IBM 3330   Introduced 1970, withdrawn 1983

Why it's important

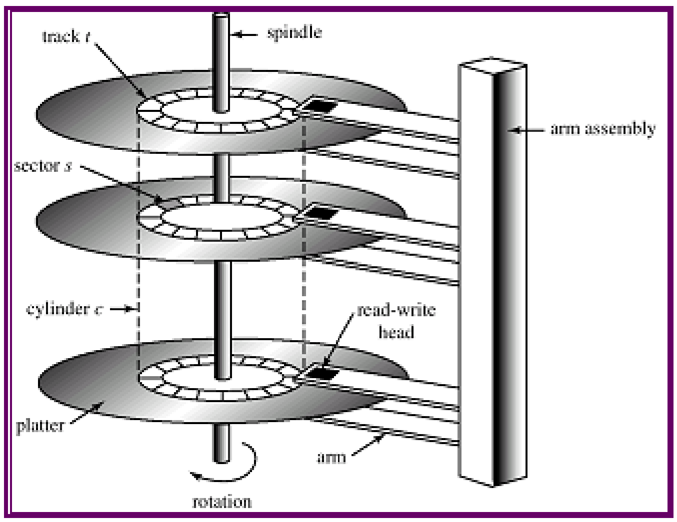
The IBM 3330 Direct Access Storage Facility, code-named Merlin, was introduced in June 1970 for use with the IBM System/370. Its removable disk packs held 100 MB (404 tracks/surface x 19 surfaces x 13,030 bytes/track). An upgrade in 1972 doubled capacity to 200MB by increasing tracks per inch from 384 to 808. Access time is 30 ms and data transfers at 806 kB/s. The 3330 family of products as a part of the IBM System/370, was one of the most successful IBM storage products. A number of innovations improved performance and reliability adding to success of the program

- Introduced track following servo system using a dedicated disk surface
- Introduced Voice Coil Actuators for large IBM drives
- Introduced glass bonded ferrite read/write heads in a ceramic body
- Introduced MFM encoding for greater storage capacity due to higher efficiency
- Introduced Error Correction Code (ECC) in IBM equipment
- Increased RPM from 2400 to 3600 to reduce rotational delay
- Introduced diamond lathe turned substrates
- Introduced particle-oriented oxide media in a disk drive (3336-II)
- Introduced controlled size particulate ceramics in disk coating for durability
- Introduced HEPA air filters to control particulates sizes below head flying height
- Innovative system performance improvement with RPS

Track following servo

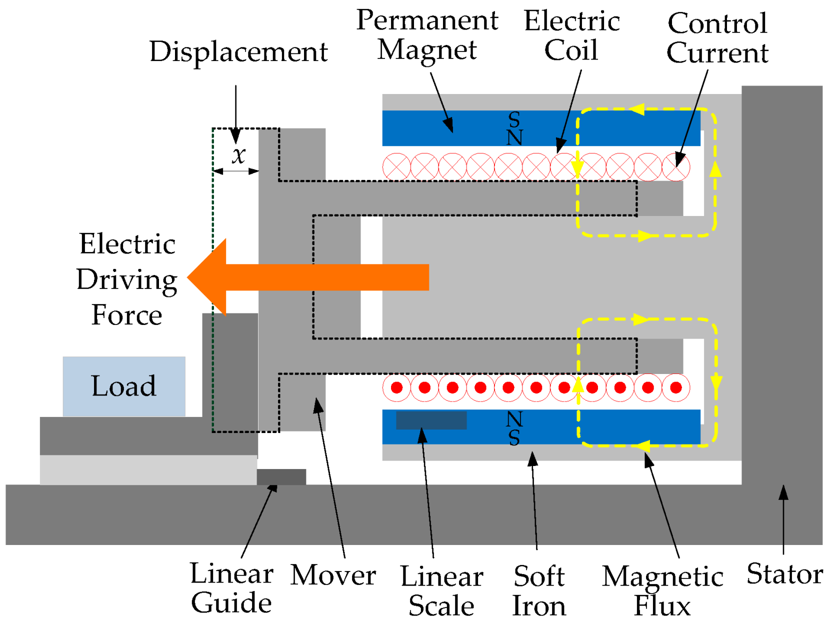
IBM disk drive pioneer Al Shugart in a 2000 interview identified track following servos as one of the four most significant events in the history of mass storage. Data track location is based on information recorded on a dedicated 3336 disk pack lowest recording surface, thereby using the disk pack itself as a location reference. The avoidance of mechanical positioning allowed tracks to be closer together (192 tracks per inch vs. prior art 100 tracks per inch) thereby enabling increases in capacity. Ultimately, all HDD's adopted variations on this technology.

