant approximation, the value of λ_s is expressed as

$$\lambda_s = \frac{3}{2}\lambda_{100}\left(\alpha_1^2\beta_1^2 + \alpha_2^2\beta_2^2 + \alpha_3^2\beta_3^2\right) + 3\lambda_{111}(\alpha_1\alpha_2\beta_1\beta_2 + \alpha_2\alpha_3\beta_2\beta_3 + \alpha_3\alpha_1\beta_3\beta_1) \quad (4)$$

where $(\alpha_1,\alpha_2,\alpha_3)$ and $(\beta_1,\beta_2,\beta_3)$ are respectively the direction cosines of the local magnetization vector and of the measured change in length, and λ_{100} and λ_{111} are the longitudinal magnetostriction for the $\langle 100\rangle$ and $\langle 111\rangle$ directions. Since the values of λ_{100} and λ_{111} can differ widely, even be of opposite sign, for a given alloy, texture control by processing can be extremely beneficial. Unfortunately, to the author's knowledge, only the iron-aluminum alloys (Alfer) have been so exploited for magnetostrictive transducer applications[7].

Iron-Aluminum Alloys

Figure 1 shows values of λ_{100} and λ_{111} in the iron-rich portion of the Fe-Al system[8]. Also shown are values of the magnetocrystalline anisotropy constant K_1. In the vicinity of Fe_3Al the values vary according to the state of atomic order as shown. It may be noted that while the value

of λ_{111} remains generally small within the indicated composition range, the value of λ_{100} first rises sharply with Al content, to $\sim 90 \times 10^{-6}$ at ~10 w/o Al, and then drops with higher Al content. Meanwhile, the value of K_1 decreases to zero in the vicinity of 12 to 14 w/o Al. Thus a compromise of a large value of λ_s consistent with low K_1 (see eq. 2) apparently resulted in the choice of 13 w/o Al in the original Japanese development of Alfer for transducer use[9].

The rather large value of λ_{100} led Borodkina et al.[10] to investigate the possibility of improving λ_s via texture control. Their early efforts on a Fe-10 w/o Al alloy are shown in Fig. 2. Adopting the Goss technique of producing the {110} <001> texture for silicon steel[11], the authors prepared sheet material by rolling to thickness reductions of 50-60% sandwiched by intermediate annealing at ~900°C. X-ray examination showed that in the rolled condition the ideal sheet texture contained three prominent components: {111} $\langle \bar{1}\bar{1}2 \rangle$, {100} <011> and {112} $\langle \bar{1}10 \rangle$, the first being the strongest. The saturation magnetostriction is fairly low, between 10 and 20×10^{-6}, with the 45° direction having the highest value, see Fig. 2. After a two-hour anneal at 900°C, the sheet recrystallized to a dual texture of {110} <001> and {100} <001>, with the value of λ_s rising to 42×10^{-6} in the rolling direction. The texture is still far from perfect, however, as λ_{100} is over 90×10^{-6} for this alloy (see Fig. 1). If the rolled sheet is annealed at temperatures greater than 900°C, the texture becomes diffuse and λ_s is decreased.

Subsequent to the initial study, the Russian group improved the texture substantially as reflected by the improved values of λ_s, shown in Curve a, Fig. 3 as a function of Al content[12]. Curve c is the value of λ_{100} as measured by Hall[8], see Fig. 1. If the material is misoriented through improper processing, a substantially lower value (Curve b) is obtained. The oriented material, with $\lambda_s \sim 75 \times 10^{-6}$, nearly twice that of Ni, was found to have higher permeability, lower coercive force and lower losses than nickel and 2V-permindur.[7] Other salient features of Fe-Al alloys are low cost and very high electrical resistivity[1].

Iron-Cobalt Alloys

Figure 4 shows values of λ_{100}, λ_{111}, and K_1 as a function of Co content for alloys within the body-centered cubic phase field[13]. Alloys near the equi-atomic composition undergo an atomic ordering reaction to the CsCl structure below about 730°C[14]. The dashed curves of Fig. 4 reflect the values of the magnetic parameters in the ordered condition. The ordered 50Fe-50Co alloy is especially attractive in that λ_{100} is a maximum ($>150 \times 10^{-6}$) while $K_1 \sim 0$. For this reason, even without specific steps for texture control, 2V-permindur (2V-49Co-49Fe) is one of the best magnetostrictive alloys available to date[15]. (The vanadium is added to improve the ductility.) Fabrication difficulties, corrosion problems and high cost, however, have so far prevented large scale use of this material.

Nickel-Cobalt-Chromium Alloys

Most of the magnetostrictive alloys in use today are nickel and its alloys with cobalt and/or chromium. Ease of fabrication, corrosion resistance and low cost have been the principal reasons for their wide-spread use. The magnetostrictive properties of these alloys have been studied extensively by Clark[16] and Neppiras[1]. Figure 5 shows values of λ_{100}, λ_{111} and K_1 for the Ni-Co binary[17]. It may be noted that the value of K_1 goes through zero at about 4.5 and 18% Ni. Clark[16] found that these alloys coincide with maximum values of the electromechanical coupling coefficient (see eq. 2). Values of λ_{111} and λ_{100}, however, are rather low in these composition ranges. The value of λ_{100} can be increased to $>100\times10^{-6}$ by increasing the Co content to ~50%, but $|K_1|$ is also increased to undesirably large values.

Clark extended the zero K_1 composition near 4.5% Co to the Ni-Co-Cr ternary and found that the electromechanical coupling coefficient remains a maximum, Fig. 6[18]. The Cr added alloys have the additional benefit of increased electrical resistivity.

Discussion

Of the three alloy systems examined, the Fe-Co alloys offer the highest value of λ_s^2/K_1, with Fe-Al alloys next and the Ni-Co-Cr alloys last. However, for reasons cited, the first two

alloys have not been used extensively. On the other hand, if the goal is to develop magnetostrictive alloys superior to what is widely available, then serious studies should be made on the Fe-Co and Fe-Al alloys. Efforts should be exerted both to improve their intrinsic properties (e.g. via better texture control and via alloying additions) and to characterize their device capabilities. Our understanding of the relationship between structure and properties has now advanced to a point where a systematic alloy development program can be pursued fruitfully.

Summary

The parameter $(E\lambda^2/K_{eff}) \propto k^2$ has been used as a material quality factor for magnetostrictive transducer design. Various examples have been cited with regard to increasing this parameter through processing. It is shown that the magnetostrictive strain λ is dependent on both the value of saturation magnetostriction λ_s and on the domain structure in the demagnetized state. The value of λ_s is governed by alloy composition and is a function of crystal orientation, the opportunity thus arises for texture control. The domain structure is governed by various types of magnetic anisotropy energy and hence may be optimized by processing. The effective magnetic anisotropy may be minimized by sound ingot practice to eliminate voids and inclusions, by annealing to reduce the level of internal stress, and by alloy selection to reduce the magnetocrystalline anisotropy. Examination of three prominent

alloy systems Fe-Co, Fe-Al and Ni-Co-Cr in terms of these considerations shows that improved properties are obtainable through processing control.

Acknowledgments

I wish to thank F. S. Gardner and R. S. Woollett for calling to my attention the oriented Alfer material of Ref. 7. Valuable discussions were held with F. S. Gardner, E. A. Nesbitt, R. C. Sherwood and J. H. Wernick.

References

1. For a detailed discussion of magnetomechanical parameters and material property requirements, see E. A. Neppiras, J. Sound Vib. 8, 408, 431, 1968.

