Fifty years of IBM innovation with information storage on magnetic tape

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On May 21, 1952, the International Business Machines Corporation announced the IBM Model 726 Tape Unit with the IBM Model 701 Defense Calculator, marking the transition from punched-card storage to digital storage on flexible magnetic tape. That bold introduction was the beginning of what is now a 50-year history of invention that has seen remarkable advances in the storage of information on flexible magnetic ribbons ten times thinner than a human hair and capable of storing more than 100 000 times more data in the same volume as the first reel of tape introduced in 1952. This historical perspective is dedicated to the people who made that first tape drive possible and to those who continue that tradition in the Removable Media Storage Solutions (RMSS) team of the International Business Machines Corporation Tape Development Laboratory, headquartered in Tucson, Arizona.

How it all began

In June 1949, reels of tape, tape cartridges—even programmable computers—had yet to be invented. Recorded music was still on 78-rpm platters, and wire recorders were the mainstay of the radio industry. Magnetic tape had only recently emerged from the laboratory to be used for a few broadcasts. Meanwhile, at IBM, it took a large room full of vacuum tubes and miles of wire to accomplish what a handheld calculator could do faster by the end of the 1980s. *Information storage* meant books, filing cabinets or, to those at the leading edge of data processing technology, punched paper cards. A handful of IBM engineers and scientists were about to launch a revolution.

In 1949, it was by no means clear that it would be wise to gamble millions of dollars and the time of some of the brightest engineers in America (to say nothing of the future of the 35-year-old IBM Corporation) on an infant technology based on gluing bits of rusted iron on strips of plastic. The suggestion that such a vaguely understood thing, called *magnetics*, could supplant the familiar and highly profitable punched card met strong and vocal opposition within the company. Some highly respected and positioned figures within IBM were convinced that it was foolish to risk the company's future on such a radical and unproven technology.

Wayne Winger, a member of IBM's first tape-drive development team and a Tucson retiree, recalls, "Once a white-haired IBM veteran in Poughkeepsie pulled a few of us aside and told us, 'You young fellows remember, IBM was built on punched cards, and our foundation will always be punched cards' " [1].

Thomas J. Watson Jr., then IBM executive vice president, and a number of the company's top engineers and scientists decided that the move to magnetic tape was a gamble that had to be taken. Today's multi-billion-dollar data-storage-processing industry is testimony to their wisdom and their courage.

In a documentary film, *The 701 Days*, produced by IBM in 1973, the opposition to magnetics is recalled by people who participated in the climactic meeting of the IBM decision makers. In the film, IBM Fellow Nathaniel Rochester recalled that Watson "went all around the room asking people if this was the right thing to do or not, and some people said 'yes' and some people said other things. And then he told all those people who said other things

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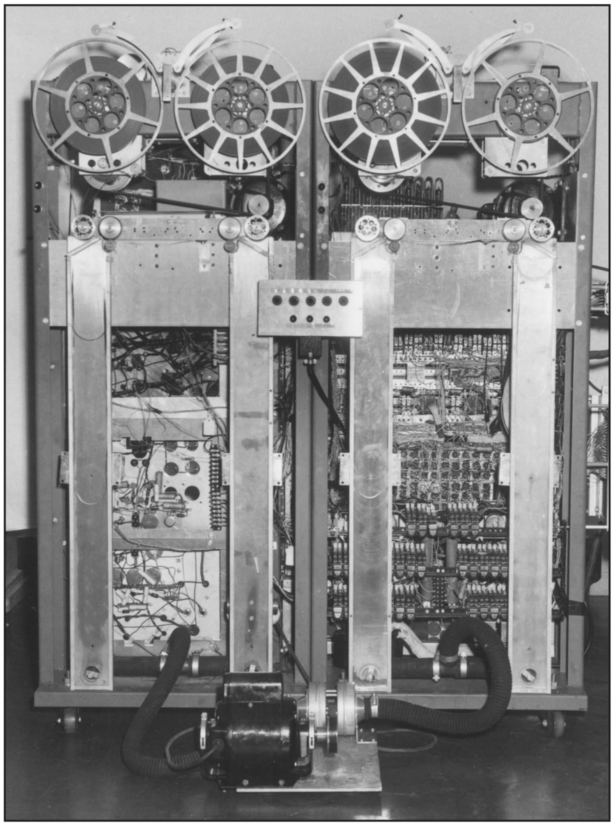

Figure 1

Early laboratory prototype (a quarter-inch tape machine) of the IBM tape drive in the Kenyon House, Poughkeepsie, New York.

that they should work on other problems." In the film, Watson himself says, "Some of us decided we just had to force ourselves into magnetic tape. And I wanted to get everyone's views out on the table as to who was going to fight against it. And of course, when you have a meeting like that and you state that your position is going to be for it, it is helpful. . . ." Here Watson chuckles at the recollection [1].