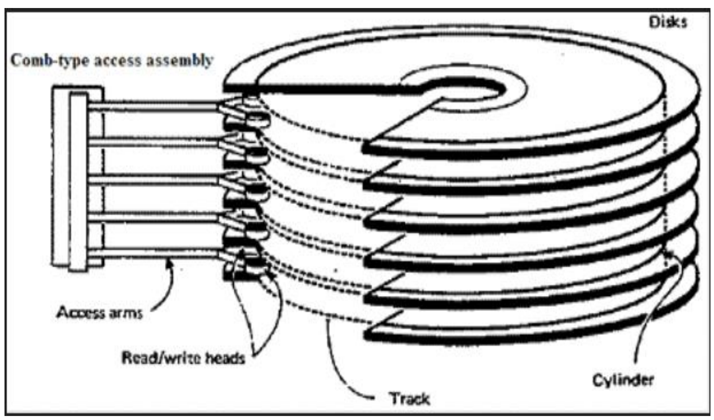
The 3330-1 achieved 100 MB with track density of 192 per inch, and linear density of 4040 bits per inch, resulting in an "areal density" of 0.78 million bits per square inch, a factor of 3.5 times the previous generation 2314. The 3330-11 version offered 2 years later doubled the tracks to 384 per inch to achieve 200MB. Track following servo was originally proposed in 1958 by IBM's Al Hoagland, see US patent 3,034,111, but not employed at IBM until the 3330 in 1970. Vertical alignment of data on 19 surfaces of the 10 disk pack was now automatic, but making all tracks on all disk drives and disk packs the same radius was no longer necessary. Location of the head array used track position and circumferential timing information recorded on a read-only "servo surface" recorded by the manufacturer.



Voice Coil Actuator

Early IBM disk-pack drives, starting with the 1311, utilized a mechanical detent for track positioning. This was essentially a rack & pinion system using mechanical means for head positioning, typically a hydraulic system to move the heads. Hydraulics required a pump, oil reservoir, piston, valves, and a location feedback system. Although successful, the mechanical systems were limited in position accuracy, bulky, slower, more costly, with more hardware and plumbing than the new system. All-electronic positioning used in the 3330 was faster, cheaper, and more reliable. The first IBM disk drive utilizing magnetic positioning was the small scale 2310 desktop storage, which had no servo but used an external optical position encoder. The basic design concept resembles a loudspeaker (hence the name "voice coil"), whereby a coil of wire surrounding a magnet moves when an electrical current is passed through the coil. The IBM implementation was a linear motor attached to an array of recording heads. The actuator was positioned using location information from the disk's servo surface, so was independent of temperature and directly related to the disk pack in use, eliminating the need to make all drives and all media to have identical track locations.

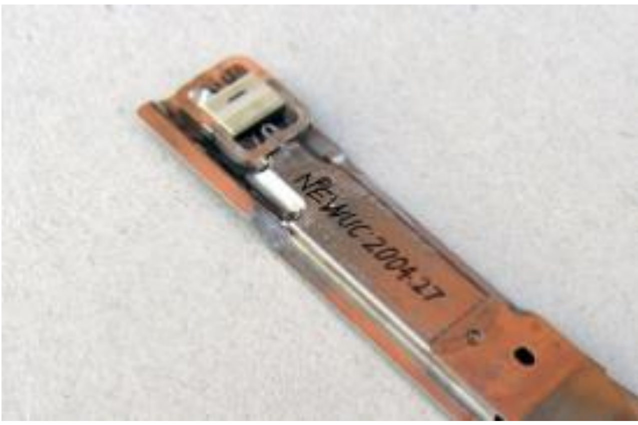
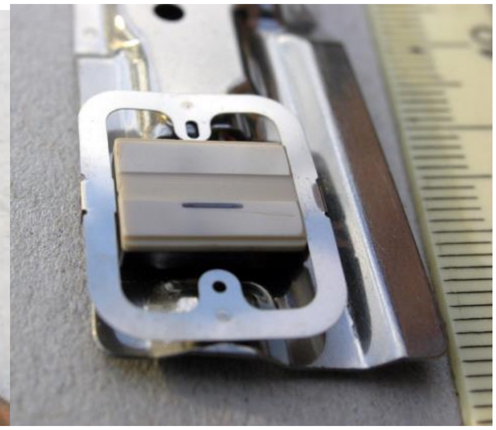




