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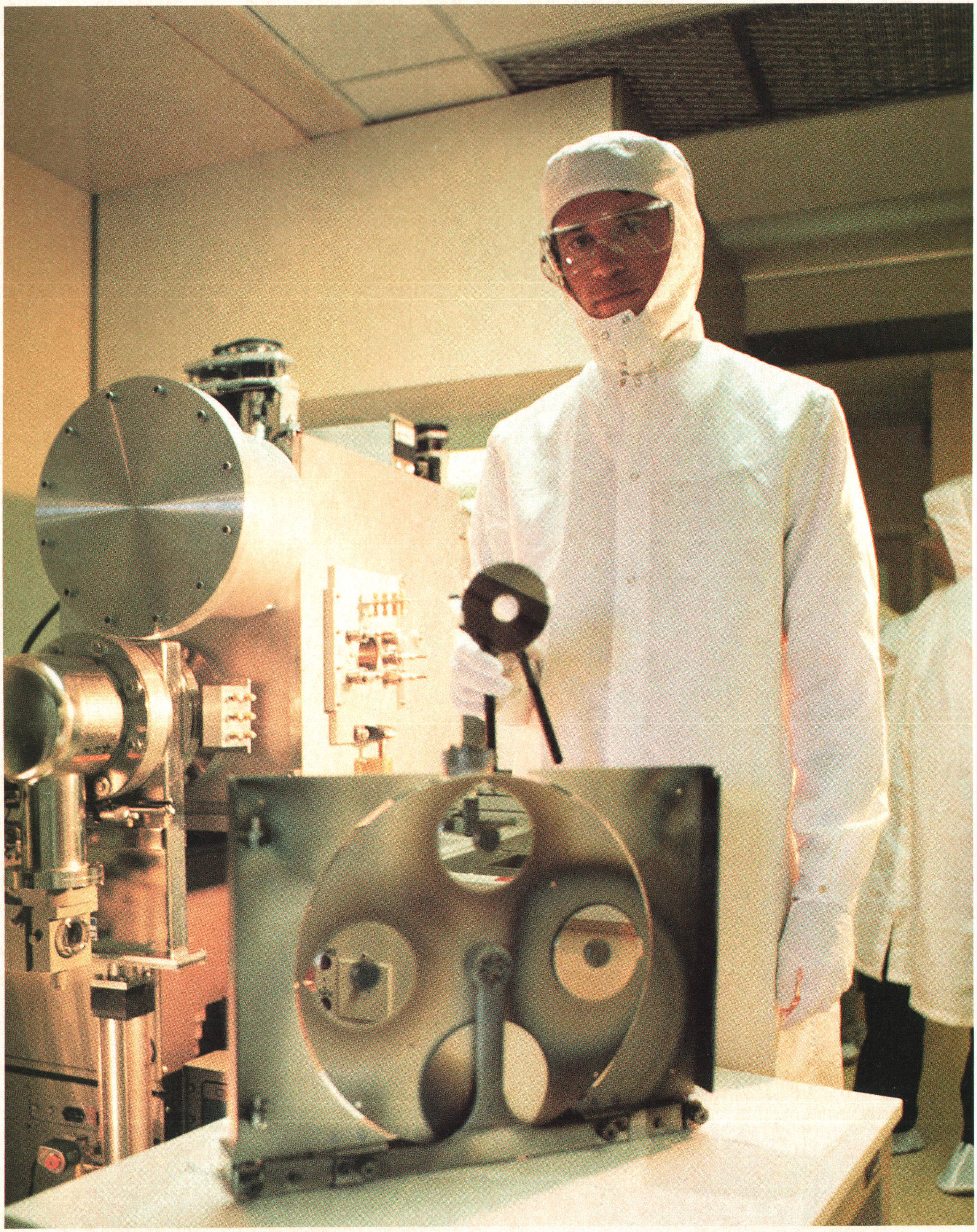

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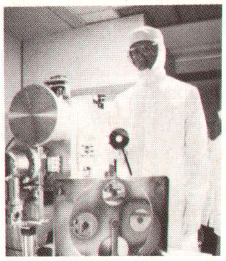
Articles

In this Issue



The incorporation of a sputtered thin-film magnetic disc in the HP 97501A 3½-Inch 10-Mbyte Disc Drive culminated several years of effort at HP Laboratories and HP's Disc Memory and Greeley Divisions. The thin-film disc, in which a magnetic metallic layer acts as the data storage medium, represents a major technology advance in rigid magnetic recording discs. HP's use of vacuum sputtering deposition instead of plating for the production of the thin films has led to much tighter process control, higher yields, better manufacturability, and lower costs.

In 1977, Dick Hackborn, then general manager of the newly formed Disc Memory Division, initiated the program. Hackborn believed that as magnetic recording technology evolved, the thin-film magnetic disc would play a crucial role in future disc drives.

The initial HP investigation of thin-film disc technology was done at HP Labs by Jim Opfer and Len Cutler and their groups and is summarized in the article on page 4. Several courses were pursued in parallel to establish a solid foundation for future work and to determine if the technology was feasible. In addition to theoretical studies of magnetic recording by Dave Bromley, Richard Baugh, and Ed Murdock, characterization equipment was developed to ensure that appropriate parameters could be studied (examples are described by Robin Gifford and Vic Hesterman and by Rich Elder in the boxes on pages 6 and 8). Various materials systems were evaluated by B.R. Natarajan with heavy emphasis on the reliability of the disc. As the program evolved, it became apparent that the disc fabrication process would be as important as the disc itself, and the first in-line sputtering (ILS) system was designed, built, and tested (see article by George Drennan on page 21).

At the Disc Memory Division, several programs were started in magnetic recording theory, process development, characterization, and reliability to complement the HP Labs work. The new programs emphasized tailoring the technology to a drive product, disc manufacturability, and disc cost. A key ingredient in the success of the thin-film disc program was the early participation of the drive development teams managed by Duncan Terry, Winston Mitchell, and Doug Mellor. Optimizing the disc and drive combination required extensive testing and cooperation between the teams. The article by Mike Allyn, Pete Goglia, and Scott Smay on page 36 gives some feel for the product-related challenges.

Much attention was also focused on the manufacturability of the disc. The article by Rick Seymour, Darrel Bloomquist, and me on page 34 summarizes the work on the manufacturing process, while the article by John Hodges, Keith Roskelley, and Dennis Edson on page 11 describes the final disc test systems. The modularity of the test systems allows them to be used for any disc and to be upgraded for future high-performance media. This continues the emphasis on a workhorse technology. The manufacturing effort included extensive cost models developed by Ken Wunderlich and Don Peterson to predict the impact of demand, process improvements, automation, and other factors on the disc cost. Finally, Cliff Day, Paul Poorman, Steve Howe, and Girvin Harkins describe the continuing reliability work in their article on page 25.

-Glenn E. Moore, Jr., Guest Editor

Cover

One of the authors is shown holding a thin-film disc fabricated in the HP Laboratories sputtering deposition development system seen in the background. In the foreground is the disc carrier used for fabricating discs for continuing thin-film investigations.

What's Ahead

In the December issue, along with the annual index, we'll have seven articles on the design of the HP 8642A/B RF Signal Generator, a state-of-the-art signal source for testing communications equipment in the frequency range of 100 kHz to 2115 MHz.

Thin-Film Memory Disc Development

Developing a new recording medium for disc memories required careful attention to the development and characterization of materials, processes, and test systems.

by James E. Opfer, Bruce F. Spenner, Bangalore R. Natarajan, Richard A. Baugh, Edward S. Murdock, Charles C. Morehouse, and David J. Bromley

THIN-FILM DISC DEVELOPMENT at HP Laboratories was begun to give Hewlett-Packard mastery over the technology of a key component of disc drives. This development, it was believed, would lead to a better understanding of the recording medium and the recording process and perhaps result in a component proprietary to HP. A thin-film medium was chosen over the traditional particulate media because of the opportunity to make a contribution to disc performance. Along with this choice came the attendant risk that thin-film discs would suffer from potentially unsolvable problems. The combination of opportunity and risk justified assembling a special team of people. This team was to develop a superior recording disc and an expanding set of capabilities to characterize important problems of magnetic recording—both those of a general nature and those known to be specific to thin-film discs.

Initial Definition

At the onset of the program, thin magnetic films had already exhibited considerable promise for use as recording media. Cobalt films were known to have sufficient magnetization for recording at high density when prepared in the form of films as thin as 50 nm. The uniformity of recording fields in these very thin films led to the expectation of high recording performance if other salient problems could be solved. Cobalt films were known to be highly susceptible to corrosion, and the wear properties of unmodified metal films, to the extent that they had been characterized, were not acceptable. Detailed recording properties of a homogeneous medium were not known, nor was the incidence of defects in a thin-film layer. Finally, it had to be demonstrated that the desirable properties of thin magnetic films could be obtained reproducibly and at a competitive price.

To deal with these uncertainties, investigations were begun in each area of concern. Investigation of corrosion effects was initiated at both the practical level and a more fundamental level. Apparatus and measurement methods were established to characterize the wear performance. Computerized test equipment was developed to measure recording properties and the distribution of defects. Finally, as development and characterization of the thin-film disc progressed, modeling of the recording physics helped to validate the experimental results and design choices.

Material and Process Development

The disc material and process development required an integrated approach. Not only was there a requirement for certain macromagnetic properties of the thin magnetic films, but these properties had to be uniform over a disc surface and had to be prepared relatively free of defects on a substrate meeting both cost and mechanical requirements.

Optimization of a disc recording system requires a match-

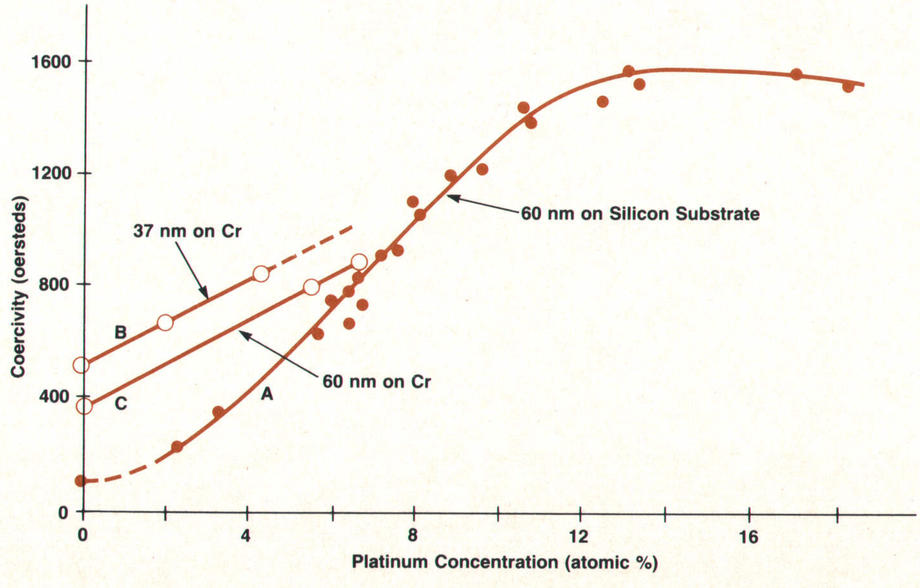


Fig. 1. *Effect on coercivity values of adding platinum to cobalt films.*

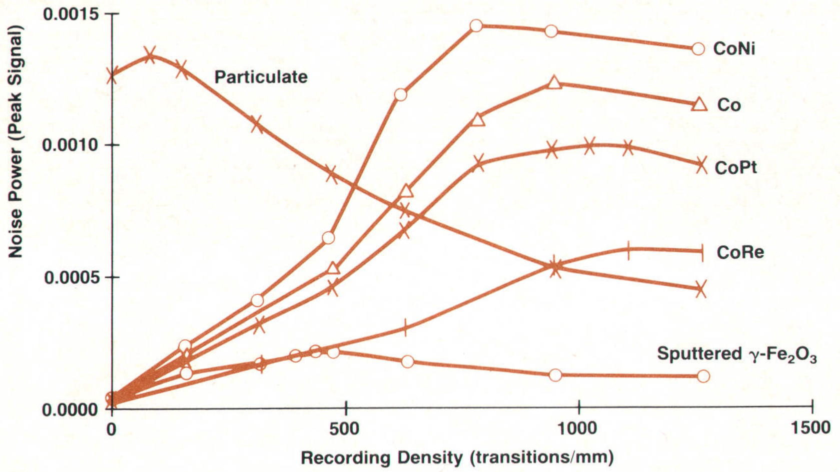


Fig. 2. *Total normalized medium noise power versus recording density for various disc memory material systems.*

ing of the recording head and disc properties. Increasing the coercivity and decreasing the remanence-thickness product of the magnetic recording layer increases the capability of a disc to store data at high linear density. However, the coercivity cannot exceed a value limited by the ability of the head to write (magnetize) nor can the remanence-thickness product be less than that needed for a minimum usable readback signal. As these considerations suggest, an ideal property of a disc material system is the possibility of independently varying the coercivity and remanence-thickness product over a suitable wide range without degradation of the associated magnetization/applied-field (M-H) hysteresis loop.

Cobalt or cobalt alloy films are attractive candidates because of their high value of magnetization and the possibility of high coercivity resulting from high crystalline anisotropy in the hexagonal (HCP) phase. Because of the high value of magnetization, a very thin (e.g., 30 to 50 nm) cobalt film provides an adequate remanence-thickness product. However, to achieve desirable coercivity, care must be taken to prepare the film with the proper structure. Pure cobalt films sputter-deposited onto most substrates exhibit low film coercivity (e.g., 50 oersteds) because of an admixture of the cubic (FCC) phase and the associated low value of crystalline anisotropy. This is an expected result because of the polymorphic nature of the pure bulk cobalt. A much larger fraction of the hexagonal phase can be realized by depositing the thin cobalt film directly on top of a newly deposited chromium film approximately 250 nm thick. The coercivity of very thin cobalt films prepared in this manner is suitably high, but decreases rapidly as the film thickness increases. At a thickness adequate for most recording signal requirements, the coercivity is already below a desirable value. Furthermore, there is no way to vary the coercivity and thickness independently over a range of values. Further effort was required to realize the potential advantages of these films.

The addition of platinum to the cobalt films deposited over chromium provided the desired capability of varying properties independently without sacrificing the squareness of the M-H hysteresis loop (Fig. 1). As the platinum content of films deposited onto silicon substrates increases, the coercivity increases up to a maximum value in excess of 1600 oersteds. The addition of platinum increases the fraction of hexagonal phase in the film and also increases the average grain size. Both factors serve to increase coercivity. As Fig. 1 shows, the coercivity also increases with platinum concentration when the cobalt films are deposited onto a chromium underlayer. Hence, there is a substantial range of coercivity and film thickness values that can be chosen independently. Additional coercivity variation can be achieved by varying the thickness of the chromium underlayer. The chromium underlayer also causes the easy axis of the magnetic film to orient itself in the film plane and it serves to mask inhomogeneities in the substrate surface. To select the optimum alloy, a special cryogenic M-H loop measurement system was developed (see box on page 6).

To provide reproducible uniform macromagnetic properties, procurement of a modular in-line deposition system was initiated. In the conceptual design of this system every reasonable attempt was made to provide a system that exposed locations at the same radius on a disc to equal deposition conditions, and to make these conditions identical from disc to disc. The in-line system (see article on page 21), with its load lock chamber to isolate the deposition chambers from exposure to ambient pressures or environments, was instrumental in making similar conditions possible as successive lots of discs were fabricated.

Because it was known that thin-film deposition could at best replicate the topographic features of the substrate, development of sufficiently smooth substrates was given the highest priority and became a division responsibility at an early stage. As the quality of the substrates improved, the process emphasis began to focus on the maintenance of substrate perfection throughout the disc fabrication process. A high-pressure Freon™ jet spray cleaner was developed to remove particulate contamination, but finding an efficient way to measure the effectiveness of the cleaning methods remained to be done. An important advance was the development of a laser-based particle scanner (see box on page 8) capable of rapidly counting residual particle-like protrusions from the disc surface. The scanner was an invaluable tool for monitoring all aspects of the process for contamination, and was primarily responsible for the achievement of nearly perfect finished discs.

M-H Loop Measurements

The efficient development of thin-film magnetic recording materials depends on the availability of suitable measuring techniques. A measurement of the M-H loop—the relationship between the magnetization of the material and a cyclically applied magnetic field—is the most basic test of the physical properties of the material, and is very useful in the evaluation of process variations. By designing and building our own measuring system that has an optimum combination of measurement time, accuracy, sample size, and convenience, we are able to obtain performance that is significantly better than was previously available.

The equipment that was developed records in about a minute the M-H loop of a sample with a maximum dimension of 1 cm on a conducting substrate. The measured values of remanence and coercivity are accurate to 3% and reproducible to 1%. Coercivities up to 800 oersteds can be measured. The measuring system is controlled by an HP 9000 Model 216 Computer and is reliable and very easy to use. Almost all of the measurement parameters are software controlled, and the instrument has proved to be a versatile research tool.

Measurement Technique

The magnetization is measured by a direct induction method (see Fig. 1). The sample is placed in an in-plane magnetic field sinusoidally varying with a peak intensity of 1600 oersteds and a frequency of 0.5 Hz. The time rate of change of magnetization induces an EMF in a surrounding sense coil. The time-dependence of the magnetization is recovered by integrating the output voltage of this coil. The flux caused by the excitation field linking the sense coil directly is "bucked out" by using a series-connected, counterwound compensating coil. Because the cross section of the sense coil is larger than that of the sample by a factor of more than 10^5, the effective balance between the sense coil and the compensating coil must remain constant to about 1 part in 10^8 during each measurement. A high degree of balance in the astatic pair forming the sense and compensating coils also provides relative immunity from interference caused by uniform time-varying external fields.

At the drive frequency of 0.5 Hz, eddy currents in the conductive sample substrate (if uncompensated) would produce an output signal larger by a factor of about two than that created by the magnetic material. Eddy-current distortion of the M-H loop can, however, be almost completely removed by placing in the compensating coil a nonmagnetic dummy sample made of a material identical to that of the sample's substrate.

An air-core solenoid is used to generate the applied magnetic field. The windings are designed to produce two identical regions of extremely high field homogeneity with an axial separation matching that of the sense and compensation coils. Liquid-nitrogen cooling reduces the resistance of the windings by a factor of seven, resulting in a lower peak power requirement of 250W, easily supplied by a standard programmable power supply. The use of a cryogenic solenoid requires a special nonconducting, nonmagnetic Dewar vessel with a room-temperature bore. Close attention was paid to the mechanical stability of the complete assembly and the use of strictly nonmagnetic materials.

The electrical output of the pickup coils is fed to a discrete dc-coupled amplifier with a noise level of about 1 $nV/\sqrt{Hz}$ at 10 Hz. The output of this amplifier drives a digitally controlled drift-cancelling integrator whose filtered output is digitized at a rate of 180 samples per second. Residual coupling of the drive signal into the pickup coils is nulled by feeding a precisely regulated fraction of the drive coil current to a toroidal balancing transformer in series with the input circuit. An extremely high degree of overall rejection is achieved by digitally processing the voltage waveforms from three measurements made in quick succession. The average of the first and third measurements, made with the sample and dummy removed from the pickup coils, is subtracted from the second measurement, for which the sample and dummy are in place. Using this technique, it is possible to resolve a signal corresponding to about 1% of the magnetization of the samples usually measured. Generation of the M-H loop, scaling, and calculation of coercivity are handled offline by the Model 216 Computer.

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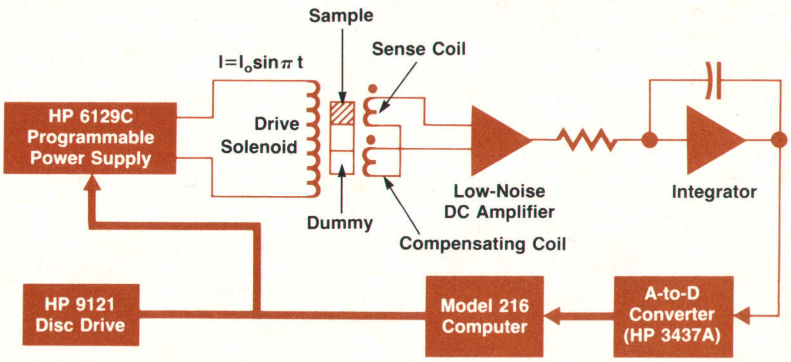

Fig. 1. *Block diagram of M-H loop measurement system. The sample and dummy are magnetized by the field of the drive solenoid, which is fed with a sinusoidal current by the programmable power supply. The voltage signal resulting from the rate of change of the sample magnetization is amplified, integrated, and digitized. The computer calculates and displays the M-H loop and stores the results of all measurements.*

Development of Characterization Equipment

Proceeding in parallel with the disc process and material development was the development of characterization equipment. It was important from the beginning to understand the advantages and limitations of competing methods for making thin-film discs. Plated thin-film media from several vendors were evaluated early in the program, and the understanding gained led to the adoption of vacuum sputtering as the preferred method of depositing the films.

Early characterization development focused on measuring recording performance as a function of linear recording density. Careful observations were required to correlate the macromagnetic properties of the discs with observed recording performance. Rapid determination of recording properties provided the important feedback that guided the evolution of the materials system. Accompanying improvement in the disc properties was an increase in sophistication of the measurement tools. The study of the noise mechanism in thin-film discs discussed later is one example of the characterization work that was done.

Another major contribution of the characterization was the separation of modulation effects into those caused by head flying height variations and those caused by material property variations (see article on page 36). The latter variations provided the most direct evidence of the sensitivity of disc properties to minor variations in the fabrication process. The elimination of process features that caused modulation also resulted in a process providing a high degree of disc-to-disc reproducibility.

A final important contribution of the characterization equipment was the measurement of the distribution of defects in discs as made and in discs that had been exposed to various controlled environments. A significant conclusion based on these measurements was that discs could be made by means of sputtering to a degree of perfection limited essentially by the degree of perfection of the substrate itself. Furthermore, the effects of hostile environments could be quantitatively assessed in terms of variations in defect count.

The evolution of this ability to characterize discs led to the capability of specifying disc performance in terms that could be readily measured. An important contribution to the overall development process was the creation of an External Reference Specification (ERS) for the thin-film disc and the definition of a procedure for testing these specifications. The combination of the specification and the test procedure, more than any other single thing, provided a template by which the divisions could gauge the progress of the effort at HP Labs.

Noise Characterization

Errors in a disc memory come from many sources, one of which is the magnetic noise of the recording medium itself. This noise arises from random fluctuations in the magnetization along a recorded track and results in random shifts in the locations of the signal peaks. Given the mean value of this time jitter, the bit error rate from the medium noise can be calculated. The challenge in measuring medium noise is to do it in a way that separates the medium noise from all other noise sources and provides a measure from which medium noise error rate can be predicted.

When the noise power is plotted as a function of recording density, an important trend is seen. As Fig. 2 shows, thin metallic media of all types get noisier as the written density increases, in pronounced contrast to the case for particulate media. This increase can be understood by noting that a spectrum analyzer takes a temporal average of the noise. As the recording density increases, more magnetic transitions pass under the head per second. Therefore, the noise curve means that in thin-film media the transitions are much noisier than the uniformly magnetized regions between them.

The objective, then, is to devise a measurement method that will enable one to predict time jitter from the noise. Our proposal was to write on the track with a sufficiently high density to completely fill the track with noisy transitions (i.e., use maximum noise), and to measure the noise and signal at the output of the differentiator rather than the preamplifier of the read circuitry.