Opponents of the magnetic tape program had well-developed arguments against it. Fortunately, those arguments proved wrong. For example, Byron Phelps, a principal figure in the development of magnetic tape and the holder of a number of key patents, wrote in a personal letter, "I can remember someone preparing a study on possible tape density and producing a graph showing that 400 bits per inch was just about the ultimate recording density we could hope for!" (Today, the IBM Ultrium† Linear Tape-Open† (LTO†) Tape Cartridge records at over 124 000 bits per inch (bpi), and densities of over 250 000 bpi seem feasible in the very near future.)

"No one person came up with the idea of magnetic tape," according to Phelps. "It grew out of a number of meetings and discussions involving principally Gordon Roberts and Steve Dunwell of the Future Demands department, W. W. McDowell, vice president of engineering, R. L. Palmer, manager of the Poughkeepsie lab, and yours truly" [1].

A number of people remember that Tom Watson Jr. immediately grasped the promise of magnetic recording as a result of his experience with electronics in the Army Air Corps during World War II. Why did Watson and a few others decide that IBM had to commit itself to magnetic tape? Phelps remembered it this way in his letter: "As I recall, the major push first came from our study of the Social Security System and their very pressing need to solve their record storage problem. Even in 1949 they had acres of file cabinets of IBM cards containing Social Security records on every working American employee.

"It was obvious that we had to find a more compact means of storing permanent records. And, there was not much choice. We had tried more dense paper cards (smaller holes, binary codes, etc.), but the projected improvement was only a few times better. Punched paper tape offered no great advantage either. Magnetic tape was just coming into its own in audio systems and it offered the most promise, so that's the way we went."

Development team member Wayne Winger recalled this perspective on the limitations of punched cards: "Prior to our first tape drive, information was put on punched cards. There are 80 characters per card, and a good [read/write] speed was 100 cards per minute, which means 133 characters per second. The 726 (IBM's first marketed tape drive) operated at 7500 characters per second, which is 56 times faster. And the tape takes up far less space."

In 1949, the whole subject of magnetic recording was virtually unexplored territory. Max Femmer, another tape pioneer, recalled that "stuff you can learn in a primer from Sam's Bookstore today, we didn't know."[1] As in any creative effort, improvisation played a large part in the success of the tape drive development program. James Weidenhammer, a key figure who invented the vacuum column, remembered that "we had no clear idea of which approach to take. Very rapid start and stop times were obviously desirable to minimize the wasted tape and read/write delays. With tape speeds contemplated in the order of 100 to 200 inches per second, it was obviously impractical to accelerate bulky tape storage reels rapidly enough, so it was evident that storage loops or buffers would be necessary in the tape path for gradual acceleration of the reels" [1].

Once the idea of the vacuum column was hit upon and the vacuum switch was conceived, "We were in a hurry to try out the idea," wrote Weidenhammer, "and needed

[1] Personal interview with Max Femmer in 1979 in Tucson, Arizona, with Carl Schroeder of IBM in preparation for the IBM General Products Division Tucson site dedication.

some very thin, flexible material in order to fabricate a sensitive pressure sensing diaphragm. Nothing suitable being on hand, the quickest solution that occurred to me was to send one of the young engineers, Jack Seely, to the nearest drug store for a pair of baby pants. They worked."

The vacuum pump provided another challenge. During development, engineers used the motor from an old General Electric** vacuum cleaner, and released the tape drive to production with that GE** motor. Dick Whalen, who was manager of procurement for the program, wrote, "It turned out that this was an obsolete vacuum cleaner. A GE sales representative searched GE warehouses all over the country to get us under way." One of the early prototypes that was used to work out a practical tape processing machine is shown in **Figure 1**.

Wayne Winger recalled the confusion that resulted in the early days because magnetic tape was virtually unknown, even within IBM: "We got a shipment of tape from our supplier, and it was delivered to the receiving dock. The man in charge came over and said, 'We just got a shipment of tape from 3M, but we're going to have to send it all back.' Why? 'It doesn't have any glue on it!' "

IBM pioneered not only tape drives, but the half-inch tape itself. Vic Witt, who retired as an IBM Fellow in 1980, played a large part in that program. "I started with the program in 1951," recalled Witt. "There were no tape experts at that time. They handed me a piece of tape and said, 'You have to know everything there is to know about this stuff.' It was quarter-inch, and we were going to use half-inch, but this was all we had then.