2. F. G. Brockman, J. Underwater Acoustics 17, 319, 1967.

3. R. S. Woollett, IEEE Trans. Sonics and Ultrasonics, SU-15, 218, 1968.

4. R. M. Bozorth, Ferromagnetism, D. Van Nostrand Co., Princeton, 1951, p. 634.

5. R. M. Bozorth, op. cit. pp. 636-39.

6. R. M. Bozorth, op. cit., p. 499, see Fig. 11-19(c) and 11-19(d).

7. O. N. Al'tgarizen, L. S. Bezuglaya, Z. N. Bulycheva and O. V. Lyubetskaya, Soviet Phys. - Acoustics 12 (No. 3), 249, 1967.

8. R. C. Hall, J. Appl. Phys. 30, 816, 1959.

9. H. Masumoto and G. Otomo, Sci. Reps. Res. Inst. Tohoko Univ. A2, 413, 1950.

10. M. M. Borodkina, Z. N. Bulycheva and Ya. P. Selisskii, Phys. Metals Metallogr. 9 (No. 3), 61, 1960.

11. N. P. Goss, Trans. ASM 23, 511, 1935.

12. Z. N. Bulycheva, M. M. Borodkina and V. L. Sandomirskaya Phys. Metals Metallogr. 19 (No. 1), 147, 1965.

13. R. C. Hall, Trans. TMS-AIME 218, 268, 1960.

14. W. C. Ellis and E. S. Greiner, Trans. ASM 29, 415, 1941.

15. H. J. Williams, E. A. Nesbitt and M. Goertz, Bell Telephone Laboratories, Incorporated, unpublished research report, 1944. See also Summary Tech. Rep. Division 6, NDRC 13, Chs. 1 and 4, 1946.

16. C. A. Clark, Brit. J. Appl. Phys. 1, 355, 1956; J. Acoust. Soc. Am. 33, 930, 1961.

17. Values of λ from M. Yamamoto and T. Nakamichi, J. Phys. Soc. Japan 2, 228, 1958. Values of K_1 from J. W. Shih, Phys. Rev. 50, 376, 1936; L. W. McKeehan, Phys. Rev. 51, 136, 1937; and R. C. Hall, ref. 8.

18. A. P. Edson, J. Underwater Acoustics 17, 285, 1967.

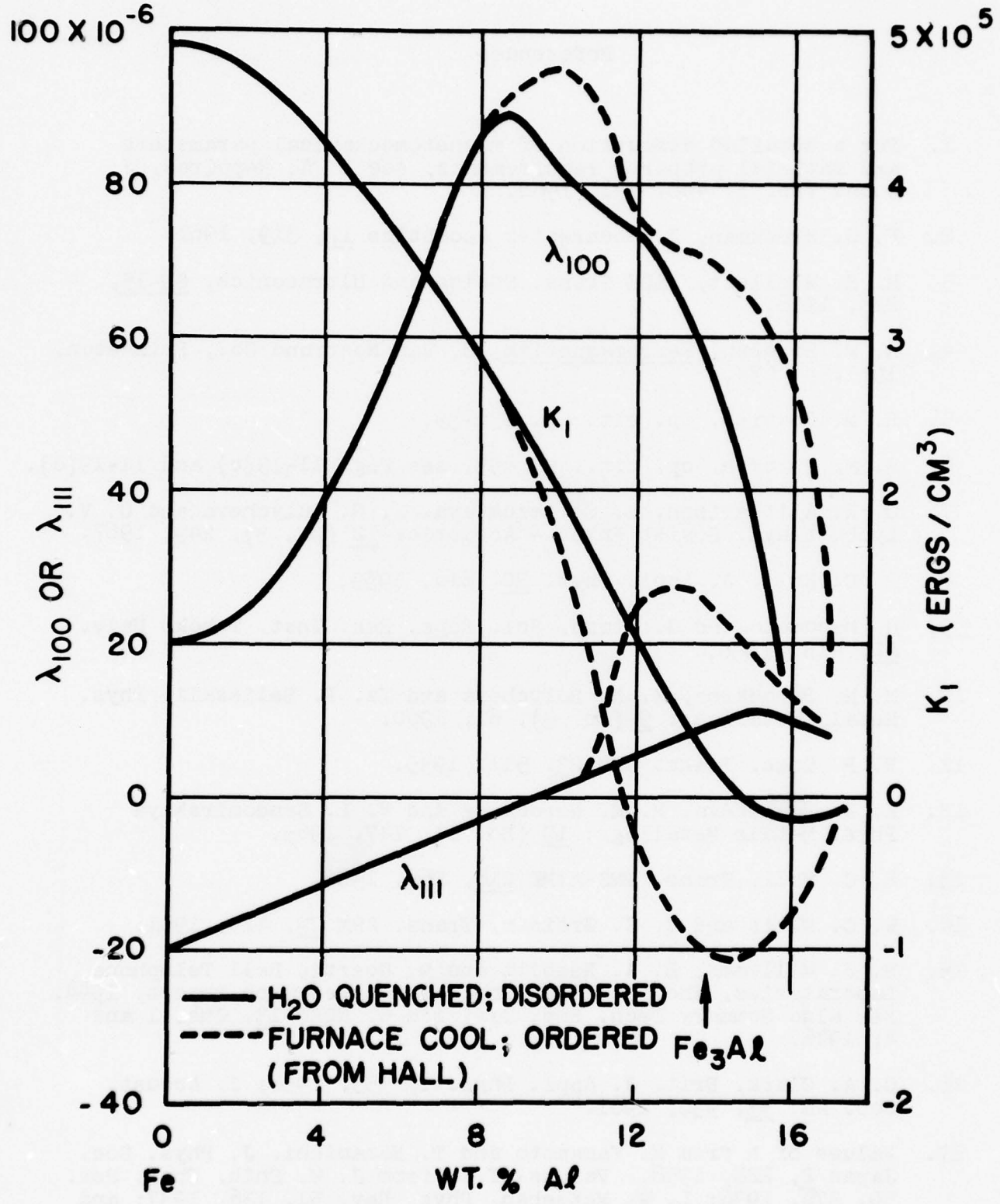

Fig. 1. Values of magnetostriction constants λ_{100} and λ_{111} and of the magnetocrystalline anisotropy constant K_1 for Fe-Al alloys. From Hall, ref. 8.