Glass Bonded Heads

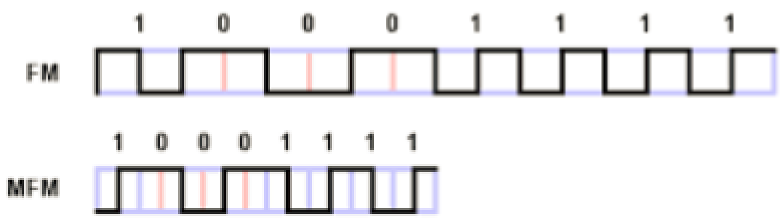
The predecessor 2314 drive design utilized ferrite magnetic cores epoxy-bonded to an aluminum oxide flying head. Unlike the 1311/2311 heads, mechanical staking of the core was not possible due to fragility of the ferrite. The 2314 solution was to secure the core in place with a filled epoxy. As with other plastic materials, epoxy has some flexibility, which allowed possible movement of the ferrite core, Recording and playback performance of heads is very dependent on the separation between the pole tips and media. In cases of pole tip recession (movement of core into the head body) poor performance resulted from greater head to disk separation. Another problem was pole tip protrusion (magnetic core “sticking out” of slider body), resulting in mechanical interference between head core and disk surface. In the heyday of "IBM compatibles" various vendors made recording heads, but at least one vendor, Data Industries in Southern California, went out of business due to instability of the epoxy bonding.

Use of melted glass as a bonding agent resolved the epoxy problem, improving stability of the core and head assembly. An "all ceramic" system was also more chemically stable and humidity resistant. Development work was carried in Dwight Brede's lab, using material from Corning Glass. After bonding, the head was lapped to the desired curvature .

3330 Introduced MFM encoding

The previous generation 2314 utilized FM (referred to as "double frequency"). In this scheme a constant stream of bits would be written to the disk, even without data. This recording served to provide reference or "clock" bits for timing reference. User data would be written between the clock bits, effectively doubling the recording frequency when data is present. Unfortunately this scheme, while robust, only allows the user to employ a maximum of half the available recording capability. MFM reduces the amount of data needed for clocking, achieving a 2x improvement in data capacity with the same recording density. MFM was a predecessor of other RLL codes (run length limited) which allowed even higher density recordings. MFM was subsequently employed in Floppy Disk drives, and early generation desktop hard disk drives, but has been super ceded by more efficient coding systems.



Error Detection and Correction Code (EDAC)

A major advance introduced with the 3330 is the use of error correction, which makes the drives more reliable and reduced costs because small errors can be tolerated, the circuitry can correct error bursts up to 11 bits long on a single track. EDAC relies on redundancy added to recorded data which is then used by an algorithm to inspect and repair received data when necessary.

RPM increased from 2400 to 3600 RPM

Access time of 30 milliseconds to data is limited in part by the disk RPM since data is (on average) on the other side of the disk. 3330 decreased this delay from the previous value of 25 milliseconds in the 2314 to 16,7 milliseconds, a reduction of 8.3 milliseconds, or 33%. RPM of the 3330 was increased to 3600 (versus 2400 for 2314), while the hydraulic actuator of 2314 was replaced by a voice coil unit, the net effect was reducing access time to 30 milliseconds, a 50% improvement. Additional 3330 data is available at this link to IBM's website.