"We settled on 3M as a source for tape, and worked with them to find a way to produce tape to our specifications. We went to them and said, 'We need tape so flawless that, if it were a highway, it would stretch from Poughkeepsie to Manhattan (about 60 miles) with no defects [larger than] the size of marbles.' We built a test center in Minneapolis, and 100 percent of our tape was inspected by an operator with a microscope and a knife. Defects would be cut out and sent back, and we'd say, 'Fix that.' Testing the tape cost as much as manufacturing it, maybe more.

"IBM designed and built the world's most advanced tape coater in Poughkeepsie, and the first clean room used in manufacturing. No one had ever heard of keeping the air in a manufacturing plant that pure, but we had to have it if the tape was going to meet our specifications. We showed the world that it could be done" [1].

IBM's first magnetic tape unit, the IBM 726 (**Figure 2**), was announced in 1952—the year Thomas J. Watson Jr. became IBM president and the employee population passed 40000. It was announced with the IBM 701 Defense Calculator, the company's first commercially marketed electronic computer. A development model was called the Tape Processing Machine by the engineers who designed and built it—an indication of the pivotal role played by magnetic tape in launching the data processing industry [2].

Figure 2

The IBM Model 726 Tape Unit, announced and shipped in 1952.

The *Wall Street Journal* article on the day the 701 was announced said it was "designed to shatter the time barrier confronting technicians working on vital atomic and airplane projects." It went on to say that the first computer would be used to "calculate atomic radiation effects and to compute the many statistical things scientists need to know about planes, guided missiles, and rocket engines."

The General Motors** Research Laboratories used a 701 in the mid-1950s, for example, to solve engineering problems. One problem in stress analysis was evaluated for more than 100000 variables. A GM** publication noted at the time that "working 40 hours a week, 52 weeks a year with a desk calculator, it would have taken the engineer 12 years to solve this problem. After allowing the mathematicians in Data Processing about a month to set up the problem, the 701 provided the required answers in 1.5 hours." As a GM employee noted, "Jobs once thought impossible are now attacked without hesitation."

The March 27, 1953, *New York Times* reported that one chemical company planned to rent time on the 701 at IBM headquarters to solve a cost-accounting problem. It would take about 100 hours of machine time to solve the problem while, according to an IBM spokesman at the time, it would take an accountant with a desk calculator 2500 years. The data processing industry's first half-inch magnetic tape drives, IBM 726 Tape Units, were shipped with the IBM 701 Defense Calculator from December 20, 1952 until February 28, 1955 [1, 2].

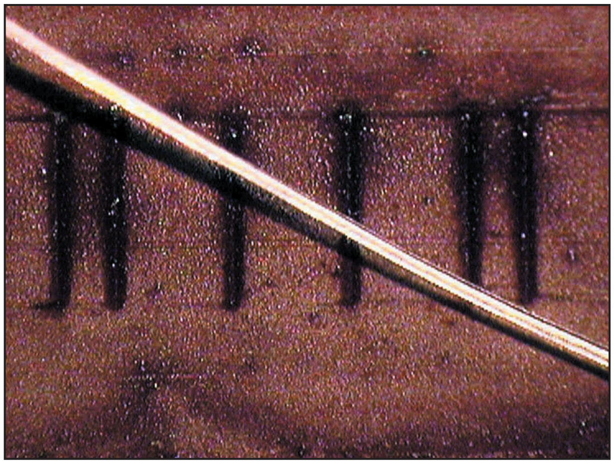

Figure 3

Developed bits on first IBM Model 726 100-bpi tape compared with a human hair.

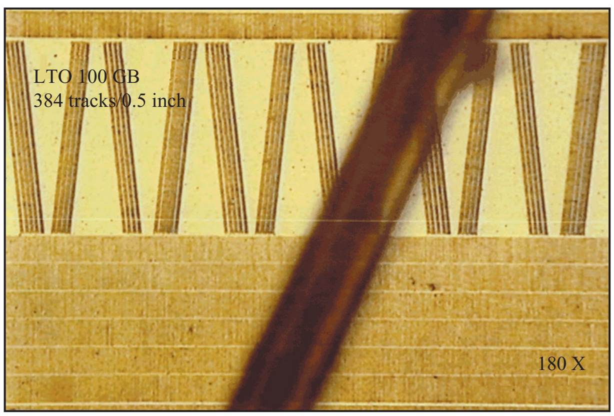

Figure 4

Developed data pattern for IBM 3580 Ultrium LTO 100-GB tape compared with a human hair.

