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RESEARCH ON A FERROACOUSTIC INFORMATION STORAGE SYSTEM

by J. W. Gratian and R. W. Freytag

Prepared under Contract No. NASw-592 *by*
GENERAL DYNAMICS/ELECTRONICS
Rochester, N. Y.
for

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ABSTRACT

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The ferroacoustic memory technique provides nonvolatile, updatable information storage, serial access to data without use of mechanical moving parts, and non-destructive data readout. The storage medium is a strain-sensitive ferromagnetic delay line. Write-in at any specified address is accomplished by the coincidence of a traveling sonic pulse and a properly timed magnetizing current pulse applied along the axis of the entire line.

Evaluation of single-line models operated at a data rate of 330 kc show practicable S/N over a temperature range of -20°C to +85°C. Performance and physical characteristics for multiple-line memories are estimated.

Investigation of advanced approaches for improving speed and data densities includes exploration of ultra-thin, mill-processed media and thin films. Improved procedures for the measurement and interpretation of strain-sensitive material characteristics, and progress in the study of both isotropic and anisotropic thin films, are discussed.

Author

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SUMMARY

The ferroacoustic memory technique provides nonvolatile, updatable information storage, serial access to data without use of mechanical moving parts, and non-destructive data readout. The storage medium is a strain-sensitive ferromagnetic delay line. Write-in at any specified address is accomplished by the coincidence of a traveling sonic pulse and a properly timed magnetizing current pulse applied along the axis of the entire line. Data readout is the axial voltage generated by changes in strain-sensitive remanence as a sonic pulse traverses the recorded flux pattern.

Extended evaluations of single-line models operated at a data rate of 330 kc with arbitrary data patterns show practicable S/N over a temperature range of -20°C to +85°C. Write-in drive energy requirements are in the order of 1×10^{-6} joule per bit. Analyses of representative memory systems, based on the aforementioned results, include a 512-word by 12-bit configuration organized for 40 microsecond access time; exclusive of memory packaging and access circuits, estimated characteristics are: 10^{-2} joules to update the entire 6144 bits, weight and volume of 2.5 ounces and 2 cubic inches for the basic memory.

Analyses of advanced approaches indicate different advantages for ultra-thin mill-processed media and thin films. Milled media are available in the basic composition and thickness expected to permit order-of-magnitude increases in data density and access time, but capacity per line is limited by relatively high acoustical attenuation. Thin films offer still higher switching speeds, but substrate characteristics require a major compromise between the low attenuation of fused silica and the better match in thermal coefficient of expansion provided by other materials. Difficulty in demonstrating the feasibility of thinner media is believed to be caused primarily by the problem of coupling fine media to the transducer without excessive variation in impedance. Improved procedures for the measurement and interpretation of basic strain-sensitive material characteristics, and progress in the investigation of both isotropic and anisotropic thin films, are reported.

INTRODUCTION

Ferroacoustic storage provides solid-state, nonvolatile, updatable storage and nondestructive readout of information. Its basic capability for sequential access to data tends toward the low cost, size, and weight per bit of information which characterize approaches using moving storage media such as magnetic drums or tape, but the usual associated mechanical problems are avoided.

The technique, as indicated in Figure 1, uses the coincidence of a propagated ultrasonic strain pulse in a delay line and a properly-timed polarizing current pulse applied axially to accomplish write-in at any specified address. The strain-sensitive remanent material

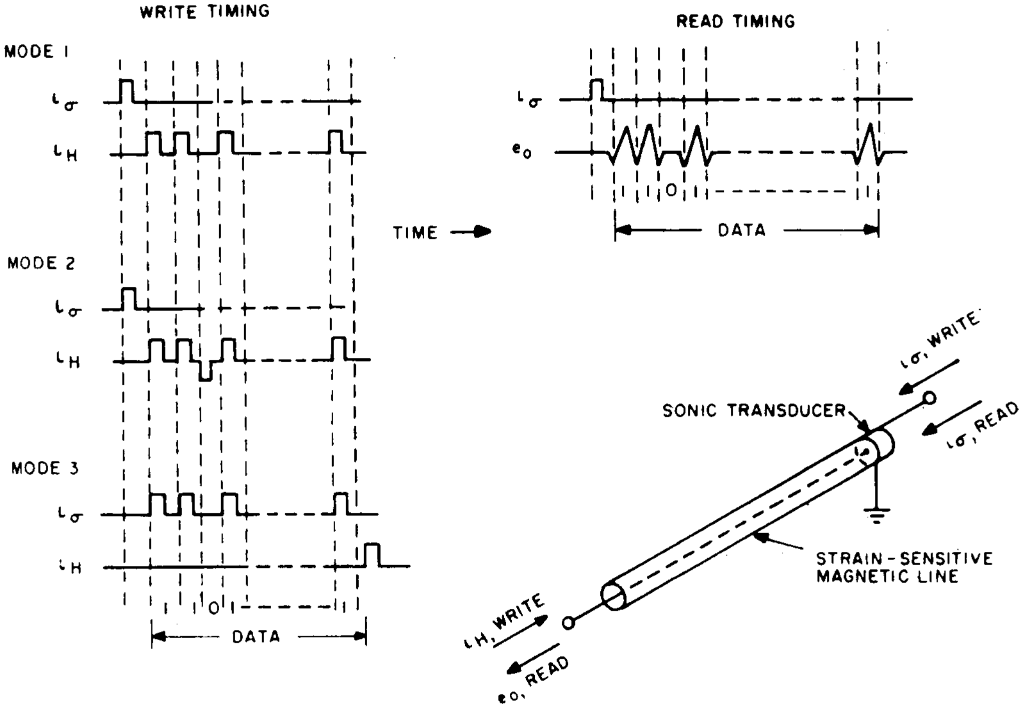


Figure 1. Ferroacoustic Memory Operation.

properties(1, 2) of the delay line then result in nonvolatile, updatable storage which can be read out nondestructively as a subsequent strain pulse is projected along the line.

Three basic modes of operation(1, 2) proposed are:

1. The data signals are applied as axial polarizing currents in the form of positive pulses to represent ONES and absence of pulses to represent ZEROS. After an entire line has been erased, data can be entered at an arbitrary rate to arbitrarily selected addresses, or entered serially, as indicated in Figure 1.

2. Data signals are applied as axial currents in the form of positive and negative pulses to represent ONES and ZEROS, respectively. This mode offers greater versatility by permitting random-access updating of portions of a single line without an intermediate erase operation.

3. The data signals are applied to the transducer to generate strain pulses representing the data; immediately after all data have been entered serially, a single polarizing

Optimization of magnetic material properties, regardless of media thickness, is needed to reduce both polarizing-field and transducer power. More important are the limitations imposed on transducer design by the high sonic stress which has been required to effect write-in with a usable S/N ratio. Elimination of acoustical horns would reduce size and cost substantially, as well as acoustical variables such as dispersion, attenuation, and reflections. Ultimate systems approaching the 100-mc range are expected to require piezoelectric-crystal or depletion-layer(3) transducers which provide lower stress than the ceramic transducers found most suitable for the 300-kc to 10-mc range and, hence, their use in ferroacoustic storage appears to require a delay line material with improved strain sensitivity.

Project objectives, summarized, therefore call for systems analysis of near-term capabilities and long-range improvement of the ferroacoustic storage technique, including analysis and evaluation of magnetic storage materials, improvement of piezotransducer line-driving techniques, and analysis of factors controlling overall performance.

Acknowledgement. - Dr. C.E. Drumheller and A.G. Balmer prepared the magnetic thin films and designed the thin-film stressing apparatus used in reported investigations. The major portion of measurements were made by A.J. DiNardo and L. Oldroyd. K. Clayton contributed to discussions and review of progress and reports throughout the project.

330-KC FERROACOUSTIC MEMORY

Three lines operated with 3-microsecond resolution were evaluated during this project to determine the overall capabilities of proven ferroacoustic storage techniques. While 1-microsecond resolution has been demonstrated for single pulse recordings(1), substantial improvements will be required to equal the reproducibility, reliability, and lower drive power obtainable with 3-microsecond resolution. Brief tests for 2-microsecond resolution appear encouraging, and available partial results are also reported.

Model Description

The test model, as shown in the photographs and sketch of Figures 2 and 3, consists of a piezoelectric ceramic driver, a brass horn with a 10:1 pressure gain, and a 12-inch storage line of 50 percent NiFe tubing with an outside diameter of 15 mils and a wall thickness of 2 mils. Horns are bonded to the transducers with conductive epoxy. One line also uses conductive epoxy to bond the line to the horn. The other two lines are bonded with silver solder to two horns driven from one transducer. The ends of the lines can be damped to prevent reflections, but they were left undamped in these evaluations so that the discontinuity at the end of the line could be used in secondary tests of a readout level which is independent of the write-in process. The axial conductor is No. 40 enameled wire.

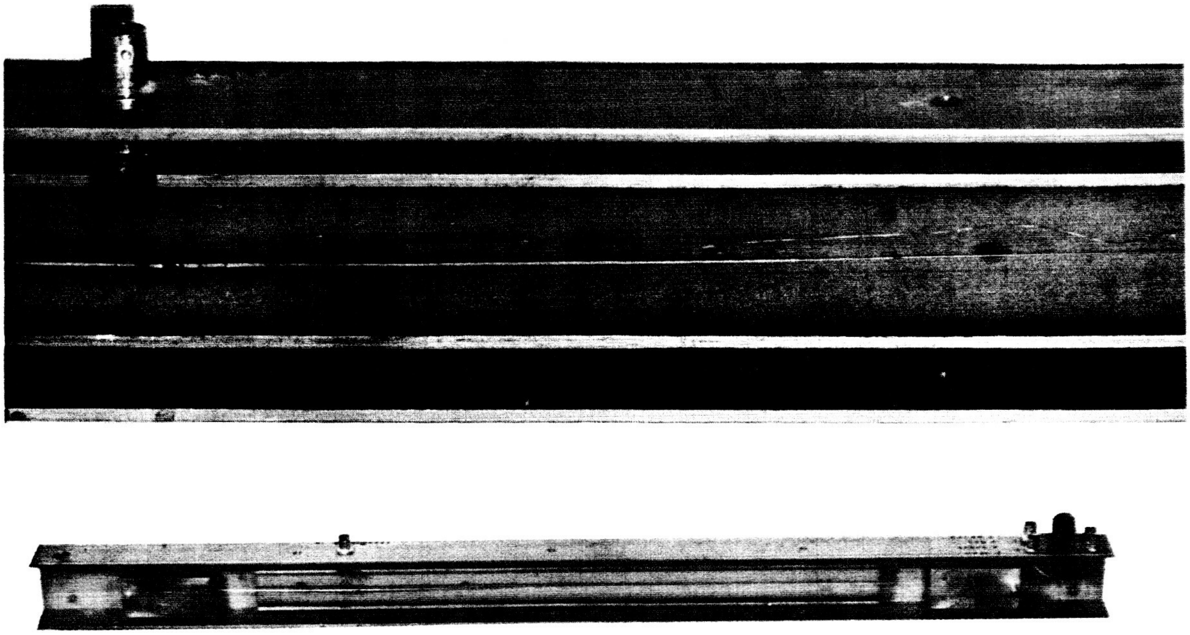


Figure 2. Ferroacoustic Memory Model.