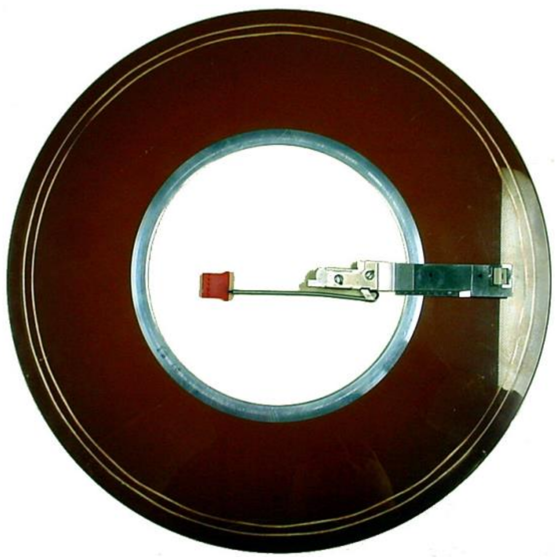
Magnetic Disk innovations

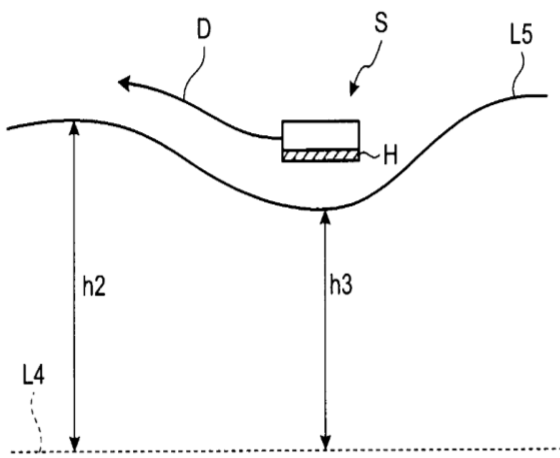
A performance improvement for the 3330-2 was obtained by physically orienting the acicular magnetic oxide particles in the circumferential direction before the wet coating was cured. This direction aligns the long axis of the physical particle between the pole tips of the recording head for maximum output and minimum noise. Particle orientation technology is conventional for magnetic tape, but this was the first application to a magnetic disk.

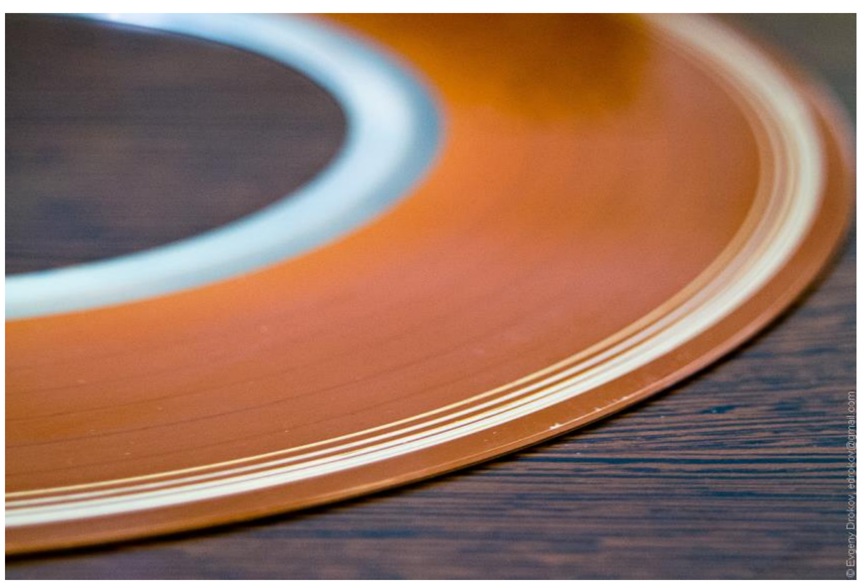
Disk Substrate Changes included increasing substrate thickness from 0.050 inches (1311, 2311, 2314) to 0.075 inches for added rigidity. Previous 14 inch diameter substrates were processed in IBM’s building-05 involving a series of steps including flat-baking to relieve stress introduced caused by handling of 7075-T6 aluminum alloy in rolls and subsequent die-punching to achieve desired ID and OD diameters. After this "flat bake" heat treatment, the stress relieved blanks were flat lapped several at a time with abrasive slurry on large rotating tables, about 12 feet across. After flipping the disk and lapping the second side, the substrates were a dull gray color, but were flat with parallel sides.

The next step was polishing to improve the surface finish, necessary to minimize electrical output variations (noise) due to small scratches subsequently filled with magnetic coating. The polishing method was via a process and machine created by Phillip (Scoop) Kimball, called the “Autotran”. A number of these were installed in building-05, resembling a collection of carrousels or merry-go-rounds each of which had several stations, using fibrous brushes and successively finer abrasive slurries to polish the surface to mirror like brightness. While 3330 was in development, a second Autotran process was being built.

A substrate process change was found necessary due to planned use of the smaller rectangular 3330 head which was designed to fly lower than predecessor 2314 designs (85 reduced to 50 micro-inches) . The problem found with IBM’s “Autotran” substrates involved a small thickness variation at the outside edge of the disk referred to internally as the “ski jump”. When using a Tally Surf or similar profilometer, a curvature was found on most substrates which was incompatible with the new 3330 head design, since there was a high probability of the head edges or corners hitting edges of the concave curvature at the edge of the finished disk. This was pointed out to manufacturing, while work on the second Autotran process continued.







