Oral History of Richard Dee

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Gardner: This is Tom Gardner representing the Computer History Museum. We're here today, October 9, 2017, at the offices of Aweida Venture Capital, in Superior, Colorado, to interview Richard Dee. Richard will go through his background in a few moments, but let me simply say that Richard is a technologist with experiences at both Storage Technology Corporation and Quantum. At one point, he was the StorageTek fellow. And his area of specialty that we'll discuss today is recording head technology in tape drives. So, Richard, tell us a little bit about yourself.

Dee: Okay. Well, as you can tell from my accent, I'm British by origin. I was born in England a long time ago, and there I got degrees in physics. I went into the field of physics and got a Ph.D. in physics in the end and moved to North America to do research at the universities. I was at University of British Columbia for three years and then UCLA, Department of Physics there. And, after that I worked in low-temperature, superconducting magnetometry. And, from there, I was recruited into StorageTek.[1]

Gardner: Let me back up. Where were you born, in what city?

Dee: I was born in Barnet,, Hertfordshire, just north of London.

Gardner: Your mother's maiden name?

Dee: Good question. That's actually a bit secret, because that's the question they always ask you on all the websites. So I can't reveal that. Otherwise some people can get into my accounts.

Gardner: Hm. That is true. And your parents are from the same city?

Dee: Yes, they were born in London.

Gardner: And what university?

Dee: I went to the University of Lancaster in the North of England.

Gardner: That's where you got your Ph.D.?

Dee: Yes, right.

[1] Richard Dee donated some material to the Museum under the lot number X8477.2018.

Gardner: And how did you get interested in physics?

Dee: Well, I guess it was at high school. I was pretty good at math and science but not very good at languages and history and stuff. So, the fact that I did well at it made it more enjoyable. So, I think I went into the sciences quite early on at high school and then decided to go to university to study physics. Actually, I almost went into a career in electric engineering. I was recruited by the electrical supply industry in England to train to be an engineer, but I only lasted there three weeks. Then I went to university to do physics instead.

Gardner: <chuckles> Why only three weeks?

Dee: Well, in England, the system at the time was you've got these exams, the entrance exams to university. And I didn't know the results. And I said, "Well, I really wanted to go to university in physics." And the people that worked at the electrical supply industry said, "Well, you can start with us. And if you get into university, fine, you can go. But if you don't, you can stay." So, I worked there, for three weeks, until I got the results and a place at university and then I left.

Gardner: Are you married?

Dee: Yes.

Gardner: Children?

Dee: Yes, three daughters.

Gardner: Your wife's maiden name?

Dee: Ross in that case.

Gardner: Ross?

Dee: yes.

Gardner: Okay. You then went to British Columbia and did some research in the university there?

Dee: Yes. I was a postdoctoral fellow there, worked in low-temperature solid-state physics to do its superconductivity on organic compounds rather than metals. So that was the hot subject at that time. And the one material I was working with was called polysulfur nitride made out of sulfur and nitrogen. And, strangely enough, it was a superconductor at 0.3 Kelvin. So, we worked on the properties of that material.

Gardner: And then to UCLA?

Dee: Yes. I was an adjunct assistant professor at UCLA in the physics department.
But I was only there 18 months, because I was looking for a permanent job. That was only a temporary position. So, I was looking for a permanent job almost the day I arrived. But I taught physics there and did research and looked after the graduate students and so forth in the lab and then finally got a job in industry, essentially, in a company in San Diego that made SQUID-based magnetometers, SQUID standing for superconducting quantum interference device.

Gardner: And when was this about?

Dee: 1980?

Gardner: More or less?

Dee: Yes, 1980. 1979, I was still at UCLA I think, yes.

Gardner: And what was your specific activities on SQUIDs?

Dee: SQUIDs? Well, I basically just used them, okay? Didn't actually make them although I did make some mechanical point-contact SQUIDs, at UBC, to use. You can make them and we made them in the machine shop. They weren't thin film devices at the time. They were mechanical ones, but they worked great.

Gardner: What did you use SQUIDs for?