Even at the first working density of 100 bpi of a half-inch tape, a 10.5-inch-diameter reel of tape could hold the equivalent of more than 35 000 punched cards. Today, the IBM Ultrium LTO Tape Cartridge is 1000 times faster and stores more information on one inch of tape than the IBM 726 Tape Unit was capable of storing on over 500 feet of tape . . . without data compression. It is interesting to compare this early format with tape today. **Figure 3** shows the bits recorded on a tape written on this early 100-bpi tape drive compared with a human hair. The magnetized region of the tape is developed using a dispersion of small iron particles (ferrofluid). When the suspended magnetic particles are rinsed across the tape surface, they are attracted to the recorded magnetic regions on the tape and oriented in a manner that reflects incident light differently depending upon their magnetic alignment. This produces a visible pattern for the alternating erased and aligned regions on the tape. **Figure 4** presents the image of a similarly developed pattern for the servo and data bits on an IBM Ultrium LTO 100-GB cartridge compared with a human hair, as done for a similarly developed image for IBM's first tape drive, the Model 726.

Tape grows up

IBM's magnetic tape development has been one of its more-traveled missions. It started in Poughkeepsie, New York, in the late 1940s and, for the first years, was housed in the old Kenyon Mansion, which became the IBM Homestead in 1955 and later served as the home of the Corporate Headquarters Management School—Northeast.

The tape mission then moved from the Kenyon Mansion to the new Poughkeepsie Laboratory in the early 1950s. The Poughkeepsie Laboratory developed refinements of the early 727 Tape Unit, resulting in the 729 family of tape drives, Models 1–6. These drives offered increased density of up to 800 bpi with the introduction of two-gap read/write heads, the first read-while-write capability in an IBM tape drive, and the beginning of what became normal tape operation for the next 25 years—*write wide*, *read narrow*. These drives also pioneered the ability of an IBM device to read and write multiple densities, making it possible to read tapes written on older machines. As the role of tape in digital information processing and storage grew, IBM's laboratory grew as well. In the early 1960s, significant advances were developed in the Poughkeepsie Laboratory that culminated in the 2401 family of tape drives, first introduced in 1964 (**Figure 5**). Nine-track non-return to zero inverted (NRZI) recording—a method of encoding binary data that offers data and clock synchronization advantages—was introduced with the 2401 Models 1–3, which added the capability of handling an increased character set within the encoded data. Cyclic redundancy checking (CRC) was introduced to provide a much improved method of error checking and correction. The ability to read backward rather than force a rewind and restart allowed improved throughput and efficiency.

The final member of the 2401 family, the Models 4–6 introduced in 1965, provided a top density of 1600 bpi and saw the introduction of electronic skew buffers to reduce off-track errors and write compression to control peak shift. The 2401 family of tape drives were to be the final contribution to tape development from the Poughkeepsie Laboratory, and the tape mission moved again—this time to the new laboratory being constructed in Boulder, Colorado. Then, in 1973, the tape mission moved again, from the Boulder, Colorado, Laboratory to San Jose, California, but it returned to Boulder in 1977.

While the tape mission was moving from Colorado to California and back, the IBM tape team developed and introduced some of the finest enhancements to reel-to-reel tape devices, whose legacy had begun some 25 years earlier, first with the 2420 Model 7 in 1968 with 1600 bpi and a tape speed of 200 ips. This device exhibited the fastest start–stop time of its day, going from a dead stop to 200 ips in less than two milliseconds. The introduction of high-torque, low-inertia (HTLI) motors coupled directly to the drive capstan in the Model 2420 family of tape drives enabled successive performance improvements in the models that followed [3].

The media

Initially, the tape was produced by the 3M** Company and several other manufacturers of audio recording tape. The far more demanding performance and durability required of tapes for computer data storage soon forced IBM to put considerable effort into developing tape specifically for IBM tape storage devices. The first significant change was to replace the acetate substrates used in earlier tapes with polyethylene terephthalate (PET) to improve the tape's resistance to breaking during the increasingly faster start–stop cycles of each successive model of tape drive [3].

In 1959, IBM introduced Durexcel, its first custom-designed tape. Durexcel provided greatly improved durability for the 726 and 727 Model tape drives. The IBM 729 Model III, with the introduction of pairs of three-position assemblies which moved pinch rollers that allowed the tape to be engaged by the appropriate capstans, called *prolays*, allowed improved start–stop performance and a significant reduction in mechanical complexity. These prolays, while providing more aggressive tape performance, required the development of an improved tape, introduced in early 1961 and called the Heavy Duty Tape. Almost all of the early tapes were produced by suppliers to IBM, but the need to optimize tapes specifically to support the requirements of computer data storage devices necessitated that IBM design and manufacture tape to enable its device technology. IBM's first internally developed and manufactured tape, Series 500, was introduced in 1967. This tape was produced at the IBM Boulder facility until the introduction of the Multi-System Tape (MST) in 1974. This gamma iron-oxide-based polyurethane and cross-linked vinyl resin binder system on a 1.5-mil-thick PET substrate became the standard for durability and performance in the 1970s and was arguably the best reel-to-reel computer tape ever made [3].