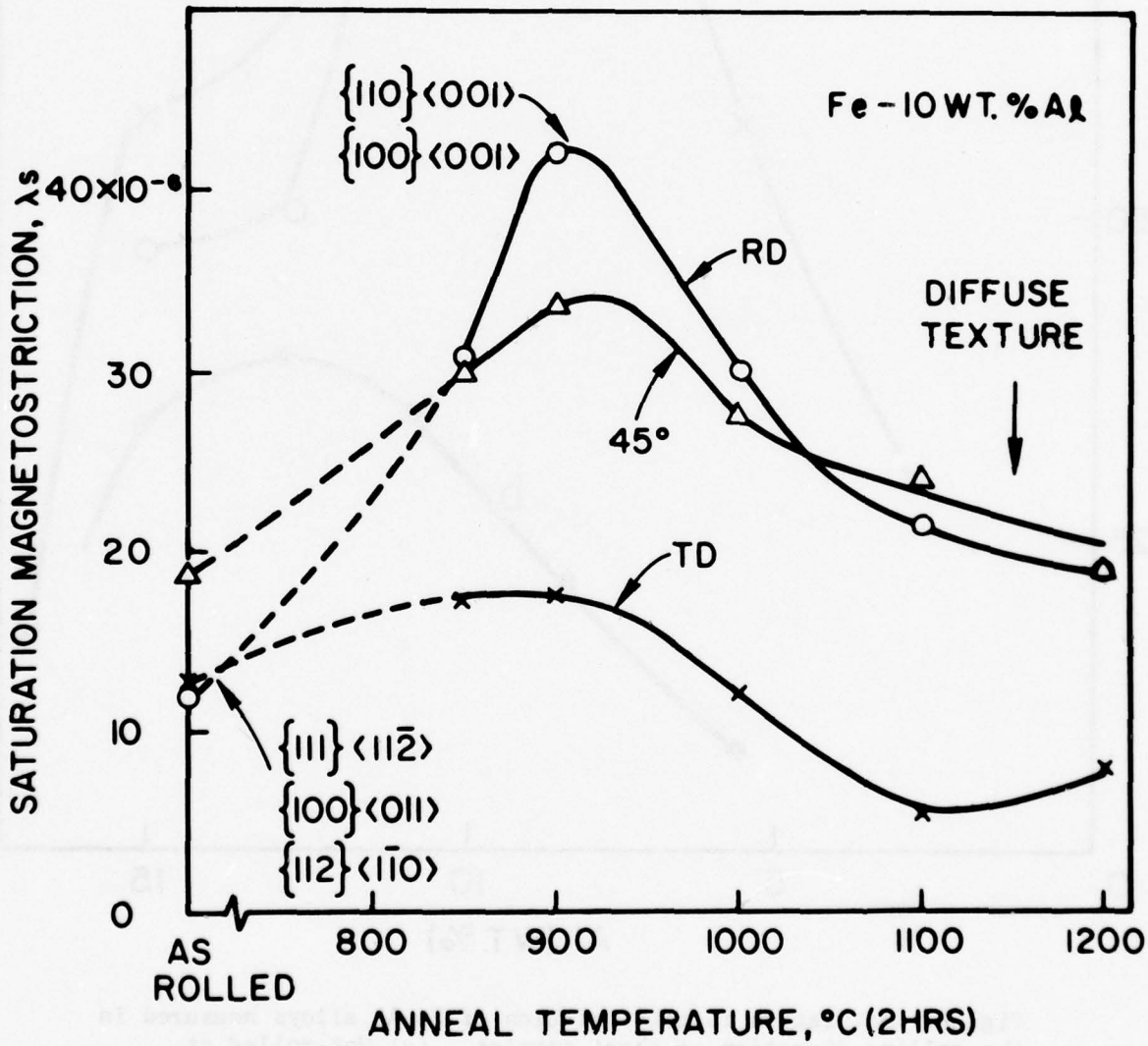

Fig. 2. Values of saturation magnetostriction measured in three directions of Fe-10 w/o Al alloy sheet, as a function of annealing temperature. RD = rolling direction, TD = transverse direction. Ideal textures after particular annealing are indicated. Data plotted from Table 3 of Ref. 10.

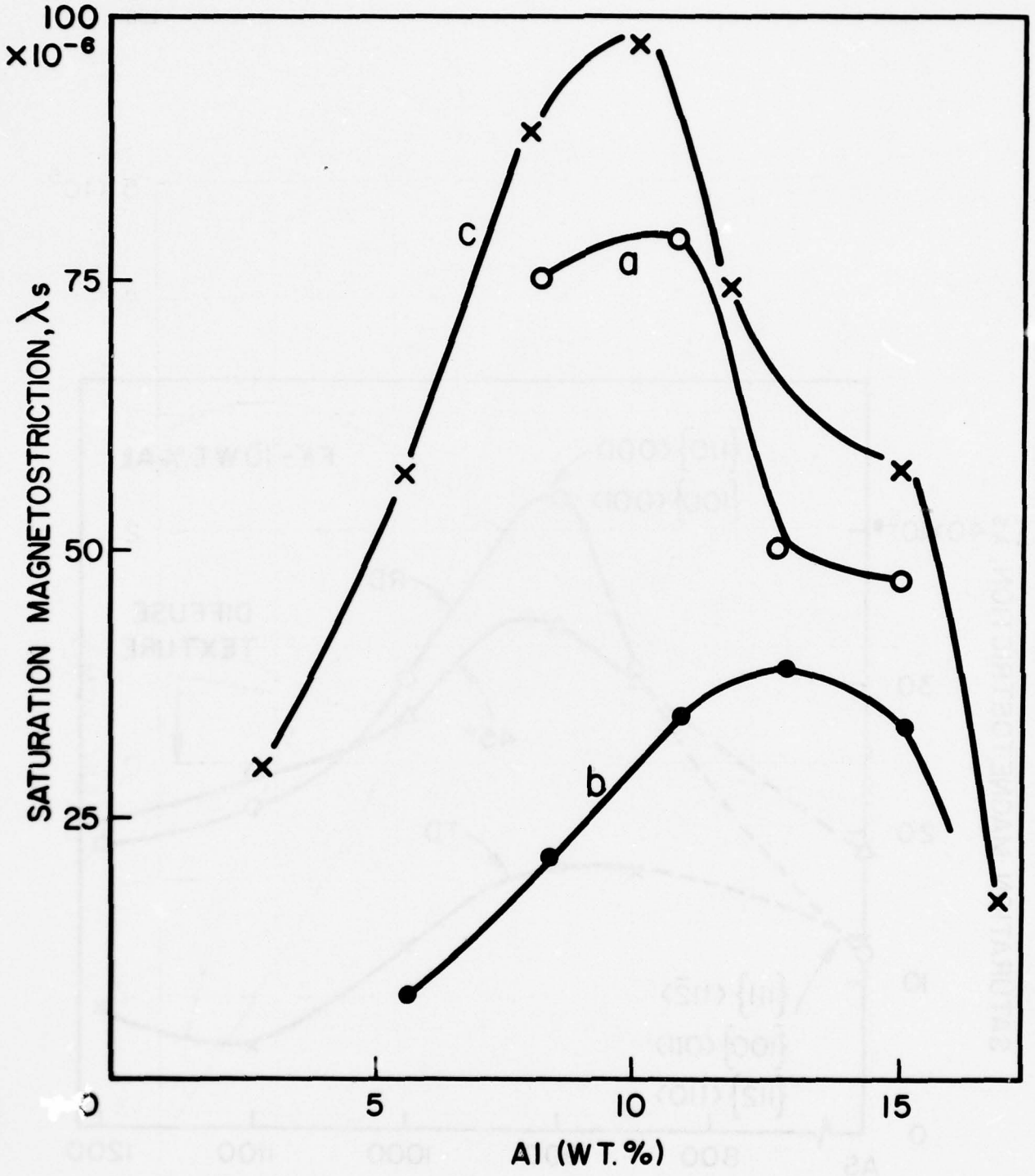

Fig. 3. Saturation magnetostriction of Fe-Al alloys measured in the rolling direction of sheet samples. (a) Hot-rolled at 1050-1100°C followed by "warm" rolling to a total reduction of 55-65 percent with two intermediate heat treatments. (b) Hot-rolling followed by warm rolling to a total reduction of 92 percent without intermediate heat treatment. From Bulycheva et al., ref. 12. (c) λ_{100} from Hall, ref. 8.