Ski-Jump – refers to an edge condition caused by rotating polishing pads which dish out the central part of the disk leaving a slightly raised outer edge. The edges of a recording head flying over this curvature could mechanically interfere with the disk causing a “head crash”

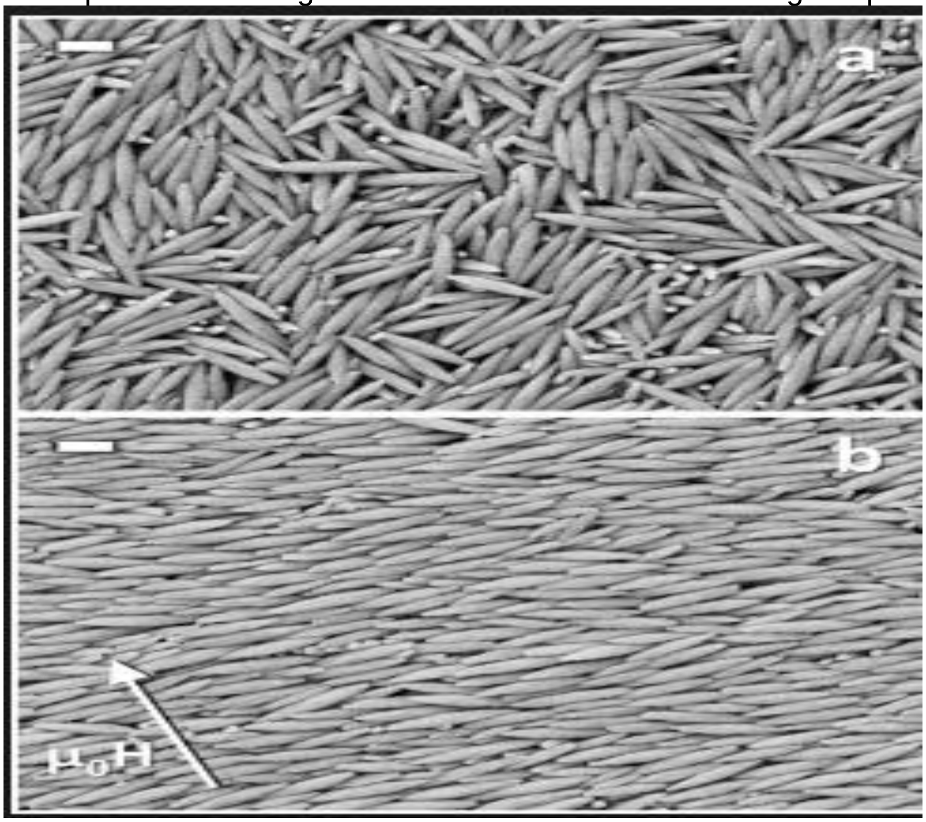
A chance meeting with manager Fred Severin from IBM Germany resulted in a discussion of this issue. His comment was that they had no such problem, as substrates were machined rather than lapped and polished. Samples were requested, and a skid of substrates arrived from Germany a few weeks later. These were measured and found to have no “ski jump”, they were perfectly flat to the outside edge. These disks were processed and built into disk packs which were successfully evaluated. Manufacturing realized after the data was presented that the substrate process would have to be changed, and the second Autotran, now finished at a cost of over $1M was never turned on. Aluminum disks substrates have been “diamond turned” ever since.

Glass substrates were evaluated by IBM in the 1960s, supplied by Corning Glass Works. These were hardened using ionic substitution at the surface (now known as "Gorilla Glass" in iPhones). The process involves submersion of soda-lime (Window glass) or similar composition into a molten potassium salt. Conventional glass has a substantial amount of Sodium oxide (13-14%) and Calcium oxide (10-15%) used to lower the melting point for ease of manufacturing commercial glassware. The temperature of the molten salt (334oC for Potassium Nitrate) expands the glass, and high concentration of potassium in the liquid salt results in diffusion of potassium ions into the glass surface replacing sodium. The ionic radius of Potassium is 23% larger than sodium (280 pico-meters versus 227 for sodium).

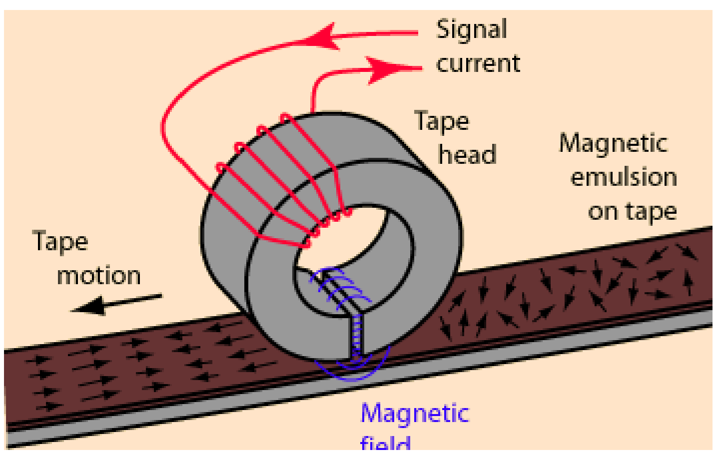
Upon cooling the glass substrate surface is under compression due to larger ions imbedded in the surface, and withstands bending and rough handling not possible with untreated glass. IBM Engineer Frank Appel was fond of throwing a glass disk on the floor to demonstrate durability. Although successful disks were made, cost was a primary issue at about $10 per substrate, which would make it the most expensive disk pack component by far. There were also some unconfirmed concerns about tribo-electric voltages produced with a spinning insulator glass disk, but the project was dropped as there was no measurable advantage of glass at the time. Many years later glass became the dominant substrate material for 2.5 and 3.5 inch diameter hard disk drives.