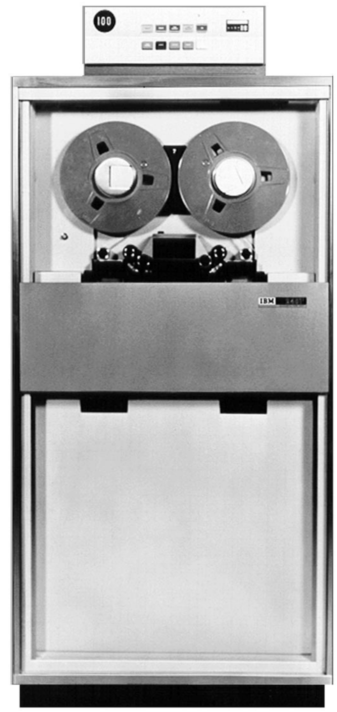

Figure 5

The IBM Model 2401 Models 1–3, 800-bpi nine-track (1964); this was followed by Models 4–6, 1600 bpi, introduced in 1965.

The IBM 3850 Mass Storage Subsystem

The IBM 3850 Mass Storage Subsystem (MSS) was a total departure from the 20-plus years of reel-to-reel tape transports. It was a truly revolutionary product that introduced information storage concepts and novel technologies that appear to have been reinvented in the years that followed. The MSS was designed and built at the IBM Boulder Laboratory in the early 1970s and introduced in 1974. It was the first attempt to *virtualize* storage by embedding software instructions within the device to control its functions; these instructions are now commonly known as *microcode*. The 3850 MSS used a helical-scan format on tape to mimic data as it would typically be laid out on the direct access storage devices (DASD) that IBM had invented in the mid-1950s. Two 3850 cartridges could hold 100 MB, which was the entire capacity of a 3330 disk pack. The 3850 cartridges could hold 470 GB when fully configured, with almost 1000 50-MB-capacity cylindrical cartridges [4]. This made it possible for a host system to use what appeared to be a huge disk storage device for a fraction of the cost.

The IBM 3850 was the first subsystem to provide a virtualized (or *soft*) image of a storage format that was

Figure 6

The IBM 3480, introduced in 1984, standing in front of the IBM 3420, which was the standard for reel-to-reel tapes prior to the 3480.

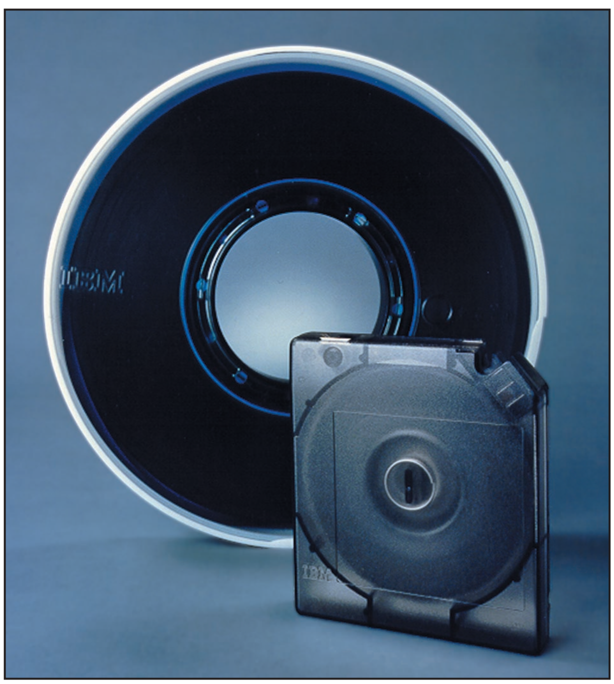

Figure 7

The IBM 3480 200-MB cartridge compared with the 3420 Multi-System Tape 180-MB 10.5-inch reel.

different from the actual physical storage target (as presented to an application or storage management software). Thus, the host and application software treated the data as if it was stored on the DASD, rather than on tape cartridges. The 3850 was also one of the earliest devices to employ automation and fault management within the device (independent of the host) [5–7].

The IBM 3480

The move to Tucson, Arizona, was announced in 1977, and portions of the tape mission began the move shortly thereafter. The move to this new site, specifically built to develop and manufacture tape, tape heads, tape drives, cards, and operational software and microcode, saw a surge in new hires and transfers into tape from all over IBM to join the team in Tucson.