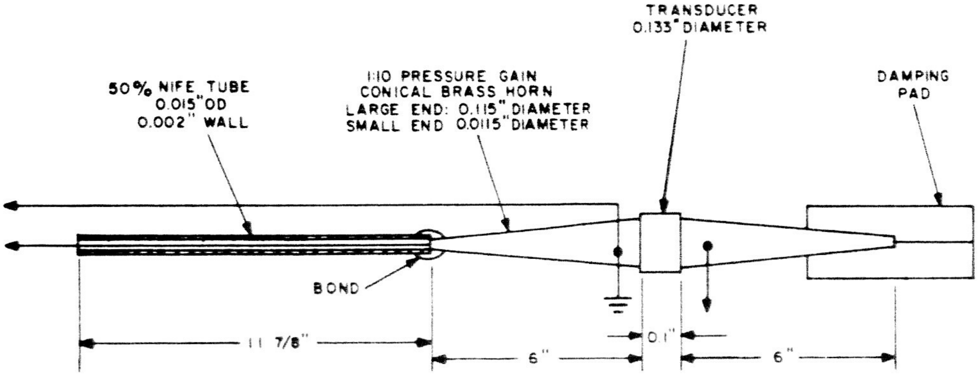
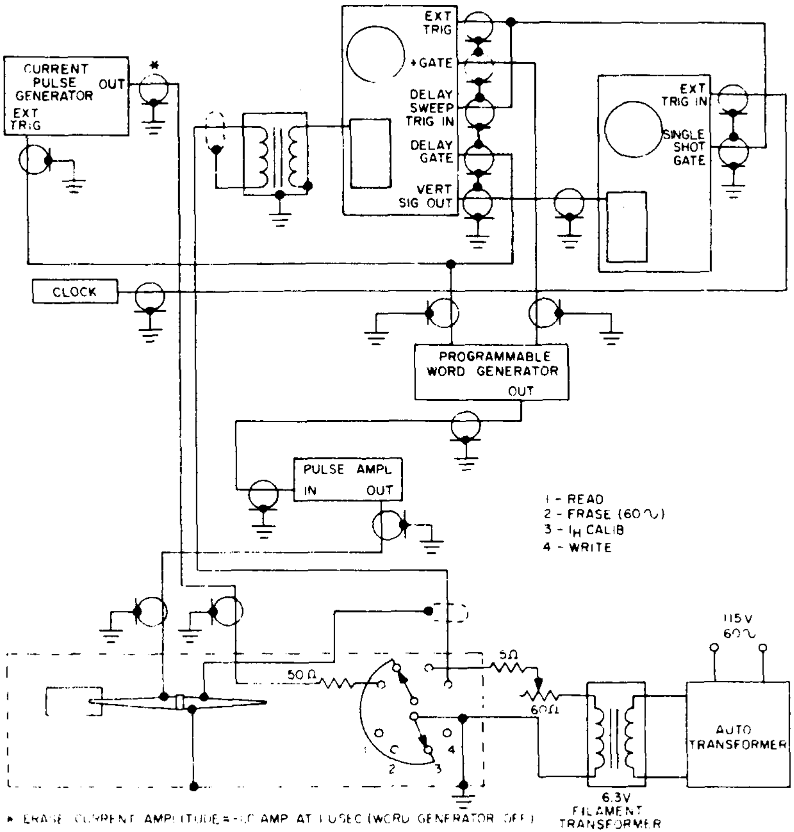


Figure 3. Model Detail.

The circuits and instrumentation for these tests are shown in Figure 4. A pair of alternative erasing procedures are provided. In one case, a 60-cps erasing field is gradually reduced from a saturating value to zero. It is assumed that the frequency can be raised and the number of cycles reduced so that the time required for erasure can be made small compared with the time required to fill a line with data. The procedure for the major portion of tests to be reported used the alternative single-pulse saturation erase or pre-bias technique previously reported(1). This latter method is especially suitable for Mode 3 operation because write-in involves only one subsequent application of magnetizing field.



* ERASE CURRENT AMPLITUDE = -1.0 AMP AT 1 USEC (WORD GENERATOR OFF)
RECORD CURRENT AMPLITUDE = +0.63 AMP AT 1 USEC

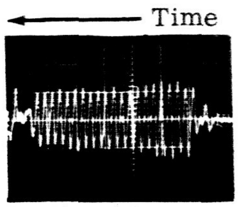
Figure 4. Test Circuits.

Model Performance

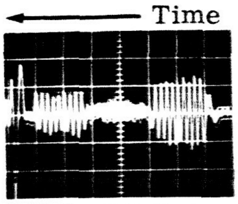
Uniformity. - The uniformity of an entire line for a series of ONES, recorded under Mode 3 operation, is shown in Figures 5A and 5B for approximate resolutions and 3 and 2 microseconds, respectively. Data rates are 330 kc and 500 kc, corresponding to linear densities of 2 and 3 bits per inch, respectively.

The pulses at the ends of the traces are caused by the magnetic discontinuities at the ends of the line. The pulse at the far end of the line can be eliminated by the damping to be provided in operational models. To avoid the first pulse, readout gating must be delayed until the readout strain pulse passes the junction between the horn and line.

Variation in the average level of ONES is 3.5 db and 4.5 db for 3 and 2-microsecond resolutions, respectively. The drop in average level as the end of the line is approached is caused by acoustical attenuation and, as shown in the two photographs, is substantially higher with 2-microsecond resolution.



330 kc Bit Rate



500 kc Bit Rate

	Vertical Sens.	Sweep Rate	Peak Transducer Volts
A	1.25 mv/div.	10 μsec/div.	320V
B	1.25 mv/div.	10 μsec/div.	420V

Figure 5. Uniformity of Readout.

For 3-microsecond resolution, the variation in uniformity, excluding the gradual decrease in level caused by attenuation, is ±4.0 to ±0.6 db, depending on drive level as discussed subsequently.

Signal-to-Noise. - Readout traces for several sequences of ONES and ZEROS recorded under Mode 3 operation are shown in Figure 6 for 3-microsecond resolution.

In previous work(1) with single pulses, it was assumed that S/N could be taken as the ratio of the ONE level to the peak noise at ZERO level; with a fixed optimum polarizing current and resulting fixed noise level, signal level could then be increased by increasing the transducer drive power and resulting strain for write-in.

The new tests for groups of pulses, however, show an overshoot, following the pulse group, which occurs at the next bit position. Since the amplitude of the overshoot is proportional to the strain level used for write-in, increased strain can improve S/N by only a few db up to the point at which ZERO level peak noise is negligible compared with overshoot amplitude.

Elimination of overshoot would permit more effective use of higher transducer drive levels; the resulting increased ONE level relative to ZERO level noise would permit use of increased line length without excessive attenuation. It seems likely that overshoot amplitude may be reduced in future work, but for this evaluation the worst cast of overshoot plus ZERO level peak noise is taken as the noise level.

Signal-to-noise on that basis averages 11 to 15 db for 3-microsecond resolution. Average peak output is 1 millivolt for a transducer drive of 250 volts and varies approximately as the square of the drive voltage, assuming the same voltage is used to write and to read.

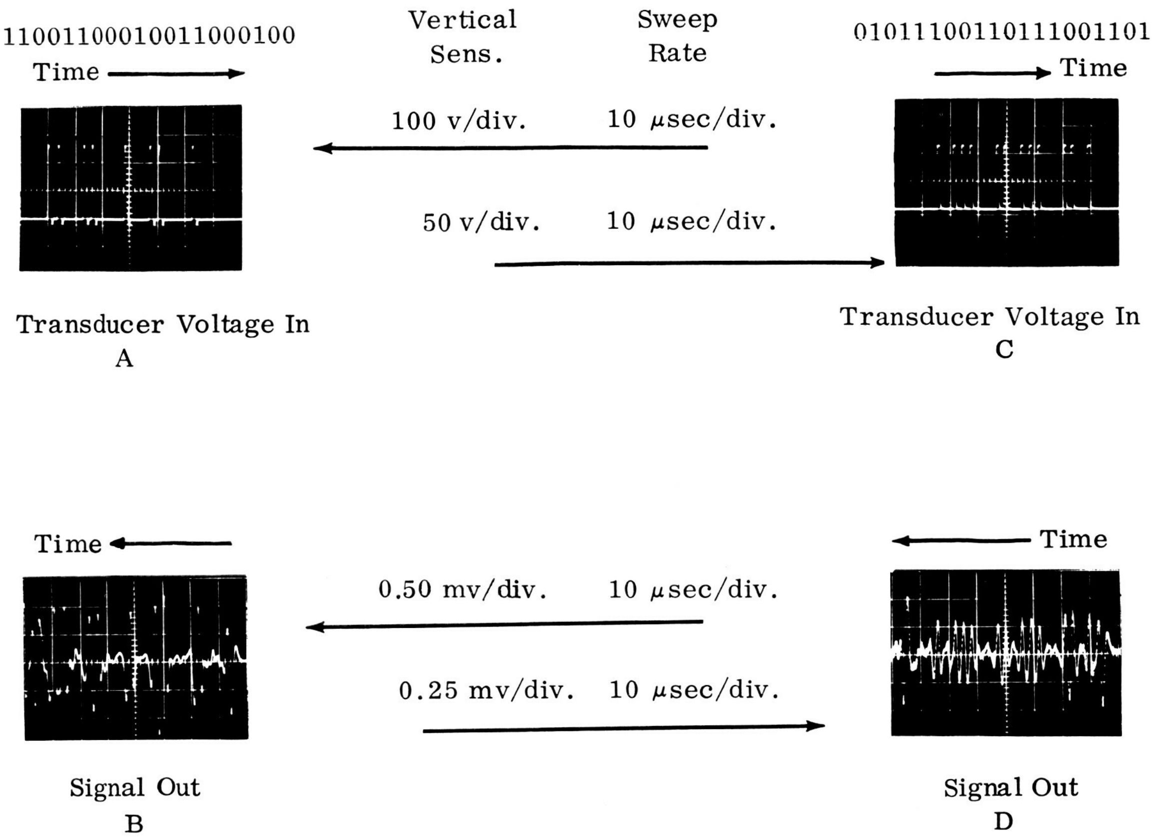


Figure 6. Data Readout Waveforms.

Drive Energy. - Polarizing drive current is 630 ma at 1 ohm. Pulse width is 1 microsecond, and corresponding pulse energy is 0.4×10^{-6} joules. The saturation erase pulse is one ampere, or 1×10^{-6} joules. Total erase and write-in energy to record the 12-inch line under Mode 3 operation, therefore, is 1.4×10^{-6} joules.

Since resistance of the line is proportional to line length, total energy for a different line length, ℓ, using No. 40 conductor will be $(1.4 \times 10^{-6})\ \ell/12$ joules. The present tubing with 11-mil ID would permit conductor area to be increased by an order of magnitude to provide a corresponding reduction in power. For Mode 1 operation, the number of write-in pulses to be supplied is proportional to line capacity and length; total energy therefore varies as the square of line length and may become the primary demand. For Mode 3 operation, however, transducer energy is dominant, and the small axial conductor was therefore used for these tests to minimize acoustical energy loss.

Transducer drive requirements, as a function of measured average S/N and uniformity, are:

Table 1. Transducer Drive Requirements.

Peak				
Volts	Ma.	Joules	S/N	Uniformity
50	3.5	0.088×10^{-6}	10.9 db	±4.0 db
115	8.05	0.46×10^{-6}	11.6	±1.2
220	15.4	1.7×10^{-6}	13.9	±1.3
260	18.2	2.4×10^{-6}	15.3	±1.3
420	29.4	6.2×10^{-6}	12.3	±0.6

A source impedance of 2000 ohms is required to limit peak current to the tabulated values.

The total energy requirement for Mode 3 operation is proportional to line capacity and length; e.g., $(0.088 \times 10^{-6})\ \ell D$ Joules at 50 volts drive, where D is the linear data density in bits per inch and ℓ is line length in inches. Two lines of length, ℓ, driven from opposite sides of the transducer are assumed; alternatively, it may be found more practical to transmit all transducer energy in one direction, thus halving the tabulated energy values. If the overshoot already discussed can be eliminated, the S/N at 400 volts drive will increase to 18 db.

Temperature Characteristics. - Variations in performance were tested over a range of -20°C to +85°C using a pair of pulses recorded 8 inches apart on the line. Readout level falls as temperature increases. Consequently, the increase in noise (as previously defined to include overshoot) at low temperature and the decrease in ONE level at high temperature combine to reduce the effective S/N over the range of temperature, even though S/N as measured at each temperature is essentially independent of temperature. The effective S/N for the 105°C range is 3 db below the S/N at 23°C when data are rewritten and read at each test temperature. With data written at 23°C and read at the temperature extremes, the effective S/N is 2 db below the S/N at 23°C.

Nominal delay for the 8-inch length of line between test pulses is 47 microseconds. Total variation in delay over the 105°C range measured 0.2 microsecond, giving $40 \times 10^{-6}/^{\circ}C$ for the temperature coefficient of time delay. This corresponds to a maximum shift of ±0.25 bit for a 60-inch line operated at a data rate of 330 kc over the 105°C range.

Memory Systems Analysis

Estimates of overall memory characteristics, exclusive of access circuits, for three representative memory configurations operated in Mode 3 at 330 kc are presented. Analyses are based on the measured characteristics for single-line models as reported in the previous section. Methods using multiple lines coupled to a single transducer, and volume and weight estimates, are projections of anticipated characteristics.