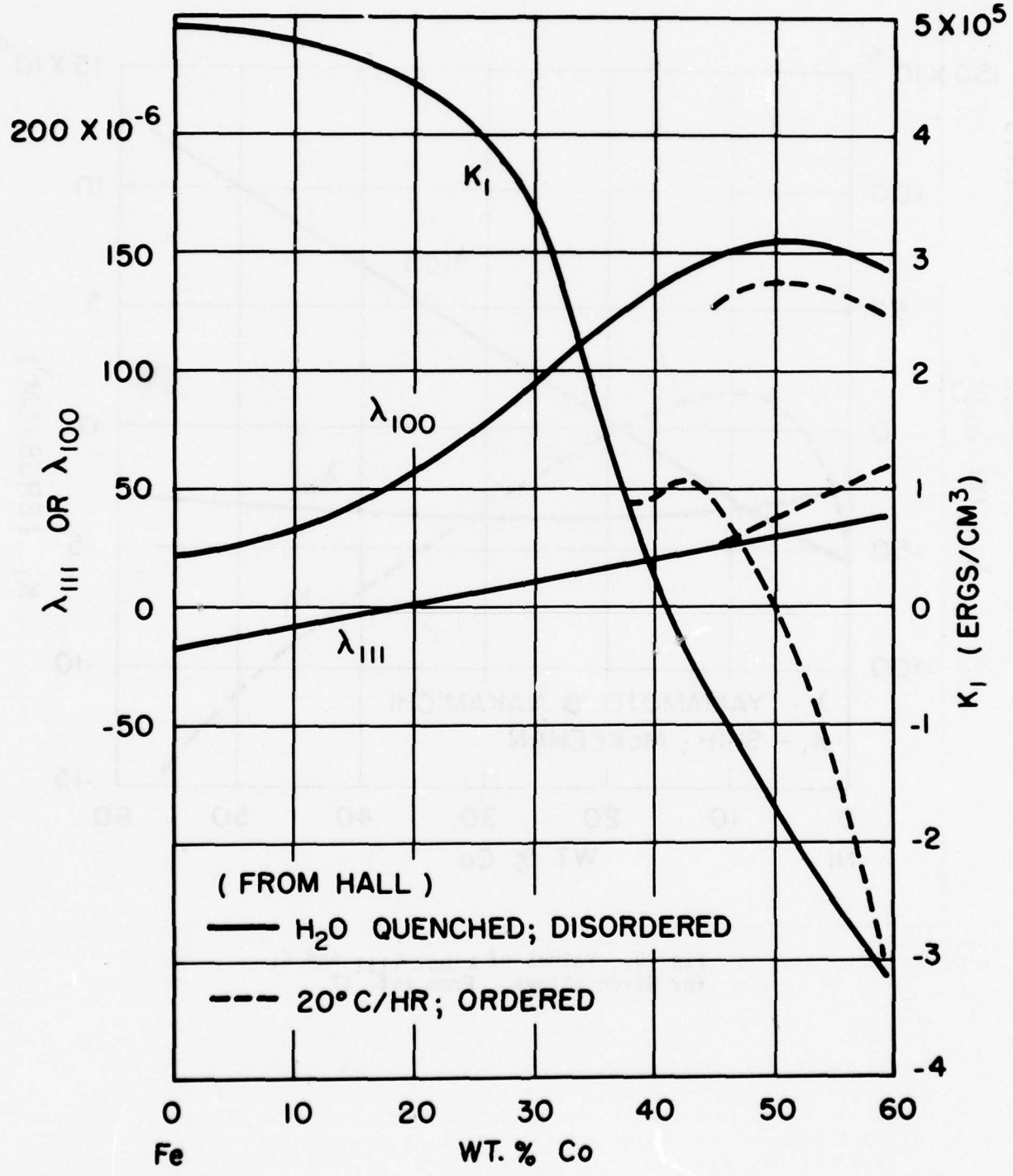

Fig. 4. Values of λ_{100}, λ_{111} and K_1 for Fe-Co alloys. From Hall, ref. 13.

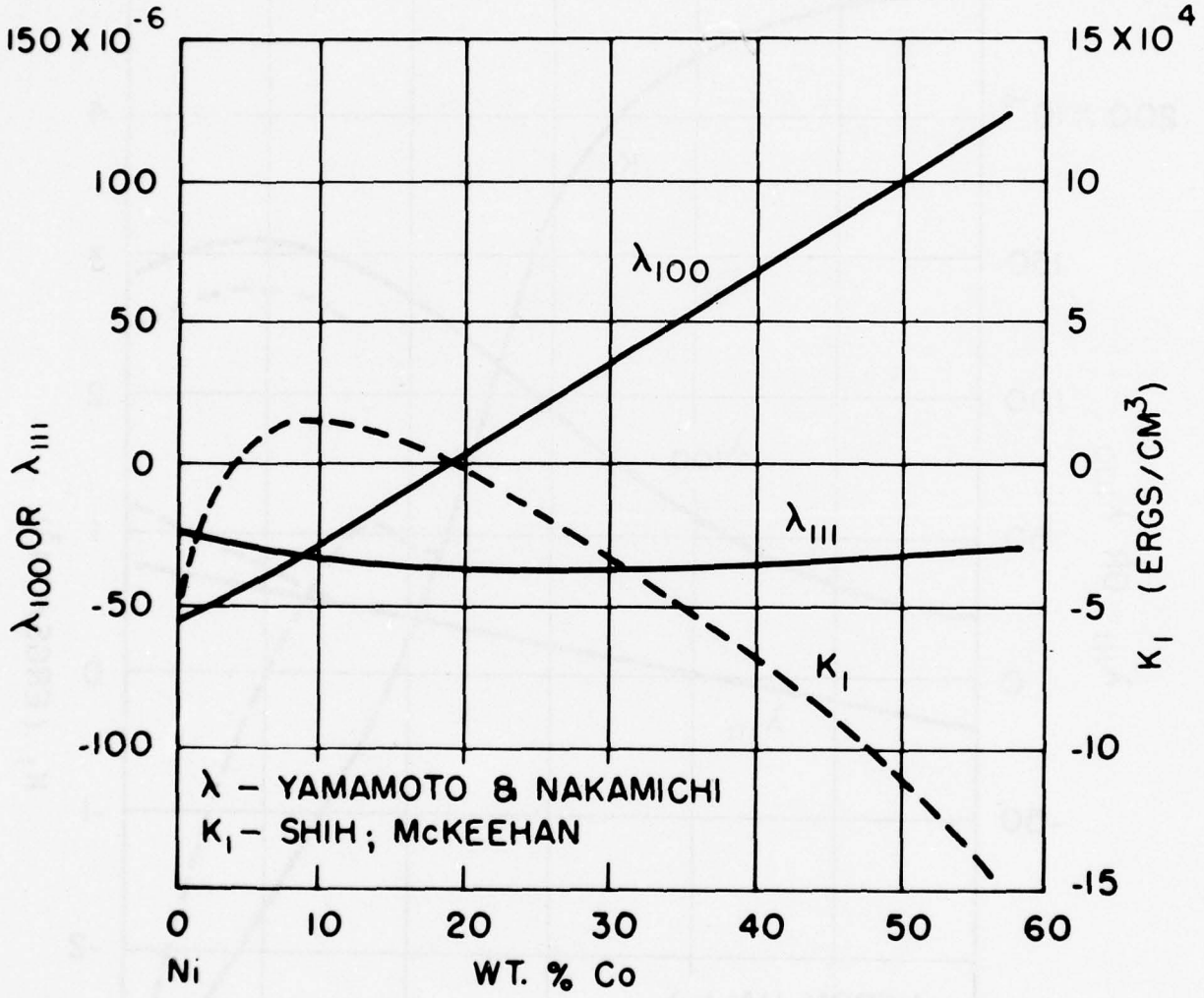

Fig. 5. Values of λ_{100}, λ_{111} and K_1 for Ni-Co alloys. From ref. 17.