The new site was officially dedicated in February 1980, with more than 3500 people on the site, a number that had swelled to more than 5000 employees by 1987. The purpose of this effort was to introduce a series of breakthroughs in tape storage technology. When the 3480 was announced on March 22, 1984, Al Rizzi, General Products Division Tucson Laboratory Tape Products manager, said, "Everything is new about this product. The result is a tape subsystem that sets the industry standard." Tape storage was the primary mission of the IBM Tucson Laboratory, and the 3480 announcement was a major milestone for the site [1].

Two of the 3480's radical new features were immediately obvious: It used tape cartridges instead of reels, and it was significantly smaller in size than the industry-standard IBM 3420 Model 11 10.5-inch-reel tape drive. While the 3420 placed 180 MB of data on a reel of tape and had an uncompressed data rate of 1.25 MB/s, the 3480 had a capacity of 200 MB in a 5.5-inch-square cartridge and a data rate of 3 MB/s. The 3480 required less than half the floor space of an equivalent installation of 3420s (**Figures 6** and **7**).

The 3480 introduced a number of technology breakthroughs: the first thin-film and magnetorestrictive (MR) head in a tape drive (and several years ahead of the introduction of thin-film heads into disk drives) [8]; the first 18-track head/channel in a tape drive; a new media format (the half-inch data cartridge) on chromium dioxide tape [9]; significant function and complex system error logging enabled by major advances in embedded software (microcode); and reduced power and space requirements with significantly improved performance and reliability. Vacuum columns, the essential component of the reel-to-reel tape drives of the previous 25 years, were replaced in the 3480 with direct reel-to-reel control. A significantly improved and highly integrated write- and read-equalization channel was introduced, and significant improvements in data error detection and correction using adaptive cross parity (AXP) were achieved [10].

To support the revolutionary new tape format, IBM once again developed and manufactured a tape to support its new technology. With a customized binder formulation that exhibited superior durability and performance, the 3480 cartridge system tape, or 3480 CST, became, within only a few years, the world standard for computer information storage on tape and forever changed the expectations for tape reliability [11].

The 3480 product family was enhanced in 1989 with the introduction of the 36-track, 3490E drive and a new extended-length chromium dioxide tape. The 3490E provided 800 MB of storage in the same cartridge format as the earlier 3480. The introduction of improved recording capability (IDRC) further increased the capacity of the 3490E, to more than 2.4 GB, the highest data capacity available at that time.

The world was moving explosively into the computer age. With the introduction of the personal computer, computers more powerful than the IBM 701 of 1952 were soon available to everyone. With the increased computerization of day-to-day transactions, an explosion of data was being generated—and stored. The sheer number of high-capacity tape cartridges in many installations was becoming staggering; there were almost 100 million 3480/3490-compatible cartridges throughout the world by the mid-1990s. It was becoming increasingly imperative not only to improve tape capacity and performance, but to provide automated tape storage and management.

As noted earlier, with the announcement of the 3850 MSS in 1974, IBM offered the first automated tape storage device. Support for the 3850 MSS was transferred to the Tucson Tape Laboratory from Boulder in the early 1980s, while manufacturing remained in Boulder during the final years of 3850 availability. The revolutionary way of looking at tape in the hierarchy of storage initiated by the development of this pioneering tape automation device left a nucleus of talented and experienced people who created a number of innovations in data storage management and architecture. The first cache-control device, the IBM 3880 Model 11/13, was developed in the Tucson Laboratory in 1984, at least in part on the basis of experience gained with the 3850. This initial cache-control system led to successive advances in data storage control function and improved utilization of both IBM DASD and tape storage. This effort was very likely the beginning of what is now called *autonomic computing* and *virtualization*.

The IBM Tape Library Dataserver

IBM had originally introduced automation with the 3850 MSS. Then, in 1993, the IBM Tape Development Laboratory reentered the automation arena by combining the strengths of world-class tape drives and control systems and advanced connectivity with ESCON* and then Fibre Channel support with its introduction of the 3495 Tape Library Dataserver. It was a collaborative effort that adapted existing robotics to a tape automation solution. This large automated tape library was IBM's first effort to provide an automated tape solution since its 3850 MSS. The 3495 was not an optimal solution, so the team in Tucson started from scratch and, in a very short development time, delivered the more-efficient and higher-capacity 3494 Tape Library Dataserver at the end of 1993.

DASD, or hard disk drives, also invented by IBM, and new storage devices using optical storage were being developed. New tape formats, disk arrays, optical devices, and technologies entered the marketplace and seemed poised to relegate the use of tape storage to little more than backup or archival repositories. Tape was beginning to seem old and destined to be displaced by other technologies. Hardly a year went by that did not see at least one pundit pronounce the impending demise of tape in the hierarchy of data storage. These assertions always assumed that innovations in tape storage had ceased to sustain its performance and cost advantages.