Single-Line Memory. - The maximum usable bit capacity for a single line is limited by line attenuation, average S/N and uniformity at a given transducer drive level. The minimum ratio of ONE level to ZERO level, $(S/N)_{min}$ equals (S/N) - U, where U is the variation in storage medium uniformity. Allowing a margin M for other system variables, maximum usable line length in inches is:

$$\ell_m = \left[(S/N)_{min} - M \right] / \alpha$$

where

α = 0.35 db/inch is the acoustic attenuation for the ferroacoustic line operating at 330 kc.

The maximum line capacity in bits is then:

$$C_m = D \ell_m, \text{ where } D = \text{linear data density in bits/inch}$$

$$= 2 \ell_m \text{ for 330 kc operation.}$$

Write-in transducer and polarizing energies, based on the above relations and the previously discussed measurements, are shown in Figure 7 for a single line operated in Mode 3 at the 330-kc data rate. The indicated voltages apply only when horn gain is 10:1. The dotted curves show the maximum line capacities which would be permissible for several assigned values of M. Line capacity for a given transducer energy level can be doubled by using both sides of the transducer.

Readout transducer energy corresponds to the single-bit values of the previous tabulation.

Multiple-Line Memory. - As an example of a small multiple-line memory, assume a requirement for 20 words of 8 serial bits per word. The ferroacoustic memory would consist of a single transducer driving 20 parallel lines. Horn area at the small end may be increased by a factor of 20, leaving a pressure gain of 2.24.

From Figure 7, a transducer drive voltage of 50 volts provides a margin of 5 db for an 8-bit line when horn gain is 10:1. With the horn gain reduced to 2.24, a transducer drive of

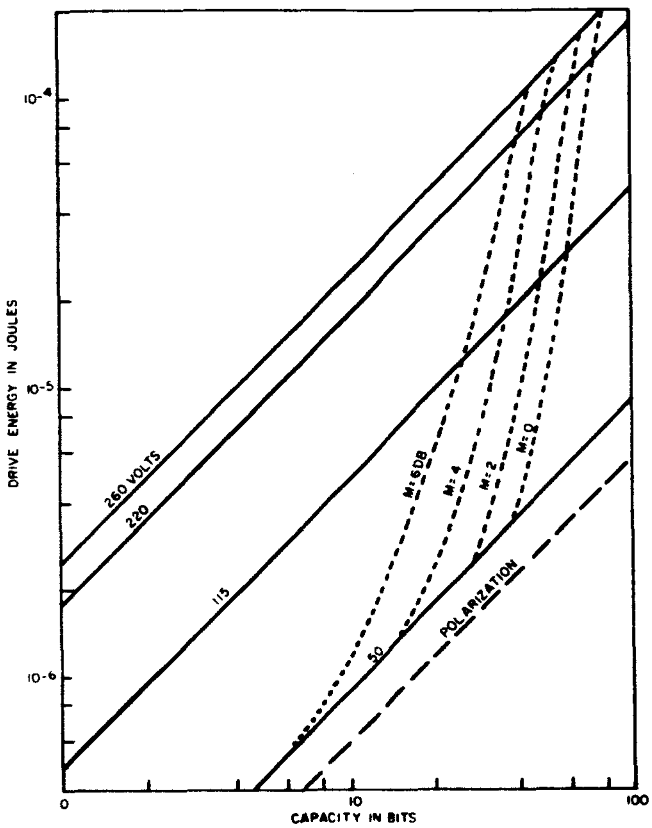


Figure 7. Write-in Drive Energy and Data Capacity Limits.

220 volts will be required to retain the 5 db margin. The corresponding energy per bit is 1.7×10^{-6} joules, 14×10^{-6} joules to write one word, or 280×10^{-6} joules to update the entire memory.

With the reduced horn gain, horn length can be reduced to 1 inch, and probably less. Storage line length for 8 bits at the 330 kc rate is 4 inches. The corresponding access time is 30 microseconds.

Allowing one inch of length for damping, if necessary, the basic memory volume and weight would approximate 0.09 cubic inch and 0.15 ounce, respectively, with a pair of 1-inch horns or 0.08 cubic inch and 0.10 ounce if horns can be reduced to a length of 0.5 inch. Housing and terminal details will require development, but are expected to increase these values by less than 100 percent.

Matrixed Memory. - For larger memories, access circuitry can be simplified and transducer drive energy reduced by matrixing the ferroacoustic memory as indicated in Figure 8. Assume a requirement for 512 words of 12 bits each. With 32 lines per transducer and 16 transducers, access to a specified word (line) may be accomplished by Y-selection of one of 16 transducers and X-selection of one of 32 axial conductor connections.

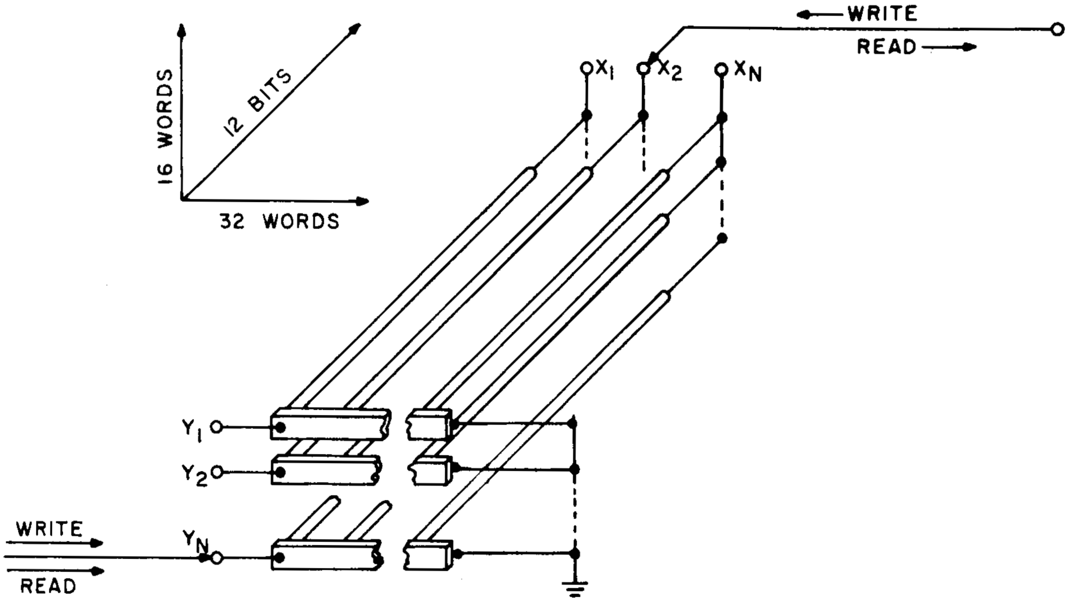


Figure 8. Matrixed Memory.

With 32 lines per transducer, horn area at the small end may be increased by a factor of 32, leaving a pressure gain of 1.77. From Figure 7, a transducer voltage of 50 volts provides a margin of 4 db for a 12-bit line when horn gain is 10:1. With the horn gain reduced to 1.77, a transducer drive of 280 volts is required to retain the 4 db margin. The corresponding transducer energy to record one line is 2.8×10^{-6} joules per bit, 34×10^{-6} joules to write 12 bits, and 17×10^{-3} joules to write 512 words.

Access time, assuming a horn length of 0.5 inch, would be 38 microseconds. Improvement of resolution to permit a 500 kc data rate would reduce access time to less than 27 microseconds.

Basic memory volume and weight estimates are 2.1 cubic inches and 2.5 ounces, exclusive of housing and terminals. As an example of possible trade-offs in design, the alternative use of 32 transducers with 16 lines per transducer would halve total write-in energy, but would nearly double the physical size.

ADVANCED TECHNIQUES

Memory Line Configuration

Configurations initially considered for ferroacoustic storage have been of circular cross-section and include:

- A tube of magnetostrictive material surrounding a separate axial conductor, as indicated in Figure 1;
- A single fine magnetostrictive wire serving both the magnetic-storage and electrical-conduction functions, and
- A cylindrical magnetic thin film deposited on a nonmetallic filament such as fused quartz to minimize acoustical attenuation.

Planar configurations, using either mill-processed or thin-film magnetic media, appear to offer advantages which were explored under this project. Rolled strip is commercially available in 50 percent NiFe down to a thickness of 1/8 mil, thus providing an effective thickness approximately one-tenth that of tubing or wire. As a tentative basis for comparing relative potentialities, it is assumed that a linear density of 6 bits per inch can be achieved with 1-mil thick media and that usable density will vary inversely with the effective thickness of other media.

Minimum media sizes located to date in suitable alloys, and estimated linear bit densities based on the above assumptions, are shown in Table 1.

Table 2. Estimated Data Densities for Potential Ferroacoustic Storage Media

	Minimum Physical Thickness	Effective Thickness	Estimated Bits per Foot	Estimated Cost Per Bit
Tubing				
45 mil OD x 3" - 6" length	0.5 mil	0.5 mil	144 bits	0.31¢
5 mil OD	1.0 mil	1.0 mil	72 bits	1.85¢
10 mil OD	1.0 mil	1.0 mil	72 bits	0.61¢
Wire				
50% NiFe	1.0 mil	0.5 mil	144 bits	0.0005¢
Strip				
1/32-inch width	0.125 mil	0.06 mil	1150 bits	0.003¢

Tubing with 0.5 mil wall, in the 50 percent NiFe alloy, is presently available only in short lengths and large outside diameters. Consequently, use of the thinner wall would limit possible bit densities to 10^7 bits per cubic foot as compared with 10^8 bits for tubing with 1-mil wall, assuming close-packed lines with center-to-center spacings equal to their respective outside diameters. For a small memory with a given package length limit of 6 inches or less, however, the thinner tubing would permit addressing twice as many bits from a single transducer, thus simplifying access circuits.

Close-packed strip, on the basis of the above estimates, would reduce weight and volume per bit by two orders of magnitude or better as compared with tubing. The indicated increase in linear packing density would reduce the number of transducers and associated switches by an order of magnitude, for applications which can use serial access to a long block of data; and access time would be reduced correspondingly for a specified number of serial bits per line.

The planar approach also offers major simplifications in fabrication using magnetic thin films. A proposed configuration consists of magnetic strips deposited on a common low-loss planar substrate which is bonded to a single transducer, thus avoiding the problem of handling and bonding separate fine lines to a transducer without introducing excessive variations in mechanical impedance. Vacuum deposition or electrodeposition of multiple lines also becomes more practicable when a common flat substrate is used instead of separate cylindrical substrates.

Possible disadvantages of the planar configuration are: a less uniform flux distribution in the transverse cross-section; and the longer flux path of a rectangular cross-section if strip width cannot be reduced to values comparable with the diameters of usable circular cross-sections. The anticipated advantages, however, appear sufficiently important to justify further investigation of the planar approaches and comparison with improved circular configurations.

Substrate Characteristics

Selection of a substrate material for ferroacoustic thin-film configurations involves optimization of two primary factors: (a) minimum acoustical attenuation; and (b) match between the temperature coefficients of expansion for substrate and thin film.

The attenuation of fused silica is an order of magnitude lower than that for glasses in general. Its temperature coefficient of expansion, however, is $0.6 \times 10^{-6}/^{\circ}C$ as compared with a representative value of $10^{-5}/^{\circ}C$ for 50 percent NiFe. The differential strain, ϵ, resulting is approximately 10^{-4} inch/inch for a temperature change of $10^{\circ}C$. The corresponding stress in the NiFe film is

$$\sigma = Y\epsilon = 25 \times 10^{6} \times 10^{-4} = 2500 \text{ psi}$$

where

Y = Young's Modulus = 25×10^{6} psi for 50 percent NiFe.

This stress is of the same order as that required for write-in with present memory models and an order of magnitude higher than that anticipated for improved storage materials. Consequently, intolerable shifts in magnetic properties could result except in applications providing relatively constant ambient temperature.

Review of data on the temperature coefficients of expansion for glasses shows that 50 percent NiFe can be matched approximately with a potash soda-lead glass. More generally, NiFe in a range of potentially applicable alloys(4) can be matched by a variety of glasses(5) having temperature coefficients over the range of 3 to 13 ppm/°C.