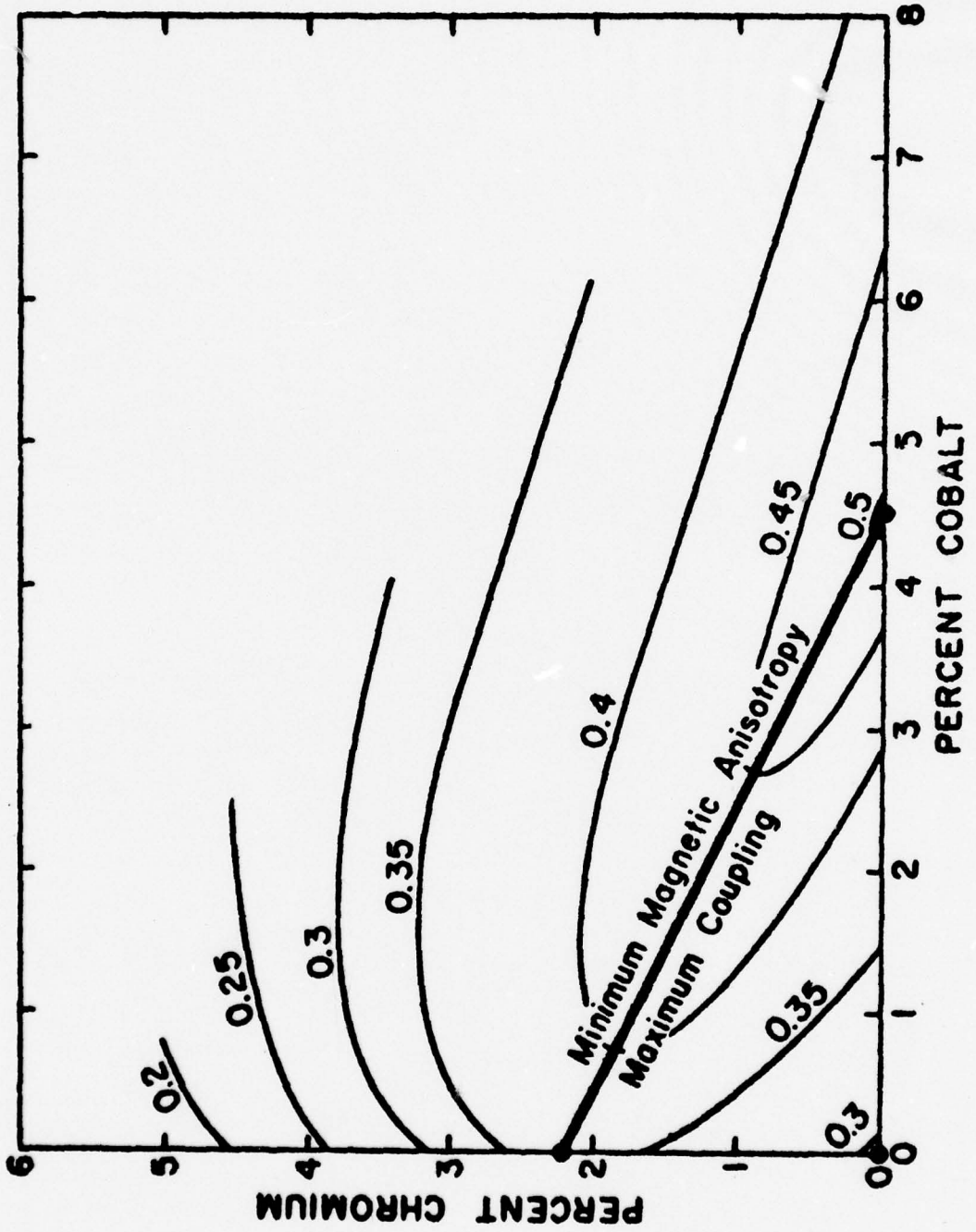

Fig. 6. Values of maximum electromechanical coupling coefficient k in the Ni-rich corner of Ni-Co-Cr ternary. Note maximum k follows minimum magnetocrystalline anisotropy compositions. From Clark as quoted by Edson, ref. 18.

SCIENTIFIC OPPORTUNITIES IN MAGNETOMECHANICAL SYSTEMS

--Metallic Magnetoacoustic Materials

A REGIONAL WORKSHOP (UNCLASSIFIED)

Sponsored by ONR Boston

25 August 1969

THE GENERAL DISCUSSION

MODERATOR:

GARDNER, Frank S.	Office of Naval Research, Boston, Mass.

INVITED PANELISTS:

Callen, Earl R.	American University, Washington, D. C.
Chin, Gilbert Y.	Bell Telephone Labs., Inc., Murray Hill, N.J.
Cullity, B. D.	University of Notre Dame, Notre Dame, Indiana
Wise, Boyd A.	General Dynamics, Rochester, New York
Woollett, Ralph S.	USN Underwater Sound Lab., New London, Conn.

VII GENERAL DISCUSSION

Scientific Opportunities in Magnetostrictive Material for Transducers

DR. GARDNER: At lunch Dr. Bozorth referred to the possibility of changing the sign of magnetostriction for a given material by means of magnetic annealing. Would you care to elaborate on this for the conference?

DR. BOZORTH: By magnetic annealing one can produce a material of either positive or negative magnetostriction. This is the case for ferrites. Now when a transducer is put into water, it undergoes pressure, hydrostatic or unidirectional. From a design point of view, is there a relation between the preferred direction of magnetostriction in transducer material and its application underwater?

DR. CAMP: As mentioned by Boyd Wise, there would be an advantage in putting magnetostriction materials under compressive force. There is something to be gained and this, of course, would call for a positive magnetostrictive effect.

DR. BOZORTH: If you take a ferrite, for example, and heat treat it in a magnetic field (in the field direction it has negative magnetostriction fundamentally), then it will come out with positive magnetostriction here, won't it?

VOICE: Yes. You can also change the sign of magnetostriction from positive to negative if the material is heat treatable in a magnetic field.

VOICE: Unfortunately, most of these devices are used under changing hydrostatic pressure conditions, and if the material happens to be particularly sensitive to the pressure, that is undesirable. However, if you can keep it under high pressure, then these changes would be relatively small and you could get around the problem.

DR. BOZORTH: I just thought I hadn't seen any indication of this, in the event you want positive magnetostriction. I think in many cases by heat treating it in a magnetic field, you can obtain it from a material which is fundamentally negative.

MR. WISE: I might add the comment that as far as I can see the pre-stressing opportunities and requirements are approximately the same for the magnetostrictive or for the ceramic transducers. The point being that the stress levels at which you intend to use these materials for sonar transducers are really not too high. The figure of 5,000 psi has been mentioned as a top value for alternating stresses. Since pre-stressing materials can be stressed to 70,000 psi or perhaps even higher, a very small percentage of the total cross-sectional area is needed to prestress the active material; this allows one to obtain the advantages of pre-stress with little penalty. This is exactly what is done with the ceramic transducers and I see no reason why, with the positive magnetostrictive transducer materials, we couldn't do the same thing.

VOICE: By pre-stressing, do you mean holding something under stress?

MR. WISE: The stress is maintained in these devices. You stretch the pre-stressing member and use it to compress the active material. As far as the variation of this stress is concerned, of course this is always a problem with any elements, including the ceramic elements. The best way to avoid

that is to not subject the active material to this variable stress: The actual mounting used in some sonar transducers achieves this. You suspend the transducer elements by the head and do not subject the active material to the varying static stress.