This proposal was verified by computing the time jitter to be expected from the noise and comparing it to the measured time jitter. Details of the calculation can be found in reference 1. The actual time jitter Δt was measured with an HP 5370A Counter. The contribution of the electronics noise to the jitter was measured by making repeated measurements on a single pair of transitions, and subtracting their average from the total jitter to give medium jitter. When calculated and measured values of Δt are compared for many different media, the resulting graph is a straight line. Statistical analysis indicates an excellent fit of the data to the hypothesis that measured Δt = calculated Δt.

With this verification of our understanding, we propose a new definition of the signal-to-noise ratio SNR, namely:

$$\mathrm{SNR} = 20 \log(\text{signal derivative/rms noise voltage})$$

where both signal and noise are measured at the predetection filter output and the noise is the maximum noise. With this definition, one can use the calculation described in reference 1 to predict the time jitter caused by medium noise in thin-film recording media accurately.

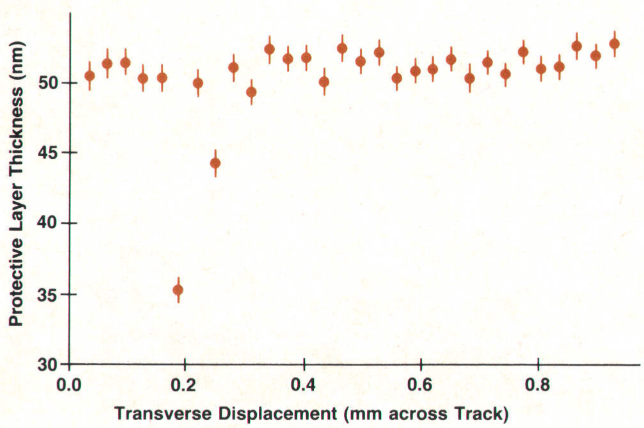

Fig. 3. *Wear profile across a single rail path for a thin-film disc after 10,000 contact start-stop cycles.*

Wear Characterization

Evaluating the wear characteristics of the thin-film medium started with the first samples produced. Attempts to learn the electrical performance of new disc samples required the discs to survive a minimum of one contact start! As one might imagine, the very earliest discs did not survive many (if any) attempts to fly heads over them. It was immediately realized that simple mechanical performance was required before other tests could be performed.

Simple testers were built to rotate the disc in contact with a head at speeds well below flying speed (speed when the head is supported by the moving air bound to the disc surface). The motivation was to imitate the sliding of the head at the start of disc acceleration. Testing on samples from the processing area was done with rapid feedback of results so that process improvements could be effected

A Laser Particle Scanner

Particles can be detected on a smooth reflective surface such as a thin-film disc substrate by illuminating the surface with a bright light source and measuring the scattered light, rather than the reflected light (see Fig. 1).

The original requirement for a particle scanner was simply for a device to measure the number of particles 1μm or larger in diameter on the surface of a thin-film disc substrate in less than one minute. In addition, for safety and convenience reasons, we wanted to avoid the use of high-power lasers for illumination and the need for high-sensitivity detectors, which require high voltages. A 2-mW helium-neon laser was chosen for illumination, and a pin photodiode with a sensitivity of 10^{-9} watts was used for detection. The amount of the laser power scattered per unit of solid angle by a 1-μm-diameter particle in the beam can be estimated as follows:

$$P_S = P_L \pi r^2 / A_L (1/2\pi) = 5 \times 10^{-9} \text{ watts/steradian}$$

where P_L is the laser power, r is the particle radius, and A_L is 0.05 mm^2, the cross-sectional area of the laser beam. The factor of $1/2\pi$ comes from the assumption that the power is scattered evenly over a hemisphere above the particle, or 2π steradians. Therefore, scattered light must be collected over a solid angle of at least 0.2 steradians to get sufficient power to the detector.

In the final test configuration, the laser illuminates a thin band radially across the disc and the disc is spun to move particles through the beam. The detector head is scanned across the disc radius at the proper speed to cover the disc surface in a spiral. The detector area is 5 mm^2, and the detector is located 5 mm above the disc surface, achieving the 0.2 steradian collection area without requiring collection optics.

A particle passing through the beam causes a pulse of light at the photodiode detector proportional to the square of the particle diameter. This light pulse is turned into a current pulse by the photodiode, amplified, and sent to a comparator circuit. The comparator voltage can be set to different levels corresponding to different particle sizes from 1 to 40 μm. When a particle larger than the set size passes through the beam, the comparator is triggered and a counter is incremented.

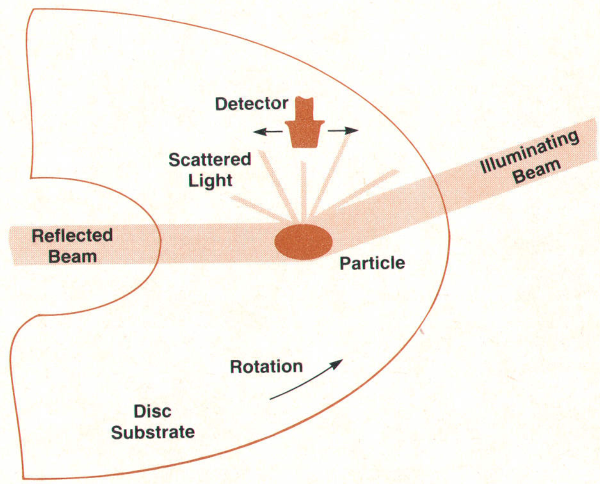

Fig. 1. *The laser particle scanner detects particles by measuring light scattered by the particles. The disc surface is scanned in a spiral pattern by rotating the disc and moving the detector along a disc radius illuminated by the laser beam.*

Operation

A substrate is scanned simply by placing it on the scanner spindle, selecting a particle size, and pressing the start button. The disc is spun and the detector is scanned across it automatically, a process that takes about 30 seconds. The particle count is constantly displayed on the front of the scanner, and is automatically zeroed at the start of each scan. If a distribution of counts of different particle sizes is desired, the scanning process can be repeated at different comparator settings.

Calibration

The initial calibration was done by placing a fairly clean disc in the particle scanner, positioning isolated particles in the laser beam, and measuring the photodiode response. The disc was then carried to a microscope and the particle size measured with a reticle. This process was repeated with various particle sizes to derive a detector-voltage-versus-particle-size response curve. This curve is used to set the particle detection comparator voltages.

There were a number of problems with this calibration procedure. It could only be used on larger particles (4 μm or larger), because the particle had to be identified visually. With particles much larger than 4 μm, the individual particle shapes had a significant effect on the angular distribution and hence the measured power of the scattered light. If large numbers of particles are measured, these differences average out, but the process was too time-consuming to take a large enough sample.

In light of this uncertainty, a method was devised to verify this calibration. A disc was cleaned, then measured in the particle scanner. A small amount of nominal 5-μm aluminum oxide particles suspended in alcohol was then spread over the disc and allowed to dry. This resulted in about 2000 particles between 1 and 7 μm in diameter spread evenly over the disc. The distribution of sizes of these particles was then measured both optically and with the particle scanner. Both distributions were found to have a dip at 4 μm and a large peak at 5 μm, confirming the initial calibration.

Periodic calibration is done using a specially prepared disc. A glass substrate was ion milled to produce particle-like features, then coated with aluminum to give it a reflective surface. This disc will produce the same particle size distribution as long as it is kept clean, and it can be recleaned without changing that distribution. This periodic calibration is used to check for laser power degradation and misalignment.

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quickly. As disc performance improved, the testing level was elevated to more realistic start-stop testing. A number of testers were built to service the processing area since start-stop testing requires about a day to complete 10,000 contact start-stops (CSS).

After discs routinely passed the specification of 10,000 CSS, test-to-failure techniques were used to characterize the wear performance of the discs. A curious result fol-

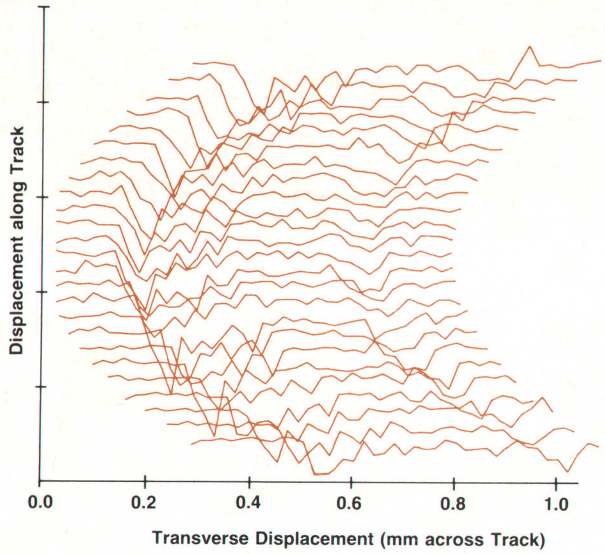

Fig. 4. *Three-dimensional view of wear along and across track after 10,000 CSS.*

lowed: discs that routinely survived 10,000 CSS would also routinely survive 100,000 CSS. In fact, we were frustrated in our attempt to perform complete failure testing by a lack of failure examples. Note that the 100,000 CSS tests required about 10 days to complete! We tried to force a failure on one disc by running a slide test for one month. The head had traveled more than 5,000 kilometers with no disc failure observed!

Efforts were made to characterize the disc wear in discs that seemed to show no signs of failure. Wear tracks could be observed, but failure had not occurred. A measurement procedure was implemented using an electron beam microprobe interfaced to an HP 9000 Model 226 Computer. Measurements of characteristic X-ray emissions (typically 100,000 per measurement point) were used to determine the thickness of the wear layer after start-stop tests. The system was capable of resolving layer thickness variations of about 0.3 nm over distances of about one micrometer. An example of a wear layer thickness profile across a single path worn by the head rail on a disc after 10,000 CSS is shown in Fig. 3. The head rail dug a groove during the wear test about 15 nm deep in a wear layer about 50-nm thick. A foreshortened perspective image of the wear layer material removal along the track is shown in Fig. 4.

From profiles of disc wear like those in Fig. 4, one can calculate the actual material removed after various wear tests. Fig. 5 shows the results of a series of tests on cobalt-oxide wear layers. The quantity plotted is the actual wear volume measured (and extrapolated to the entire wear track) as a function of the test performed. As can be seen, only for the thinnest wear layers can any wear volume be measured. For 50-nm and 100-nm wear layer thicknesses, no material removal was observed even after 100,000 CSS. Hence, only an upper limit to the wear volume can be indicated.

Modeling the Recording Process

A theoretical understanding of the recording process played an important role in the validation of results and the evolution of an understanding of the limits of the recording process.

Data is stored on the HP thin-film disc by controlling the in-plane magnetization of the CoPt layer. Much attention has been focused recently on an alternative form of data recording in magnetic films which supports only magnetization perpendicular to the film plane. To understand the potential of this perpendicular recording, an analysis of the theoretical distinctions between the two formats (see Fig. 6) was carried out.

The resulting models of the recording processes reveal a surprising equivalence in the fundamental limiting densities of the two alternatives.[2] It was concluded that the ultimate choice between the two formats would depend on defect densities and noise levels in the media and on system manufacturability.

Most of the excitment over perpendicular recording was based on the fact that the demagnetizing field of an isolated transition (of the perpendicular magnetization) vanishes in the center of the transition. This makes very narrow transitions stable, much narrower than are stable in the longitudinal mode. However, the model developed at HP shows that it is impossible to write such narrow transitions. To see why, note that in a magnetic layer with a perfectly square M-H loop, the entire transition must occur at a single value of the total H field, called the medium's coercive field. This constant field is achieved during the writing of

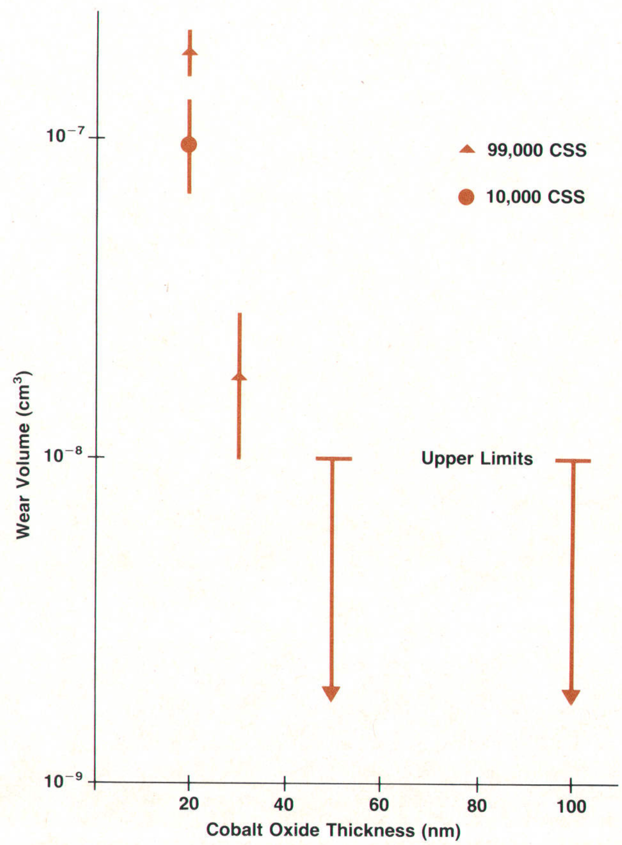

Fig. 5. *Material volume worn away from a cobalt oxide wear layer for various tests.*

the transition by balancing the gradients of the demagnetizing field and the applied head field. The process of writing narrow transitions causes large demagnetizing field gradients and thus requires large head field gradients. Fundamental limitations to head field gradients give rise to a minimum transition width that for both longitudinal and perpendicular recording is larger than the simple stability-versus-demagnetization limit.

Separate optimization of the two formats combined with ultimate materials limits on parameters like the saturation magnetization and coercivity led to the surprising, and to some extent coincidental, equivalence between longitudinal and perpendicular recording. Recent experimental study of both formats confirms this rough equivalence and supports the idea that magnetic recording is write field limited and not demagnetization limited.[3] Furthermore, in the short term, perpendicular recording has a severe disadvantage because the magnetization achieved so far in the recording media in that mode is only half that achieved with longitudinal magnetization. These conclusions, combined with the mature state of longitudinal recording, make longitudinal recording the proper choice for data recording.

Validation of Results

In the course of the HP Labs development, a disc was designed that could support recording at a linear density of 12,000 flux reversals per inch and a track density of 1000 tracks per inch. The harmful effects of corrosive gases in the environment were mitigated by the use of a sacrificial filter that effectively removed these gases before they could reach the disc surface (see article on page 25). An oxide overcoat provided a substantial degree of wear protection for the recording layer.

A number of discs fabricated in an identical manner were systematically characterized to verify the reproducibility of all properties. The evaluation showed that the discs HP had developed were superior to other available discs in those properties that were defined in the External Reference Specification (ERS). Later developments were to show that additional properties needed to be specified, but the first attempt to meet a set of specifications revealed several important points about sputtered thin-film discs:

- These discs can be tailored to match existing heads for optimum performance.
- They can be made with remarkably few defects.
- Because the fabrication process replicates the smooth substrate features, it is possible to achieve much lower head flying heights.

Transfer of the Program

The process of transferring the technology to the Disc Memory Division was initiated when discs fabricated in the in-line deposition system began to meet the ERS routinely. This deposition system, capable of producing one disc at a time, was transferred with the understanding that developing methods for producing multiple discs simultaneously remained a challenge. The critical component of the transfer was a fairly complete understanding of the dependence of disc properties upon process variables. Handing off the tools and methods used to evaluate the medium was essential to ensure continuous efficient development. The transfer of the technology from HP Labs to DMD did not mark the completion of the development of the technology; rather it marked the achievement of real benchmarks of performance, quality, and test methods.

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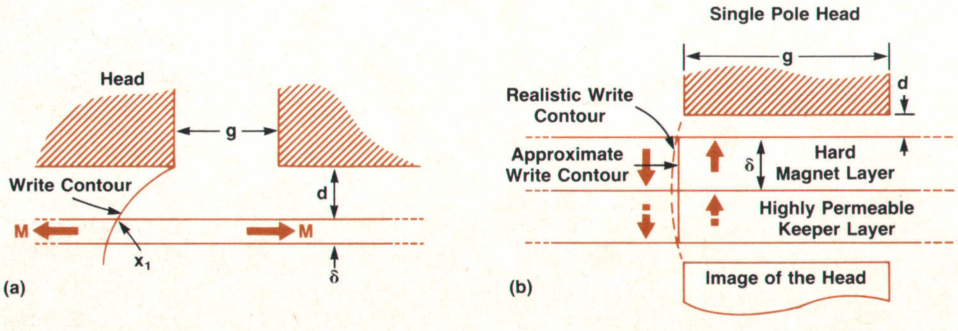


Fig. 6. *(a) Longitudinal and (b) perpendicular recording formats.*

Dynamic Testing of Thin-Film Magnetic Recording Discs

by John Hodges, Keith S. Roskelley, and Dennis R. Edson

DYNAMIC TESTING of parameters is a major function required for the development and subsequent production of a disc memory product. The test apparatus required for magnetic disc testing must be capable of measuring many electrical and mechanical parameters. The operator interface is of prime importance. Production personnel should be provided with simple, easy-to-use equipment. Design engineers, on the other hand, require test apparatus that has the utmost in flexibility and thoroughness. In either case the measurements must be performed with excellent accuracy and repeatability.

A Modular Approach

In the course of developing HP's thin-film magnetic recording discs, over a dozen testers were built to measure recording performance in both development and production phases. Developing this equipment was a significant part of the total engineering effort that went into the disc program. We greatly reduced the time and money necessary to build these testers by building each of them out of a handful of functional modules and leveraging the module design across the whole program.

Traditionally at HP's Disc Memory Division tooling development teams have been organized around specific tools, for example, a production disc certifier for a particular disc drive. The tool engineers met with the drive designers about a year ahead of the anticipated need to set specifications for the tool. If a check with outside vendors found no suitable product, design responsibility was turned over to the tool engineering team, which was given freedom over design choices and usually divided the work by discipline (electrical, mechanical, and software).

This approach frequently led to redundant design efforts for similar needs. For example, separate teams building research and production testers for a 5-inch disc would each design a test spindle. Requirements would be identical, yet the engineers involved would fail to leverage the work of the others because of organizational or communication difficulties. In addition, once given the charter to design a tool, engineers often failed to use existing, commercially available subsystems.

Much of the equipment built in this manner became obsolete earlier than expected. A change in required performance would cause the entire tester to be scrapped and restarted. Tools built to year-old specifications tended to be inflexible in meeting the rapidly changing needs of a technology development program.

At the start of the thin-film disc development program, we recognized that many testers of different specific capabilities would be needed, yet that there were many similarities among them. This realization led to the decision to divide the design work by functional units rather than by

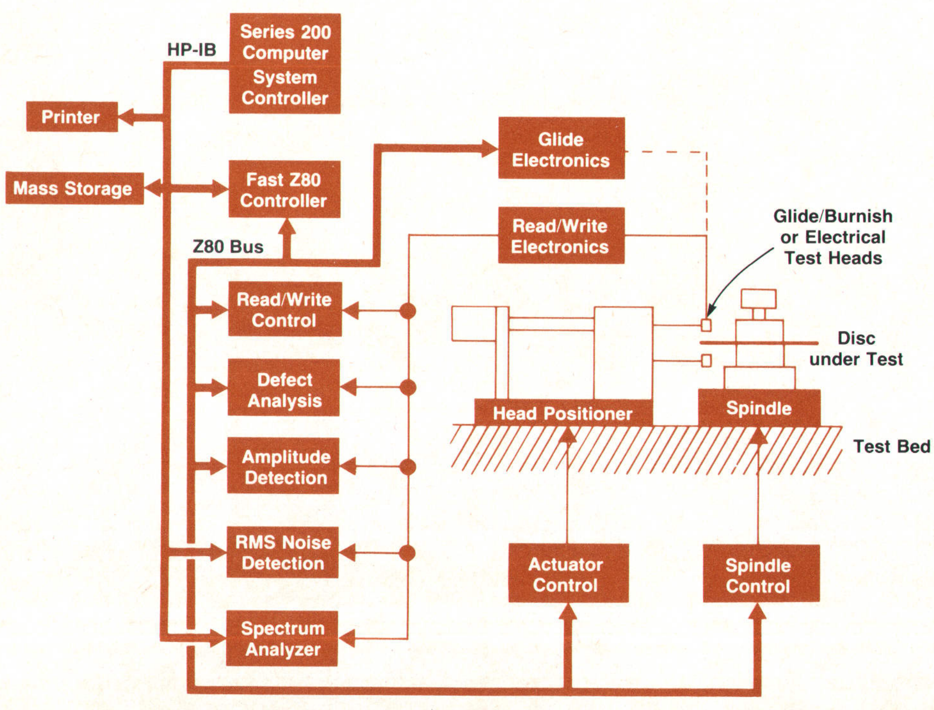


Fig. 1. *Test system block diagram.*

tester application. We divided the disc testing into functional areas as shown in Fig. 1: disc rotation, head positioning, recording/readback, signal analysis, head flight dynamics measurement, and control. We designed one or more solutions for each of these areas, and defined simple interfaces that allowed the modules to be combined easily into a variety of configurations.

We found numerous advantages to this approach. Primarily, flexibility of the finished tool was greatly enhanced. If a special experiment called for a second head and read/write channel on a tester, it could be added with no modification to the existing modules. If requirements for readback signal/noise performance became tighter, the read amplifier could easily be replaced without changing anything else. Engineering time could be focused on improving the weak unit.

Each module, as it was designed, was treated as a separate product, with a separate tool number, documentation package, and specification sheet. Each module, once designed, became part of our catalog of solutions that test engineers could order by tool number.

Fewer designs, each used more widely, lead to savings in several areas. Higher build volumes reduce unit costs. We could predict the needs of several testers and combine part build orders, allowing use of more automated fabrication methods. Document preparation work was also reduced. We developed a documentation system that allowed the document package for a tester to be composed of the document packages of its component modules, with cross-references so document revisions could be distributed to all users. Maintenance and operator personnel had fewer systems to learn, reducing training time. It became feasible to keep modules as spares, allowing rapid servicing by swapping out defective modules.

Over time we developed a number of interchangeable sets of functionally equivalent subsystems, optimized around different parameters. For example, we had a low-cost spindle, a high-performance air-bearing spindle, a high-acceleration spindle, and one designed for smooth operation at low speed. Any of these could be installed on any tester in a few minutes without modification. We were able to build an inventory of tester modules, which could be used for maintenance spares, enhancing existing testers, or building new ones. Volume savings on build costs made keeping this inventory inexpensive. In one case, we were able to assemble and use a new tester two weeks after a problem with the disc created a special need for it.

Another goal of the overall system design was to maximize use of commercially available subsystems, specifically HP-IB (IEEE 488) instrumentation. To that end, we used HP-IB protocol to interface the test control computer to all of our specialized test circuitry. This kept the system architecture unified and test sequencing programs simple.

Methods of Implementation

Achieving these advantages required forethought in establishing interfaces between modules, and discipline in adhering to them throughout the program. The interfaces had to be simple enough not to add complexity to each module, yet general enough not to restrict expandability.

Spindles and actuators are mounted on a flat-surface-plate test bed. The spindle is mounted at the center of a radial pattern of mounting holes, and an actuator can be mounted on any of the radials (see Fig. 2 and Fig. 3). We use two expanding mandrel pins to clamp an actuator to the test bed. The pins provide both clamping force and lateral repositioning to 0.001 inch. Each actuator is required to fit within a 30° pie slice so it will not interfere with others on the same test bed. The mounting holes are placed every four inches along each radial so the same actuator can be positioned for use with any disc diameter.