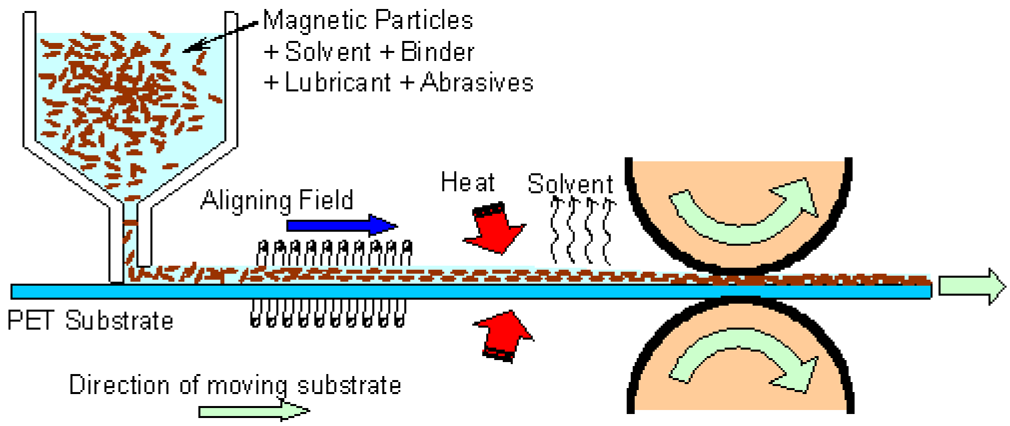
Magnetic Particle Alignment

Magnetic oxide particles are “acicular” or needle-shaped, and can only be magnetized only along the long dimension. The common patent for making acicular magnetic particles was issued to Marvin Camras at Armor Research in (US patent # 2,694,656). Only a few suppliers made magnetic iron oxide, leading to eventual shortages and allocations by C.K. Williams & Co., the primary manufacturer. When the oxide is dispersed via ball-milling (as done for IBM disk media) or other methods used for magnetic tape, the particles are jumbled and randomly oriented. This random orientation persists when coatings are applied to tape or disk, but tape manufacturers had found they could improve recording performance by orienting the particles towards the direction of tape motion. Image below shows random versus aligned particles.

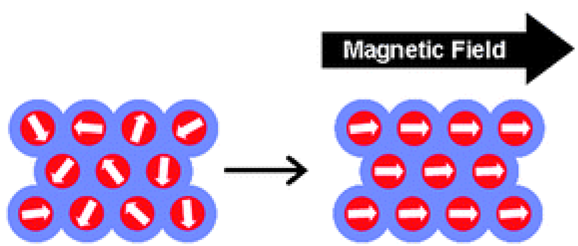


This alignment more efficiently couples the magnetic field from magnetized particles into the head structure. Tape is simpler to orient, since it travels in a linear direction, so magnets placed above the wet coated tape prior to oven curing of the coating binder will provide a particle-oriented media.





Rotating disks also benefit from particle orientation, so IBM "reinvented the wheel" to take advantage of the technique. Experimentation was carried out in the Building-13 development lab to see if particle orientation would help disk performance. A modified electromagnet from a 2311 disk drive brake was used to magnetize a single spot on a wet coated disk with orientation in all directions, like the spokes of a wheel. This was quite visible, with iridescent oriented sections. A few disks made this way were evaluated on single disk test equipment (spin stands) to verify the optimum angle of orientation. Results were promising, so a second particle orienting apparatus was built with cylindrical electromagnets placed above and below the disk, which applied a field in the direction of circumferential head travel. As with tape the orientation field was applied after the disk had been spin-coated, but prior to cure-bake. These disks had better electrical performance than the non-oriented media, and the orientation process was adopted for the use in the 3330-II disk drive and all subsequent IBM programs using coated media.



Abrasives in the disk coating

Abrasives added to magnetic tape coating was another process employed by manufacturers to improve mechanical durability, and a similar process was found to be useful in disk coatings.