DR. GARDNER: How serious a problem is the difference in language -- that used by the transducer designer and that employed by the materials man?

PROF. BESHERS: I will comment on that, although I'm just on the fringes of this area. I have worked more with dislocations and other things, but I have turned up some magnetic effects in materials of interest to me, and it seems to me that there are three groups that you are interested in.

One is composed of the designers; one are the scientists typified by Dr. Callen, and one are the scientists typified by Dr. Cullity and Dr. Chin, if I may say it this way.

As to the point of view of the designers, I refer to the piezo-magnetic question raised in the discussion of Professor Cullity's paper. It is a general point, and provides a general jumping off

place. From the designer's viewpoint you have a material which changes its magnetic properties under stress or its electrical properties under stress and similar things like this, and it is natural to use one language for all the phenomena you see.

You see the magnetization changes under stress. It is natural to use one language, but it turns out that some of those things where the properties change under stress are changes in the bulk (single domain) properties, and others are due to rearrangements involving many domains, and when you try to control these properties, it is very easy to confuse the two. This is the basic question.

I think the two definitions of piezomagnetism are more far reaching than the gentleman appreciated this morning -- the fact that there are two different effects, if you will. One is the effect of pressure on a single crystal, single domain magnetic properties, and the other includes the effect of pressure or stress on multi-domain specimens, either single crystal or multi-crystal. When you seek to control the materials as Dr. Chin has talked about, you really do have to start thinking about which is involved, a bulk or domain wall motion property, and it is important to keep these separate.

The other point refers to the equations of state which Dr. Woollett wrote on the board. They aren't really because there isn't thermo-dynamic equilibrium with these domain wall structures and so on. They are always something meta-stable, almost always, so while it is a useful term and I know what he means, yet it is misleading.

I say I know what he means, but many times I run over it in the technical literature. I will forget to make that little notation; "Yes, I know that these people mean that and so on." It is misleading and it makes the literature on this subject hard to read. It makes it hard for the two groups to get together and speaking somewhat from the edges this way, I think I can see it better.

There is a linguistic difficulty that runs through this. I think you see it in Dr. Bozorth's answer, too, just now. I think you are using pressure in several different senses. In the discussions of it, and the stresses you are talking about, both static and dynamic stresses, I thought that the answers and the discussions could be clarified if there had been better specification of that. I think there is quite a bit that you could do to improve your communication from both sides.

PROF. CALLEN: I suspect that this is not going to help at all, (Laughter) but speaking about the bulk properties, the circumstances which are required to have the material respond with a magnetization proportional to the stress, and now I am again talking about the fundamental bulk properties, not a domain effect, is this. The quantity, $\bar{I}$ bar, that is something which transforms as a pseudo-scaler, must generate the same irreducible representation at let's say XY or XZ or Z squared, or something like that, and I am sorry about that. (Laughter.)

But what that means is that the material must lack an inversion center. It cannot have inversion symmetry and it must at least have some unique axis. For example, it will not be true in any cubic crystal, but if it has hexagonal symmetry and lacks an inversion center, then it is possible to have a magnetization proportional to a stress, or something. But again, it will never occur in a material which has only one type of atom. It will have to have more than one atom in it. So, it is not going to happen in any of these cubic things we have been talking about or any material made up only of one component.

That is the fundamental thing. It is not going to be true in an operating state where domains are around which is what we really care about here.

MR. EHRLICH: There is a basic problem in trying to get everybody to talk the same language, and you may never actually achieve it; but the thing that Dr. Woollett and I are interested in is to try to get the nomenclature to be standard from a user standpoint, so that the user can

select whether he should use a magnetostrictive material or an electrostrictive material or a piezo-electric material. It turns out most of the users are not as bright as some of the people who are doing materials research and, therefore, if the materials research people wanted to be of more service to the users, really they should try to have some of their results come out in the same language as the users would like to have it; in addition to keeping track of the details that are peculiar to their own interests. Unless he translates his ideas into a basic language that cuts across the transducer technology, the material designer should not assume that the user is going to try and understand what he has to say.

PROF. RICHMAN: The question was asked whether it is that important that we keep all the nomenclature standard. It seems that we have managed to get by with thermodynamics where no one uses the same terms. Whether they use a G or F for Gibb's free energy, whether they write the first law of thermodynamics with a minus or plus sign, the people in basic research seem to understand it, based on the context in which it is written.

I think that our own language is ambiguous enough, if we take the words out of context, but as long as we have it in a definite article, we can understand it. It takes a little getting used to, but I think we have been doing it all our lives and we can still do it with the use of the words piezo-magnetic and magnetostrictive. This seemed to have started, as Dr. Woollett said, in the electromechanical analogue where we had electrostrictive and piezo-electric materials, and I think maybe the problem is there is no common word which embraces both of these properties.

In other words, is there a term which includes both electrostrictive and piezo-electric activity? If there were such a term, then I

think we could use that and the people wouldn't have to specify whether they meant one or the other; and does anyone here know whether there is a term that could be used for that purpose?

PROF. HUNT: How about piezo-activity?

VOICE: Does that include both electrostrictive and piezo-electric activity?

PROF. HUNT: I just made it do that. (Laughter)

VOICE: There are two kinds of electrostrictive activity or phenomena, electrostrictive and piezo-electric. There is the kind you have in quartz and the kind you have in the domain walled materials. It is helpful, if you really have to think about the properties of the materials to distinguish between these two. To apply the reasoning that Callen brought up, and to use his theoretical description, is a horse of another color.

VOICE: The problem is for the electrical engineer or the user who is trying to talk about these terms in general and these materials in a general way. He has certain equations which will equally well describe either one of these materials and he would like to have a term that could be used to cover all of these. If there isn't such a term, I don't think you can blame him too much for taking one of the ones we have and trying to generalize it to all these terms.

DR. GARDNER: Let us shift to another subject. Is there a general area of agreement on the values of power limits for piezo-electric and magneto-strictive materials to use in design?

MR. WISE: I have tried to make that one of the chief points of my presentation. The requirements are actually the same for electrostrictive and magnetostrictive materials. They derive from the power levels to be used in the water and the bandwidth.

The many papers we have seen on the theoretical maximum power capability of the materials don't have much to do with the conditions of use that apply to sonar. It turns out that several of the common magnetostrictive materials "------- do have enough power generation capability, per se, if this is the only question." I think that this is an almost direct quote.

What you really want to know, however, is the dynamic range of magnetostrictive strain over which you must operate the material for the needed power level and bandwidth. This is going to determine whether the material has enough magnetostrictive strain and whether the average coupling coefficient that can be achieved over the dynamic range of magnetostrictive strain is satisfactory.

DR. GARDNER: Does everybody agree with that or does anyone want to take a different point of view?

DR. WOOLLETT: Well, perhaps we are thinking along the same lines, but expressing it differently. Anyway, I don't think that you can say that magnetostriction transducers have ample power, becuase I assume that we have specifications on mechanical Q and other things.

Now, Boyd mentioned that the literature states if you can let the Q become very high, magnetostriction can produce a lot of power until it

is limited by fatigue; but that is not the typical situation.

We do have to work with low Q and, therefore, we are concerned with the basic magnetostriction limit on the power; that is, the saturation magnetostriction or the blocked force, or however you want to specify it.

So we certainly want materials that can give us more power. Again, if you have no limits on weight or size and so forth, of course, you can get the power usually by adjusting the geometry, but in sonar, we are concerned about weight in many cases. We want the most power per pound of material that we can get.