All special test circuits are built on the 6.75×11.5-inch printed circuit cards that are standard in our division. Control interfacing to the test circuits is done over a standard microprocessor data bus assigned to one edge connector, with 8 data and 8 address lines. A microprocessor system interfaces this bus to the HP-IB. This was simpler than putting an HP-IB interface on every card, and allows the microprocessor to control time-critical functions of some cards at speeds beyond HP-IB limits. Card interface circuitry uses about a third of each breadboard card, and provides six digital and six analog ports on each. As the individual circuit cards were developed and went through the printed circuit layout cycle, the designers could reuse the interface layout, reducing layout costs.

Our control software is written in HP BASIC, which we found gave us much greater programming productivity than compiled languages. We try to write the control routines in modules that correspond one-for-one with our hardware modules so that test control programs can be easily configured for each different hardware configuration. We also wanted these driver routines to provide the top level of test control programs with simple interfaces in MKS units. For example, the driver routine for a step motor actuator called Seek (mm) moves the head to the given millimeter radius. Background calculations, such as radial calibration or the number of steps required should be transparent to the next level of software.

A sample test program that reads the amplitude at a particular radius using such routines might be:

```
Seek (Id_radius)
Erase
Write
Read/Track_amplitude.
```

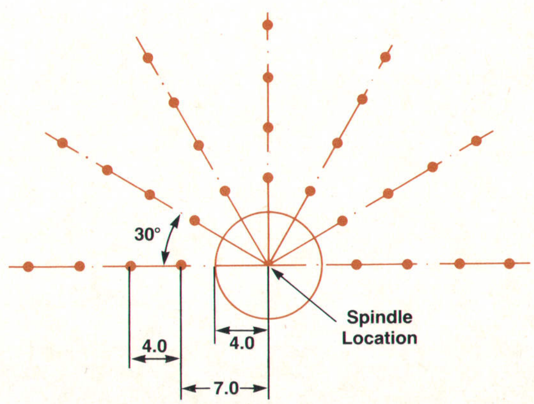


Fig. 2. *Actuator test-bed layout. An actuator can be mounted on any radial at different distances from the spindle.*

If all the driver routines for interchangeable hardware modules have the same software interface, then this program will work with a step motor or linear motor actuator, or with a read/write system using monolithic or thin-film heads. The library of driver routines then becomes a test extension package for BASIC, allowing users to program custom tests easily with a few simple calls.

Achieving this proved our greatest challenge. Software modules would work in one tester, but not when combined with certain other modules. The problem was usually name, pass parameter, or global variable conflicts, but the fix would frequently make the module cease to work with yet other modules. There were also some problems maintaining modularity with hardware. For example, a spindle controller would work well with 5-inch discs, but become unstable when used with lower-inertia 3-inch discs. The technician would fix this by adding new circuitry that wouldn't work with the 5-inch discs. Thus, we would end up with noninterchangeable units, making problems for documentation and spare-unit inventories. However, once we recognized this problem, we could usually design fixes that preserved the modularity of our units.

Characterization of the Air Bearing Surface

Reducing the flying height to increase linear density leads to difficult and sometimes crucial characterization of the head flight stability. The reduced flying height can cause head flight fluctuations caused by disc surface asperities in the submicrometer range. These fluctuations can lead to incorrect writing or reading of data. In some cases the disc surface asperities can cause a head-to-disc contact leading to an eventual head crash.

Two methods are commonly used by the disc industry for the characterization of the disc's air bearing surface. Both of these methods involve mounting a transducer to either the head's flexure or its slider. The transducer output is monitored while flying the head over the disc surface. One method uses a piezoelectric crystal mounted on top of either the leading or the trailing edge of the slider.[1] The second method uses an acoustical emission transducer mounted on the flexure.[2,3]

The piezoelectric crystal method is used at Hewlett-Packard. The piezoelectric crystal is more sensitive to head flight variations not caused by head-to-disc contact, for example, a scratch not high enough to touch the head. Since head flight variations that do not contact the disc can be as fatal as head-to-disc contact, the piezoelectric crystal method offers the best measurement technique.

The major problem with the piezoelectric crystal method is the calibration of the output from the head/crystal assemblies, called glide heads. A thin-film disc with a chrome calibration bump was developed to calibrate the glide heads. The bump height is one-half the flying height of the heads being calibrated. The design provides the long life desired for a calibration disc.

Glide Head Calibration. A standard thin-film disc is used for the calibration disc. This disc is coated with photoresist and then exposed through a mask to define the desired bump shape—a radial bar. This shape produces a step stimulus for the glide head during calibration. After the photoresist is developed, the disc is deposited with the desired amount of chrome. The remaining photoresist is then removed and the disc is cleaned. Since chrome is used in the processing of standard thin-film discs, a special setup is not required for deposition of the bump.

The edges of the calibration bump must be smooth and

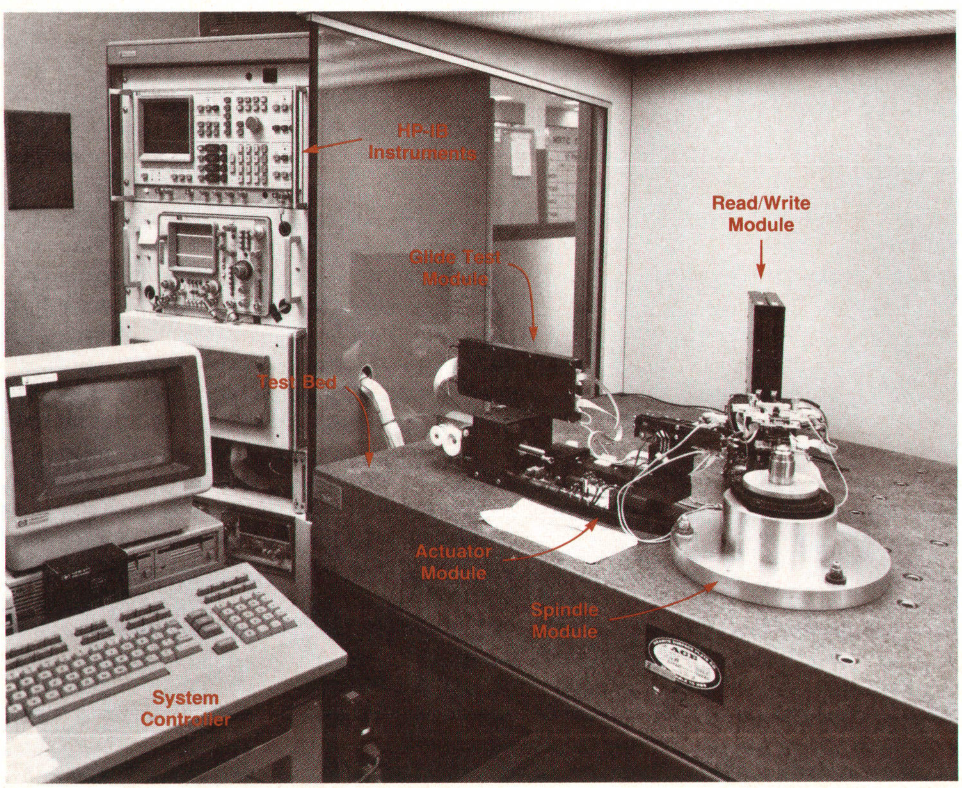


Fig. 3. *A typical test system. Any of the electrical/mechanical modules can be easily intermixed to form one test system.*

free from chips or flaking. A bump without smooth edges can chip. Chipping can ruin either the glide head or the calibration disc and usually both. Rough edges on the bump will also collect debris and make cleaning of the disc impossible.

During normal glide head calibration, debris collects at the leading edge of the bump on the calibration disc. This requires cleaning at regular intervals, or when evidence of debris is indicated by the glide head output (refer to Fig. 4). To remove the debris, the bump is lightly scrubbed using a lint-free cloth and acetone. The disc is then cleaned ultrasonically in a bath of acetone to remove any residue.

The glide heads are calibrated by flying the heads at a specified radius over the bump on the calibration disc. The maximum output of the glide head as it flies over the calibration bump is recorded. This measurement is repeated 50 times. The 50 measurements are then averaged to determine the mean output of the glide head. The glide head can fail calibration for two reasons:

- Head output too high or too low
- A large standard deviation of the 50 measurements.

Glide Electronics. To detect large head flight variations and head-to-disc contact, the glide electronics system is tuned to amplify the natural resonant frequencies of the

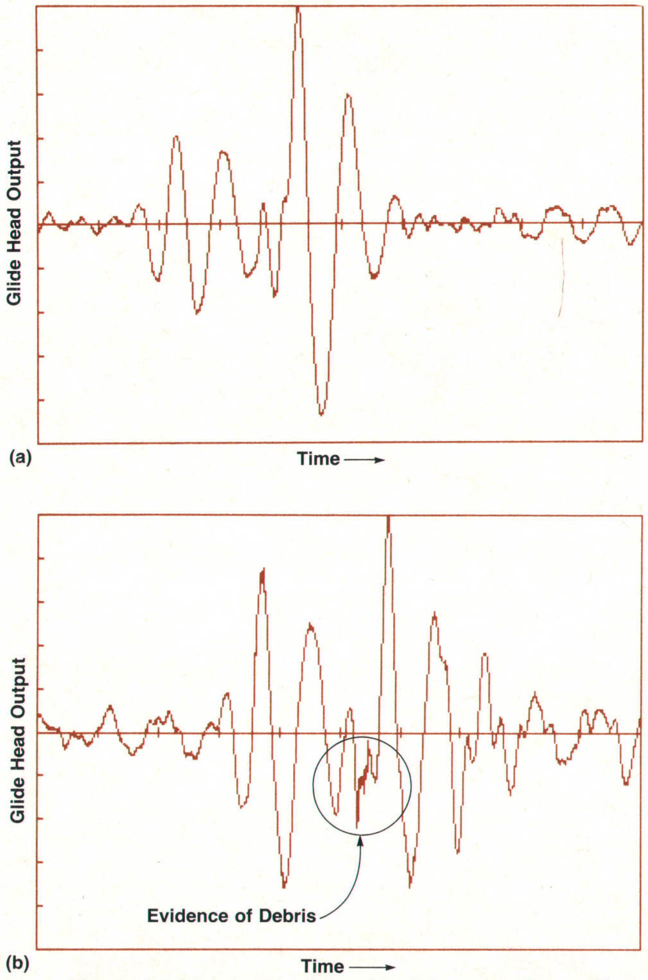


Fig. 4. *(a) Glide head output when flying on a clean calibration disc. (b) Output when flying on a calibration disc with debris.*

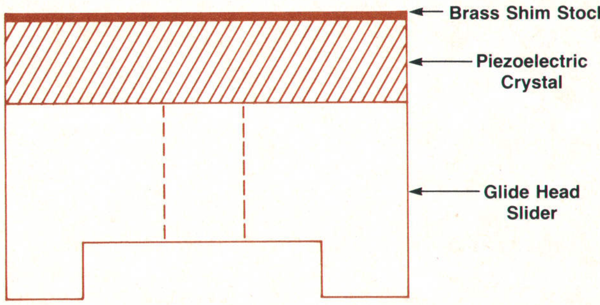


Fig. 5. *Glide head with brass cladding on piezoelectric crystal.*

slider/flexure assembly. This method allows the piezoelectric crystal to function as an accelerometer. Acceleration of the slider as it flies over the air bearing surface can now be measured. Brass shim stock is glued with conductive epoxy to the top of the piezoelectric crystal as shown in Fig. 5. This increases the sensitivity of the crystal and improves its response to the acceleration of the glide head. A block diagram of the glide electronics is shown in Fig. 6.

The preamplifier is a voltage amplifier with high input impedance. By using a voltage amplifier instead of a charge amplifier, variations in crystal output caused by crystal size differences can be minimized. As a result, variations in output are primarily caused by differences in the head flight dynamics. But, using an amplifier with high input impedance increases the susceptibility to electrical noise. However, with proper attention to grounding, this susceptibility can be reduced to acceptable levels.

For large-scale media production, the glide testing must be totally automated. No pass/fail decisions should be made by the test operators. This requires the glide electronics to detect undesired head flight variations.

The glide electronics contains an envelope detection circuit and a peak detection circuit. The peak detector is enabled when the glide head envelope exceeds a set threshold. The threshold is selected to accept undesired head flight variations while neglecting normal head flight variations. When flight variations cause the envelope detection circuit output to exceed the threshold, the peak detector captures the maximum output. When the head flight variations return to normal, the peak value is read and the peak detector is reset. An error is then reported and the peak value of the head flight variation is recorded along with its location (track radius and angle).

Glide Testing. During the glide test, the glide head flies at a height lower than the electrical read/write head during normal conditions. This ensures that any asperity high enough to hit the electrical head will be detected. This lower height also allows better detection of flaws in the air bearing surface that might cause data errors or a head crash.

If abnormal glide head flight is detected, a burnish process is performed to remove the asperity. The burnish process consists of reducing the flying height of the glide head to half its normal height. The complete air bearing surface is then scanned at this height to allow the head to burnish off any asperities.

Glide testing consists of a maximum of three glide scans and two burnish scans. First the disc is glide tested. This

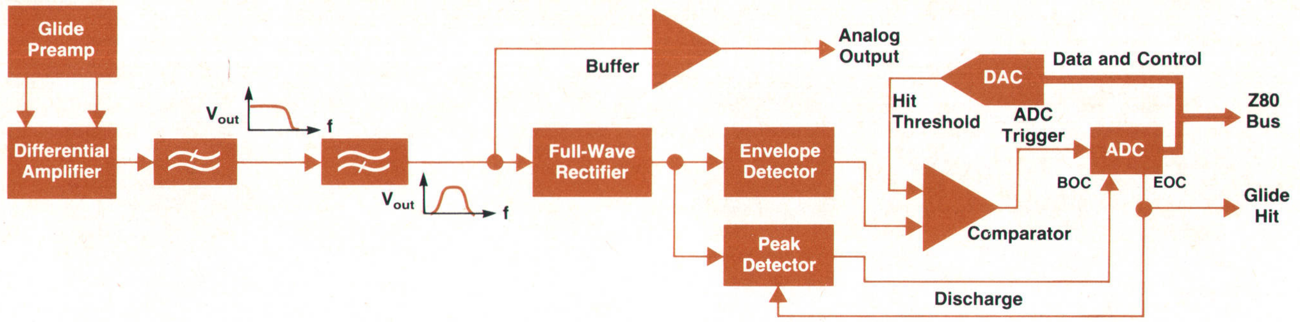


Fig. 6. *Block diagram of glide electronics.*

determines if a burnish scan is required. If no hits occur during the glide test, then the burnish process is omitted. If a hit occurs, a burnish scan is performed. A second glide scan will determine if the asperity has been removed. If the asperity still exists, the burnish and glide scan procedure is repeated. If the asperity is not removed by the second burnish, the disc is rejected.

Dynamic Electrical Testing

Dynamic electrical testing of disc recording media requires the measurement of many parameters. Typically these parameters are (see article, page 36):

- T_{AA} (track average amplitude of a 1f and 2f frequency)
- Resolution (ratio of 2f/1f)
- Overwrite (ability of the 2f frequency to write over the 1f frequency)
- Modulation (envelope modulation of the written track)
- Defects (voids or missing pulses in the recorded transitions)
- Noise generated by the media.

A block diagram of a typical disc testing read system is shown in Fig. 7. Signals are detected from the disc by the read head, amplified, and passed on to a peak detector. The output of the peak detector is a varying dc signal representing the envelope of the recorded track. This signal is now passed through a low-pass filter to measure the T_{AA} and a bandpass filter to measure the track modulation.

To measure overwrite, the amplified signal from the read head is fed to a bandpass filter. This filter is tuned to the 1f frequency. The passband of the filter is typically less than 1 kHz. This method requires expensive bandpass filters and very low system noise (<1 μV p-p within the 1f passband). Since a new bandpass filter is required each time the 1f frequency is changed, system flexibility is minimal.

A series of steps is performed to make the measurement. The first step requires the test area of the disc to be erased. The 1f frequency is then recorded and its amplitude is read through the bandpass filter. Finally, the 2f frequency is recorded on top of the 1f frequency and the residual 1f signal is measured through the bandpass filter. Overwrite is expressed as the ratio of 1f output to 1f residual in dB.

Defect testing has been quite simplistic. The 2f frequency is recorded on the disc and then read. During readback the signal is passed to a threshold detector. If the signal falls below a set threshold (usually 30 to 50% of T_{AA}), the area is flagged as a defect (see Fig. 8). Although we know that a defect exists, we know nothing about its characteristics. For example, the following parameters need to be determined: the minimum track level, the number of transitions that are below threshold, and the maximum difference in level between any two adjacent transitions.

Conventional magnetic disc media are formed from small iron oxide particles. If the disc is magnetized with a constant flux, the particles become separate small magnets. When these magnetized particles pass under the read head, white noise is generated. Typically, to measure noise, the medium is recorded with a constant flux and then the noise level is read. The noise performance of a disc is normally stated in dB as the ratio of the rms noise level to the

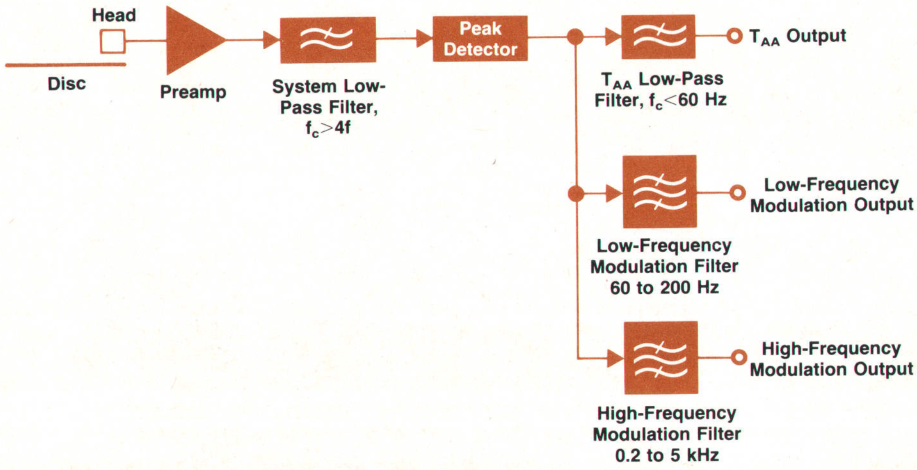


Fig. 7. *Block diagram of typical disc testing read system.*

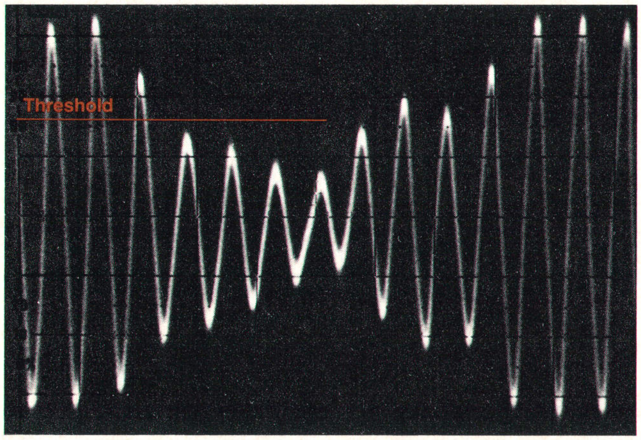


Fig. 8. *A typical defect response with threshold level indicated.*

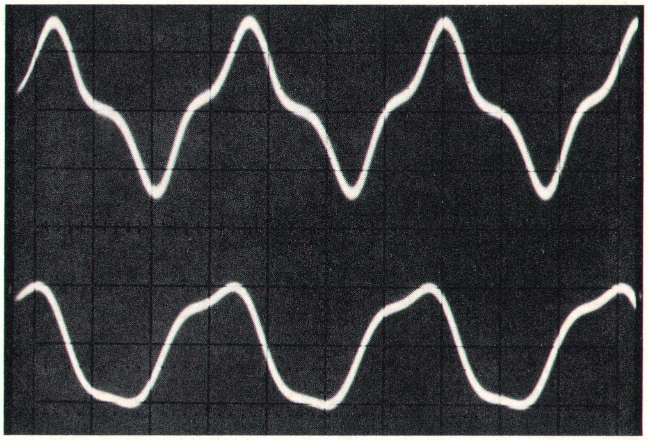


Fig. 10. *Upper trace: linear-phase filter response. Lower trace: nonlinear-phase filter response.*

minimum peak 2f output.

To improve upon the above techniques, several new measurement methods were introduced at Hewlett-Packard.

Measurement of T_{AA}, Resolution, and Modulation

Fig. 9 shows a block diagram of the read system used for thin-film disc measurement. As in Fig. 7, the read signal is detected by the head and amplified. The amplified signal is passed through a linear-phase low-pass filter to remove unnecessary high-frequency system noise. This filter must be a linear-phase type to prevent distortion of the 1f read signals (see Fig. 10). Following filtration, the differential signals are fed to two peak detectors. The outputs from the peak detectors represent the positive peak and the negative peak levels of the read signal. Using separate peak detectors allows for the testing of amplitude asymmetry (nonequal levels) between positive and negative peaks of the read waveform.

The bandwidth of the peak detectors is controlled by a low-pass filter at their outputs. The filter bandwidth is normally determined by the AGC characteristics of the disc drive for which the media is being manufactured. This bandwidth is typically 5 kHz.

The peak detector outputs are fed to two analog-to-digital converters (ADCs) where they are read by the microprocessor. During one revolution of the disc, the microprocessor samples the levels 250 times. The characteristics of the read signal amplitudes are now stored digitally within the processor and are passed to the HP 9000 Series 200 Computer used as the system controller.

The above procedure provides a high degree of flexibility. Once the signal has been stored digitally, it can be manipulated with software instead of hardware. Amplitude levels, resolution, and asymmetry can be calculated. More than one revolution of the disc can be read to provide amplitude averaging. Averaging the signal amplitudes for five revolutions of the disc has provided measurement repeatability within 2% (2σ limits) for thousands of readings of the same disc. Modulation of the read signal can also be processed by software. Modulation amplitudes and frequencies can then be determined and plotted for study.

Overwrite Measurement

To perform overwrite measurements, a new method was adopted. Signals from the linear-phase filter are fed to an HP 3585A Spectrum Analyzer rather than individual narrow-band filters. The HP 3585A has programmable frequency and sensitivity, and bandwidths as low as zero hertz. It is also capable of great dynamic range. Overwrite is measured using the standard series of steps, but each amplitude measurement is made with the spectrum analyzer. The analyzer readings are passed to the Series 200 system controller for processing. By taking an average of three to five overwrite readings, repeatability of 0.2 dB can be achieved.