IBM's disk coating was patented (US# 3,058,844 filed 1959, granted 1962) by San Jose CA engineers Don Johnson. Ralph Flores and Marcel Vogel. The patent describes in detail a formulation which remained basically unchanged for all of IBM coated disk products, except possibly for the original 1956 RAMAC. An earlier patent by Jacob

Hagopian (patent # 2,914,480 filed in 1955), is consistent time-wise with the first RAMAC delivery in 1956.

The coating was made by mixing ingredients in a 210 gallon ball mill using ceramic alumina-zirconia balls, and the slurry produced was subsequently filtered using Moyno pumps (positive displacement types used in food processing for thick materials) and a series of ever-finer Cuno filters to remove ball mill debris. The process control lab run by Ed Kettman in building-05 monitored each batch of coating by measuring the amounts of solvent, resin, and Iron Oxide by successively baking, burning, and dissolving small coating samples in aluminum cups. In the end, a small amount (few percent) of white residue remained. When asked, the lab technicians were unsure what it was, perhaps residue from the silicone additives, dissolved aluminum cups, or ball mill debris?

At the same time Dr. Leo DiRicco in the development lab was working on a “better” disk coating called SP-2, based on his experience as an adhesive chemist at Boeing where adhesives were replacing mechanical attachments for aircraft. Although the new formulation was theoretically superior, it was not as durable as the old RAMAC coating.

The durability measurement method employed a combination of impact and abrasion using device called a “Tap-Tap” tester. The test employed a ½ inch diameter stainless steel button repeatedly pushed into a rotating disk surface until there was a breakthrough of the coating resulting in electrical contact with the aluminum substrate. The factory coatings always performed better than the lab coatings. When a similar sample of lab coating was analyzed in the production lab, there was almost no white residue at the end. Suspicion arose that this unknown white powder might be the “magic durability ingredient”, so the process control lab contributed a number of residue samples from their routine testing which were added the development lab coating to approximate the same content as factory coating …. and Voila!, the lab coating was now equal in durability to the factory material.

The conclusion was that the factory coating contained a small amount of very hard ceramic material from ball milling, whose particles were small enough to get through the filtering process. The durability enhancement was somewhat analogous to the use of aggregate in concrete, the rocks are harder than the adhesive and provide improved surface abrasion resistance. Once this phenomenon was understood, a subsequent study and patent resulted (#3,843,404 by Joe Haefele, Cecil Hawkins, and Ron Kubec) regarding introduction of controlled size abrasive into disk coating. This patented idea was used in 3330-II and all subsequent coated media.

IBM had in fact experimentally "re-discovered" what the magnetic tape industry had determined many years earlier. Patent literature (TDK, Fuji, BASF & others) cite non-magnetic ceramic additive (usually aluminum oxide) added to the tape formulation for improved mechanical durability with a side benefit of polishing the recording heads. The TDK patent, for example, cited abrasive content at 5 to 15% of iron oxide by weight. In some cases high levels of ceramics in tape coatings led to excessive tape drive head wear. An IBM field engineer confided that they could not dictate which type of tape customers could use, but Graham brand was referred to as “old gritty” by some engineers due to more frequent head replacements required by customers using that tape brand..

Disk Lubricants

Coated disks were polished smooth, but friction was a concern due to abrasive nature of iron oxide and ceramic additives, plus the issue of "stiction" whereby two polished objects in contact can "stick" due to lack of air or lubricant between them. In the San Jose development lab, IBM experimented with various disk lubricants, some of which gave excellent lubrication, but evaporated (e.g. Oleic Acid). DuPont patented a fluorinated ether named "Krytox" which had zero vapor pressure. Ball Research in Colorado had successfully used the fluorinated oil for on movie film to reduce friction between layers of film, and as a lubricant for NASA space vehicles. When used on a coated disk, however, the centrifugal force spun off the lube over time. A variation of lube with chemically active ends which could adhere to the coating was eventually used on disks subsequent to 3330.

High Efficiency Particle Air Filters (HEPA)

Due to airborne contamination problems observed in earlier drives (see CHM article on IBM 1311-2311), it became apparent that outside air would have to be "cleaned" of small particles and aerosols which could interfere with the head flying height of 50 micro-inches. Previous drives used an automotive style air filter. Typical pleated paper offer between 80-90% rejection of particles greater than 2 or 5 microns (80 or 200 micro-inches) in diameter, exceeding the flying height of the 3330 head. HEPA filters reject over 99% of particles exceeding 0.3 micron (11 micro inches), so these were introduced in all production models of the 3330.