Corning(6) gives attenuation figures (shear mode) of 6×10^{-3} and 0.15×10^{-3} db/µs-mc for glass and fused silica materials, respectively. Mason(7) notes that shear and longitudinal attenuations per unit of delay are approximately equal in fused silica. The mean from several sources of data is approximately 0.3×10^{-3} and 7×10^{-3} db/µs-mc for fused silica and soft glass, respectively. Using these figures and assuming, e.g., that a loss of 2 db in a line can be accepted, comparative storage characteristics would be as shown in Table 3.

Table 3. Comparative Storage Characteristics

	Substrate	
	Fused Silica	Soft Glass
Maximum line capacity	3335 bits	143 bits
Line length for 1-mc rate	65 feet	2.4 feet
Line length for 10-mc rate	6.5 feet	0.24 feet

The foregoing shows the advantages of fused silica for applications permitting close control of ambient temperature, but the glass substrate appears to be required where temperature control is not permissible. Further investigation is needed to determine whether thin-film temperature coefficients differ appreciably from the published data for bulk materials, as well as to determine more thoroughly the significance of temperature-induced strains versus the write-in strain which has been used tentatively as the basis for comparison.

Acoustical Attenuation in NiFe Materials

Mill-processed media, in contrast to magnetic thin films, require no substrate and, so, avoid the problem of matching temperature coefficients of expansion. Acoustical attenuation in polycrystalline metals(8), however, is known to be relatively high and is expected to be a major limitation in the use of mill materials.

Acoustical attenuation was measured for two 50 percent NiFe materials. One is tubing with 1-mil wall which was annealed at 1800°F. The other is half-mil strip which, as discussed subsequently, is processed to provide a cube texture; the final anneal is carefully held below the temperature range in which recrystallization and larger grain growth occur.

Attenuations of 0.5 and 0.16 db per inch for the tubing and strip, respectively, were measured using 1-microsecond pulses. With the strip lying on polyurethane foam or on smooth mylar, additional attenuations of 0.02 db/in and 0.05 db/in, respectively were observed.

The test fixture which was constructed and used for these measurements consists of a properly biased, fixed-position, magnetostriction receiving transducer and a driver transducer mounted on a slide which can be moved along the length of the line under test. The line can be suspended vertically from its end to avoid the need for intermediate supports which could otherwise add to the true line attenuation. To correct for nonuniformity of the line, a large number of measurements are made at peaks and valleys along the line. The method of least squares is then used to calculate the average slope of the curve for attenuation versus distance.

Mill-Processed Storage Media

Isotropic Materials. - Initial material investigations(1) under this program were concentrated primarily on isotropic materials. Magnetization or cyclic hysteresis curves for materials with and without fixed stress applied were found suitable only for preliminary evaluations of material applicability. Improvements in the precision of mechanical alignment for applying compressive axial stress to tubular material samples permitted measurement of small increases in the transverse induction of a sample of 49 percent NiFe, but no significant increase was observed in a sample of 50 percent NiFe which was otherwise outstanding in its sensitivity to changes in tension. Curves of remanence, B_r, versus maximum field intensity, H_{max}, showed the same trends as the magnetization curves for B versus H.

Quasi-static measurements were then utilized to permit point-by-point investigation of the specific B-H-σ sequences which occur in the ferroacoustic storage process. It was shown that readout strain sensitivity is not simply proportional to stored remanence; it is so strongly dependent on the previous history of H, σ, $\bar{\sigma}$, and $\bar{H}$ that two different sequences produced equal strain sensitivities when remanences differed in the ratio of 6:1. It was also shown that output level and S/N should increase as the ratio of the readout strain sensitivities for the ONE and ZERO recorded states is increased. If the uniformity of the storage medium varies ±10 percent, e.g., in accordance with the commercial tolerance on the wall thickness of tubing, a ratio of 2 should produce an S/N of 10 db.

Those results led to the development, during the present project, of revised quasi-static test procedures which are believed to be much more pertinent. Whereas fully annealed 50 percent NiFe shows no appreciable difference in curves of transverse induction versus H for the material with and without compressive axial stress, the new data indicate that this material should provide higher S/N at lower stress than the harder materials which appear more suitable on the basis of conventional B-H measurements. As shown in Figure 9, readout strain sensitivity is plotted as a function of write-in field intensity for each of the possible

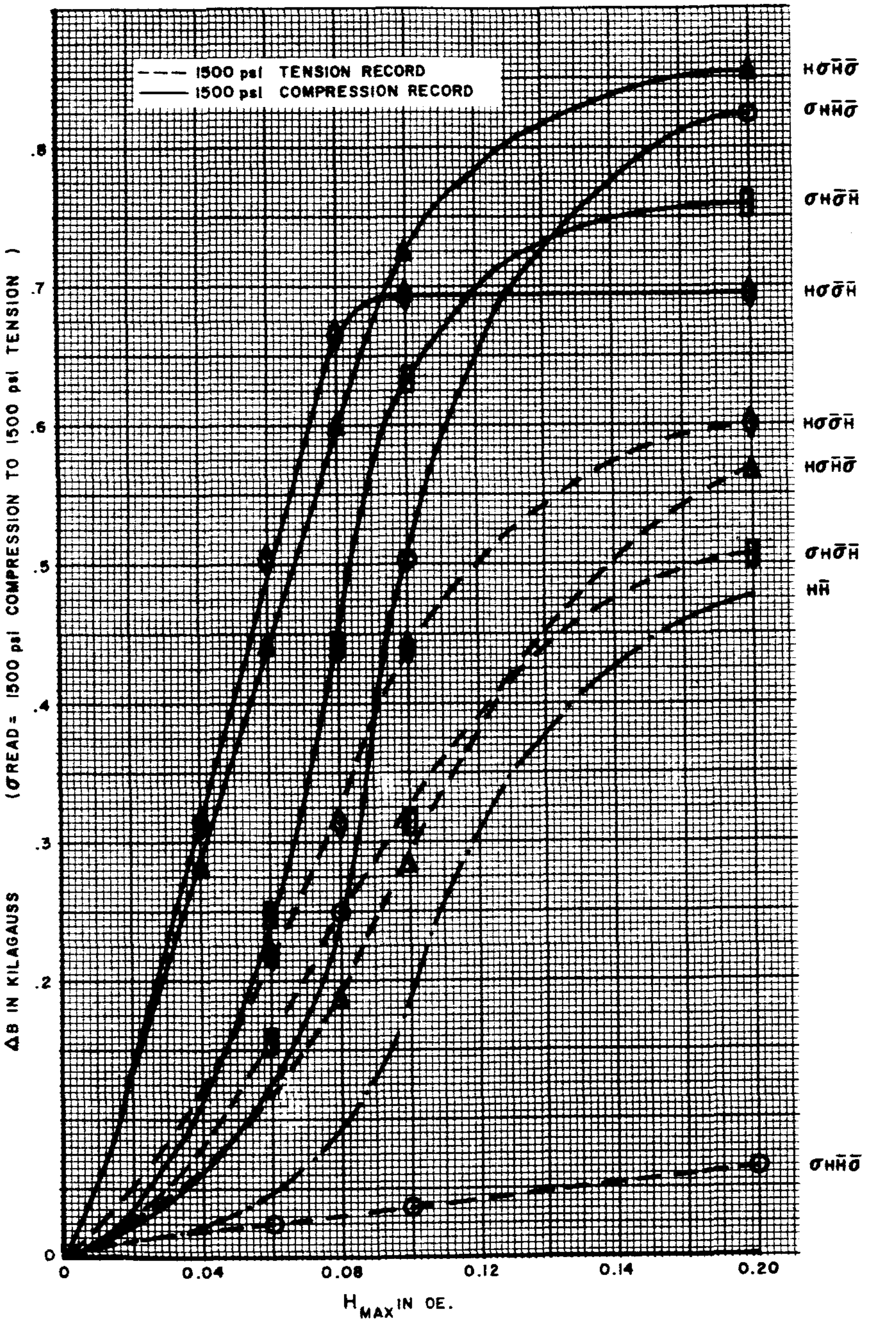


Figure 9. Strain Sensitivity of Fully Annealed 50 Percent NiFe.

write-in sequences. Readout strain sensitivity is the change in remanence, ΔB_r, which results from a change in stress, $\Delta\sigma$. The same peak values of stress are used for the write and read operations. The $H\,\bar{H}$ sequence corresponds to ZERO write-in, and the sequences involving stress are alternative ONE write-in sequences. Test apparatus is that previously reported(1).

The data of Figure 9 for 50 percent NiFe annealed at 2100°F indicates excellent ferro-acoustic storage properties. The ratio of readout strain sensitivities approximates 12:1, e.g., for the $H\sigma\,\bar{\sigma}\,\bar{H}$ and $H\,\bar{H}$ sequences when write-in H is a relatively low 0.04 oersteds. Other indicated relationships appear to be generally true for magnetostrictively positive materials. The application of compressive write-in stress after field ($H\sigma$) results in substantially higher readout strain sensitivity than the reverse ON sequence when followed by either the $\bar{H}\,\bar{\sigma}$ or the $\bar{\sigma}\,\bar{H}$ sequence. To a less important degree, removal of stress after removal of field ($\bar{H}\,\bar{\sigma}$) produces lower strain sensitivity than the reverse OFF sequence ($\bar{\sigma}\,\bar{H}$) when preceded by either the ($H\sigma$) or the (σH) ON sequence. The misleading character of hysteresis loops for this sample when stressed are shown in Figure 10; remanence, B_r, actually decreases when compressive stress is applied under the same mechnical conditions as employed for the data of Figure 9.

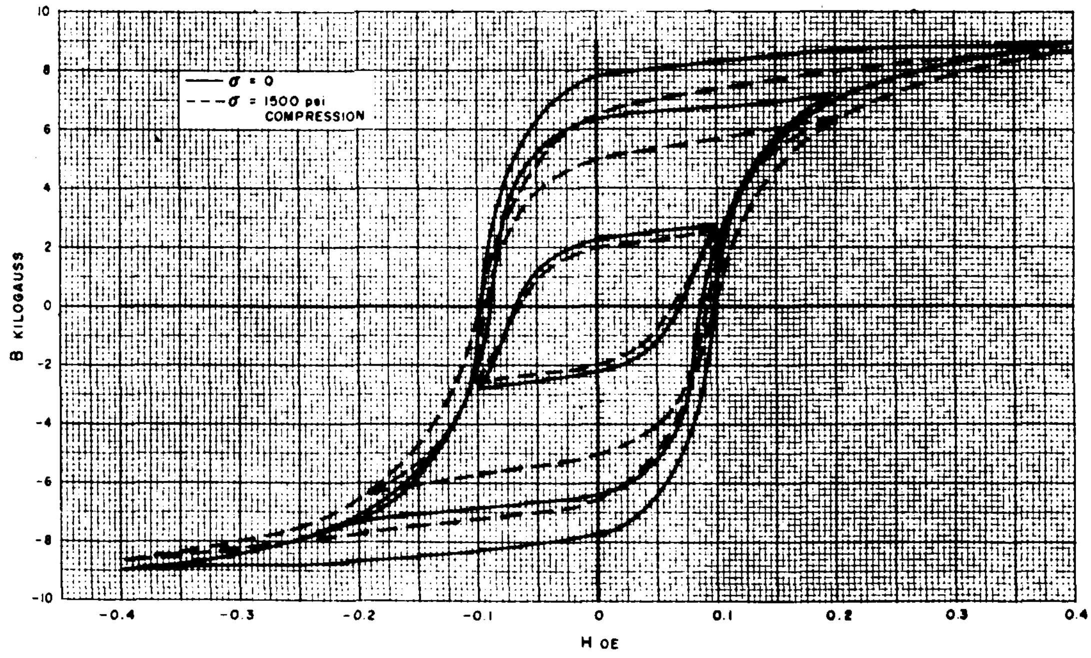


Figure 10. Hysteresis Characteristics of Fully Annealed 50 Percent NiFe.

Figure 11 shows the ratio of readout strain sensitivities for one of the ONE write-in sequences and the ZERO write-in sequence versus write-in stress. The strain sensitivity ratio exceeds 2 when stress is only 250 psi. Similar results were obtained with a sample of the 50 percent NiFe which was annealed at 1600°F.