So, I think we want very much for the materials people to give us better magnetostrictive materials, if they can; that is, materials with greater saturation magnetostriction.

As far as what the limits are, and whether they are agreed upon, of course, first of all you have to recognize that there are many different limiting conditions. These may stem from mechanical limits, fatigue, or fracture, and thermal limits where the material gets too hot, and there are probably many others that you can list. The one that I emphasized in my talk was the basic field limit; that is, assuming that you are not mechanically limited, the problem is to generate enough internal force or enough magnetostrictive strain. When you make a comparison on that basis with magnetostriction you run into a very definite limit of saturation.

So, I would say the power limits of magnetostrictive materials are known better than those of ceramics, because you have such a definite cutoff in magnetostriction whereas, in piezo-electric ceramics, there is a tremendous range of power that people will argue over. I mean, a 20 to 1

range of power, for instance. You know, the power goes as the square of the electric field and some people say you should only drive ceramics with maybe two kilovolts per centimeter and others say with 12 kilovolts. That will be a range of 1 to 36 of power, and maybe they don't go to that range, but there is a tremendous range over which different people think the limit should be set.

So, in piezo-electric ceramics, I would say we are much further from agreeing on what the power limits are. For the purposes of this conference we want to compare the piezo-electric ceramics with the magnetostriction, and since there is so much vagueness about the power limits of the piezo-electric ceramics, it is hard to make a definite comparison.

PROF. CULLITY: May I change the subject a bit and ask Dr. Woollett about the applied bias magnetic field? What are the main purposes of this bias field?

DR. WOOLLETT: Well, to get linear operation. It depends on what kind of a signal you want to put out. If you are using a complicated signal and you would like to have it faithfully reproduced in the water, this means you want to try to have a linear operating characteristic and that requires bias.

Now, if the only object is to radiate a sine wave, you can operate without bias. If you drive with a sinusoidal voltage, your input current will be distorted, but it is possible to get a sinusoidal output at double the input frequency.

VOICE: Suppose it is inherently linear right from the origin, would you still put a biasing field on it for any reason? I mean, is the frequency doubling objectionable?

VOICE: Quite.

VOICE: So even if the magnetostriction is linear, you would still put a bias on it?

MR. EHRLICH: Just as in an electrostrictive transducer you bias it so it appears to be piezo-electric, the same thing (happens) in the magnetostrictive case. The people like to operate on the linear portion of the curve, because that is what they understand best sometimes.

VOICE: And life is so non-linear.

MR. EHRLICH: Yes, it is.

VOICE: Just extend that straight line back through the origin into the negative region and we would be in business.

MR. EHRLICH: Right

VOICE: It would be a different business, but ---- (Laughter).

DR. HUNT: Can I change the subject again? We have a mixture of theorists and designers and I get the impression that no designer would go back and design a magnetostriction transducer for any job he has in the shop at present, but he talks sort of wistfully about its great advantages of shock resistance, high temperature survival, pressure withstanding, this, and this, and this, and the questions of power-handling capacity. If the theorists are going home and make us some new materials, the question is, can the designers come up with the consensus of what is the number one thing for the materials people to go home and do for them?

I get the impression that no matter how much power-handling capacity it might have, no matter how light and so on, no present designer is going to touch this stuff unless it has got a coupling coefficient that is above 50 percent.

Now if this is true, then let's not waste the theorist's time by asking them for higher power handling capacity or higher permeability or this or that; let's get that coupling coefficient up in the competitive range.

My question is, will the designers agree with that consensus?

MESSRS. WISE AND WOOLLETT: Provided you have also a higher power handling capability.

DR. HUNT: You won't touch it unless you have the coupling; get that first and then ask the other questions.

VOICE: I say get them both.

MR. EHRLICH: If you get the power handling capacity up, you can operate with a lower coupling coefficient, with 50 percent, because all you are worried about with the high coupling coefficient is having a high power handling capability over a broad frequency band. When you talk about the Q combination, if you have high enough power handling capability, you can stand being down a little bit.

DR. HUNT: You can stand it, but you wouldn't go home and build it that way in competition with the ceramics. What does it take to make the magnetostrictive type competitive?

MR. EHRLICH: I think we would, if we had enough power handling capability.

VOICE: With what coupling capability?

MR. EHRLICH: You are talking about the fact that the coupling coefficients are going to have to be up in the general vicinity of 0.3 or better, but whether they have to be up to 0.5.---

VOICE: You get around to relating the coupling coefficient to the mechanical Q.

MR. EHRLICH: If you can have everything, then you want the whole works, but when you say, if you want one thing more than any other, then it is the power handling capability. If you want two things, then you add the coupling coefficient.

MR. WISE: One thing you can add is, if all you want is power handling capabilities, you must be talking about something like the scroll transducers that are used just to generate power and don't have the other requirements. If, on the other hand, you start talking about scanning sonar elements, I don't see that you can get away from the requirement that you have a high coupling coefficient.

MR. EHRLICH: I think you can.

DR. GARDNER: What numbers do you have in mind when you talk power handling requirements? I wouldn't know them myself.

MR. EHRLICH: I think it is fairly safe to say that the ceramics will be the things that we would tend to use until the magnetostrictive materials show that they are notably better, because it would require a major shift in the industry to change back.

DR. GARDNER: What are the watts per centimeters?

MR. EHRLICH: I think Dr. Woollett put up the general idea of the relative merits for the PZT type ceramics and as a first cut, you ought to have maybe 50 to 100 percent margin above what they can do.

MR. EDSON: I am sitting here finding myself amused at my continuing frustration. (Laughter) Part of

which arises when I put together some of the remarks that have just been made, that to apply magnetostrictive materials we need more power and we need more than the ceramics; but nobody knows within a factor of 20 or 100 what the ceramics will do.

Furthermore, we need more coupling coefficient, where we have power. We need power where we have coupling coefficient. My continual question in this thing is, some grasp of what combination of factors would need to be had. Even if it has to be specified in the performance of a device, I would undertake to translate it into what it means in the magnetostrictive material. But I am completely baffled, hopelessly, by the suggestion that well, now, maybe the ceramic has a figure of 650 or whatever or maybe 20 KV per centimeters, but maybe it breaks down to one thing. I don't know, anyway, how to put it into the frame of reference for a magnetostrictive material.

MR. EHRLICH: You hit on a good point, because the saturation electrostriction for the ceramic material is really not well-defined. This is a problem we are stuck with at the moment.

DR. CHIN: So what do we want to do? The kind of material property and the figure at which it begins to look attractive, both seem to be undefined. That is the problem, and until that is done, I don't see how we can start improving the material.

MR. WISE: I would like to say that I had looked over the background of the past conference and saw the same lack that you are now talking about, and I tried (in my talk) assidously to bring forth some numbers that relate to sonar.

Now, you can't bring forth any numbers without relating them to something. If you say the whole world is out there baby, they could be related to any end application whatever, and this leads one to say that the more power you can generate, the better, because I might want it for something someday and more is better. However---

MR. EDSON: Being for virtue and against vice.

MR. WISE: Yes. For instance, if you are going to make a scroll transducer that sits on the bottom of

the ocean, if you tell me you can generate more power, I will take it. Right? There isn't any upper limit of desirable power density if that is the type of device you are talking about. Again, if you tell me that you are going to design a bender element that has a small active section in it, that has to drive great big flexing discs, well, I will certainly tell you that you need high power density capability in this active material.