System performance enhancements

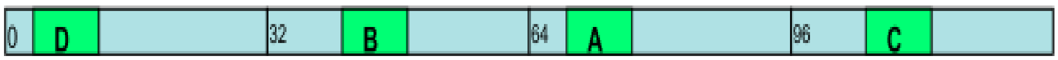
RPS (rotational position sensing) was an innovation which improved system performance by reducing the waiting time after a seek completed from half a track to 1/128 of a track, and allowed multiple transfers to occur in a single rotation.

The CKD (Count Key Data) disk format provided variable length recording. A popular use during the early years of a /360 installation was of 80-byte records which mimicked the Hollerith card to assist in migrating applications from punched cards. For efficiency, sorting software wrote single track records. The record size was defined by software, and RPS provided a way to identify the relative location of a record on the track, so the channel could re-connect in time for data transfer. On a read, the RPS was set for just prior to the record. On a write, the RPS was set to the record before because there was no n i.e. Search n-1/Write n.

The 2880 block multiplexer channels introduced on the /360 Models 85 and 195 were integrated in the /370 series. The channel could disconnect during mechanical delays because sub-channels held the status/control functions for each attached device.

Swapping between sub-channels allowed transfers from multiple devices to be interleaved.

RPS allowed multiple drives to transfer data during the same rotation e.g. if there were channel programs executing concurrently on disks A, B, C, and D and RPS requests were outstanding for 69, 45, 105, and 10 respectively then all four could be transferred in the same rotation if they were on track at the same time e.g.



This was a vast improvement over the /360 Selector Channel which could only function with one device at a time. A large proportion of /360 systems were owned by leasing companies, and the /370 channel improvements impacted the residual values of /360s coming off lease. Customers wanting the higher storage capacity and performance were eager to get out of their /360 leases because IBM restricted the 3330 to /370 systems. Plug Compatible Manufacturers (PCMs) had no such inhibitions.

Information Storage Systems (ISS) implemented a combinatorial Seek and Set Sector command (Patent 4,200,928) to provide the effect of RPS on a Selector Channel. This boosted performance on a /360 to that approaching /370 levels, and along with similar variations by other PCMs, it stabilized the value of /360 residuals.

Potential problem areas

Cross-contamination remained an unresolved issue for removable disk packs. So-called ”Typhoid Mary” syndrome involved moving a mechanically damaged disk pack (e.g. head crashed) to another drive to retrieve data, contaminating heads of both drives in the process. Subsequent products combined heads and disks in a sealed package, starting with 3340 “Winchester”. All current drives use the HDA (head disk assembly) concept of a sealed package containing heads and disks.

Due to minute head-to-disk distances, contamination between them could adversely affect reliability. If inspection by a field engineer revealed “dirty” heads or disks they could be cleaned on site. The causes could be poor computer room environment or momentary head to disk contact when heads are loaded, transferring small amounts of disk coating material to the heads. Heads and media were cleaned in the lab with 100% isopropyl alcohol, but field engineering cleaning kits contained 67% isopropyl alcohol. TSA rules limit air shipments of alcohol content to 70% reducing flammability (“flash point”) hazard. In a few cases Field Engineers substituted drug store rubbing alcohol (70% isopropyl) with disastrous results if the product contained fragrances or contaminants leaving residue on the disk.

The 3336 disk pack weighed 25 pounds, a potential handling difficulty for people of limited strength compared to 9-3/8 pounds for the 1316 and 14-1/8 pounds for the 2316. Operator mishandling could lead to various problems (mounting thread damage, dropping packs, etc.)

Additional Information and References

(1) IBM San Jose, A Quarter Century Of Innovation," David W. Kean, 1977.

(2) IBM Corporation 3330 webpage:
https://www.ibm.com/ibm/history/exhibits/storage/storage_3330.html.

(3) Al Shugart remembers the 4 most significant disk drive technologies:
https://www.thefreelibrary.com/Al+Shugart+Remembers.-a059628939.

(4) http://wikivisually.com/wiki/History_of_IBM_magnetic_disk_drives.

(5) Two patents describing the "ski jump" issue for drive designs subsequent to 3330: US Patents 7,976,967 and 6,154,438.

(6) Glass bonded heads – US Patent 5,273,948.

(7) US Patent #3,034,111, "Data storage system" May 08 1962 Albert S. Hoagland and Leonard D Seader.

(8) Reference Manual for IBM 3830 Storage Control and IBM 3330 Disk Storage.

(9) US Patent #4,200,928 "Method and apparatus for weighting the priority of access to variable length data blocks in a multiple disk drive data storage system having an auxiliary processing device," April 29 1980, Iain D Allan/Per-Erik Walberg.

Moderators: Michael Warner, Bill Carlson, Dal Allan.