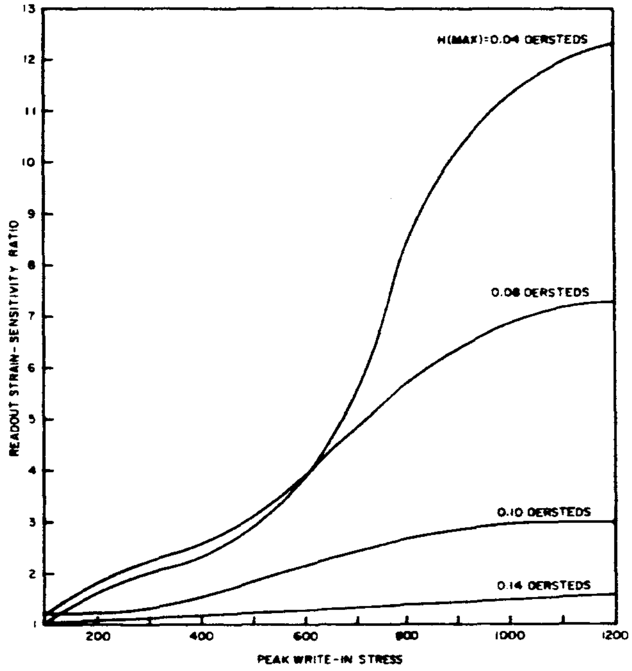


Figure 11. Strain-Sensitivity Ratio vs. Stress for Annealed 50 Percent NiFe.

Figure 12 shows quasi-static data for 50 percent NiFe annealed at 1000°F and tested in accordance with the new procedures described with reference to Figure 9. This is the annealing temperature required to approximate the hysteresis and magnetization curves of the tubing with 15 mil outside diameter by 2-mil wall, which proved successful in the model tests reported. Heavier tubes of 125 mil outside diameter by 20 mil wall are required for the quasi-static tests, and data for thin-wall tubing are limited to hysteresis and magnetization curves. Comparison of Figures 9 and 12 shows that the best strain sensitivity ratios for the 1000°F anneal are only about one-sixth those for the 2100°F anneal, and polarizing field requirements are several times higher. Hence, it appears that substantial improvements in S/N and decreases in the drive requirements of operating memory models should be possible through the use of annealing temperatures in the range of 1600 to 2100°F. Efforts to confirm this in dynamic tests are reported subsequently.

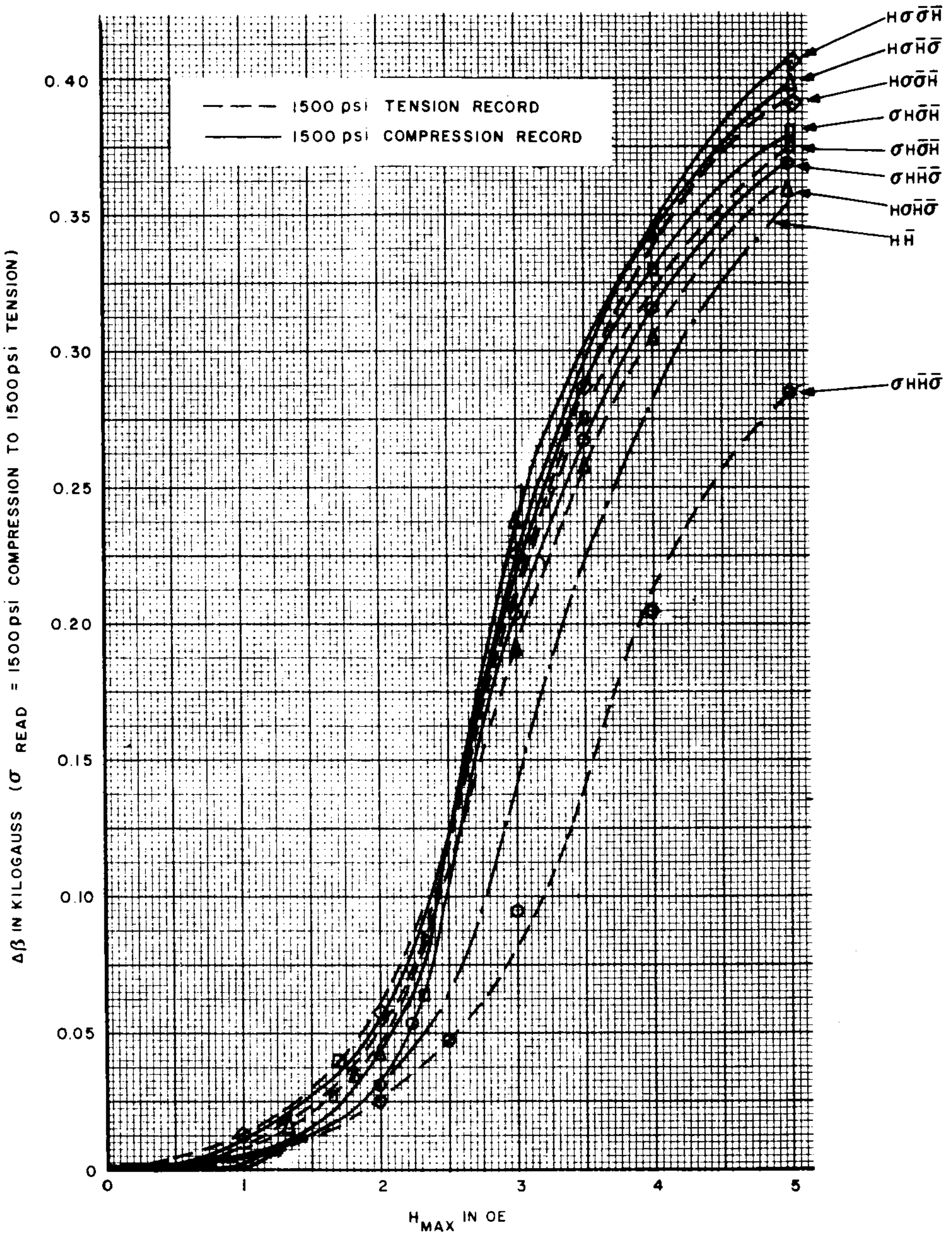


Figure 12. Strain-Sensitivity of Partially Annealed 50 Percent NiFe.

Grain-Oriented Material. - The material selected for initial investigation of thin strip is a cube-textured(9, 10) 50 percent NiFe, the basic composition used successfully in tubular form in previous demonstrations of the ferroacoustic storage technique. This composition has a face-centered cubic crystal structure with easy directions along the cube edges. To produce the cube texture, the rolling and annealing processes are controlled to orient crystals with cube faces in the rolling plane and cube edges in the direction of rolling, with the result that easy directions of magnetization are provided both longitudinally and transversely. Optimum magnetic properties are provided by an annealing temperature just below that at which recrystallization and grain growth occur. Hence, acoustical attenuation, due to scattering at grain boundaries as wavelength approaches grain size(8), should be reduced relative to that observed in NiFe materials which are usually annealed at higher temperatures to produce optimum magnetic properties.

The square hysteresis loop and low coercivity for a test sample of half-mil strip measured in the longitudinal direction are shown in Figure 13. The hysteresis loop is more nearly ideal for storage purposes in general than the loops for isotropic materials. Since the strip sample is too thin to support compressive stress for transverse tests, the longitudinal sensitivity to tensile stress, as shown in Figure 13 was measured. The sensitivity is comparable to that of isotropic materials under longitudinal test conditions, except that the cube-textured material shows more of a threshold and a step in strain sensitivity.

These tests give a much less conclusive indication of material applicability for ferroacoustic storage than the data of Figure 9 because they demonstrate neither transverse characteristics nor the effects of H σ sequence on readout strain sensitivity. However,

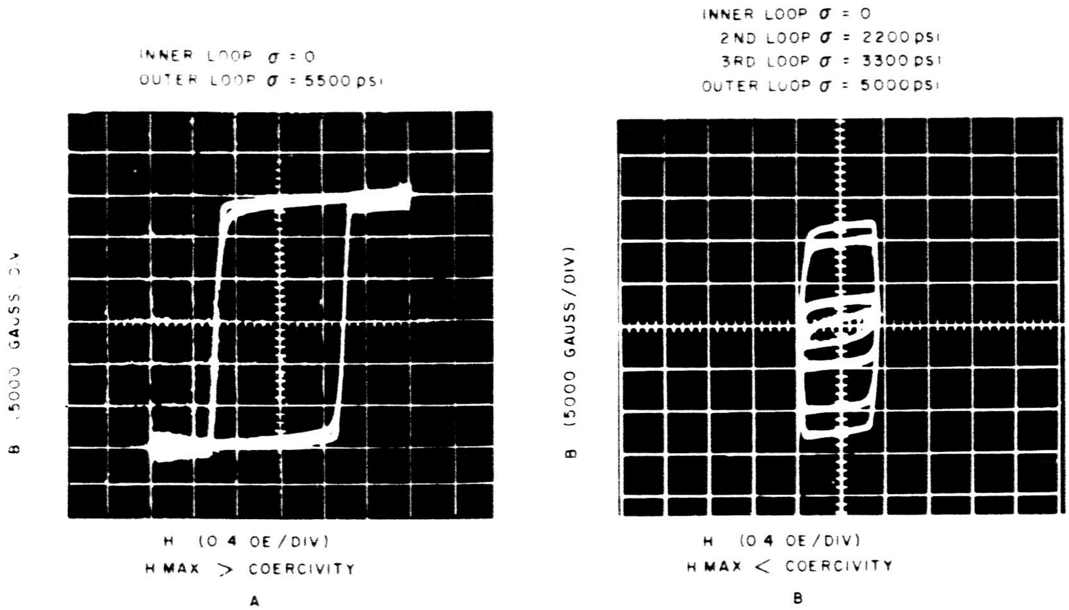


Figure 13. Magnetic Characteristics of Grain-Oriented Strip.

because of difficulties expected in preparing for quasi-static measurements on the thin strip, exploratory dynamic model tests based on these data were undertaken first.

Model Tests. - Three models were built and tested in the effort to demonstrate the improved resolution expected of thinner materials and the higher strain sensitivity indicated by the quasi-static material measurements reported above. Two models used 50 percent NiFe tubing of 10-mil outside diameter by 1-mil wall in place of the previously evaluated 15 mil outside diameter by 2-mil wall; one line was annealed at 1000°F and the other at 1800°F for the reasons previously discussed. The third model used 31-mil by 1/2-mil, 50 percent NiFe, cube-textured strip.

Model tests for the tubing annealed at 1000°F showed approximately the same resolution and S/N as previous data(1) for a 15-mil by 2-mil line operating with 1-microsecond resolution. Drive current requirements, however, were approximately halved, as expected because of the smaller tube cross-section.

One possible explanation for the lack of improvement is that there may be a significant difference between the strain sensitivities of the thin-wall tubing used in model tests and the thick tubing required for quasi-static measurements, even though the two samples show equivalent hysteresis loops. A second possible cause needing future investigation involves the mechanical problems encountered in producing an impedance match between the driving horn and the very thin tube wall. The technique which was used consists of flattening the tubular line on one end so that its cross-section changes gradually from the annular form to a 2-mil thick rectangle; the solid brass conical horn has two flats ground on opposite surfaces at its small end so that the resulting rectangular cross-section matches the flattened rectangular tubing to which it is butt-bonded with silver solder. Small mechanical deviations from intended construction may be responsible for pulse distortion which prevents the anticipated improvement in performance.

The line of tubing with 10-mil outside diameter by 1-mil wall, annealed at 1800°F, was coupled to the horn by inserting it in a dummy section of hard-drawn (effectively non-magnetic) NiFe tubing having 15-mil outside diameter by 11-mil inside diameter. Both tubes were then coupled to the horn using the same techniques previously found successful with the larger lines. Tests showed S/N to be below 0 db. Dynamic readout for a strain-biased quasi-static recording was then attempted. For this test, contacts spaced 0.1 inch apart were attached to the line, polarizing current was applied through these contacts, and the biasing tension was reduced to effect a ONE write-in. Tension was then re-applied and the entire line was polarized via the axial conductor to simulate the ZERO level. Readout pulses generated by the transducer then produced a S/N of 6 db. Since frequency-dependent losses are expected to reduce the signal and noise levels in the same ratio, dynamic readout should produce the high strain-sensitivity ratios indicated by the quasi-static data of Figure 9. S/N, however, is also dependent on the uniformity of the storage medium. Consequently, the development of a procedure for separate evaluation of media uniformity, especially for the study of thinner media, appears necessary in future work.