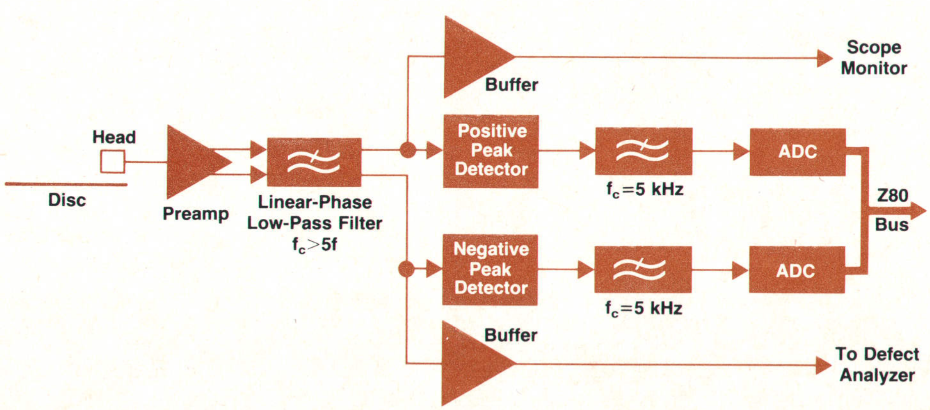


Fig. 9. *Block diagram of thin-film disc testing read system.*

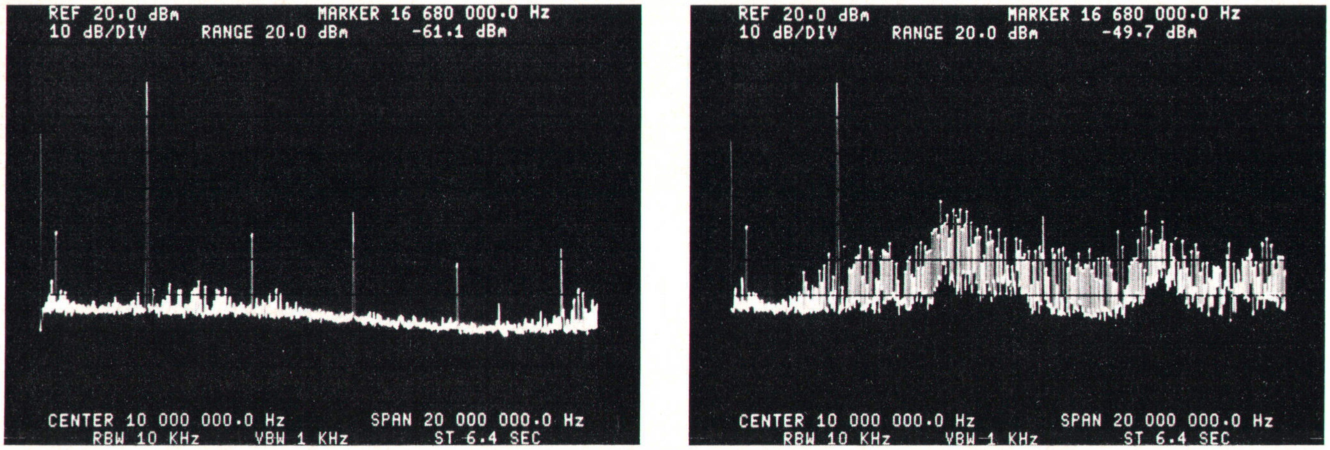


Fig. 11. *Calibration signal (a) without noise and (b) with noise.*

Including the spectrum analyzer within the test system has proven invaluable. The analyzer is used frequently to monitor the noise performance of the test system. By setting the analyzer to display the frequency domain for wide bandwidths, test system noise can be observed. It is particularly important to check system noise during calibration. This procedure requires the coupling of a signal generator to the input terminals of the test system to provide calibration signals. Since the input signals are very low in amplitude (10 μV to 100 μV), it is quite easy to insert as much noise as signal into the input terminals. The HP 3585A immediately warns the operator of the problem (see Fig. 11).

Defect Analysis

To provide a thorough evaluation of magnetic defects, it is necessary to evaluate the amplitude of every transition recorded on the disc. By sampling every transition, it is possible to determine the number of transitions below threshold, the minimum level reached by transitions within the defect zone, and the maximum difference between any two adjacent transition levels. This is achieved through the use of a high-speed or flash analog-to-digital (A-to-D) converter. Signals are fed from the linear-phase filter of the read system to this flash A-to-D converter, a peak detector, and a phase-locked loop (see Fig. 12). The output of the peak detector provides a real-time T_{AA} reference for the 4-bit (16-level) flash A-to-D converter. The phase-locked loop provides a clock to enable transition counting and to reset the A-to-D converter.

Data from the A-to-D converter is fed to a programmable 4-bit comparator and two PROMs (programmable read-only memories). One PROM is used to determine the minimum level reached, while the other PROM is used to compute the maximum level between any two adjacent transitions. The comparator is programmed from the microprocessor with the desired defect threshold level. With this hardware it is possible to analyze defects occurring at rates up to 9 MHz. When a defect occurs, its length, depth, maximum slope, radius, and angle are passed from the microprocessor to the system controller. Defects can now be analyzed, compared, or stored into a data base. To help separate hard and soft defects, the operator can specify the number of tests for each track and how many times the defect must be present to be considered a hard defect.

Two analysis modes are available, a normal scan or a scan with pause. During a normal scan the head is moved along the disc radius from track to track. Each test track overlaps the previous track by 30% to ensure total surface testing. Defects are reported to the system controller as they occur and the test continues. In the scan and pause mode, the actuator stops scanning and provides continuous reading of the track. A synchronization pulse is provided at the defect position to allow observation with an oscilloscope. Fig. 13 shows a defect displayed using this mode. Once the radius and angle are known, an SEM (scanning electron microscope) photograph of the defect can be obtained as shown in Fig. 14.

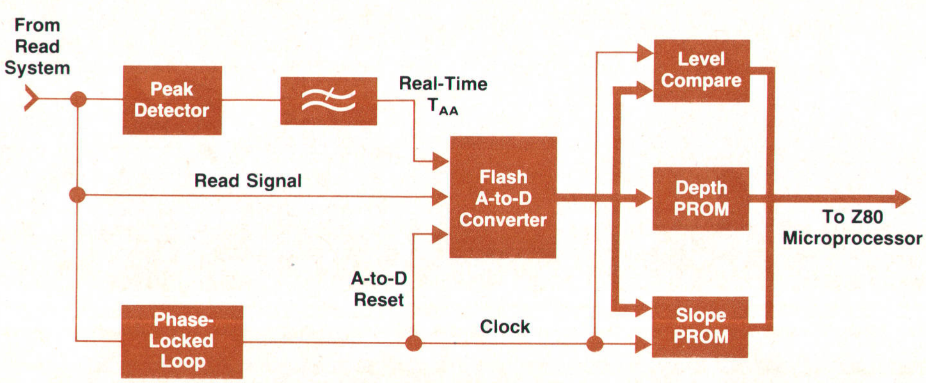


Fig. 12. *Block diagram of defect analysis system.*

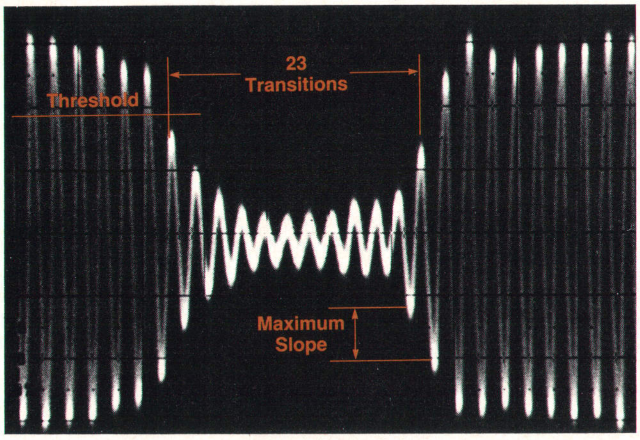


Fig. 13. *Defect displayed by the scan and pause mode.*

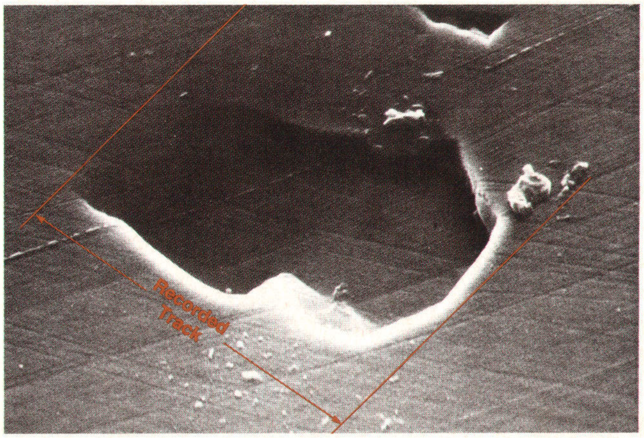


Fig. 14. *SEM photograph of the defect found in Fig. 13.*

Noise Testing

Noise testing of thin-film media differs from the methods used for conventional particulate disc media. Thin-film disc media are constructed of homogeneous magnetic films that are devoid of particulate structure. This homogeneous property produces discs that exhibit extremely low noise when recorded with constant flux. In fact, the constant-flux noise level (lower trace, Fig. 15b) is usually lower than the read system's electronic noise (lower trace, Fig. 15a). Noise is produced in thin-film media, however, when the magnetic film is recorded with transitions[4] (upper trace, Fig. 15b). This noise is commonly referred to as the ac noise. Normally ac noise is measured by a spectrum analyzer. The procedure involves breaking the frequency domain into many small bands of discrete bandwidth. This is easily accomplished by using the resolution bandwidth of the spectrum analyzer. A noise/$\sqrt{Hz}$ measurement can be made in each band. If the band containing the recorded frequency is omitted, and a replacement value is interpolated from the remaining bands, the error will be small. The total noise can be computed using the following equations:

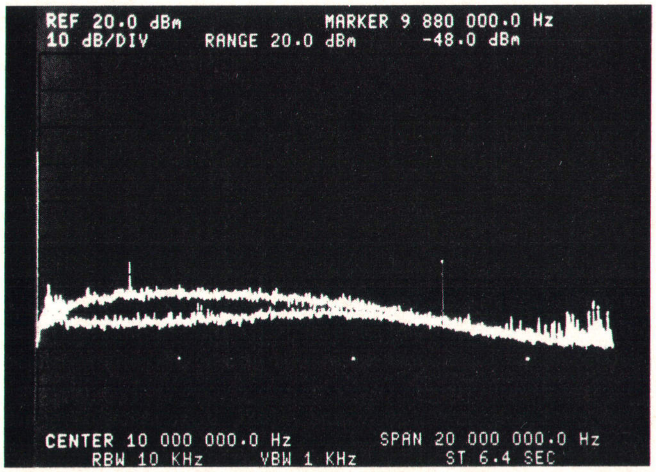
$$\text{Average noise for each segment} = N_{rh_i}(\sqrt{BW}) \quad (1)$$

where N_{rh_i} = the rms noise/$\sqrt{Hz}$ measured by the analyzer and BW = the bandwidth of the measured band. Then:

$$\text{Total noise} = \sqrt{\sum_{i=1}^{n} (N_{rh_i})^2} \quad (2)$$

This method has high accuracy but is very time-consuming. To provide a reasonable production test for noise, another method is used. Fig. 15b illustrates the fact that the ac noise can be generated with recorded signals outside the normal passband. This allows the measurement of ac noise by using a sharp-cutoff low-pass filter. Read signals are fed from the read system through a low-pass filter to a true-rms voltmeter. The low-pass filter passes all frequencies up to 4f and attenuates those beyond 4f. The filter has a notch or point of maximum attenuation at the recorded noise generation frequency (see Fig. 16). The maximum attenuation is at least 60 to 70 dB. Filters with eight or nine poles are commonly used for this purpose.

Noise testing is now trivial. First, the 2f signal is recorded on the disc and measured with the true-rms voltmeter. This



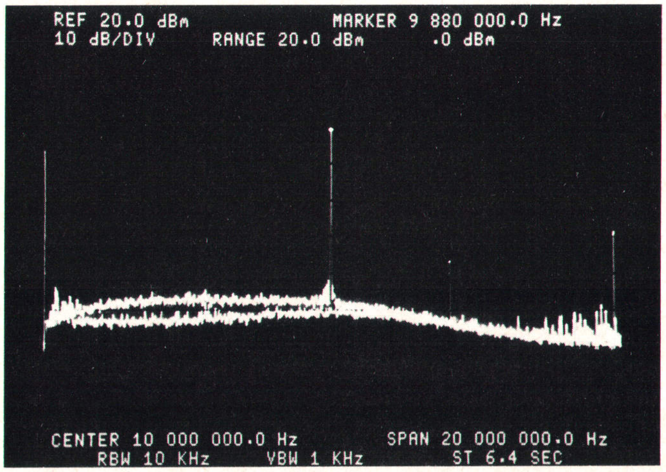


Fig. 15. *(a) Upper trace: dc noise level from conventional particulate disc media. Lower trace: test system noise level. (b) Upper trace: ac noise level from thin-film disc media. Lower trace: dc noise level from thin-film disc media.*

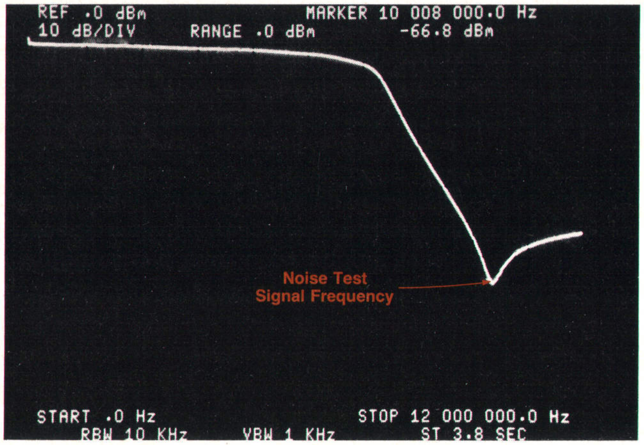


Fig. 16. *Response of ac noise filter. The notch is placed at the recorded noise-generation frequency.*

value is multiplied by 1.414 to obtain the peak value (2f signals are typically sinusoidal). Next, the disc is dc erased and the noise frequency is recorded and read by the voltmeter. The noise performance is now expressed as the ratio of ac noise to 2f peak amplitude in dB.

Characterization of Measurement Errors

Before a tester can be used on a production line, its measurement error must be characterized. Knowledge of the measurement errors is necessary to understand the risks of shipping bad parts or scrapping good parts. There are two types of errors to be determined for each parameter being measured. The first is the precision of the measurement (the ability to reproduce the same result given the same conditions). The second is the measurement drift (the long-term change in the measurement results).

The operation of a tester can also be verified during the process of characterizing the measurement error. If the type of distribution for a measured parameter is known, then variations in the distribution will indicate when a measurement technique is due for calibration. For example, if a measurement usually has a normal distribution, and the tester being characterized gives a binormal distribution, the test is not functioning properly. The size of the measurement errors can also be used to warn of tester problems. By comparing the measurement errors of one tester to another or to earlier measurement errors on the same tester, the tester can be verified to be operational or nonoperational.

Measurement Precision. The precision of the tester is estimated by repeating the production test without changing any parameters. Typically, the production test is repeated 100 times. The repetition rate is as fast as the tests can be run without changing either the heads or the disc. The population of values obtained for each parameter measured is then checked to determine if it fits a normal distribution. If the values are normally distributed, then the precision of the tester is specified in terms of the estimated standard deviation of the parameter. A few measured parameters, such as defect count, are not normally distributed. To determine the precision of these parameters, other methods must be used.

Graphical Analysis. Graphical techniques provide an easy and quick method for analyzing a set of measurements. Plotting the data as a histogram, as a scattergram, and on normal probability paper allows easy analysis of measurement precision. Fig. 17 shows example plots for the measurement of T_{AA}.

When using these graphical techniques, certain guidelines should be followed to ensure that the data is inter-

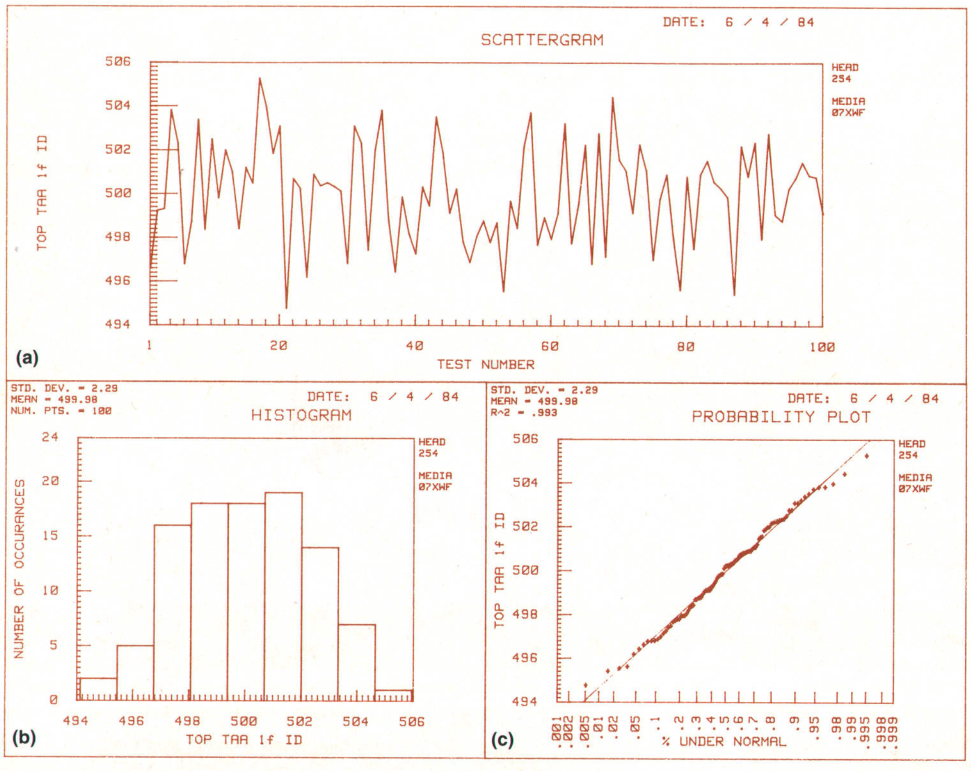


Fig. 17. *Graphic analysis of measurement precision of a calibrated tester. (a) Scattergram. (b) Histogram. (c) Probability plot.*

preted correctly.[5] To determine if a set of measurements is normally distributed, a straight line is drawn through the points plotted on normal probability paper. If the points fit the straight line, the measurements can be estimated as being normally distributed. The data shown in Fig. 17 can be estimated as a normal distribution. If the data does not fit a straight line, either the tester is uncalibrated or the measurement distribution is not normal. A thorough understanding of the measured parameter is then relied upon to make that decision.

Fig. 18 shows an example of how a scattergram can be used to help diagnose tester problems. By fitting a straight line to the points on the normal probability plot in Fig. 18, the data looks like a normal distribution. But when the scattergram is examined there is a continuous drift in values as the tests are performed. Therefore, the data in Fig. 18 is not actually normally distributed.

Measurement Drift. The measurement drift in a tester may be caused by several mechanical and/or electrical factors that can change on a daily basis. These changes cannot be determined when the precision of the tester is measured. To determine the random day-to-day variations, the production test is repeated 20 or more times every day for five or more days. Each day the heads and disc are removed.

Using the techniques for determining measurement precision, the results of the 20 or more tests run each day are tested for normal populations. Populations that are not normally distributed usually show that a tester is uncalibrated. To determine if the variations from day to day are significant compared to the measurement precision, a two-way analysis of variance is performed. This analysis establishes confidence intervals for determining if the measurement drift and measurement precision are statistically different. If this occurs, the means of the daily tests are analyzed.

The means of the daily measurements are analyzed by plotting scattergrams and normal probability plots. Deviations in the means from a normal distribution indicate a variable that is not under control. When this occurs, the variable must be isolated and the necessary corrections made. When the means fit a normal distribution, the measurement drift is calculated by using the standard deviation of the means. When calculating the measurement drift, Student's distribution is used. This distribution will accurately estimate the area under the normal distribution for small sample sizes. By using Student's distribution, accurate estimates of the measurement drift can be estimated with only five days of testing.

Acknowledgments

The development of complex measurement systems requires the talents of many individuals. The authors would like to acknowledge these people. Many of the initial mechanical concepts and subsequent designs were provided by Brian Hastings, Al Johnson, Lou Mueller, and Bob Reynolds. Candy Charity and Raul Fuentes provided the main portion of the Series 200 system controller software. Embellishments were added by Andy Rad. A superb dc motor controller for the air bearing spindle and its software module were developed by Dan Haman, Boyd Shelton, and Dale Wolin. Gary Erickson developed the latest version of the glide testing electronics. Considerable work towards the development of the voice coil actuator system and the defect analysis system was provided by Dan Gilbert. Pete Brod, Ron Chase, Mike Jones, Stan Miller, and all the people of Don Moore's electronic tooling group provided hours, weeks, and years of effort in the construction and verification of the test systems. A special thanks to all of the test

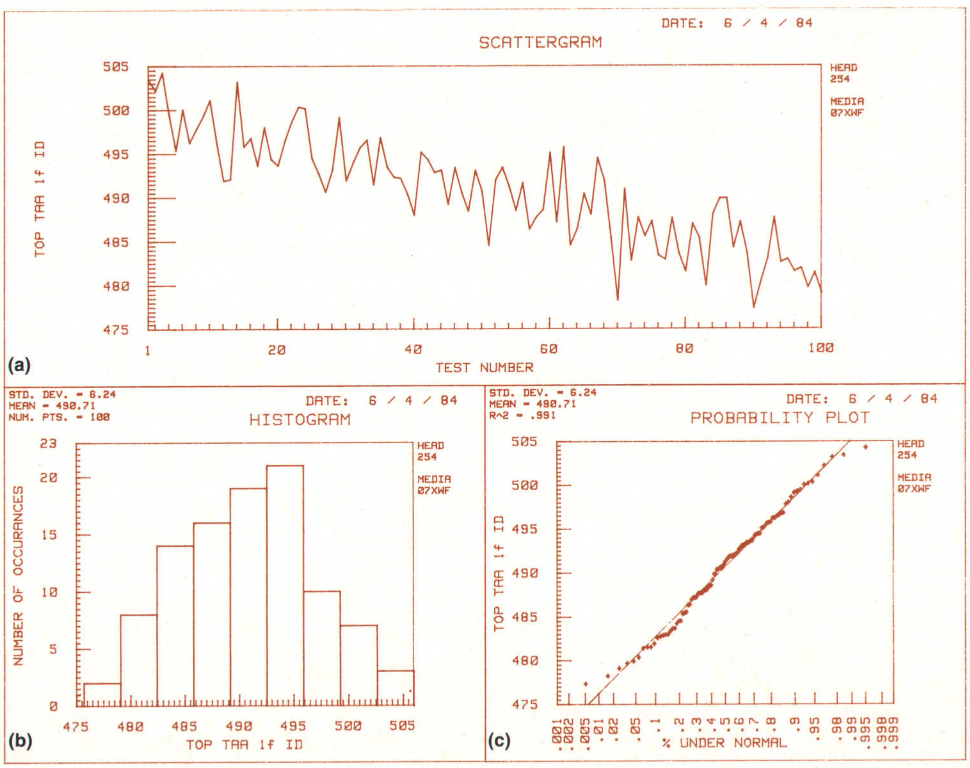


Fig. 18. *Results for an uncalibrated tester with a probability distribution that appears to be normal, but exhibits a sloping scattergram.*

equipment operators. The feedback provided by these people guaranteed an efficient and accurate test system.

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In-Line Sputtering Deposition System for Thin-Film Disc Fabrication

by George A. Drennan, Robert J. Lawton, and Michael B. Jacobson

TO SATISFY the increasing performance requirements for magnetic recording media, several improvements on the technology existing in 1979 were necessary. The thickness of the magnetic layer had to decrease, the head-to-disc separation had to be smaller, the occurrence of defects had to be reduced, the magnetic parameters had to be enhanced (specifically, the magnetic remanence had to be increased), and the electrical and magnetic properties had to be controlled more closely.