Dee: Detecting very small magnetic fields, really small, down to 10^{-6} gauss or below. Looking at small changes. In these superconductors that we were looking at, we were looking for the magnetic expulsion that you get due to the Meissner effect. And in this material, it was really small.

Gardner: The what effect?

Dee: The Meissner effect. When a metal goes superconductive -- from a normal to a superconductor, it expels all the magnetic flux from its interior, okay?

Gardner: Okay.

Dee: That's a phenomenon of superconductivity. So, you can prove that that material is a superconductor if that happens.

Gardner: Gotcha.

Dee: Because it only happens with a superconductor.

Gardner: So that's the beginning of your serious work in magnetism.

Dee: Little bit, Yes.

Gardner: Somehow you wandered or went from that company to StorageTek?

Dee: Yes. That was because a lot of times they always say it's not what you know, it's who you know. But it's bit of both sometimes. In this case, that was the case. A gentleman worked at the company in San Diego who was from Boulder, Colorado. And he and his wife decided to return to Colorado. And so, a few months later, about six months later, I got a phone call from him. Because I worked with him closely at a company in San Diego, and he invited me to go work at StorageTek. And it took him two attempts to get me to come here at StorageTek primarily because of the job that was being offered.

Gardner: The first job was not so interesting.

Dee: No, no. It was a manufacturing position that really wasn't my forte. But then six months later, he phoned back and I came out to visit. And it was a job to develop thin films for magnetoresistive devices and tape heads. Because at the time, StorageTek had a fledgling group that was doing some advanced R&D work in the area and they needed someone, I think, that understood magnetism and thin films, which I'd worked a bit in thin films at UCLA and also at a company in San Diego -- they made thin film SQUIDs, there and other thin film magnetometer types.

Gardner: Did you name the company?

Dee: It was called SHE Corporation, SHE, it stood for Superconductivity Helium Electronics. It was called SHE Corporation, and doesn't exist anymore. It morphed into something else as a lot of companies do.

Gardner: So the second time was a charm at StorageTek.

Dee: Well, yes, that time the work seemed more interesting. It was a research and development job, and they invited me out to Colorado. And, of course, I fell in love with Colorado, which is not difficult. And we, my wife and I decided it was a good move to make. So, [in 1982] we left San Diego. We like San Diego, too. But I think we like Colorado better.

Gardner: So now you're in the world of tape heads.

Dee: Right. Which was unusual. This was the first time I'd had a job where everything was at room temperature. Because I'd been working in low-temperature physics, which practically everything had to be done at 4 Kelvin and quite often below 0.1 Kelvin to see what we were looking at. So, this was quite different. It made life a lot easier. Let's put it that way, okay?

Gardner: In some ways I presume.

Dee: Yes.

Gardner: Some ways not so.

Dee: Some ways not so. But to do the experiments and design or whatever at room temperature rather than hanging it on the end of a stick and dipping it in liquid helium made a big difference.

Gardner: So what did you find when you arrived in this research group[2] at StorageTek?

Dee: Well, what I first found was they put me in a cubicle -- I got some strange looks. Because the Friday before, there was different person sitting there and they got laid off. And this was kind of disconcerting at least for the first week or so. But, no, I found that we were in Building 6 over here on

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[2] [Editor's note] Fledgling R&D group managed by Robert Billington and included Joe Schaps, Marybelle Blakeslee, Dave Montrose, Mick Lierley, and one other I can't remember. Others joined later.

StorageTek campus. And it was because downstairs there was a cleanroom where they were developing a thin-film disk head for the upcoming disk drives using plated permalloy and copper coils and so forth. And they felt that this tape fledgling R&D group could use a lot of the vacuum [equipment] and the cleanroom for that matter. They didn't think they wanted to build another cleanroom at the time. So, we borrowed the cleanroom. And we were supposed to-- and I was there to develop a magnetoresistive thin film. They'd already started but not making a lot of headway apparently. The first thing we tried was-- they were trying to evaporate permalloy to make thin films.