The half-mil, cube-textured strip was tested in a model using a four-coil, sequentially-pulsed, magnetostrictive transducer(1) in order to avoid the problems of mechanically bonded transducers initially. This material has a lower coercivity than the tubular materials, is magnetized by the earth's field and, consequently, was tested inside a solenoid with current adjusted to cancel the ambient field. No appreciable recording was observed under these test conditions. More systematic investigation of transverse quasi-static characteristics and media uniformity will be needed to determine this material's applicability for ferroacoustic storage.

Strain-Sensitive Magnetic Thin Films

Three basic differences exist in the requirements of thin films for ferroacoustic storage as compared with the properties which have received extensive study for conventional memories. First is the requirement for high strain sensitivity. For this purpose, investigation of compositions in the vicinity of 60 percent NiFe has been proposed(1), as opposed to compositions near 80 percent NiFe which approximate the zero magnetostriction desired in conventional memories. Second, the ferroacoustic memory does not require that the storage medium have a square loop and a threshold in its magnetization curve, since write-in is accomplished by coincident field and stress, rather than coincident half-currents; whether such characteristics are advantageous in ferroacoustic storage, however, needs to be investigated. Third, since complete switching is not essential in ferroacoustic storage, isotropic films as well as anisotropic films may be applicable, and their respective merits have to be determined.

Procedures. - Planar films have been used in exploratory work during this project. This approach bypasses problems reported by Shahbender and Onyshkevych(11) in the deposition of tubular thin films, and it also permits basic measurements under conditions of stress and orientation which are more difficult, if not impossible, with tubular configurations. It is expected that results from the planar films will be applicable to tubular configurations if the latter should be found preferable to proposed strip lines.

The NiFe films are electrodeposited in the form of discs, one centimeter in diameter, using procedures reported by Brenner(12). The substrates are vacuum-deposited copper over chrome on glass. Anisotropic films are deposited in an orienting field supplied by a Helmholtz coil. Coil current is adjusted to cancel the ambient field during deposition of isotropic films. Conditions for preparation of samples to be discussed were as shown in Table 4.

Test apparatus includes the BH loop tracer(13) shown in Figure 14 and the specially designed fixture shown in Figure 15 for applying calibrated strains to the thin films. The substrate with film can be forced by a pneumatically operated pouch to conform to a cylindrically contoured stop whose radius determines the strain in the film. Measurements can

Table 4. Conditions for Sample Preparation.

Sample	Orienting Field in Oer.	Electrodeposition Current (ma)	Electrodeposition Time (min)	Nominal Thickness
D-3	6	3.7	8.1	10,000A
N-3	0	15.0	2.3	10,000A
D-17	0	3.7	2.3	3,000A
24-3	-	(Vacuum Deposited)		1,400A

Bath Composition: Metal percentage of Iron in Bath - 4.9 percent

Total metal content - 0.84 moles/liter

be made using either tensile or compressive strains applied longitudinally, transversely, or at any other desired angle relative to the direction of measured induction.

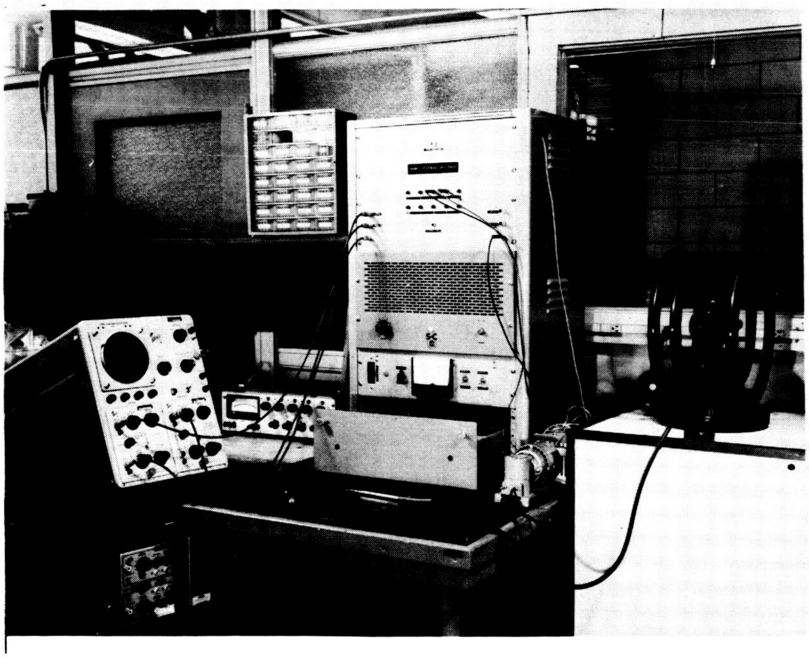


Figure 14. Apparatus for Thin-Film Measurements.

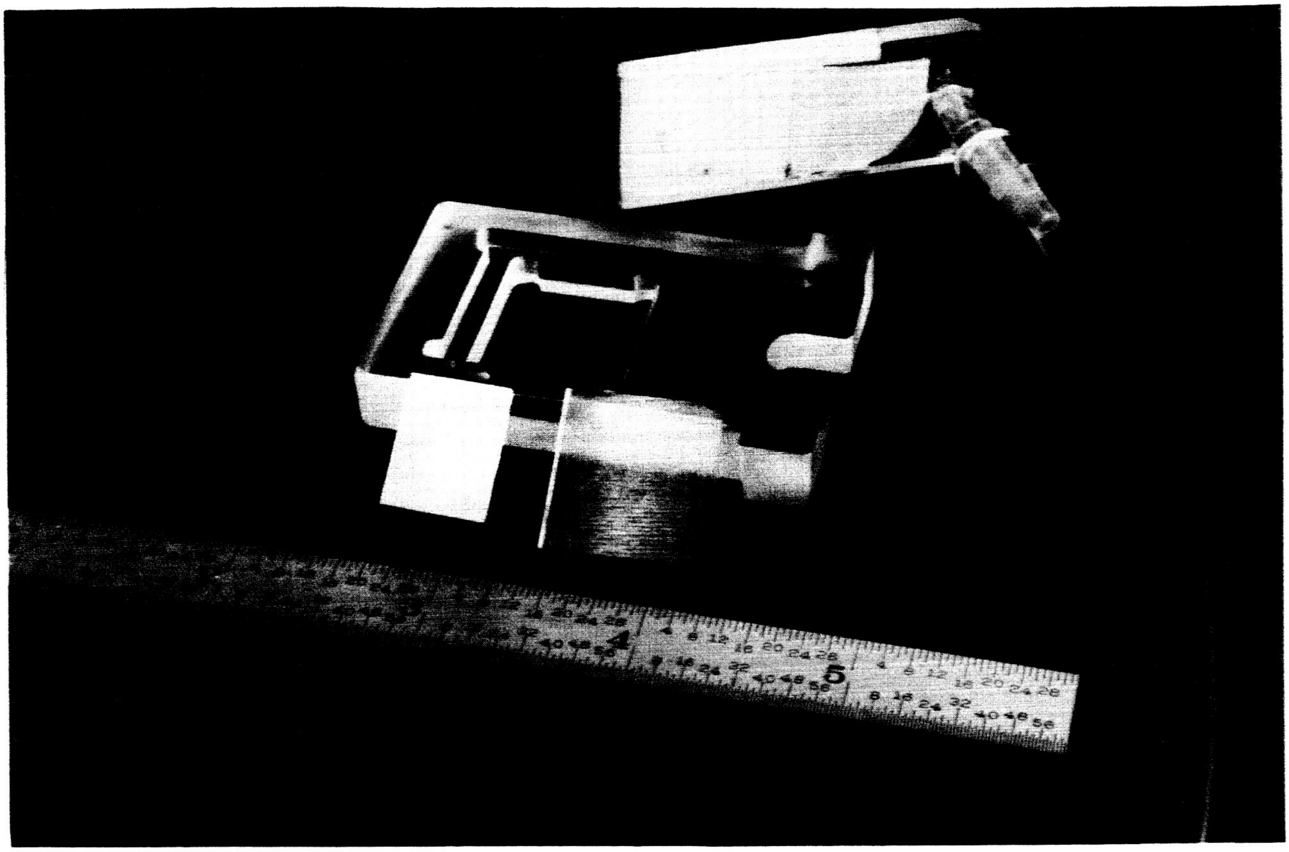


Figure 15. Thin-Film Stress Fixture.

Anisotropic Films. - The effect of applying strain to films with uniaxial anisotropy is treated in recent publications by Crowther(14) and by Mitchell, Lykken and Babcock(15). Crowther shows that, in order to find the angle θ between the direction of magnetization and the unstrained easy axis, the expression for total energy

$$E_t = K_o \sin^2 \theta + K_s \sin^2 (\theta - \varphi)$$

can be differentiated, set equal to zero to find the equilibrium energy minimum, and solved for θ to give

$$(1) \quad \tan 2\theta = (K \sin 2\varphi) / (1 + K \cos 2\varphi)$$

where φ is the angle between the applied strain and the unstrained easy axis, and $K = K_s/K_o$, the ratio of strain energy to the anisotropy constant of the unstrained material. Further development leads to a normalized value of H_k, the new anisotropy field:

$$(2) \quad H_k/H_{ko} = (1 + K^2 + 2K \cos 2\varphi)^{1/2}$$

where

$$H_{ko} = 2K_o/M.$$

According to equation (1), strain applied along the original easy axis should cause no rotation of the easy axis. The magnitude of the anisotropy field, however, should vary with stress in accordance with equation (2). Consequently, for ferroacoustic storage it appears worthwhile to consider configurations in which the easy axis is strained, as well as the converse case where stress is applied in the hard direction and both write-in and readout occur along the easy axis.

Mitchell et al. show a more detailed treatment and conclude, from the applications standpoint, that it will be impossible to make films of the same anisotropy on a commercial basis unless average magnetostriction is low (such as that provided by a composition of approximately 80 percent NiFe). This suggests that efforts to use uniaxially anisotropic films in ferroacoustic storage may prove impractical since high strain sensitivity is a basic requirement of the new technique. On the other hand, anisotropy does not appear to have the same significance in ferroacoustic storage that it has in conventional thin-film memories using coincident magnetic fields for switching.

The ferroacoustic technique as previously described(1) utilizes the increase in magnetization-curve slope which results from coincident stress. In isotropic materials this change corresponds to "magnetic softening" of the material, which implies an accompanying decrease in coercivity, H_c. Pinch and Pinto(16) have published experimental results on the variation in θ and H_k as functions of stress, which agree with Crowther's analysis for small stresses when angular dispersion resulting from stress is small. They have also included data on the variation of H_c with stress in one example for a 77 percent NiFe film with $\varphi = 71$ degrees, and show that H_c follows H_k, but in a much less sensitive manner.

Data reported by Onyshkevych(17) for an electrodeposited film on a 30-mil outside diameter fused silica tube show a substantial decrease in H_c as measured in the circumferential direction, when axial tension is increased. However, photographs of the associated BH loops (which are similar to Figure 16A of this report) show that as H_c decreases with increased tension, the slope of the demagnetization curve also decreases. No loops for compressive stress are shown.

With characteristics of that type it appears that coincident stress does not enhance the reversibility of B_r for write-in by the ferroacoustic storage technique. The characteristic which is desired, and which appears necessary for Mode 2 operation, is an increase in the slopes of the magnetization and demagnetization curves when the material is stressed, such as has been reported by Buckley and McKeehan(18) for bulk materials subjected to longitudinal stress.