In 1979, rigid magnetic recording media were fabricated by evenly spreading a layer of gamma-ferric-oxide particles (held in a slurry of epoxy and alumina) onto an aluminum substrate. This process was adequate until the storage density requirements exceeded 10^{12} bits per square inch. At these densities, the size of the particles in the layer approached the size of the magnetic bits, and the roughness of the particulate media surface limited the recording head flying performance.

Sputtered thin-film deposition technology was an obvious answer to these limitations, since it can produce homogeneous films that are extremely thin (<100 nm). The advantages of thin-film processing do not, however, include a friendly environment. First, it must be performed in a chamber capable of being evacuated to a pressure of 10^{-6} torr, then the chamber must be filled with an inert gas whose pressure must be controlled within a few μm of Hg, and, as if those were not rigorous enough conditions, the entire deposition process is fastidiously intolerant of contaminants of any kind, particulate or chemical.

Sputtered thin-film deposition processing has been used for over twenty years in the manufacture of solid-state devices and integrated circuits. Typically, the process involves sequential steps of pattern definition and deposition of multiple layers with intricate and accurate features, but has a forgiving tolerance to μm-sized defects. By contrast, sputtered deposition for thin-film discs is totally featureless, but is most intolerant of the smallest of defects. HP's thin-film media are specified to have less than one defect per 250,000 bits of information.

Design Evolution

In 1979, there was no commercially available system tailored to the needs of thin-film magnetic disc fabrication. The fundamental requirements for such a system were multiple, isolatable, modular vacuum chambers, each capable of the simultaneous deposition of a specific thin-film layer on both sides of a vertically held substrate.

One concept was to gather several deposition systems in a clean room and carry the substrate from one system to the next, each accounting for its own thin-film layer, until the desired composite layer of films was completed. However, this approach is extremely vulnerable to contamination of the partially processed substrates. In addition to the airborne particulates present in all clean rooms, contaminants such as oxygen and water vapor would create serious oxidation and corrosion problems.

We decided that if any processing was to be done in a sputtering deposition system, then *all* of the processing should occur in that deposition system. Faced with the task of designing equipment capable of depositing several thin-film layers on each disc, we decided to build several deposition systems (one for each thin-film layer) and link them together in a line. This in-line-system (ILS, Fig. 1 and Fig. 2) is arranged with large high-vacuum valves between each chamber. These slit valves allow each chamber to be isolated from adjacent chambers, but permit the interchamber transfer of the disc substrates when the valves are opened. Each chamber has systems for vacuum pumping, process gas handling, pressure instrumentation, sputtering sources, and materials handling. Each chamber is equipped with its own step motor robot drive system. The step motors are coupled to optical angular encoders for step confirmation information.

An important design feature of the chambers is that they are modular. Modularity provides the system with a versatility that greatly facilitated the process development cycle. The chambers can be easily configured for either dc magnetron or RF diode sputtering. It is possible to add or delete an entire chamber with minimal effort. The line of chambers has a load chamber on one end and a mirror-image unload chamber on the other.

The ability to isolate each chamber makes it possible to optimize each deposition process independently. Process parameters such as deposition rate (cathode power), deposition time, and process gas conditions (composition, flow rate, and pressure) can be adjusted to produce the best possible film for each layer.

Planetary Carrier

The sputtering deposition of a thin film of target material onto a substrate is easily controlled, but not perfect. The sputtering rate can vary up to 10% across the surface of the source target. If the disc substrate is held fixed relative to the target, this variation will show up as a nonuniform film thickness across the disc surface. This thickness variation affects certain magnetic properties (coercivity and thickness-remanence product), and results in an undesirable modulation in the read/write performance of the disc drive. Passing the disc substrates in front of the source targets in a unidirectional manner during the sputtering operation can reduce this variation to approximately 5%, but cannot eliminate it. Ideally, the substrates should move in front of the targets such that each bit of substrate area experiences an equal encounter with all areas of the target's surface.

Of all the equipment requirements the one easiest to describe was the most confounding to satisfy—hold the substrate such that neither side is masked or marred during the deposition processes. The added requirement of presenting multiple substrates to each sputtering target simultaneously in a random fashion without contamination did not simplify the matter. A mechanical device that approximates the desired motion is a simple planetary carrier. A special version of this planetary concept has been implemented in the ILS substrate carriers (see Fig. 3). Each substrate moves in a compound rotation—about the center of the carrier plate and simultaneously about its own center. The averaging of deposition nonuniformities by the planetary motion is somewhat analogous to the high-quality surfaces obtained by a circular lapping process.

The planetary carrier is made up of a circular plate with round openings that are slightly larger than the substrates. Supported in the center of each opening is a sheave whose flange diameters are slightly smaller than the inside diameter of the substrate. The discs are loaded onto the carriers by hanging them onto the sheaves. As the planetary carrier is rotated about its center, the inside diameter of the substrate rolls on the minor diameter of the sheave. This rolling motion approximates a rotation of the substrate about its center. The speed of this rolling rotation is influenced by the ratio of the inside diameter of the substrate to the minor diameter of the sheave.

By presenting the disc to the targets with a planetary motion, uniformities of 0.1% can be achieved on both sides simultaneously. In addition, the rolling motion of the disc on the sheave produces no measurable particulate contamination. The planetary carriers can be made for the various disc sizes with essentially no other system changes. Thus, an ILS can be used to process many disc sizes and need not be dedicated to any particular disc size.

Fig. 1. *In-line deposition system developed by HP for fabrication of thin-film magnetic discs.*

ILS Control System

The ILS is a versatile, complicated assembly of sophisticated equipment. Coordinating the simultaneous control of the sputtering parameters in multiple chambers with the manipulation of the materials-handling robotics requires an automated control system that provides several levels of interaction to the human operator. The ILS control system is a combination of hardware and software designed to take advantage of the vast capabilities of the system without overwhelming the operator with an extremely complex set of instructions.

The control system architecture emphasizes centralized control with convenient access to the elemental facilities of the machine. The central control element accounts for the interactions of over 200 mechanical actuators and measurement transducers. It can also be altered easily to meet the changing needs of a developing media deposition process.

The HP 1000 A-Series Computer was chosen for the central control element because it provides multitasking, multiuser capabilities. It meets the requirements of industry-standard IEEE 488 (HP-IB) and RS-232-C interfaces, and has the potential for handling the protocols required for interfacing to measurement and control devices such as the HP 3497A Data Acquisition Unit. It also has the capability for networking multiple control systems together and supporting them from a central location.

The HP 1000's ability to perform at many levels of control has been an invaluable feature for production quality and capacity, process development, and maintainability. The levels range from the ultimate sophistication of one-button control of the entire deposition process to the equivalent of a panel of toggle switches for each of the more than 200 ILS devices for fundamental troubleshooting. Some of the highlights of the HP 1000 control system for the ILS are:

- Many levels of interactive and automatic control:
  - Primitive—the operator has complete control of every device in the system.
  - Function—the operator can initiate simple actions involving many of the ILS's devices.
  - Process—the operator can choose to initiate any of several independently executed processes.
  - Automatic—the operator can initiate the automatic processing of an entire load of planetaries (one-button control).
- A soft configuration allowing the process parameters to be adjusted while the system is in operation.
- Complex processing can be implemented by programming in Pascal and using the ILS software libraries.

The ILS control system contributes to the quality of HP's thin-film disc media by operating the deposition processes in a consistent manner. It contributes to throughput by making it possible to process in more than one chamber at a time; and to operational reliability and safety by isolating the operator from the details of machine operation.

Some of the notable features of the ILS control system are the color graphics display of the system status (Fig. 4), a trace file that logs operations to both the operator's terminal and a disc file for future reference, and a menu-driven operator interface. In addition, the hardware configuration can be modified without changing any programs, and operations can be performed on individual devices or groups of devices.

Processing Sequence

Discs are fabricated in the ILS using a combination of batch loading and continuous processing. Several planetary carriers are held on a supporting rack and placed into the load chamber. After the load chamber has been evacuated, a loader mechanism places a planetary carrier onto a robot sled. The slit valve separating the load chamber from the first deposition chamber is then opened and the robot carries the planetary carrier from the load chamber

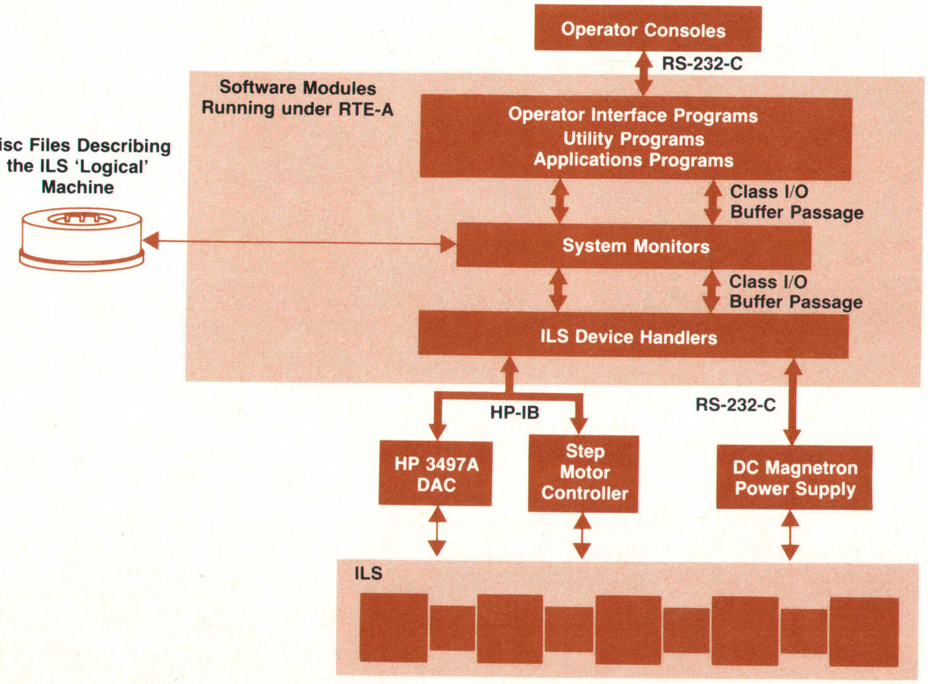

Fig. 2. *Schematic diagram of in-line deposition system and its control system.*

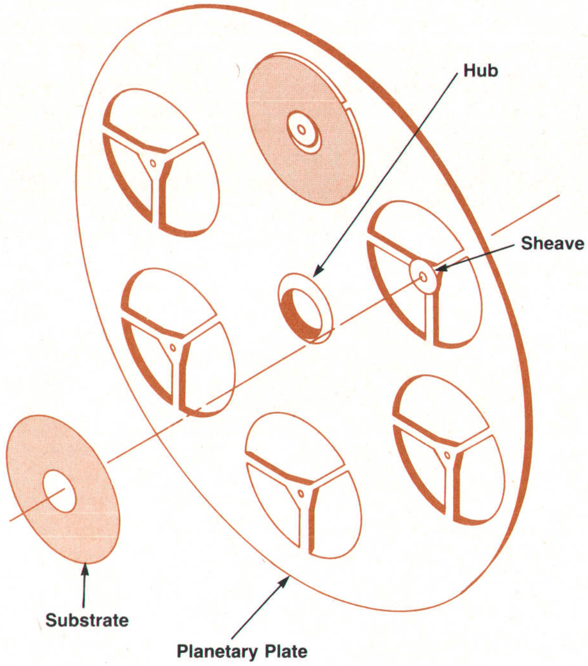

Fig. 3. *Deposition uniformity across the surface of a thin-film magnetic disc is assured by using a planetary carrier with each disc mounted on a sheave that allows free disc rotation as the carrier is rotated.*

to the center of the first deposition chamber. A plunger from the back wall is then inserted into the hub of the planetary carrier. The plunger tip lifts the hub from the robot sled and then securely holds it. The sled is then moved from between the planetary carrier and the sputtering target. After the chamber is isolated by closing the slit valve, the plunger rotates the carrier (imparting planetary motion to the substrates), and the deposition process begins. When the first layer has been deposited, the plunger places the planetary carrier onto a second sled for transfer to the next deposition chamber while the first sled returns to the load chamber for another carrier.

Each planetary carrier is sequentially processed in each of the chambers and finally placed into a holding rack in the unload chamber. As soon as a planetary carrier exits a particular chamber, the next carrier takes its place in that chamber for processing. Once the ILS pipeline is filled, deposition processing occurs in all chambers simultaneously. The discs arriving at the unload chamber are completely finished and are ready for certification of their electrical and magnetic specifications.

Maintenance and Reliability

From the beginning, the reliability and maintainability of the ILS were key considerations. The extensive capital investment represented by the ILS demands that it operate as intended over a long production lifetime, with very little downtime. These reliability considerations have been accounted for in many ways. First, representatives from our maintenance team were included in every design review. Second, if possible, we selected standard components with known performance (vacuum pumps, power supplies, vacuum instrumentation, computer hardware, cathodes, etc.). Third, the design of all mechanical equipment included greater than normal stress margin. Extensive training of the maintenance technicians and a comprehensive documentation package have also been very effective. Finally, the

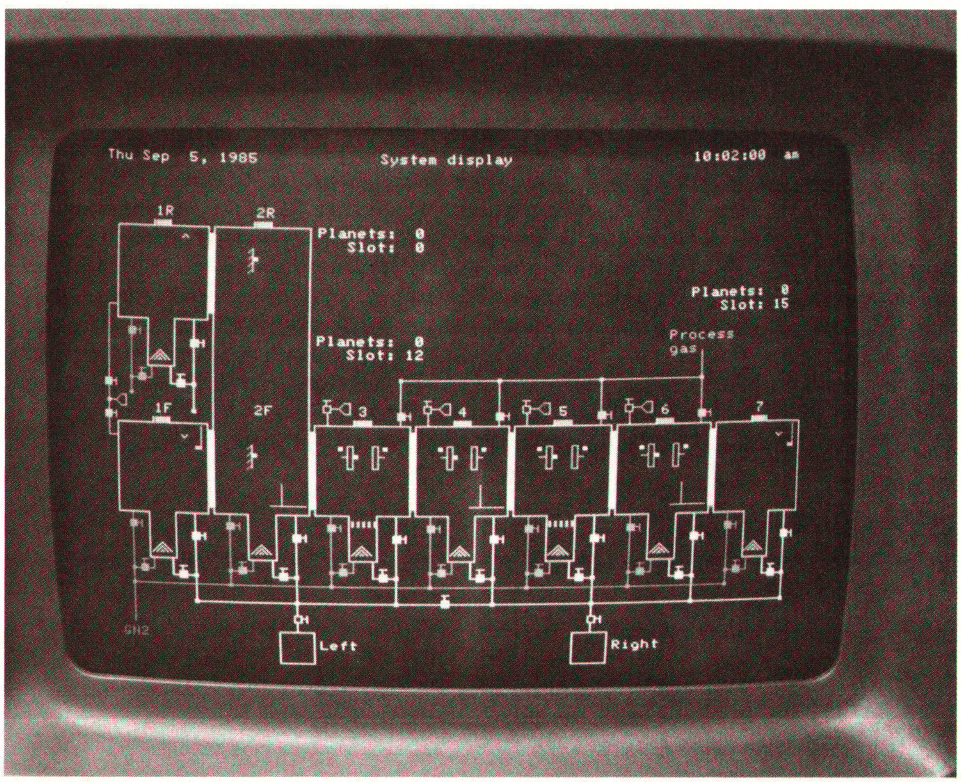

Fig. 4. *Display showing status of in-line deposition system.*

power of the HP 1000 Computer controller has been used to prevent downtime through fail-safe interlocks and status graphics and to aid troubleshooting by providing system diagnostics and self-test programs.

Acknowledgments

The design of the disc deposition system has evolved over several years and is a composite of the coordinated efforts of many individuals. A special thanks goes to Jim Devine, who has been associated with HP's thin-film disc program since its origin, and has been a consistent source of sputtering system knowledge and insight.

Several others should be singled out for recognition of their contributions: Bill Hutchison for his design and guidance in defining the control system architecture and software, Cameron Smith for providing the engineering support for the system electronics during the transition from development to manufacturing, Tats Yamamoto for his mechanical design of the cathode assemblies, Glen Bodman for coordinating the design and construction of the special facilities required for the disc processing areas, Mike Williams, whose intimate knowledge of the system operation has been extremely valuable in checking out each new system and in training the system operators, Scott Leadbetter and Sue Haman for providing the drafting support for the great number of mechanical and electrical drawings that were always accurate and up-to-date, and finally, Debbie Bennett for orchestrating all of the documentation efforts and producing a truly comprehensive package.

Credit is also due to our excellent maintenance team of Mike Buckley, Harvey Torres, Herb Jordine, Steve Blanchard, Jim Feagin, Barry Broom, and Gary Larsen for their design recommendations and technical skills that have kept the deposition system running smoothly.

Thin-Film Disc Reliability—the Conservative Approach

by Clifford K. Day, C. Girvin Harkins, Stephan P. Howe, and Paul Poorman

WHEN A COMPANY with a reputation for reliable products introduces a new technology, it has the obligation to ensure that this technology will achieve at least the same level of customer satisfaction through reliable performance as did the technology it replaces.

This is particularly important when implementing a new disc memory technology, since data integrity and reliability are primary performance criteria. Hence, when Hewlett-Packard undertook the development of thin-film discs for its new memory products, a significant part of the program was concerned with evaluating and improving the reliability of the new technology.

Reliability Goals and Testing

Reliability experience was reviewed for HP disc drives that used the older particulate media head/disc technology. Based on this experience, two goals were established that would represent a considerable improvement in disc reliability. The first represented the warranty period, which is the easiest measure of reliability success since it can be measured in stressful lab and field environments within a reasonable amount of time. The second was a long-term goal equivalent to ten years of drive use by the customer. These two goals became the focus for our accelerated testing efforts.

Several accelerated tests were devised to simulate different customer environmental stresses. These included:

- Wear tests that evaluate effects caused by head takeoff and landing on the disc surface
- Friction tests that evaluate start-up and dynamic head/disc friction as a function of wear and humidity
- Atmospheric pollutant and galvanic corrosion tests
- Oxygen diffusion tests
- Shock and vibration tests
- Thermal stability tests (including some that simulated a customer transporting the disc drive in the cold trunk of a car and then using the drive in a warm office environment).

The major challenge facing the engineer responsible for qualifying the reliability of a new disc memory materials system is the need for realistic accelerated tests that will establish the failure rate of the disc to various stresses. Typically, one wants a test that can be completed in a few hours, days, or weeks that would simulate ten or more years of customer use. Some environmental stresses, such as atmospheric pollutants, are difficult to simulate in the laboratory. In such cases, extensive field tests are needed to supplement lab results, and additional design precautions may be required to ensure reliability with a high degree of confidence.

As the thin-film disc testing program unfolded, it became apparent that the major areas that would contribute most to disc failures were wear, friction, and corrosion. The rest of this article will focus on the testing done to ensure that these stresses would not result in problems for Hewlett-Packard's disc drive customers.

Wear

Ensuring adequate protection for customer data during drive power-up and power-down was one of the biggest challenges the designers of the thin-film disc faced. Since the head rests on the disc after power is removed from the drive, it is important that the disc surface support many head takeoffs and landings without suffering damage that could lead to drive failure.

We chose as our goal for the initial phases of testing 10,000 start/stops, according to the guidelines offered by the American National Standards Institute. This simulates a customer powering the drive up and down three times per day, 365 days per year, for over nine years.

Later, as the disc reliability improved because of new developments, it became apparent that 10,000 start/stops were not adequate to determine the reliability margin that existed. Hence, we instituted a test-to-failure program. Now the discs are routinely tested to 100,000 start/stops or failure, whichever comes first.

The main disc wear failure mechanisms are severe head/disc contact that gouges out disc material (known as a head crash) and localized demagnetization of magnetic recording material because of stress caused by head-to-disc contact. A head crash can result from a weakness in the disc thin-film structure, a head that has been improperly manufactured, or head or disc contamination. The result is severe film damage in the landing zone accompanied by either failure of the head to fly (lift off the disc) upon disc rotation or data degradation by head-to-disc contact in the data zone from debris attached to the head.

To make a high-confidence statement about the reliability of the disc, it is necessary to test a large number. To shorten the feedback time needed to accomplish this testing, the thirty testers shown in Fig. 1 were constructed. These fully automated testers allow a wide variety of disc sizes and head types to be evaluated. The acceleration and deceleration profiles of the disc can be conveniently modified by software changes. This ensures that the head and disc contact time are properly simulated for a given disc drive product.

Two types of wear tests are used. The first simulates a dedicated landing zone common to most of today's drives. The second simulates taking off and landing on some type of recorded data (e.g., information to help start the drive or customer data). The latter is important to drives that want to maximize storage capacity by using all of the available disc surface. These tests differ in the way the reference data is recorded. The land-on-data test records 70 reference tracks spaced 0.002 inch apart while the landing zone test has the reference data outside the landing area.

Nearly 1500 wear tests were completed as part of the reliability qualification testing before releasing the thin-film disc to manufacturing and the ongoing reliability audit program. These accelerated tests have demonstrated that thin-film head/disc wear characteristics are excellent and exceed the drive design team's component reliability goals.

Friction

When the disc starts spinning, the recording head drags on the disc surface until, at higher disc speeds, the head lifts (flies) and the two are separated by a thin layer of air. During this process, there are two friction coefficients that are important to the drive designer. The static coefficient of friction describes the amount of initial force required to break the disc free from the head while the kinetic coefficient defines the amount of force needed to keep the disc

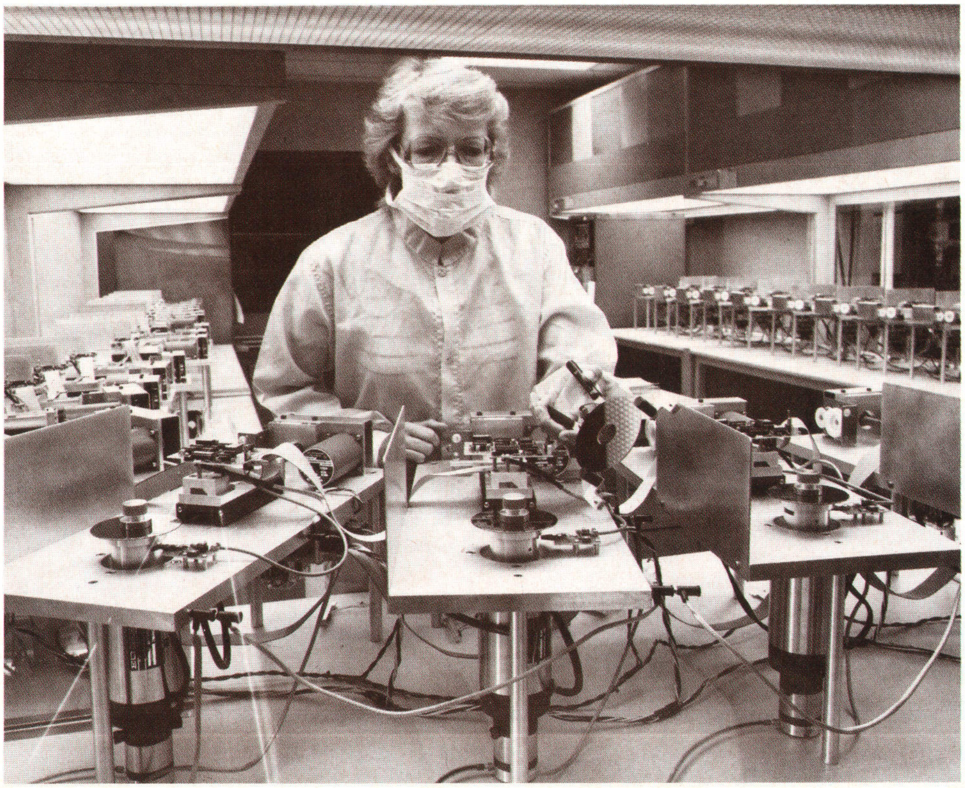

Fig. 1. *Thirty wear test systems allow a quick statistical comparison of disc process changes or different disc drive design alternatives.*

spinning at 50 revolutions per minute.