Gardner: Just one interruption. This was now before there was any magnetoresistive tape heads shipping in any tape drives?

Dee: Oh, yes.

Gardner: This was before the IBM 3480.

Dee: Oh, yes. Yes, that was tape drive by the way. But, yes, tape drives, as you know, came out with magnetoresistive heads many years before disk drives did.

Gardner: This was before any tape drive was shipping with a magnetoresistive head.

Dee: **…**yes.

Gardner: So somehow your group was anticipating the future direction.

Dee: **R**ight. Not quite sure how, whether they got some intel from somebody. I don't know. But there you go. That's how the industry works, right? You typically go to conferences and so forth and you see what's going on, and you can put two and two together quite often.

Gardner: Was it 18 tracks at that time or just a lot of tracks?

Dee: I think it was 18. Yes, think it was 18 from the get-go. So obviously there was some information that was coming out,-- everything was 9 track up to that time. So, 18 was doubling. And so that made kind of sense, because pretty much capacities and so forth in tape drives for a long time been doubling. And so, yes, it was-- I think it was 18 from the get-go. And we managed to make 1 or 2 tracks work now and again at that time, but that's what R&D's all about. Yeah, so.

Gardner: What were some of the interesting experiences during this development stage?

Dee: Okay. Well, one of the first things I discovered-- you asked me what I discovered. Okay. One of the first things was we were evaporating these thin films and you had to evaporate them onto a substrate that was elevated temperature, 200 centigrade or so forth. And the first thing was, from a technical standpoint, was I said, "How do you know what the temperature of the substrate is?" And they had this thermocouple stuck on the back of this substrate with a big heat lamp on it. And I said, "I can tell you this much, that your thermometer is probably at 200 centigrade but I have no idea what the temperature of substrate is." So, the first thing we had to do was to figure out what the temperature profile of the substrate plates were. And it took some time to feed in thermocouples on the front surface and characterize it we did temperature time curves to figure out that the temperature on the back on the thermometer had to be considerably different if you wanted the surface to be at 200 centigrade. So, we fixed that. And the next thing that happened was using test coupons on silicon substrates to measure the magnetic properties of the films that were resulting from this. And I used this magnetic loop tester, which we used to call a Bacon tester. In the industry, again, a man named Stanley H. Bacon, don't know whether you've heard of him…

Gardner: I haven't.

Dee: **…**he made magnetic loopers to do hysteresis loops. And I think everybody bought one that was doing this. He made quite a lot of them. And he put this substrate into these coils that excite the film. And then you detect the resulting magnetization change, and it plots it out on an oscilloscope as a hysteresis loop. And there were certain properties you needed, which was a high magnetic anisotropy had to be in this MR film. In other words, the magnetization had to align on a very strong easy axis, they called it, where the magnetization would prefer to lie even when no magnetic field applied. And so, you had to rotate the sample to see what the anisotropy was. And I noticed that the tech that was running this put this film in, and you got this horrible-looking magnetic loop that wasn't what you wanted. And he said, "Oh, well, if you turn this knob, it looks great." So, he turned this knob on this machine, and the film looked perfect. A lovely straight line, hysteresis loop in one direction, a perfectly square loop in the other. Great anisotropy. I said, "What does that knob do?" He said, "I don't know." Okay? And I said, "Well, we got to find out what that knob does." Okay? All it was doing was applying a DC magnetic field in one direction across the film. So, it was aligning the magnetization before you did the excitation. I said, "We need to get that film to look like that perfect loop that you wanted without that knob being turned, okay? The film has to do it, not an external field." And so, when we got the temperature fixed, we got the applied field and the deposition fixed. Didn't take long. Only about two or three weeks, that month after I arrived. We got the films to run with the correct anisotropy without faking it with this DC bias field that was in the Bacon tester we called it. And that film was the first one we put into a head to test, and fortunately that first prototype head actually worked.

Gardner: Really?

Dee: Once you got the film correct, it was fine.

Gardner: Were you at single element or 18 elements at this time?