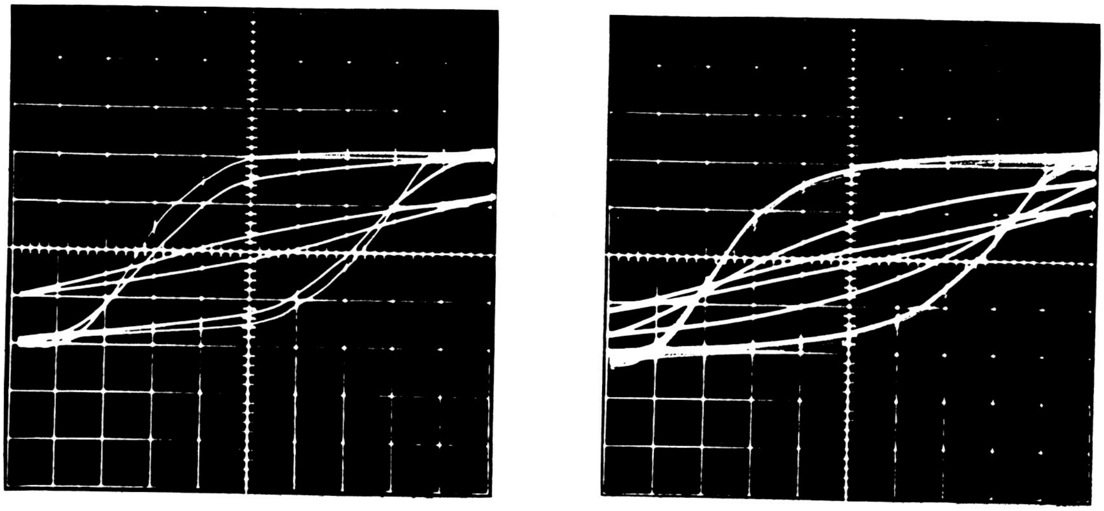
An alternative investigated under this project is the provision of film properties to permit Mode 1 or Mode 3 operation. The data of Figure 16 show promising characteristics for a 60 percent NiFe film. For Figure 16A, induction is measured along the unstrained easy axis for strain $\epsilon = 0$ and for two values of transverse tensile stress. Coincident stress lowers the coercive force, but it also lowers the residual induction, B_r; transverse compressive stress (not shown) causes no appreciable increase in B_r beyond the value for $\epsilon = 0$ in this sample. However, as shown in Figure 16B, when induction is measured along the hard axis, transverse compressive stress does produce the desired increase in B_r; i.e., under these conditions, coincident stress raises the residual induction nearly to the saturated value whereas residual induction is very small in the unstressed material.

Figure 17 shows normalized residual induction as a function of peak magnetizing field for $\epsilon = 0$ and several values of transverse compressive strain, 1.75×10^{-5} being the smallest calibrated value available with present apparatus. For that strain, corresponding to a stress of 400 psi, the ratio of B_r's for the stressed and unstressed conditions increases from approximately 5:1 at high values of H_{max} to still larger values at lower H_{max}. Hence, it appears that a ratio of 2:1 can be obtained with a stress of less than 100 psi and a peak polarizing field of approximately 1 oersted.

The important result is that positive anisotropic films show a large increase in B_r when subjected to transverse compression, whereas soft isotropic bulk materials, as previously explained, show no appreciable increase. It remains to be shown that the required difference in remanence values can be obtained after removal of a write-in stress, and that the resulting ratio of readout strain sensitivities for the ONE and ZERO states then yields a usable S/N.

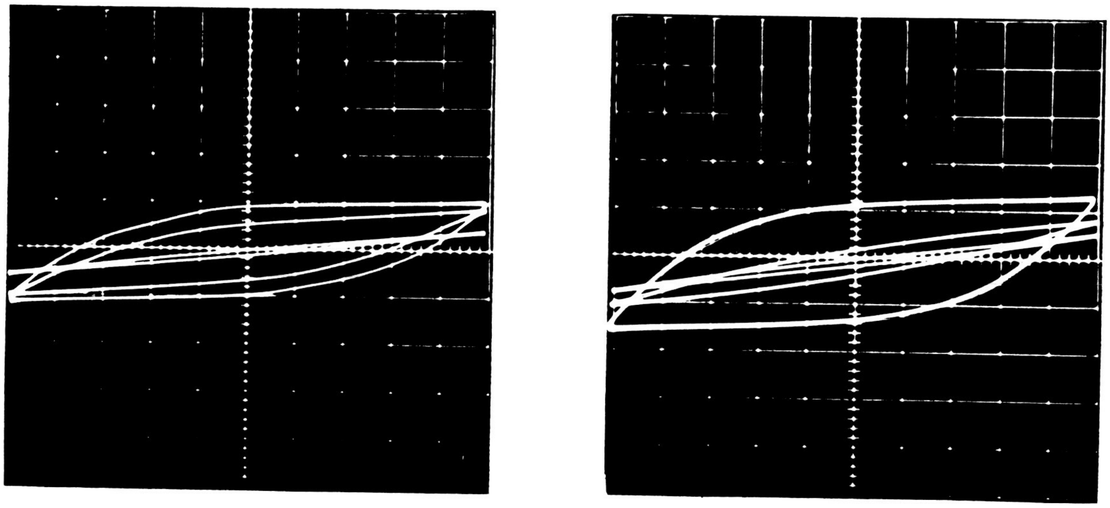
Dispersive Films. - Sample N-3 is an unoriented electrodeposited film with composition of approximately 80 percent NiFe and negative magnetostriction; its BH loops show essentially isotropic properties. Under longitudinal conditions with induction measured along the axis of strain, as shown in Figure 18A, tensile strain causes induction to decrease and compressive stress causes induction to increase, as expected for a negative material. For the transverse case, with induction measured perpendicular to the axis of strain as shown in Figure 18B, compression causes induction to decrease; however, tension causes either no significant increase or a decrease. This is similar to the properties found generally true for mill-processed tubing.

Sample D-17, the 60 percent NiFe film of Figure 19, was electrodeposited without complete cancellation of the ambient field and shows some orientation. Its transverse strain-sensitive characteristics, as indicated in Figure 20, show an increase in induction for transverse compressive strain when measured along either the easy axis or the hard axis of the unstrained film. This film, however, is less sensitive to the minimum strain, 1.75×10^{-5}, than the anisotropic film of Figure 17.



H_{max} = 3 oe

H_{max} = 2.5 oe



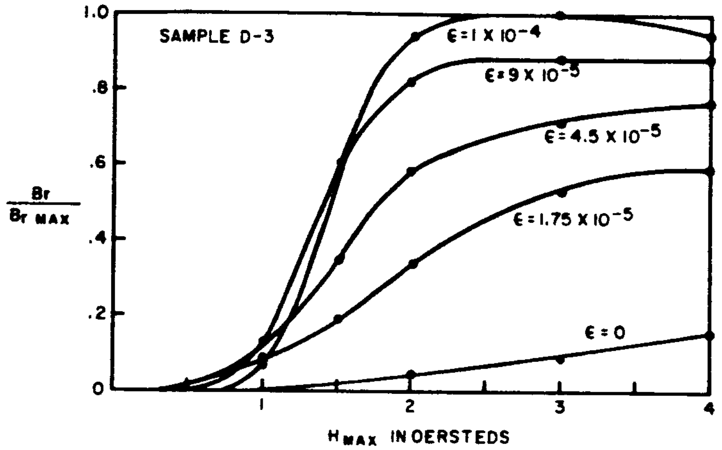
H_{max} = 1.5 oe
A

H_{max} = 1.5 oe
B

Easy Axis Observed
Hard Axis Stressed
in Tension
Outer Loop $\epsilon = 0$
Middle Loop $\epsilon = 4.5 \times 10^{-5}$
Inner Loop $\epsilon = 3 \times 10^{-4}$

Hard Axis Observed
Easy Axis Stressed
in Compression
Outer Loop $\epsilon = 3 \times 10^{-4}$
Middle Loop $\epsilon = 1.75 \times 10^{-5}$
Inner Loop $\epsilon = 0$

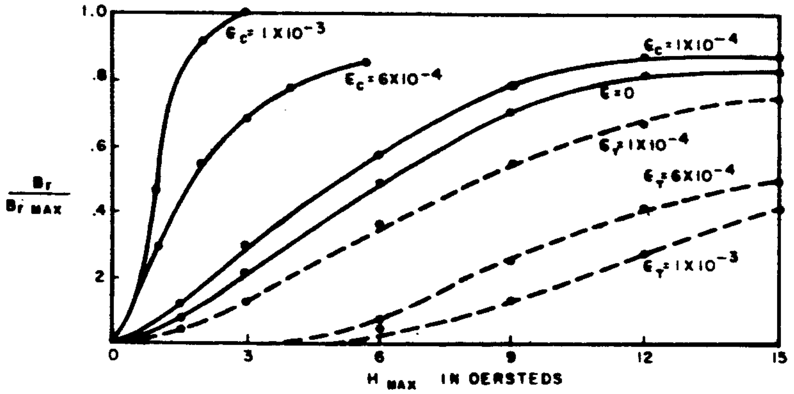
Figure 16. Hysteresis Characteristics for Anisotropic 60 Percent NiFe Thin Film.



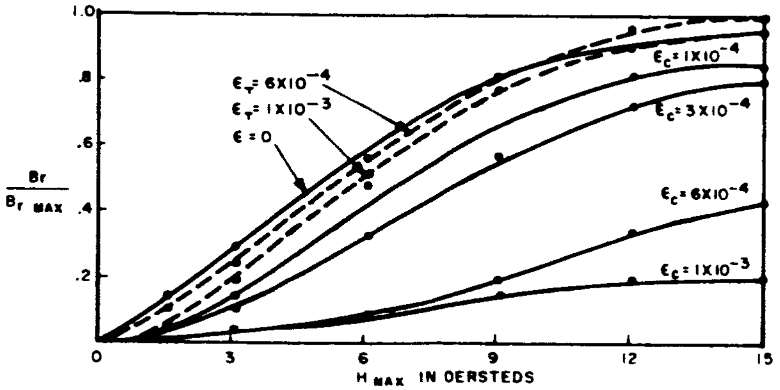
HARD AXIS OBSERVED

EASY AXIS STRESSED IN COMPRESSION

Figure 17. Remanence of Anisotropic 60 Percent NiFe Thin Film.



A. LONGITUDINAL STRAIN



B. TRANSVERSE STRAIN

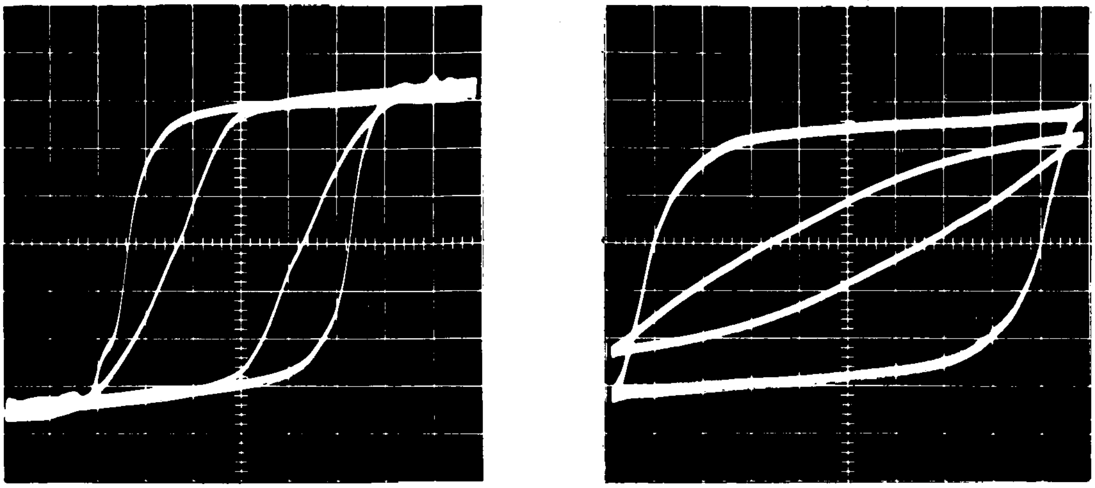
ϵ_c - COMPRESSION

ϵ_T - TENSION

SAMPLE

N-3

Figure 18. Remanence of Unoriented 80 Percent NiFe Thin Film.