IBM's New Tape Program

Dr. Paul Low, president of the IBM General Products Division, and Dr. Juri Matisoo, director of the IBM Almaden Research Center, convened a group early in 1988 to examine the viability of tape as a storage medium for the future. One member of that task force, Dr. James Eaton, recalled, "Early in the study it became apparent we had to make radical improvements in linear tape-system density and performance. Dramatic improvements were clearly possible. Tape technologies were available with over 100 times the density of the very successful IBM 3480/3490 family of tape devices."[2]

Although such existing tape technologies improved capacity, they did not offer the data rate required by the applications on which IBM storage products were focused. The goal was to achieve *both* increased capacity and increased data rate without sacrificing the proven reliability of the 3480/3490 products, which had become a world standard for information storage on tape. The prevailing attitude among the group members at the conclusion of the task force was that of excitement, with a reinvigorated focus on advancing IBM's presence in tape technology. Dr. Eaton summarized, "At the end of the task force study, it was obvious that data storage tape areal density could be increased by hundreds of times. We had to get busy to make it happen or risk losing the business to whoever did!" Thus began IBM's New Tape Program (NTP) to explore novel directions for tape.[2]

[2] Private communication with Dr. James Eaton, June 2002, with reference to internal documents summarizing the Tape Task Force, May 1989.

The NTP effort explored a small-form-factor fast-access-time tape format. What emerged from this advanced technology group was a totally new, revolutionary device using a timing-based servo, an advanced recording channel, highly integrated signal processing, and a completely new design for a low-mass head mounted on a precision actuator assembly. The technology promised to produce a small-form-factor device with a 5-GB native capacity, a high data rate, and a very unique attribute for tape—rapid access to data (less than 11 seconds). This was enabled by the use of a novel dual-reel midpoint load cartridge. The technology implementation was delayed for several years as the product focus shifted to address a replacement for the aging 3480/3490 Enterprise tape products. Many of the key technology patents, however, were issued two or three years before the NTP product was finally introduced [12].

While a focused effort was underway to deliver the NTP products, a very small team within the Tucson Laboratory carried out a skunk-works project to move some of the NTP technology into the aging 3480/3490 Enterprise tape market. In 1995, a new family of devices, the IBM Magstar* 3590 tape drives, were introduced as the final products from the project, which had started so slowly in the early 1990s[3] [13]. This new family of high-end IBM tape drives reset expectations for Enterprise tape and quickly became the platform upon which growing support for operating systems and applications was based.

The Magstar 3590 provided 10 GB of native capacity with a 9-MB/s data rate on a new servo-written metal-particle tape in a 3480/3490-type cartridge, so it remained compatible with existing automation devices. This marked the first time that a new format was introduced while preserving the investment in automation and addressing the migration of tape technology to a new generation. As a result, a tenfold reduction in the number of cartridges needed to store the existing 3480/3490 formats was achieved without requiring changes to the automation or significant disruption of customers' operations. The 3590 was a remarkable success and, within a few years, became the new standard for Enterprise tape storage [14].

A significant advance in performance and connectivity soon followed with the 3590 Magstar ESCON Control Unit Model A01 in 1996. The next year, the 3494 Model B16 Virtual Tape Server (VTS) was introduced. This device was the first to present a tape image to the host system (the 3850 MSS presented a disk image to the host) and greatly improved utilization of tape resources. The VTS optimized the filling of tapes while presenting a single image to the host computer and operational software. This seemingly simple function dramatically improved and optimized tape storage and the migration of large data sets [15].

The 3590 was expanded in performance in 1998, with the 3590E model doubling native capacity and improving performance. This was followed by the Magstar Extended Length Cartridge media in 1999, which provided 40 GB of native capacity while preserving the existing automation and installed devices. The Enterprise tape family was thus given four times more capacity and better than double the data rate with the new device and tape combinations, while reliability and cost per gigabyte were improved as well [14].

Finally, the revolutionary tape architecture begun in the early 1990s as NTP was unveiled in 1996. The IBM 3570 Magstar MP with its 5-GB cartridge was the first small-form-factor midpoint-load tape device. It marked the introduction of a track-following timing-based servo and a number of innovations that leveraged the technology of IBM disk storage. In 1997, the capacity and performance of the Magstar MP 3570 was extended to 7.5 GB with the enhanced-capacity cartridge [16].

An open-system solution

An informal, internal push within the IBM Tape Development Laboratory began in late 1997 to move the exciting technology developed for the Magstar MP 3570 into the existing product architectures. Eventually, this push evolved into an aggressive effort to establish, with other storage industry leaders, a truly open-systems tape solution—Linear Tape-Open, or LTO. In less than two years, this technology went from the laboratory to the marketplace. The IBM Ultrium LTO drive brought with it new automation solutions and reemphasized the cost advantage of tape storage. It also provided a new impetus for the future. As the 20th century drew to a close, the IBM LTO was announced, and a new technology roadmap began for tape [17].