As data recording densities increase, head flying heights must be reduced to maintain adequate signal levels. This requires both the head and disc surfaces to be extremely smooth to prevent head disc contact and possible data loss during operation. However, smooth surfaces in contact can mean unacceptably high friction coefficients.

Typical engineering surfaces are quite rough, so that when they are placed together, contact occurs only over a small percentage of the apparent contact area. The smooth head and disc surfaces have a higher percentage of their area in contact and thus have more area available for chemical bonding. Smoothness, combined with high humidity and disc wear, can lead to very high values of both static and kinetic friction coefficients. These high values can prevent the disc from spinning up or cause damage to the head or disc.

Several researchers have studied friction on smooth surfaces in the presence of liquids.[1,2] Many factors such as disc and head materials and roughness, head load, moisture affinity, humidity, dwell time, wear, moisture condensing and drying, surface area, and resting separation are important in determining friction coefficients. For HP's thin-film disc, most of these variables are fixed by other design considerations.

After the thin-film materials system was selected, based on all of the design criteria, our studies focused on the environmental and customer use factors and how they affected the reliability of the head-to-disc interface. A combination of one-factor and factorial experiments implicated start/stop wear and humidity as major effects on the static friction coefficient and start/stop wear as the major influence on kinetic friction.

Smooth heads and discs can become a concern at relative humidities above 50% where an adsorbed water layer condenses between the head and disc from capillary action. The water enables Van der Waals forces to act over a larger surface and increase the force required to separate the two materials.

Every time the drive is powered up or down, the head and disc slide relative to one another for some time. This sliding action increases the friction in a way that is not yet understood in detail. One theory suggests that wear shaves off the peaks and fills in the valleys of the sliding surfaces, which leads to smoother surfaces. Another suggests the increased friction results from the formation of frictional polymers. The energy dissipated by friction shows up as heat and active bonding sites in the interface. If hydrocarbons are present in the air, they polymerize on the active sites, leaving a tar-like deposit. This residue could act much like moisture does to increase the friction. In all likelihood, both effects are important.

Knowing the important environmental effects for friction, we were ready to design a testing program to simulate actual drive conditions and determine if our reliability goals would be met. Five stress levels were selected ranging from low humidity (20%) and few start/stops to high humidity (95%) and thousands of start/stops. We used a custom strain gauge head arm (Fig. 2) to measure the force components and two high-speed HP voltmeters to digitize the data. An HP 9000 Series 226 Computer (formerly HP 9826) processed the data and plotted the friction coefficient as the disc spun.

Test results demonstrated that the static friction coefficient averages 0.26 at low humidity and start/stops. After 2000 start/stops and 95% humidity, the average increases

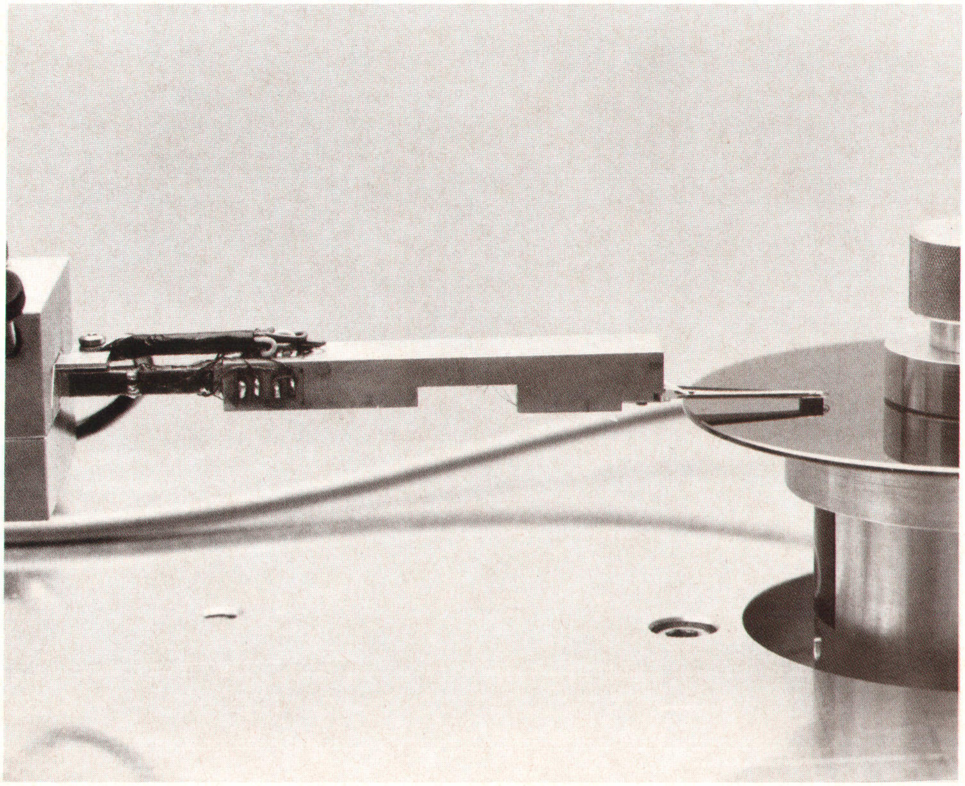

Fig. 2. *Strain gauge head assembly used to measure friction forces.*

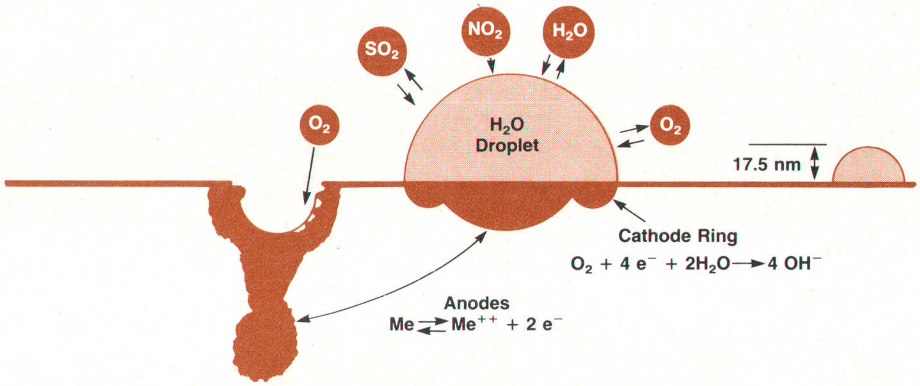

Fig. 3. *Electrochemical cell model for corrosion initiated by water adsorption and atmospheric pollutants.*

to 1.18. Some head/disc combinations resulted in friction levels high enough to prevent the low-power spindle motor from spinning up the discs. The disc drive team overcame this by moving the heads slightly with the head/arm step motor as power was applied to the spindle motor. This was only done when the controller sensed the spindle could not start by itself. This action freed the head and disc and allowed the drive to operate properly in the most severe environmental conditions.

Our testing program has demonstrated that thin-film disc friction coefficients are higher than those for heads on the older technology gamma-ferric-oxide discs that are lubricated. However, reliable drives can be built in spite of the higher friction levels.

Corrosion

The electronic structure of a ferromagnetic metal provides for interesting physics, because of the large amount of chemical energy stored in that structure when the metal was reduced from its ore. The tendency to release this energy and return to an ore is the driving force for thin-film discs to suffer atmospheric corrosion. One result of corrosion on a thin-film disc is loss of ferromagnetism (and stored information) at the reaction site. Another result is the accumulation of reaction products leading to mechanical failure (head crashes, wear) on data tracks not corroded.

Corrosion-related problems are not common in conventional ferric oxide media since those materials are already "rust." Compensation for this basic difference between metal and oxide recording media has been a long-known prerequisite to bringing thin-film disc technology to the marketplace.

During HP's thin-film disc development, corrosion engineering was an integral part of the disc materials research rather than a postdevelopment afterthought. Even this ideal development approach proved an interesting challenge because (1) indoor atmospheric corrosion research is a relatively new and complex field, (2) the analytical chemical techniques need to be pushed very hard but very carefully, and (3) the boundary conditions of magnetic recording itself severely limit the application of many standard corrosion control strategies, especially those in which material is added to the disc.

Additive Technologies for Corrosion Control

Most corrosion control relies upon establishing chemical barriers at the metal/environment interface. Coatings and inhibitors are two examples of this principle. From a physics viewpoint, however, adding a nonmagnetic layer to a magnetic recording surface increases the head-to-disc gap and exponentially decreases the recording signal level.

To satisfy the physics requirement for thinness, one must generally sacrifice the continuity and damage resistance of applied hard coatings. Any pinholes and scratches are potential corrosion initiation sites. The simultaneous requirements of thinness and film continuity are more easily obtained with adsorbed organic films, but in this application, organic films often show unwanted adhesive properties, or serve as the precursors for "frictional polymers."

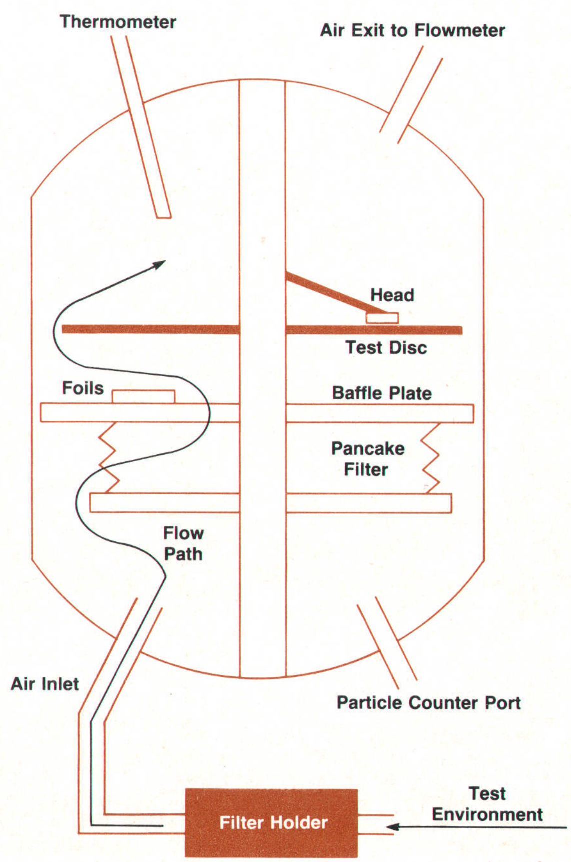

Fig. 4. *Cross section of test chamber for evaluating environmental corrosion effects.*

The third additive approach is to mix other metals with the ferromagnetic ones in hope of obtaining a corrosion-resistant alloy, just as chromium is added to iron to make stainless steels. Unfortunately, the amount of metal that must be added to provide a self-repairing corrosion product film at the alloy surface is usually more than enough to alter the magnetic properties of the original metal. The general result of alloying experiments is that good recording films show poor corrosion resistance, while good corrosion-resistant films show poor recording properties.

Atmospheric Corrosion Processes

If it is not feasible to establish a chemical barrier at the disc surface, then it becomes necessary to address the question "Why are ferromagnetic films so sensitive to atmospheric corrosion in indoor environments?"

Part of the answer is that ferromagnetic elements are good electrical conductors, and they react with oxygen and water vapor at low temperatures to form hydrated oxide surface films containing both chemically and physically adsorbed water. The remaining requirement to complete an electrochemical corrosion cell on the metal surface is an accumulation of ions into the surface water layer to form an ionic conductor. Atmospheric particulates. such as small salt crystals, are concentrated sources of ions, and are often controlling factors in outdoor atmospheric corrosion. However, even in conventional disc drives, particulates are removed by filters to prevent head crashes. In many indoor environments, and certainly in the filtered environment of a disc drive, gaseous pollutants such as H_2S, SO_2, Cl_2, and NO_2 not removed by these filters are the default sources of the ions dissolved in the water layer on the disc surface.

This electrochemical cell model is summarized in Fig. 3. Atmospheric oxygen also plays a role, establishing an oxygen concentration cell that defines the center of the droplet as the metal anode where actual metal loss occurs.

This model also helps explain why the rates of corrosion and the chemistry of the resulting corrosion products can be quite variable. Relative humidity is a major parameter determining both the continuity and the thickness of the electrolyte layer on the disc surface. The composition and concentrations of trace pollutants in the air and the rate at which they are transported to the disc surface determine the electrolyte conductivity and the mixture of corrosion products. The average concentration of these pollutants ranges between 0.1 and 10 micrograms/cubic meter of air. Essentially only one molecule in a billion is a pollutant molecule, and this requires either analytical techniques that are very sensitive or the sampling of very large air volumes.

Laboratory Corrosion Testing

Analytical technique development, materials evaluation, quantitative corrosion measurements, and accelerated tests are several reasons to set up laboratory test chambers mimicking conditions in working disc drives. Fig. 4 indicates a few features distinguishing our particle-free, parts-per-billion (ppb) pollutant disc testing from standard ASTM or commercial corrosion tests.

When a gaseous pollutant in concentrations of 5 to 10

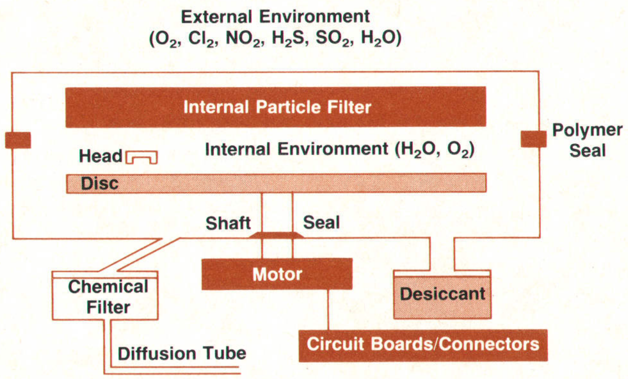

Fig. 5. *Thin-film disc drive protection against corrosion and pollutants.*

parts per billion can be an accelerated corrosion environment, the starting materials must be much purer. Our test air is synthesized from oxygen and nitrogen evaporating from their liquids so that any background pollutants and water are frozen out. These dry gases are particle-filtered, humidified by bubbling through distilled water, and refiltered to eliminate water droplet entrainment. Pure "pollutants" carried in dry nitrogen are then added to the humid gas stream. As indicated in Fig. 4, this test mixture flows across the lower disc surface in the same radial direction as flow in a typical disc drive. Special samples sized for various analytical techniques are also placed in the gas stream.

All chamber, tubing, and flow control devices exposed to wet gases are made from fluorocarbons to provide an inert water-repellent surface. Then, the chambers are run several hours before the metal samples are added. Gas concentrations are measured by various techniques, such as coulometry, colorimetry, and gas chromatography. Weight change, X-ray fluorescence, and ion chromatography are used for measuring corrosion rates. The ultimate detection of disc corrosion is, of course, the error mapping, exposure, burnishing, and remapping of full discs before and after environmental exposure in the test chambers.

The general result of the laboratory corrosion studies was confirmation of the previously reported synergism in the reactivity of pollutant species.[3] Mixed gas tests are required to mimic the rates and the mixed corrosion products found in field tests and to provide acceleration factors not available simply by increasing the concentration of single gases.

Subtractive Technology for Corrosion Control

Since water and the molecular pollutants are critical to disc corrosion, an alternate approach to corrosion control is not to let these species accumulate at the disc surface. Instead of adding a surface barrier, we subtract the electrolyte. For the pollutants, the final scenario is to intercept them upstream of the disc in a multicomponent filter developed for this specific purpose. The laboratory test chambers proved invaluable in testing various combinations of filter layers for the selective removal of pollutants.

Removing water from the disc drive environment is much more difficult since it is normally present at the parts per thousand level rather than the parts per billion concentrations of the pollutants. Dessicants were tested for this purpose, but their capacity is quickly reached unless a diffusion control restriction is used. Even then, permeation of water through polymeric gasket material is a significant water source unless gaskets are made from materials selected for low permeability constants. All four of these subtractive or molecular impedance technologies developed for reducing corrosion in HP's thin-film disc drives are summarized in Fig. 5.

Field Tests for Laboratory Test Verification

Correlation of accelerated laboratory tests with field exposure and confirmation of the effectiveness of the composite pollutant-removal filter under operating conditions were the objectives of a two-year field testing program.

Sample cards made from printed circuit boards carried both filter-protected and freely-exposed ferromagnetic alloy samples. Sets of these cards, illustrated in Figs. 6 and 7, were installed at a variety of operating industrial electronic and computer equipment locations. Cards were removed at 3, 6, and 12 or 24 months and the samples, filters, and circuit boards were analyzed for corrosion product composition and corrosion rate. The distribution band of corrosion rates of unprotected thin-film samples located in chamber 1 of the sample board is summarized in Fig. 8.

We expected reduced but similar distributions for the thin-film samples protected by the multilayer filters in chamber 2. These samples corroded far less than expected under field conditions, since the thin-film samples remained protected below our detection level in sites severe enough to destroy the traces on the circuit board. The results imply that the corrosion reliability of subtractively protected thin-film disc drives can be determined by components other than the disc, and that a basic difference between conventional and thin-film discs has been technologically compensated.

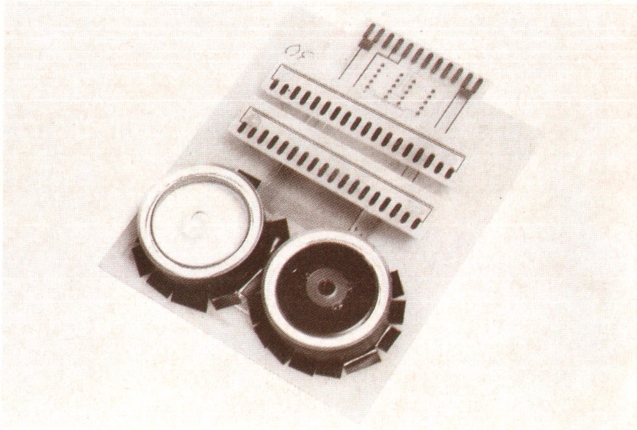

Fig. 7. *Photograph of sample card used in evaluating environmental corrosion and contaminant effects.*

Acknowledgments

Many people have contributed to the reliability testing program during the past seven years and without their help the success of the thin-film disc program would not have been possible.

We gratefully acknowledge the contributions of the following individuals and teams: Don Peterson for his many

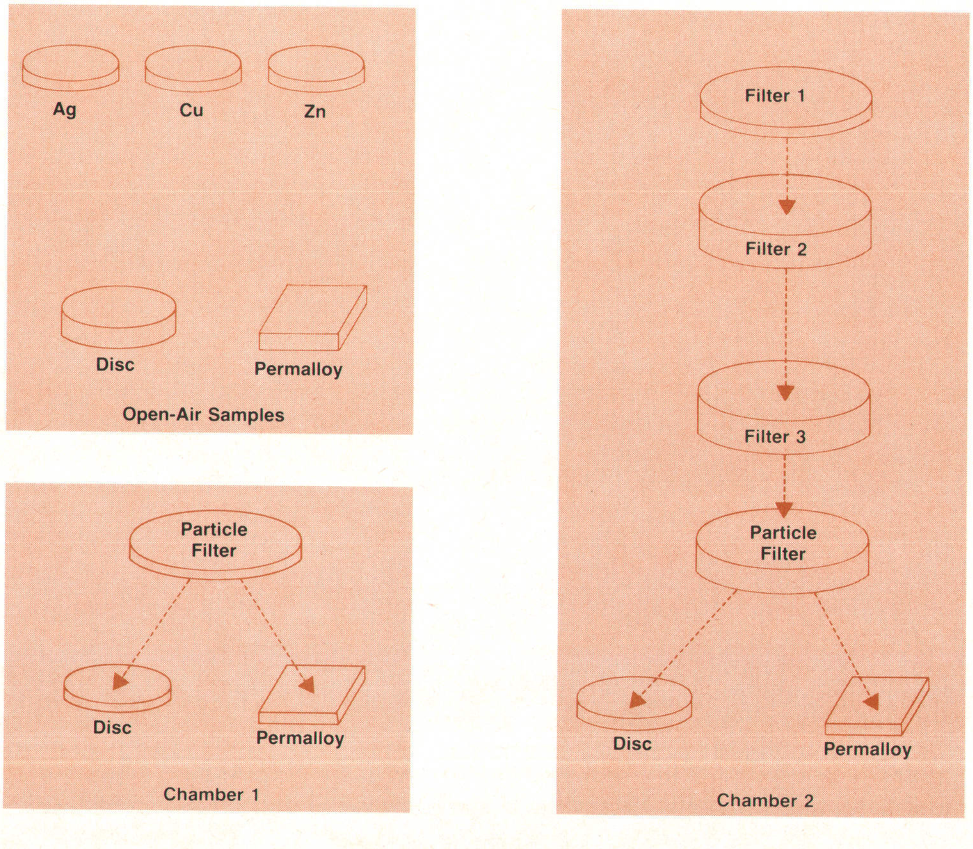

Fig. 6. *Field sample configurations on board shown in Fig. 7.*

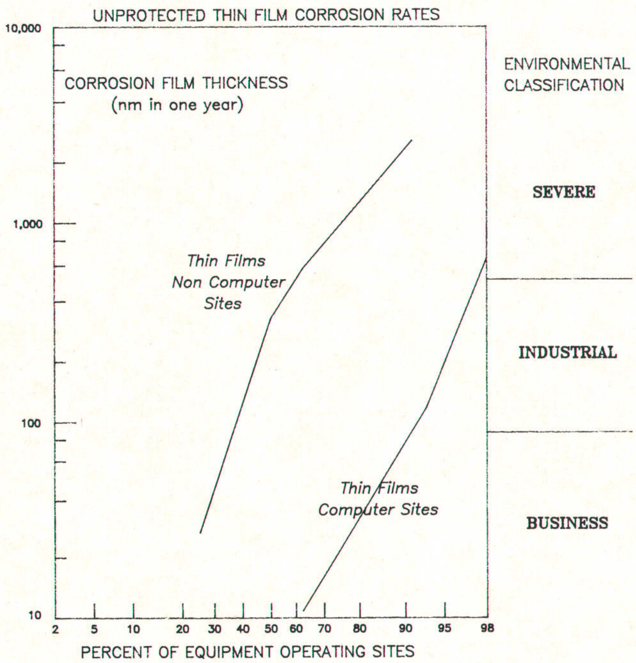

Fig. 8. *Corrosion results from field tests conducted using sample boards illustrated in Fig. 6 and 7. These results are for samples located in chamber 1 of the sample boards. Samples in chamber 2 were protected below the detection level.*

contributions in all aspects of reliability testing and failure analysis, Marla Schneider, Ted Barnes, and Bob Reynolds for their contributions to the development of a reliable wear layer, Jeanette Ford's valuable reliability test team, John Dunn for his contribution to the corrosion studies, Larry McCulloch, Gay Sitzlar, and their teams for the support of head and other special tests, Al Johnson, Quintin Phillips, and the other members of the materials lab for special analyses, Ove Thompson and Nancy Phillips for the SEM expertise, and Ron Kee and the Corvallis Division team that always provided the fast response for Auger analysis.