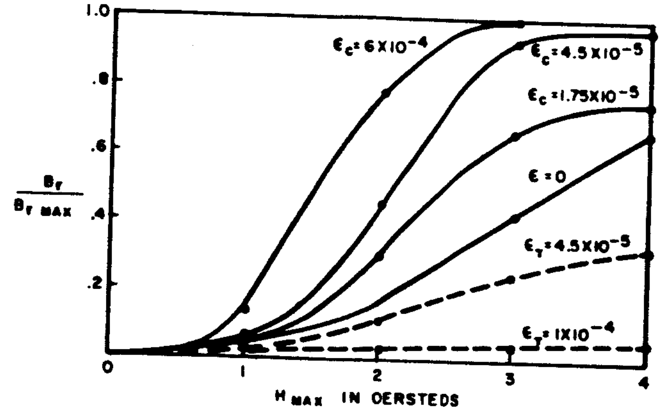
H_{max} = 5.0 oersteds H_{max} = 2.5 oersteds

Sample D-17
Outer Loop - Easy Axis
Inner Loop - Hard Axis

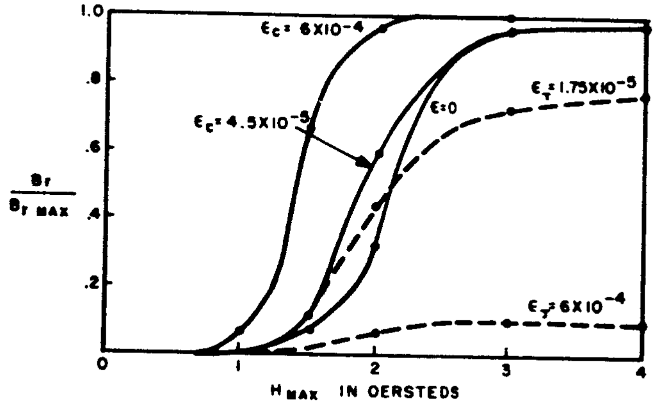
Figure 19. Hysteresis Characteristics for Dispersive 60 Percent NiFe Film.

Figure 21 shows hysteresis loops for a vacuum-deposited film of approximately 80 per cent NiFe, negative magnetostriction, and somewhat less dispersion than that of the two films just discussed. Its transverse strain sensitivity is as expected when measured along the hard axis as shown in Figure 22A. With induction measured along the easy axis, as shown in Figure 22B, transverse compression causes B_r to decrease for high values of H_{max}, also as expected; however, for low values of H_{max}, B_r increases in the manner of a material with positive magnetostriction. The abrupt step in the curve for $\epsilon = 0$ results in an infinite ratio of B_r's for the strained and unstrained states using polarizing fields between 0.4 and 1.2 oersteds.

In summary, these exploratory tests for dispersive films were undertaken as a first step to establish ranges of interest for more systematic subsequent investigations. Results for the 80 percent NiFe film indicate that transverse strains in isotropic films do not cause an appreciable increase in induction beyond the value at zero stress and, in this respect, behave like the isotropic bulk materials previously reported. Sensitivity to small strains appears low relative to other compositions, as expected, but the sharp transition observed at low fields merits further study. The 60 percent NiFe film with high dispersion appears less strain-sensitive than the anisotropic film. This is representative of other films deposited in the process of developing better control of the degree of dispersion, but measurements for a series of films deposited with improved controls is needed to provide reliable conclusions.



HARD AXIS OBSERVED
EASY AXIS STRESSED



EASY AXIS OBSERVED
HARD AXIS STRESSED

ϵ_c – COMPRESSION
ϵ_T – TENSION

SAMPLE
D-17

Figure 20. Remanence of Dispersive 60 Percent NiFe Film.

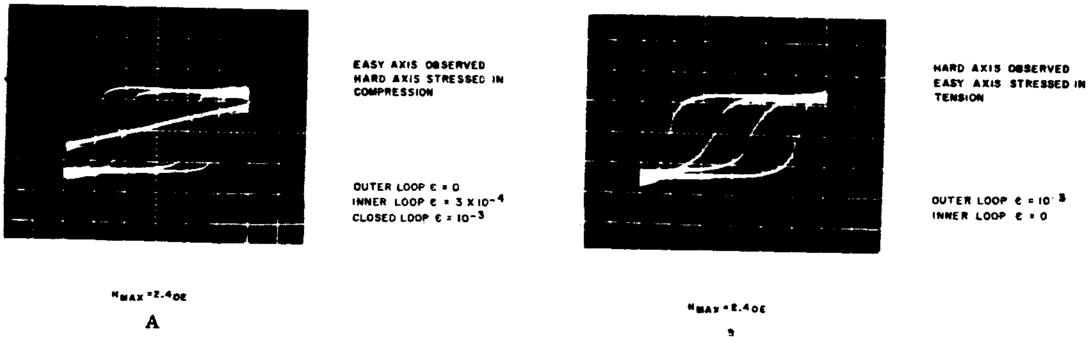


Figure 21. Hysteresis Characteristics for Dispersive 80 Percent NiFe Film.

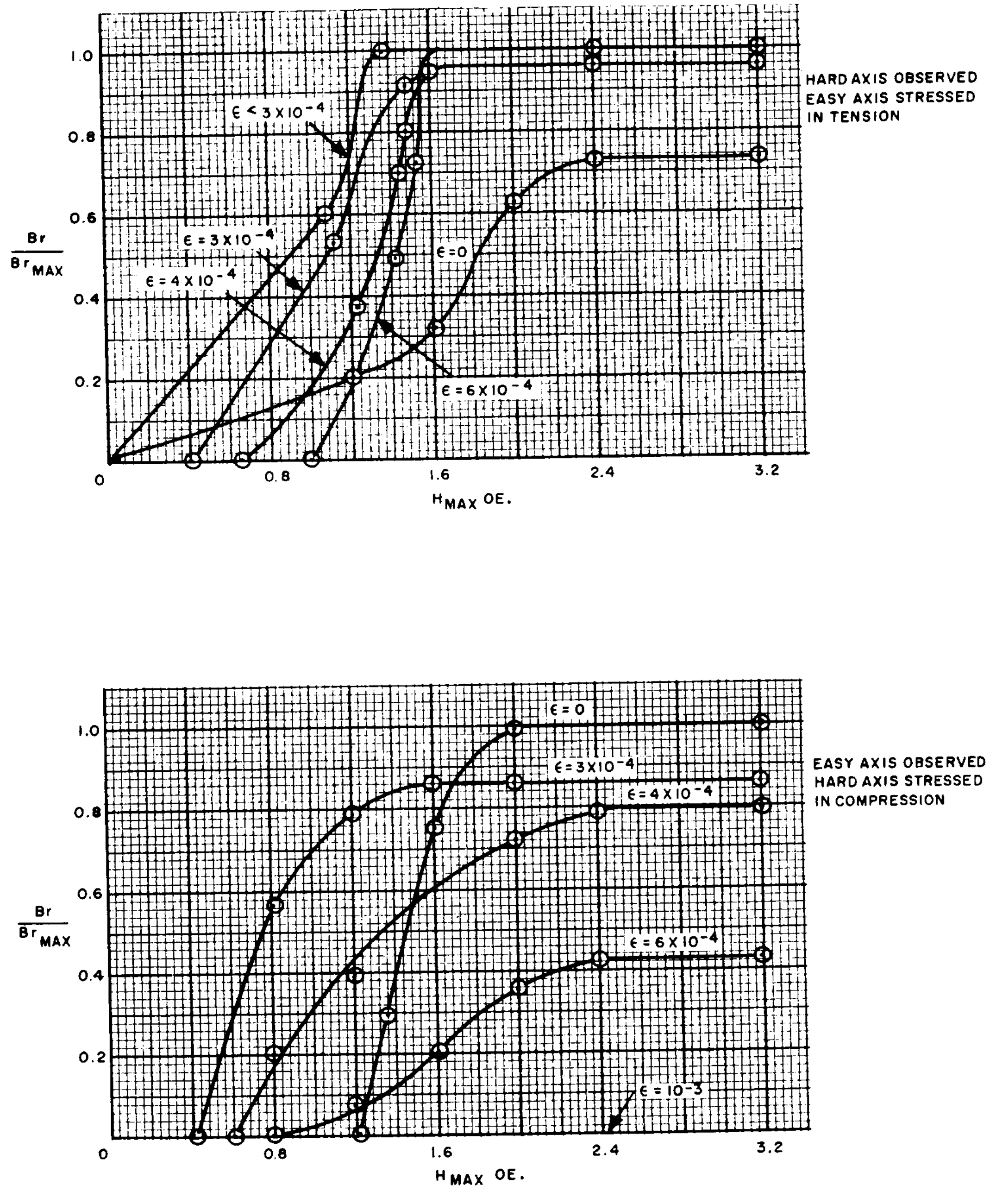


Figure 22. Remanence for Dispersive 80 Percent NiFe Film.

CONCLUSIONS

1. Single-line ferroacoustic memory models operating at a data rate of 330 kc show practicable S/N over a temperature range of $-20^{\circ}C$ to $+85^{\circ}C$. Write-in drive energy requirements are in the order of 1×10^{-6} joule per bit.

2. Data capacity is a function of S/N and line attenuation. For transducer drive voltages in the range of 50 to 260 volts, maximum capacity per line varies from 6 to 40 bits with a minimum S/N of 6 db or 40 to 80 bits for a minimum S/N of 0 db.

3. Estimated characteristics for representative multiple-line memories, exclusive of packaging and access circuits, are shown in Table 5.

Table 5. Characteristics of Multiple-Line Memories.

	20 Words X8 Bits	512 Words X12 Bits	
Energy to update entire memory	0.3×10^{-3}	17×10^{-3}	joules
Access time	30	38	usec
Weight	0.1	2.5	ounces
Volume	0.1	2.1	cu. in.

4. Successful development of strip line configurations, in place of present tubular lines, would permit:

   a. Use of ultra-thin mill-processed media with estimated order-of magnitude improvements in data density, access time, power requirements and cost; also, simplification of transducer-to-line coupling problems.

   b. Use of multiple thin-film strips on a common substrate which is bonded to a single transducer, instead of processing individual fine tubes; also, simplification of film deposition procedures.

5. Ultra-thin, cube-textured, 50 percent NiFe strip shows relatively low acoustical attenuation. Its strain-sensitivity properties merit further study.

6. Improved quasi-static test and analysis procedures, which show remanent strain sensitivity as a function of applied field for alternative sequences of field and stress,

indicate excellent ferroacoustic storage characteristics for materials annealed at high temperature, in contrast to the negative results obtained for B-H characteristics as a function of transverse stress.

7. More extensive study of transducer-to-line coupling problems, media uniformity, and strain-sensitive material properties appears necessary to explain difficulties encountered in dynamic model tests using ultra-thin materials and materials with improved quasi-static characteristics.

8. Analysis of substrate considerations for thin films indicates that materials other than fused silica will be required to avoid excessive thin-film strains caused by differential expansion when ambient temperature control cannot be applied. Where control is permissible, fused silica can be used to obtain minimum acoustical attenuation and resulting order-of-magnitude increases in line length and information capacity.

9. Strain-sensitive films for ferroacoustic storage have basically different requirements from the anisotropic thin films of low strain sensitivity developed for coincident-current memories. Both isotropic and anisotropic films show properties deserving further investigation. Measurement of remanence as a function of strain appears more significant for immediate objectives than measurement of coercive force. Anisotropic films show large increases in remanence when subjected to transverse compression, in contrast to isotropic, fully annealed, bulk materials which show no appreciable increase.

RECOMMENDATIONS

The following research and development program for near-term utilization of the ferr-acoustic memory and longer-term advancement of the technique is recommended:

1. Development of a multiple-line memory for operation at a data rate of 350 kilobits per second. Work should include:
    a. Investigation of techniques, materials, and dimensions for optimum coupling of multiple lines to a single driver.
    b. Evaluation of uniformity for larger quantities of storage media.
    c. Investigation of methods for supporting and packaging groups of multiple-line assemblies for matrixed operation, to include minimization of acoustical and electrical coupling between multiple-line assemblies and minimization of line attenuation caused by support structure.
    d. Investigation of access-circuit approaches.
2. Evaluation and analysis of performance characteristics for data rates above 330 kc using tubular storage media with 2-mil wall thickness operating in Mode 3.
3. Investigation of methods to couple ultra-thin media to transducers, or short horns, without excessive variation in mechanical impedance.
4. Investigation of strip-line geometry and comparative analysis relative to tubular configurations.
5. Determination of the applicability of mill-processed ultra-thin strip and tubing, to include analysis of acoustical attenuation, material uniformity and strain sensitivity.
6. Investigation of the quasi-static transverse strain sensitivity of materials, including effects of stress/field sequence, material composition and orientation, alternative ferroacoustic-storage modes of operation, and correlation with dynamic test results.
7. Systematic investigation of the strain sensitivity of magnetic thin films, including the effects of composition, thickness and orientation, and confirmation of thin-film ferroacoustic operation.
8. Investigation of substrate considerations, including composition, attenuation, thermal coefficients of expansion and time delay, dimensional criteria, and the effect of a magnetic film on sonic transmission characteristics.
9. Improvement of piezo-transducer techniques to match improvements in storage media switching speed.

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