The innovations in data storage and processing on tape that had begun in the 1950s moved relatively slowly in its first 20 years, but the advances, particularly those related to density and performance, were being achieved at an accelerating rate. The unfolding of a new century found 100 GB of native capacity already available on a single LTO cartridge. Magstar 3590 had just doubled the capacity of its full-function enterprise-level tape solution by introducing extended-length media. The performance and reliability of both the initial 10-GB media and the new extended-length media were attained through an intensive co-development with leaders in the magnetic tape industry. By 2002, the Magstar 3590 Model H had been introduced. It provided up to 60 GB of native

[3] Internal memo from John Gniewek to Steve Vogel, October 25, 1991 (IBM Confidential).

capacity and greatly improved reliability and stability to a now mature enterprise tape format.

Many of the breakthroughs in IBM disk storage in the early 2000s made their way into tape and tape controllers, including the ability to partition physical libraries into a number of logical libraries, Fibre Channel support, peer-to-peer duplication of data, support of Linux** and other Open Systems, and new connectivity options across a growing number of storage platforms. At the same time, the reliability, serviceability, and overall cost of IBM tape subsystems improved while tape technology in general was called upon to hold increasingly greater amounts of the world's data [18].

The IBM LTO Model 3580 head was the first IBM tape drive recording head to break away from the older modular closed and contoured head designs that had carried the burden of linear tape drive recording for so long. Given the proven capabilities of these disk head technologies, significant increases in tape track density were possible. This improved head process allowed the mass of the head to be reduced while achieving synergy with disk head technology and process advances.

A timing-based servo, invented by IBM, provides very precise position information to the drive so that interleaved bands of data can be written in a serpentine manner, eight tracks at a time, to construct 384 tracks capable of storing 100 GB of uncompressed data in the first-generation LTO cartridge. Coupled with improved media, actuator, and format innovations, significant increases in the reliable placement of very narrow tracks on a thin tape were demonstrated with the first LTO tape product.

The IBM LTO family of tape drives will deliver increased storage capacity and performance for several generations. Consistent with the LTO roadmap, a 200-GB-capacity cartridge was announced in 2002. It delivers a significant improvement in data rate from 15 MB/s to 35 MB/s. LTO storage currently provides more than several hundred terabytes of uncompressed capacity in a fully automated IBM tape library that takes up a space equivalent to only eight five-drawer file cabinets. These automated tape solutions are able to support multiple tape formats in the same physical library separated from the host by distances of 100 or more kilometers. Additional capacity increases, serviceability features and functions, support of multiple tape formats within a single physical library, and logical partitioning of libraries are being introduced to sustain the viability of tape storage well into the future. IBM's long history and experience with tape and, indeed, all forms of digital information storage, provides it with a unique ability to offer the seamless integration and management of information storage and retrieval that emerging on-demand businesses will require.

Summary and conclusion

IBM continues to push the boundaries of tape storage technology. In 2002, the 50th anniversary of IBM's introduction of tape storage, one terabyte of uncompressed information was successfully written and, more significantly, read back successfully in a single half-inch tape cartridge equivalent in size to the current LTO tape cartridge. The compression of one terabyte of data into a four-inch-wide by five-inch-long by one-inch-thick cartridge exceeds a density of one gigabit per square inch on the recorded media.

This advantage was achieved using advanced particulate tape technology coupled with improved high-density track placement, made possible by utilizing a novel track-following timing-based servo invented by IBM and the most advanced recording head technology used in linear tape drives. By leveraging the technology breakthroughs pioneered by IBM for hard disk storage into tape storage applications, one terabyte is only a milestone, not a barrier. The next 50 years look as good as the last 50 years have been. We should expect to see capacity improving, substantial gains being made in data rate and reliability, and greater efficiencies in tape storage management.

Acknowledgments

The authors acknowledge the support of both active and retired IBM workers who provided reviews and commentary as well as copies of hard-to-find documentation of the early pioneering efforts in tape storage. A special thanks goes to Wayne Winger, Max Femmer, Bill Phillips, Billy Joe Mooney, John Carter, and the IBM Tucson Communications Group, who found and digitized the photographs of the early hardware. No history of IBM tape could be made, furthermore, without a sincere acknowledgment of the many people who hold the patents, designed the devices and subsystems, integrated the software and functions, built the products, sold IBM tape to customers, and serviced and supported tape products all over the world for more than 50 years, and who will continue to do so.

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Received February 26, 2003; accepted for publication March 13, 2003

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