Karin Bredfeldt was the key person preparing and analyzing field samples for the corrosion studies and developing ion chromatography techniques. Frank Perlaki was our long-term consultant on the SEM/XRF analysis of lab and field-test samples.

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3. D.W. Rice, et al, "Indoor Atmospheric Corrosion of Copper, Silver, Nickel, Cobalt, and Iron," *Atmospheric Corrosion*, W.M. Ailer, editor, John Wiley & Sons, 1982, paper 46.

Authors

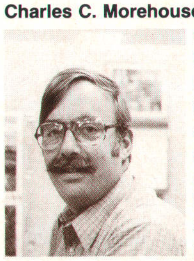
November 1985

4 Thin-Film Disc Development

David J. Bromley

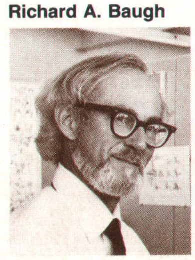
With HP since 1980, Dave Bromley's professional interests include theoretical physics and mathematical models. He has made a theoretical comparison of vertical and longitudinal magnetic recording and has investigated error avoidance on tape drives and high-performance mass storage systems. He is also the author of three published papers. Born in Rochester, New York, he was awarded a BA degree from Harvard University in 1975 and a PhD degree in physics from Stanford University in 1980. Dave and his wife live in Sky Londa, California and are the parents of an infant daughter. He enjoys hiking, skiing, running, photography, and bird-watching.

Charles C. Morehouse



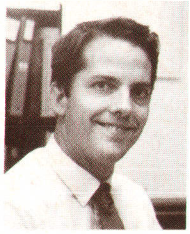
Chuck Morehouse was born in Hagerstown, Maryland and studied physics at the University of California at Berkeley, earning an AB degree in 1964 and a PhD degree in 1970. He has been with HP since 1979 and has investigated thin-film disc magnetics and wear and robotic circuit board assembly. He is now a project manager working on machine vision for manufacturing. Before coming to HP he worked in the fields of experimental physics and computerized tomography and is named inventor for two patents on computerized tomography. He is also a coauthor of over 40 papers on particle physics and radiology. Chuck is married, has one daughter, and lives in Cupertino, California. He coaches youth soccer and raises funds for his local school district. In his spare time, he enjoys fishing and playing the trumpet. He started HP Brass, a brass ensemble of HP employees.

Richard A. Baugh



Born in Mount Vernon, Washington, Dick Baugh came to HP in 1960. His work has involved atomic clocks, low-noise frequency synthesis, and magnetic bubbles. He is named inventor on a patent on magnetic bubbles and is the author of a number of technical papers and other published material. An electrical engineer with a PhD degree from Stanford University (1969), he also earned BSEE and MSEE degrees from the California Institute of Technology in 1959 and 1960. Dick is married, lives in Palo Alto, California, and has two children. Off the job, he teaches wilderness survival and experimental archaeology. He also makes hunting bows in the ancient American Indian fashion using native materials.

Edward S. Murdock



With HP since 1980, Ed Murdock is a project leader at HP Laboratories who has worked on longitudinal and perpendicular recording media for thin-film discs. He was born in Fort Dix, New Jersey and served for three years in the U.S. Army. He also earned degrees in physics from the University of Kansas (BS 1970) and the University of California at Davis (PhD 1980). Ed is a member of the American Physical Society and author or coauthor of three technical articles. He lives in San Jose, California, is married, and has two children. He is active in teaching adult Bible classes at his church.

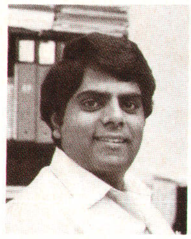
James E. Opfer

Manager of the thin-film department at HP Laboratories, Jim Opfer has been with HP since 1976. He has been responsible for the development of cryogenic devices, magnetic bubble devices, thin-film discs, and thin-film heads. He was born in Lincoln, Missouri and received a BSEE degree from Valparaiso University in 1959 and a PhD degree in physics from Washington University in 1966. He was an assistant professor of physics at Stanford University and then worked on magnetometer instrumentation at another company before coming to HP. He is the author of 11 papers on low-temperature helium physics and cryogenic magnetometers and applications and is also named inventor on three patents related to magnetics. He is active in his local IEEE chapter and is the reviews editor for the IEEE Transactions on Magnetics. Jim lives in Palo Alto, California, is married, and has one child. His outside interests include skiing, jogging, motorcycle riding, and studying Japanese.

Bruce F. Spenner

Bruce Spenner has been with HP Laboratories since 1978 and currently manages the applied technology department, which develops advanced mass storage systems. He has also worked on thin-film discs and tape storage devices. He was born in St Louis, Missouri and studied electrical engineering at Washington University, receiving a BSEE degree in 1968, an MSEE degree in 1970, and a DScEE in 1976. Before joining HP he was a research associate at Washington University Biomedical Computer Laboratory. He has written a number of papers on biomedical computing, medical instrumentation, and software development tools. A resident of Los Gatos, California, Bruce is married and has six children. He enjoys swimming and golf.

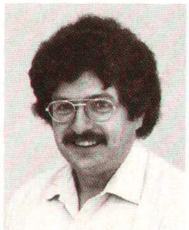
Bangalore R. Natarajan



Natu Natarajan was born in Bangalore, India and studied metallurgical engineering at the University of Illinois, completing work for his MS degree in 1975 and for his PhD degree in 1979. He came to HP in 1979, is now a project manager, and has worked on thin-film disc material research and development and on magnetic recording. He is the author or coauthor of several papers on thin-film sputter deposition technology and on medium noise in magnetic recording media. Natu and his wife live in San Jose, California and he likes music, traveling, and tennis.

11 Dynamic Testing

John Hodges

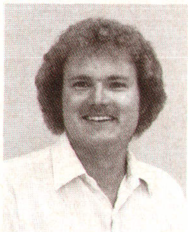


John Hodges grew up in Berkeley, California and was educated at the Massachusetts Institute of Technology and at the University of California at Berkeley (BSEE 1977). With HP since 1977, he supervised tester design and implementation for thin-film discs and heads and is now working on industry standard interfaces for disc controllers. John and his wife are residents of Meridian, Idaho. He plays guitar and pedal steel in a country rock music band, runs a home recording studio, and is a private pilot and avid tinkerer.

Dennis R. Edson

Dennis Edson has specialized in electronic design and production engineering since joining HP in 1967. He contributed to the design of the HP 3960A, HP 3968A, and the HP 7970 Tape Drives. He also worked on the HP 7900 and HP 7906 Disc Drives, has managed an electronic tool design group, and has designed automated test equipment. Born in Toronto, Canada, Dennis received a BSEE degree from California State University at Los Angeles in 1963. He's married, has two children, and lives in Meridian, Idaho. He enjoys computers and photography and is an amateur radio operator (WB7WCR).

Keith S. Roskelley



Keith Roskelley was born in Pocatello, Idaho and attended Utah State University, from which he earned his BSEE degree in 1979. Since joining HP's Disc Memory Division the same year, he has worked on thin-film disc and head test equipment and methods. Keith lives in Boise and enjoys camping, hiking, travel, and computers during his leisure time.

21 Deposition System

Robert J. Lawton

R. J. (Bob) Lawton was born in Elgin, Illinois and attended the University of Illinois, where he earned a BSME degree in 1980. After coming to HP the same year, he worked on the HP 7911, the HP 7912, and the HP 7935 Disc Drives. His work on a vacuum-compatible collet spindle is the subject of a pending patent. Bob lives with his wife and two sons in Boise, Idaho and lists bicycling, camping, and flying as outside interests.

Michael B. Jacobson

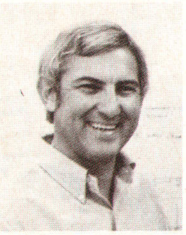
A graduate of Washington State University, Mike Jacobson earned a BSEE degree in 1981 and came to HP the same year. He has worked on the design of the in-line system for processing thin-film discs and is currently working on disc controller design. He is interested in computer systems and software. Mike was born in Yakima, Washington and now lives with his wife in Boise, Idaho. His outside interests include music, skiing, hiking, camping, fishing, and basketball.

George A. Drennan

A project leader at HP's Disc Memory Division, George Drennan has been responsible for fabrication process and equipment design for thin-film discs and heads. Since coming to HP in 1967 he has also worked on a variety of projects at both the Microwave Division (now Stanford Park Division) and HP Laboratories. He was born in Berkeley, California and has a BSME degree awarded by the University of California at Santa Barbara in 1966. He is named inventor on two patents and is the coauthor of two research papers. George is a resident of Eagle, Idaho and has two sons. He is remodeling his house and is interested in softball, skiing, and gardening.

25 Disc Reliability

C. Girvin Harkins

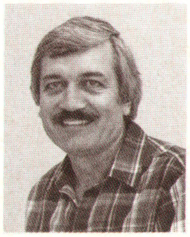


Born in Colorado City, Texas, Girvin Harkins earned a BA degree from McMurry College in 1960 and advanced degrees in physical chemistry from Johns Hopkins University (MA 1962 and PhD 1964). Before coming to HP Laboratories in 1978, he was an assistant professor at the Southwest Center for Advanced Studies and an adjunct professor of materials science at Rice University. He is currently a project manager for surface mount technology and teaches corrosion short courses in his spare time because he still loves the classroom. Girvin is married, has three children, and lives in Sunnyvale, California. A retired Scoutmaster, he enjoys backpacking and skiing.

Stephan P. Howe

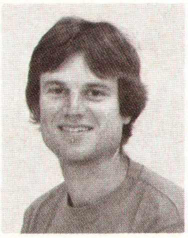
Stephan Howe is a structural and mechanical engineer with degrees from the University of California at Los Angeles (BS 1971) and the University of California at Berkeley (MSME 1973 and MEng in Civil Engineering 1975). He joined HP in 1985 after working on mass storage recording technology for a number of other electronics and computer companies. At HP he has investigated disc reliability, including corrosion, wear, and glide/burnish issues. Stephan was born in Panama City, Florida and currently lives in Boise, Idaho with his wife and two children. His outside interests include ski racing and tennis.

Clifford K. Day



A project manager at HP's Disc Memory Division, Cliff Day has been with HP since 1979. His work has centered on disc and head reliability, test system development, and product engineering. He was born in Caldwell, Idaho and served in the U.S. Air Force before receiving a BSEE degree from the University of Idaho in 1966. He also earned an MSEE degree from Washington State University in 1969 and a PhD degree from Iowa State University in 1971. Before joining HP he worked on instrumentation development for two other companies. During his career he has authored or coauthored a number of technical papers on instrumentation systems, and his work has resulted in several patents in the same field. Cliff lives in Meridian, Idaho, is married, and has three children and one grandson. A pilot since age 16, he also enjoys fishing and hunting.

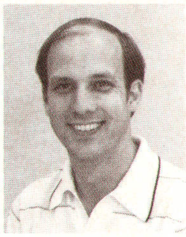
Paul Poorman



Born in Ivyland, Pennsylvania, Paul Poorman graduated from the University of Illinois with a BSME degree in 1979. After coming to HP's Disc Memory Division the same year he worked on magnetic head development and on the friction and corrosion aspects of disc reliability. He also completed work for an MSME degree from Stanford University in 1984. Paul is a resident of Meridian, Idaho and likes bicycling and cross-country skiing. He says he has found out that life on a farm is not filled with leisure.

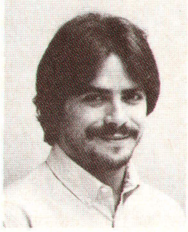
34 Manufacturing

Darrel R. Bloomquist



With HP since 1980, Darrel Bloomquist has worked on all aspects of the manufacturing process for thin-film media. He earned a BA degree in chemistry in 1975 from Northwest Nazarene College and a PhD degree in physical chemistry in 1980 from Washington State University. Several patent applications have resulted from his work on sputtering target design and in-line deposition equipment and tooling. He is also the author of ten articles on various subjects in chemistry. Darrel was born in Elkhart, Indiana and now lives in Boise, Idaho with his wife and two children. He's a private pilot and enjoys radio-controlled model airplanes, camping, and other outdoor activities.

Richard S. Seymour



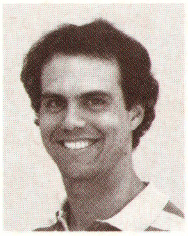
At HP's Disc Memory Division since 1980, Rick Seymour is the section manager for thin-film disc production. He has also worked as an R&D engineer on dielectric thin-film sputtering and ceramic polishing. He was born in Champaign, Illinois and earned a BSEE degree from the University of Illinois in 1980. A resident of Boise, Idaho, he's married and likes high-performance automobiles and auto racing.

Glenn E. Moore, Jr.

Manager of HP's Magnetic Recording Technology Center at Boise, Idaho, Glenn Moore has been with HP since 1977. He managed the thin-film disc program from its inception in 1977 and also directed the thin-film head program. He was born in Washington, D.C. and studied physics at the University of Illinois, receiving a BS degree in 1963, an MS degree in 1965, and a PhD degree in 1968. Before joining HP he worked on magnetic transducers and III-V semiconductors at Bell Laboratories. His work has resulted in a patent on magnetic transducers and he is the author of over ten technical papers. Glenn is married, has three sons, and lives in Boise, Idaho. One of his hobbies is growing roses.

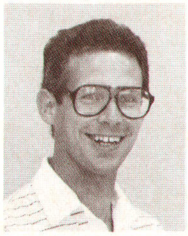
36 Thin-Film Discs: Design

Michael C. Allyn



Born in Fort Madison, Iowa, Mike Allyn has a BSEE degree awarded by Iowa State University in 1981. After coming to HP in 1981 he was a characterization engineer for thin-film head design. More recently he has developed specifications and interpreted test data while working with disc drive project engineers. His professional interests include magnetics and circuit design. Mike lives in Boise, Idaho and is a volunteer at Boise Valley Samaritan Village. He enjoys astronomy, backpacking, kayaking, and skiing during his leisure time.

Peter R. Goglia



Peter Goglia was born in Syracuse, New York and was educated at Cornell University (BSME 1975) and at the University of Illinois (MSME 1977 and PhD Mechanical Engineering 1982). An R&D engineer at HP since 1982, he has contributed to the development of thin-film discs and heads and is currently working on head/media technology. He is the author or coauthor of nine articles on elastohydrodynamic lubrication and high-speed rotor balance optimization. His professional interests include disc head flight and flexure dynamics and disc mechanical properties. Peter, his wife, and his son live in Boise, Idaho. He enjoys running, cross-country skiing, and touring the Sawtooth Mountains. He is also restoring his home, which dates from 1909.

Scott R. Smay

Scott Smay was born in Minneapolis, Minnesota and studied electrical engineering at Iowa State University, from which he received a BSEE degree in 1980. After joining HP's Disc Memory Division the same year, he contributed to the development of thin-film discs and heads and helped design the HP 97501A Disc Drive. Scott lives in Boise, Idaho, is interested in magnetic recording, and likes to study physics. He also enjoys kayaking, skiing, and exploring Idaho.

Manufacturing Thin-Film Discs

by Glenn E. Moore, Jr., Richard S. Seymour, and Darrel R. Bloomquist

THE HP THIN-FILM DISC provides significant performance advantages in rigid disc drives. To realize the full potential of the thin-film disc, however, its cost must be minimized. The disc manufacturing process (Fig. 1) offers a perfect vehicle for production optimization and cost reduction, because in contrast to disc drive production at the one extreme and IC fabrication at the other, it combines a minimum part count with a small number of relatively simple processes (no pattern definition, for example). The challenges are to optimize the individual processes within the framework of the overall production sequence and to integrate the disc into the disc drive in an optimum manner.

Product Cost

In a rigid disc drive, the disc and accompanying heads represent the largest single component of the drive material costs. Because of an inadequate understanding of the disc and head and their magnetic, electrical, and mechanical interactions, discs and heads often also account for the bulk of manufacturing reliability problems associated with rigid disc drives. Based on this experience, the disc costs should be minimized first at the product level and then at the component level. This leads to a better understanding of the true cost of the disc and better cost trade-offs.

The total cost of the disc at the drive product level is the sum of the disc component, incremental drive manufacturing, and reliability costs. The disc component cost is discussed in the next section. The incremental drive manufacturing costs consist of direct costs and costs incurred because of disc quality problems. Direct manufacturing costs include the cost to test, or certify, the disc and the cost to incorporate the disc into the drive. Since, in many drive production lines, discs are mechanically and electrically certified on different test beds, the disc certification cost can be nearly half the cost of the disc. Thus, elimination of disc certification can result in significant savings at the drive product level.

The cost to incorporate the disc into the drive includes indirect costs as well as assembly costs. As an example, the error correction electronics in a drive can be reduced or eliminated by reducing the defect count on the discs. By working with the drive product design teams, disc specifications can be set that minimize the disc cost to the product. The challenge then becomes to minimize the disc component cost within these specifications. Thus, the disc is not designed to the drive, or vice versa, but rather the system is optimized.

The drive manufacturing costs caused by disc quality problems are easier to quantify, that is, the cost of poor disc quality = scrap costs + rebuild costs. Because of the complexity and cost of the top-level drive assembly, the rebuild costs are significantly larger than the scrap costs. Drive production yields of less than 100% result in rapidly escalating costs. This problem is aggravated in multidisc drives because the probability of drive rebuild $= 1 - P_D^N$, where P_D = the probability a disc works in the drive, and N = the number of discs in the drive. Thus, disc quality becomes even more critical in multidisc drives.

Drive reliability costs caused by discs are potentially larger than either the disc-related manufacturing or component costs. The direct costs of disc-caused reliability problems are quantifiable in terms of scrap, rebuild, field stocking, and service costs. The indirect costs (customer dissatisfaction because of data loss and system downtime) are potentially much larger.

The product cost can be minimized by thoroughly understanding the failure mechanisms of the disc in the drive, by defining a specification that assures adequate manufacturing and reliability margins and optimum drive cost, and by minimizing the disc component cost within the specifications. The first two objectives are met by working with the drive teams during the drive design phase (see articles on pages 25 and 36). Achieving the third objective requires a thorough understanding and optimization of the disc manufacturing processes.

Component Cost

Low disc production cost is dependent on such obvious factors as high volumes, high process yields, and high throughputs. Other, less apparent means can also be used

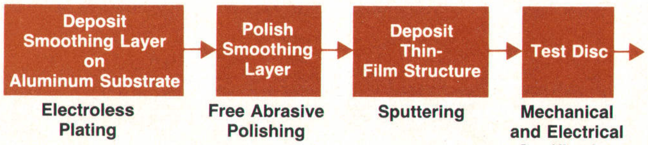


Fig. 1. *Thin-film disc manufacturing process.*

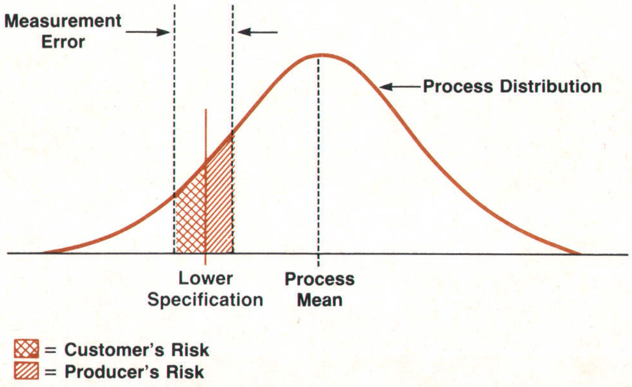


Fig. 2. *Comparison of the three independent variables—process distribution, measurement error, and specification—for any process parameter.*

to reduce the disc cost. Three examples are cost modeling, sample testing, and process risk minimization.

Although the disc fabrication is a relatively short process, a number of complex trade-offs must be made. To understand these trade-offs and minimize the disc cost, a cost model of the entire manufacturing process was developed early in the program. Using this model, the various alternatives for each process can be quickly evaluated. As an example, it was apparent that final test represented a large component of the cost and that the most effective way to reduce test costs was to minimize the number of discs tested. This led to a study of sampling theory and criteria for sampling levels with lot pass, 100% test, and lot reject actions based on the percentage of the sample that passed.

For any given parameter, three independent variables affect the yield and, more important, the customer's and producer's risk. Fig. 2 illustrates these factors. The producer's risk includes components that meet the specification, but fail the test because of measurement error. Such parts increase the producer's cost. The customer's risk represents parts that do not meet the specification, but pass the test. Since these parts may go on to drive production or beyond before failing, they are potentially more costly than parts that fail the test. The customer's and producer's risks are reduced by minimizing the measurement error and/or optimizing the process with respect to the specification.

During HP's disc development, the measurement error, process distribution, and specification for each parameter were measured and compared, and appropriate action was taken to reduce the error and improve process yield. Fig. 3 shows an acceptable (high-yield) process. Fig. 4 illustrates an unacceptable process. In the latter case, measurement accuracy was improved first and then the process distribution was tightened to achieve high yields and acceptable customer and producer risks. Once the three variables are optimized for each critical parameter, statistical quality control (SQC) is implemented to ensure that the entire process remains under control.

Conclusion

By using the above techniques while developing HP's thin-film disc manufacturing process, the cost of the HP 97501A Drive was quickly minimized. Within six months of manufacturing release, the component yield goals had been exceeded in all but one area (subsequent development resulted in the necessary yield improvements). Even more important, top-level drive production yield losses as a result of discs were reduced by nearly two orders of magnitude compared to earlier drive products. Early results indicate that the field reliability has also improved.

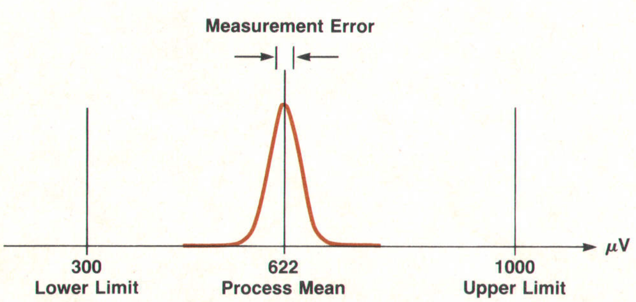


Fig. 3. *A high-yield parameter example (track average amplitude at the disc outer diameter). Process standard deviation = 24.8 μV. Yield = 100%.*

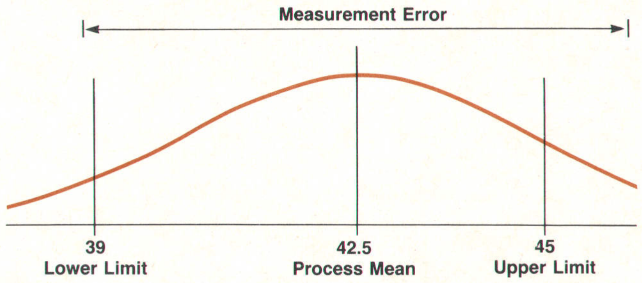


Fig. 4. *A low-yield parameter example (magnetic remanence-film thickness product). Process standard deviation = 2.3. Yield = 80%.*

Acknowledgments

The thin-film disc manufacturing process is the culmination of the efforts and ideas of many people. John Rausch, Darrel Bloomquist, Carol Schwiebert, Bill Britton, Jack Smith, Todd Cramer, and Rob Hurd developed the various processes, supported by Sharon Johnson, Grace Watson, and Bennett Brown and their teams. Ken Wunderlich refined the cost model initiated by Don Peterson.