Now let's get back to the question: Are we, or are we not, talking about the lion's share of the market, which is the scanning sonar transducer? Is that what we are talking about? If you can agree that it is, then you will know fairly well what the requirements are.

DR. GARDNER: Well, I tried to keep it broad. At first, I was persuaded that this conference should include both the ceramic and magnetostrictive types of materials, and then it appreared it was hard enough to handle just the magnetostrictives. But there has been no thought in my mind about which kind of sonar is involved.

MR. WISE: My question was meant to be a rhetorical question. The answer in my opinion is this: If you want to know what the important material is, and if most of your transducers are a particular kind, then that is the

kind of transducer you want to relate to.

DR. GARDNER: In other words, the desired transducer material is device-related.

MR. WISE: Yes, and in that sense, I would say the device you are talking about is the scanning sonar transducer element, and that you can establish the power requirements based on said element.

DR. FELLOWS: It seems to me that we have been skirting around the question that has to be answered eventually, and that is, what is it worth to do this?

MR. WISE: Someone should have brought that up at the very beginning. For many of these things that we are talking about today, when the question is, "Can the problem be solved?", the answer is, "Not without money".

DR. GARDNER: Well, I say that talking costs a lot less money than actually making transducers and sonar systems. For example, you people who are here today, out of your

own kindness and generosity, are generating some good ideas that will be significant when they are issued. To tell how much it is going to be worth, when you have the situation that we have heard about, would be premature, I think.

DR. FELLOWS: Well, obviously your objective has some value in terms of what you are willing to invest in materials or design mechanics and what-not, and I would think that there would have to be a pay-off feature here evaluated.

DR. CAMP: Well, shipboard sonar transducers are by far the most common. In the last two or three years there has developed a great interest in proper sonar sources for deep immersion in the ocean.

Now, Dr. Hunt made a statement implying no designer would go home and develop a transducer using magnetostrictive materials. I think that is too broad. If I was asked to design a proper sound source for operation at 750 Hertz, for example, for immersion in the deep ocean, I would certainly design it with magnetostrictive materials.

VOICE: I might add that our company presently manufactures cross span beam, high resolution, echo-sounders, and they are magnetostrictive, because we find they give us all the power we need in this application, and are good and rugged. We put them on the bottom of the ship and leave them there for several years without worrying, but we don't need as much power as the people in the ASW who need extremely long-range, and so it depends on the application.

DR. HUNT: Now that this awful specter of money has been raised, if you had only so much money right now, and you wanted to design transducers, which is better to invest in: in improving magnetostrictives, or improving ceramics?

DR. GARDNER: We haven't touched on all the problems with ceramics.

DR. HUNT: I will go wash my mouth out with soap (Laughter).

DR. GARDNER: I think we would have to have a separate conference for the one, wouldn't we?

DR. HUNT: It is a haunting thought.

DR. GARDNER: Maybe somebody wants to respond to that. Should we, assuming there is only a limited amount of effort available, would it be better, knowing the Navy need and the Navy mission, would it be better to allocate it in the ceramic area or would it be better to allocate it in the magnetostrictives?

MR. WISE: I will respond just slightly off the point. It might be better to invest it in hydroacoustics. (Laughter)..

DR. GARDNER: I am glad you are keeping the subject open. (Laughter).

VOICE: Well, that was the point I wanted to raise. Really, these questions should be looking at not what is the state of sonar technology now, but what is projected as the advance in sonar technology. Maybe that is something that is difficult to talk about in open conference, but this is really what you are asking; it is not improving the current devices, but looking towards the devices that are going to become of importance in the next few

years.

DR. GARDNER: It is also important to take advantage of scientific opportunities, and it seems to me that the magnetostrictive materials haven't had a proportionate share of effort. In the last few years materials, that is ceramic materials, have come in for heavy support. I think we have heard today some avenues for improving magnetostrictive materials that bear watching.

DR. BOZORTH: If you project far enough ahead, I would think somebody ought to measure the magnetostriction constants of rare earths at the temperature of liquid helium just to see how well you can do it.

DR. GARDNER: Would you recommend building a transducer to operate at cryogenic temperatures?

DR. BOZORTH: I would measure the constant first. Yes, I think I would recommend seeing how good a transducer you can make at any cost. I mean, not one that can profit commercially.

DR. GARDNER: At this time I would like to invite remarks from each of the invited speakers.

PROFESSOR CULLITY: I have more questions than answers. For example, this morning I have seen an equation on the board for a coupling coefficient. To optimize it I should maximize $\lambda^2 E$ and keep the anisotropy low. How about this question of power that has been brought up? Would

somebody write me a nice simple equation for a material property that will optimize power output?

DR. WOOLLETT: Well, there is a simple equation, if we are field limited, which is the interesting case: The energy that is available for work, U_{em}, is equal to one-eighth the saturation magnetostriction squared divided by the compliance modulus.

Incidentally, S_{33}^{H} is simply the reciprocal of Young's modulus. λs is the saturation magnetostriction.

Now, this gives the power density which I think is what we want; but to get the actual power, as I had indicated before, you have to multiply several other things like the resonant frequency, the mechanical Q, times this factor here which is the power density, times the volume of the active material.

So, you see these other things enter in to get the actual power, but the interesting thing is the power density that is available for work.

This is just another way of saying that power, when you are magnetically limited, depends on the saturation magnetostriction.

Now the compliance constant comes in, but there doesn't seem to be much you can do to vary this over any great range. So this seems to be an unimportant item.

VOICE: I gather that it is the same functional form as the equation for k^2, namely $\lambda^2 E$.

DR. WOOLLETT: It is a different λ. That is, our λ was saturation magnetostriction, not piezomagnetic constant. Of course, I like to use the other notation, $(D\text{-}33)^2$ divided by $\mu\text{-}33T$ in the equation for k^2.

MR. EHRLICH: The problem is the two λ's aren't the same kind of thing. One is Delta L over Delta.

MR. RICHMAN: Are they directly proportional or inversely proportional?

MR. EHRLICH: The D and the Lamda have nothing to do with each other. That is why it is unfortunate they have both been called Lamda.

DR. GARDNER: We have only a few minutes left. Do the invited speakers have any concluding remarks?

MR. WISE: No, not really.

PROF. CALLEN: No, I don't think so.

DR. WOOLLETT: Well, I have already said this, but I will say it twice. We do need more power. Now, if you look for the reason why magnetostrictors were displaced by ceramics; part of it was just a fad, just following the trend. But there are other cases where magnetostriction won't give us the power we want in relation to weight.

So, I don't think we can say that the battle will be won with present materials. We do want more power. You can't give the details of this withoug getting into classified areas, but there are many applications where we are pushing the limits and we want more power.

DR. CHIN: I just want to comment that as far as material properties are concerned, k^2(k=electromechanical

coupling coefficient) is proportional to $E\lambda^2/k_{eff}$ where E is Young's modulus, λ is the magnetostrictive strain and K_{eff} is the effective magnetic anisotropy (see eq. 2 of Chin's paper). The power output is proportional to $E\lambda^2$ (see Woollett's paper). The saturation magnetostriction of Permindur (2V-48Fe-48Co) and oriented Alfer (Fe-13Al) is about three times that of nickel (with or without Cr and Co) presently in use. Hence, k^2 or the power output is expected to be increased nine times. But we don't know if this improvment is enough for the designers. I feel these materials should be looked at in more detail.

DR. GARDNER: Gentlemen, we are at quarter of five. I want to thank each of the speakers for the efforts that they took to prepare these excellent talks. I also wish to thank all you people for coming and participating. The Workshop stands adjourned.

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