Thin-Film Discs: Magnetic, Electrical, and Mechanical Design

by Michael C. Allyn, Peter R. Goglia, and Scott R. Smay

THE DISC RECORDING MEDIUM is the memory in a disc drive, providing either a source or a destination of user information. The rest of the drive exists to facilitate the rapid recall or storage of information on the medium. The details of the write and read processes (storage and retrieval) depend strongly on the physical properties of both the disc and the read/write head. For this reason, it is convenient to think of the head and disc together forming a recording system.

The head/disc system figures prominently in the disc memory performance specifications of error rate, capacity, and reliability. Error rate refers to the probability of incorrectly retrieving stored data. A typical disc memory specification requires that the error rate be less than 10^{-10}, that is, less than one bit read incorrectly for every 10^{10} bits transferred. Capacity refers to the amount of information that can be stored. At the head/disc level, it refers to the density of stored information. Reliability at the head/disc level refers to the permanence of stored data over the life of the disc drive, degradation of error rate performance over time and under various environmental conditions, and the probability of catastrophic mechanical failure of the head/disc interface (head crash). The goals of HP's thin-film disc design were to realize very high-density recording capability with excellent error rate and reliability performance.

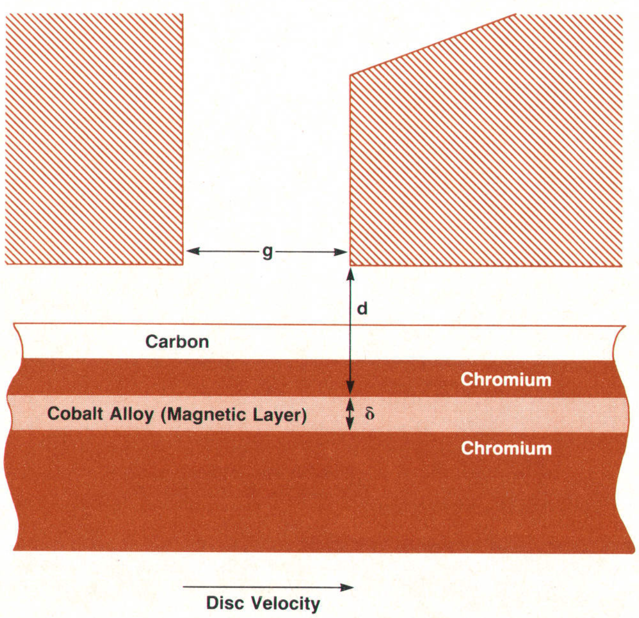


Fig. 1. *Head-to-medium geometry for magnetic disc memory.*

Magnetic and Electrical Design

The inherent error rate of a recording system depends on its ability to locate the symbols of the write and read processes. The write symbol is a magnetization reversal, or transition, which is created by rapidly reversing the magnetic field applied to the rotating disc by the head. Transitions may be shifted during the write process from their intended locations by interfering fields from previously written transitions, and by inhomogeneity in the recording medium (medium noise).

The read symbol is a voltage pulse which is generated when a magnetization reversal on the disc passes under the head gap. The location of these pulses is determined by amplifying and differentiating the head output signal and detecting the zero crossings corresponding to the pulse peaks. These peaks may be shifted from their desired locations (the centers of the transitions) by several mechanisms. At high densities, magnetic flux from several transitions can affect the head at the same time, resulting in peak shift. Overwritten previous data may not be sufficiently erased, which will cause shifts in current data. If the head output signal is small, noise in the electronics can also cause a significant shift in the apparent peak locations.

A good design trades off these several sources of symbol mislocation to minimize the chances that any mislocation will become great enough to result in a data error. The system requirements for limits on symbol jitter are translated into a set of requirements for the head readback signal under various written conditions (e.g., various data patterns or overwritten data). The main parameters are:

- Peak amplitude, a requirement set by signal/noise ratio
- Peak shift caused by intersymbol interference
- Overwrite, so that a rewrite erases an previous write
- Medium noise, which causes random transition mislocation during write.

The estimated requirements on these parameters can be translated further to specifications concerning magnetic

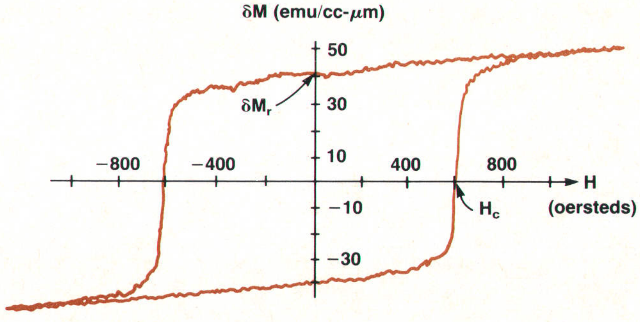


Fig. 2. *Total magnetic moment versus applied field for magnetic disc media.*

properties and head/disc geometry. Fig. 1 shows a cross section of the head/disc interface. The important parameters are:

- Head-to-medium separation (d)
- Medium thickness (δ)
- Gap length (g) and head geometry
- Medium remanent magnetization
- Medium coercivity
- Medium coercive squareness.

For adequate read/write performance, the head-to-medium spacing must be quite small. Designing a recording system with the very small separations required (approximately 0.2 μm) is a significant mechanical engineering challenge (see "Mechanical Design" on page 39). There is no recording penalty for decreasing the separation—only a challenge to realize and maintain it reliably.

The product of the medium thickness and the remanent magnetization, δM_r, is another important determinant of recording performance. The remanent magnetization is fixed by the material chosen for the magnetic layer; it is very high for the cobalt alloy used in HP's thin-film disc. This allows HP to use a very thin (≈0.04 μm) magnetic layer, compared with conventional particulate media (typically 0.5 μm thick). The thinner layer effectively decreases the head-to-medium separation, an advantage for read/write performance. The optimum δM_r product is determined experimentally. Signal amplitude and magnetic transition length are both roughly proportional to δM_r, indicating a trade-off between signal-to-noise ratio and intersymbol interference.

Another trade-off is available in the choice of H_c—the medium coercivity. The coercivity indicates the magnetic field strength required to reverse the magnetization of the magnetic layer. Large values reduce the transition length, and therefore intersymbol interference, but they increase the magnetic field required to write on the disc and overwrite obsolete data. The write field available is limited by the head material and geometry as well as the head-to-medium separation.

The coercive squareness $S*$ is a measure of the switching properties of the magnetic layer. Large values (approaching unity) are desirable, indicating the potential for writing and maintaining short transitions. $S*$ is determined primarily by the choice of the material system selected for the magnetic layer.

The choice of a recording head is a critical part of implementing a head/disc system. Industry standard head geometries have been used in most HP drives to date. A few key parameters in these geometries are specified by the designer, such as track width, number of windings, and gap length. Air bearing surface specifications, such as those discussed later, are also user specified.

Medium noise is possibly the least understood of recording phenomena. Thin-film media, unlike particulate media, exhibit a rise in the apparent background noise level as the density of transitions on a track increases. This suggests that, for thin-film media, the transitions themselves may be thought of as a source of noise. This noise manifests itself as apparent random shifting of transition locations during the write process, that is, an uncertainty in the ability to create transitions precisely. Good correlation exists between transition length and medium noise, and shorter transitions appear to improve the ability to locate transitions precisely. The specific relationship between error rate and medium noise is not known.

The design of a head/medium system is an iterative process. Once the initial design is complete, a substantial amount of characterization is required to determine if the fabrication process is capable of producing the desired properties, and if the desired properties realize the performance goals set down by the application. Feedback from these two types of characterization may result in a final design substantially different from the first pass.

Characterization

Component-level characterization of the magnetic and dynamic recording performance of a thin-film disc provides fast feedback to the designer. Tests that measure the bulk properties of the disc are typically fast and can be implemented in a production process after the design cycle is complete. While these tests are no substitute for in-drive qualification, they allow for process control and the isolation of process variables. The parameters of interest are measures of bit shift or are related to bit shift, since this is the medium's contribution to error rate. The spectrum of tests extends from window margin testing in the drive itself to measures of the bulk magnetic properties of the medium alone. In general, the more direct measures of bit shift are of most value in the ultimate qualification of the

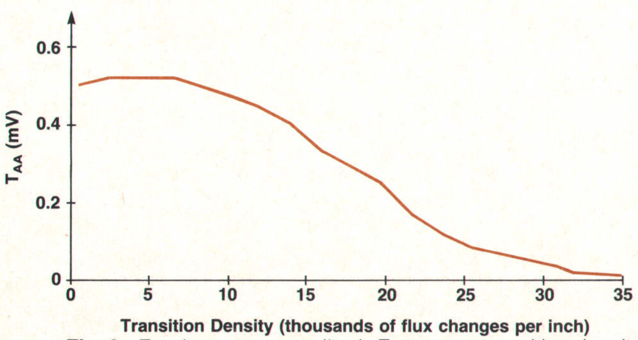


Fig. 3. *Track average amplitude T_{AA} versus transition density along the recording track.*

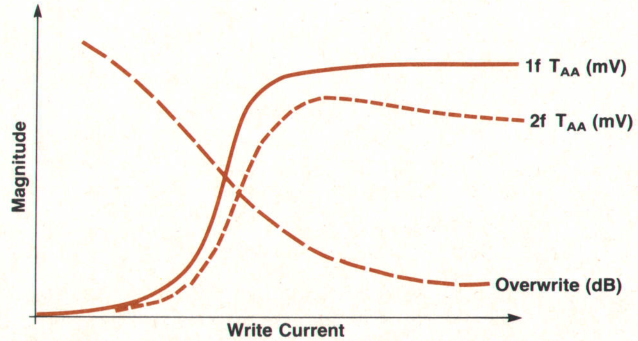


Fig. 4. *Typical saturation plots showing 1f T_{AA}, 2f T_{AA}, and overwrite versus write current.*

medium but are farther removed from its process parameters (deposition times, film composition, etc.).

A vibrating sample magnetometer provides information about the bulk magnetic properties of the disc. Together with film thickness measures, this data is used to steer the thin-film sputtering process to the desired magnetic parameters. Fig. 2 shows a typical M-H loop obtained from an HP thin-film disc with a vibrating sample magnetometer. The parameters of interest include the coercivity H_c (the H-axis crossing point), the thickness-remanence product (the δM-axis crossing point), and the coercive squareness $S*$ (relating to the slope of the loop at the H-axis crossing point), where:

$$S* = 1 - \frac{M_r}{H_c}\left(\frac{dH}{dM}\right)\Bigg|_{H=H_c}$$

Many dynamic recording tests are available to characterize the head/medium system. With a careful choice of test head, medium performance can be evaluated. Following are some of the key parameters used throughout the disc memory industry to characterize media. Each parameter relates to a different mechanism for shifting the location of the readback pulse peak. (Implementations of tests that measure these parameters are described in the article on page 11.)

Track average amplitude (T_{AA}). This is a measure of the readback signal strength from the head and relates to the distribution of flux at each magnetization reversal in the recording medium.

Resolution. This is a measure of the wavelength response of the magnetic medium. The resolution is defined as the ratio of the 2f T_{AA} to the 1f T_{AA}. 1f and 2f refer to the extremes in frequency that are used in an MFM-code drive. Hence, they produce the worst-case linear densities on the disc. Fig. 3 is a typical plot of T_{AA} versus transition density along the track. T_{AA} decreases at higher transition densities because of interactions of adjacent pulses during both the write and read processes. Resolution is useful in estimating the amount of interaction and its effect on final transition placement.

Overwrite. This measures the ability of the system to obliterate previous data by writing new data over it. Expressed in dB, the overwrite value is the ratio of the strengths of a 1f signal before and after being overwritten with a 2f signal. This is important because any remaining old data cannot be filtered out and becomes coherent noise, adding to the bit shift.

Signal-to-noise ratio (S/N). This parameter relates to the medium noise in the disc.

Amplitude modulation. This is the amount of low-frequency modulation around a track, expressed as a percentage of T_{AA}. It relates to the mechanical and magnetic circumferential uniformity of the disc. Its value is important to the drive electronics designer for determining AGC bandwidths, servo considerations, etc.

Defects. Defect densities and size distributions are important to drive engineers designing sparing and error recovery schemes.

All of the above parameters are based on amplitude measurements and can be implemented as fast production tests. They are all functions of process parameters and, to some degree, can be optimized independently. The design tradeoffs between physical parameters such as H_c and δM_r show up as trade-offs in these parameters. For example, the film thicknesses may be changed to give more T_{AA} on small discs, which may have lower outputs because of lower linear velocities. This increase in T_{AA} is often at the expense of some other parameters such as resolution and medium noise. Likewise, the T_{AA} performance of large discs can be traded off for gains in other parameters.

In addition, the above parameters are functions of the current applied to the recording head during the write process. Saturation plots are typically used to determine the

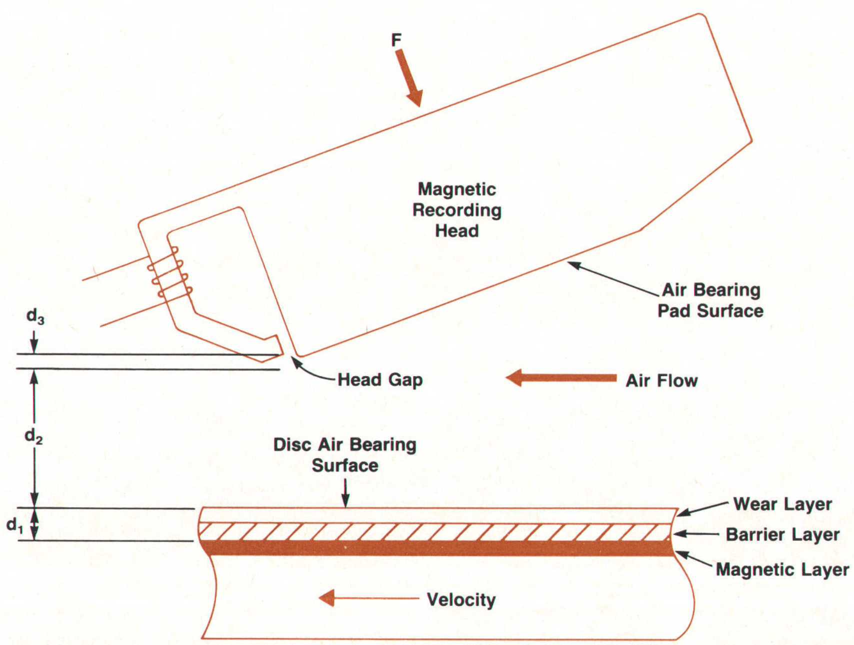


Fig. 5. *Head-to-disc spacing components of a recording head flying over a disc moving at a velocity V. Spacing components d_1, d_2, and d_3 are the thickness of the barrier and wear layers, the flying height, and the magnetic pole recession in the head, respectively. The air flow created by the moving disc surface forms a wedge that lifts the head against the spring force F.*

proper write current. Typical saturation plots for T_{AA} (1f and 2f) and overwrite are shown in Fig. 4. A resolution saturation plot can be obtained by dividing the 1f T_{AA} by the 2f T_{AA} at each write current.

Since these amplitude-based tests are very sensitive to test head parameters, the design of the magnetic medium must be tested with heads of varying performance so that the specifications on each parameter's distribution can be set. Once these are set, the specifications on the medium process parameters can be derived.

Mechanical Design

A hydrodynamic air bearing is formed between the spinning disc surface and the air bearing pads on the recording head (see Fig. 5). Air is carried around by the disc surface as the disc spins. This air is forced into a relatively wide converging wedge section taper at the front of the recording head air bearing pad. The air continues through a much narrower converging wedge formed between the air bearing pad of the recording head and the disc surface. Pressure generated by the hydrodynamic action of the air flow balances the applied spring load force F and lifts the head a small distance away from the disc surface. The air finally exits at the trailing edge of the air bearing pad. The geometry of the air bearing pad is shown in Fig. 6.

Flying height is the thickness of the air film separating the magnetic recording head and the disc wear layer surface. The flying height is a major component of the head-to-medium separation d. The HP 97501A recording system is designed to work with a 0.25-μm head-to-medium separation at the innermost track. The flying height accounts for 0.20 μm of this, while the barrier layer and wear layer thicknesses account for the rest. These components of the separation are shown in Fig. 1. The barrier layer and wear layer are thin films deposited over the actual magnetic recording layer and are discussed in the article on page 4. These small flying heights provide a significant challenge in head, media, and disc drive manufacturing.

The required properties of the disc surface are evaluated by simulating and measuring the flying characteristics of the recording head in response to various surface features. Head flight simulation is done by modeling the head as a mass-inertia system responding to pressures generated at the air bearing surface of the head and restrained by a spring force opposing the pressure. A detailed map of the pressure acting on the head air bearing surface is calculated using a finite-difference solution to the equations of motion of a fluid applied to thin spacings (Reynolds equation). The flying height at the recording head gap is held within limits to ensure the performance of the head/disc system.

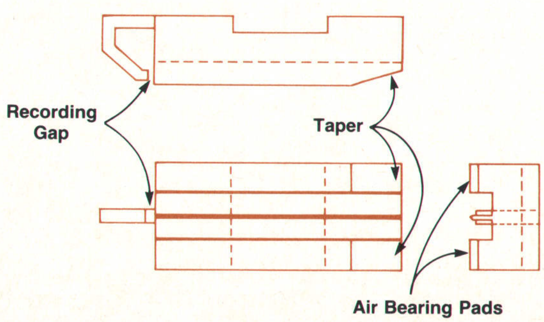


Fig. 6. *Views of recording head showing air bearing pads and tapered edges.*

Head flight is modeled for many cases of surface waviness. The frequency response profile of the head to surface waviness is used to set the specification for the disc surface. The basic description of the surface wave model is shown in Fig. 7. The wave is sinusoidal with amplitude Z and wavelength λ. The waveform is described below by equations 1 to 3 for the time domain and 4 to 6 for the spatial domain. The vertical velocity is given by equation 2 while the spatial equivalent, slope, is given by equation 5. Acceleration in the vertical direction is given by equation 3 and the spatial analog, curvature or surface profile, is given by equation 6.

$$z = Z \sin(2\pi f t) \qquad (1)$$

$$dz/dt = (2\pi f) Z \cos(2\pi f t) \qquad (2)$$

$$d^2z/dt^2 = -(2\pi f)^2 Z \sin(2\pi f t) \qquad (3)$$

$$z = Z \sin(2\pi x/\lambda) \qquad (4)$$

$$dz/dx = (2\pi/\lambda) Z \cos(2\pi x/\lambda) \qquad (5)$$

$$d^2z/dx^2 = -(2\pi/\lambda)^2 Z \sin(2\pi x/\lambda) \qquad (6)$$

The time domain and the spatial domain are related by the following relationships:

$$f = V/\lambda, \qquad x = Vt, \qquad a = V^2/\rho$$

where: f = frequency of the surface waviness
V = surface velocity of the disc
t = time in seconds
x = distance along the track
λ = wavelength of the surface waviness
a = vertical acceleration of the disc surface
ρ = radius of curvature of the surface
= $1/(d^2z/dx^2)$

The surface wave amplitude limit versus frequency is shown in Fig. 8 for velocity and head location corresponding to the innermost track of the HP 97501A Disc Drive. Each data point represents the amplitude of surface waviness to produce a ±0.025-μm dynamic flying height. Also

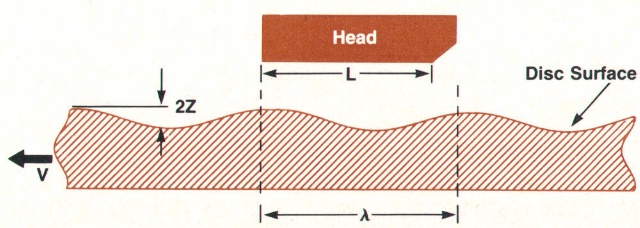


Fig. 7. *Disc surface waviness model. L = length of air bearing surface.*

shown on the graph is a line representing a constant acceleration of 2.2 m/s^2. The data on the curve points naturally to a disc surface specification that covers three regions. At very low frequencies, the waviness amplitude to produce the acceptable acceleration limit would cause severe head mounting height problems. The surface waviness is amplitude limited below 66 Hz (λ = 120 mm, or a little less than once around the disc). At intermediate frequencies, the disc surface is acceleration limited. A line of constant acceleration closely bounds the acceptable surface waviness amplitude between 66 Hz and 3.5 kHz (λ between 120 mm and 2.3 mm). At higher frequencies, the head is not moving in response to the surface waviness; therefore the dynamic flying height consists of the waviness amplitude. For disc surface features corresponding to frequencies above 3.5 kHz (λ < 2.3 mm), the disc is surface profile limited. A similar study was used to determine the disc surface specification at the outermost track of the disc drive. Table I lists the specifications for the discs used in the HP 97501A Drive.

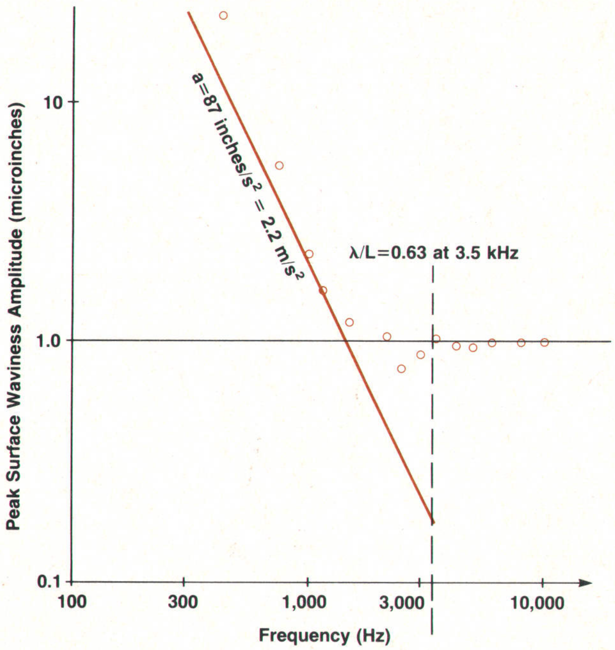


Fig. 8. *Plot of peak surface waviness amplitude versus frequency for innermost track of HP 97501A Disc Drive. Surface velocity = 0.75 inch/s, radius = 1.0 inch, and variation in flying height = ±1.0 microinch.*

Table I

HP 97501A Media Surface Specification

Innermost Track:
- Radius = 25.4 mm, V = 12.4 m/s
- Waviness <0.025 mm (p-p), 0 to 66 Hz
- Acceleration <4.4 m/s^2 (p-p), 66 to 3500 Hz
- Profile <0.025 μm (p-p), f>3500 Hz

Outermost Track:
- Radius = 45.5 mm, V = 22.1 m/s
- Waviness <0.025 mm (p-p), 0 to 110 Hz
- Acceleration <12.2 m/s^2 (p-p), 110 to 6250 Hz
- Profile <0.025 μm (p-p), f>6250 Hz

A specification is meaningful only if there is a way to confirm that the system is meeting it. The discs are monitored for runout and acceleration on the heterodyne laser interferometer and associated data acquisition system. This system has a wider bandwidth, better resolution, and a lower noise floor than the conventional capacitive probe technique. The innermost and outermost tracks are measured for compliance with the specifications. The surface profile is sampled with a stylus or optical profilometer.

Acknowledgments

Many people have contributed to our understanding of design methods and requirements. Mike Covault and Ralph Simmons provided a foundation for the magnetic design. Greg Mowry and Arnold Slezak contributed greatly to our early efforts to realize a working thin-film disc. Duane Gray, Chuck Hessing, Bob Kier, and Bruce Jackson gave feedback on disc performance in product applications. Bob Davidson designed and developed the heterodyne laser interferometer system.

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