Dee: We had 18 elements. But we didn't wire them all up, because we didn't have any good wiring schemes then. It was basically a jeweler we hired to hook up little wires with little tiny soldering iron. His name is Joe Schaps. He had a jewelers down in Boulder, and he worked at StorageTek in our lab to do the very fine work. He used to fix-- he was great at repairing antique watches. That was his skill. So, we had him in the lab to do all the little fine work on these devices.

Gardner: As I understand it, in tape head technology, one of the challenging problems is getting all the wires out of an 18- or 36-track head.

Dee: Yes, the interconnect. There's a lot of wires. There's two for each channel plus a few hangers-on, right?

Gardner: Right.

Dee: There's a lot of wires.

Gardner: In a small space.

Dee: Yes. We used to fan them out a bit to help get a bit bigger. But still pretty small. And then you had to wire them all up. So, there's 40, 50 connections. And they all had to be good every time, right? And that was a challenge. But initially the first head was essentially discreet wires that were hand soldered by Joe Schaps. He was good at it, too, yeah.

Gardner: Tough to scale.

Dee: Yes. No, that wasn't the point. We were the on leader. We were proving that the science and technology of the devices themselves, the scaleup to batch fab the whole structure, was the next step. The masks were made to do that, but we only tested a few of the devices initially.

Gardner: This is now '83, '84?

Dee: Yes, ’83, Yes, and ’84, right. And during ’83 we started to work on the interconnect with a flexible circuit, a flexible printed circuit with copper leads on a Kapton base with the same pitch as the pads on the thin film device. And the initial connection system we used was ultrasonic bonding gold to gold. So, you plate gold on the flexible circuit pins sticking out and gold on the thin film circuits. You lay them on and come down with a high-pressure ultrasonic energy source to try and bond them together. And that worked after a fashion, but it wasn’t very reliable. Films tend to peel up and that’s not good, okay? And eventually the technology we use was stitch bonding, where it’s a thin aluminum silicon wire which comes down and bonds onto the flexible circuit pad, then loops over and bonds onto the thin film. So, there was some flexibility -- it wasn’t as rigid and brittle as the other contact. It had some flexibility. And this thing used to be programmed X-Y. So, it would stitch along <makes stitching sounds> and stitch all the wires automatically.

Gardner: This was still a Storage Technology unique design. You were designing it to your own parameters that were intended for an OEM product or intended just as a research product anticipating an IBM product?

Dee: Yes, anticipating IBM’s 18-track product coming out, which came out, I think, in 1985 if I’m not mistaken, 3480. Came out with a magnetoresistive 18-channel head.

Gardner: It was announced March 24, 1984 with general availability in the first quarter of 1985.

Dee: So we had in place, in ’84, already the MR elements, which were differentially biased and sense elements. They weren’t singles. They were center tapped with the differential bias, and we had that already in 18 channels. And the write head was several turns of gold with a ferrite base for its magnetism to form the Write gap. Was between two ferrite blocks with a thin film write coil __________.

Gardner: Was this a write-read-write or just a read-write head at this point?

Dee: Yes, one module had 18 readers on it and one module had 18 writes. So, it only ran tape in one direction in one pass to fill the tape.

Gardner: This was working in the lab, then IBM product is announced and then you get an IBM product.

Dee: Yes, that’s right. StorageTek was one of the first customers to buy one. And, of course, it was interested in how it could make a tape drive, because it was already working on it, such that it was compatible and an interchange using the tapes so they could read and write the same tapes as IBM in that case. And our head was a slightly different design than theirs after looking at the IBM head. Of course, it would be because different engineers and scientists developed it. One thing I learned years ago, if you give two groups of engineers the same problem, they'll come up with different solutions. And that was the case here. It was 18 channels, it was a differential MR head, that was the same, thin film write coil. But they were different designs magnetically. The write coil had more turns. The read head was biased differently. The MR head was biased. Has to have a DC field applied to it to linearize it, and that was done differently in our design compared to what IBM used. And we didn't change it. The only thing we changed from what we ended up with to make it compatible was we dropped the write head to two turns from four. So that was how we ended up with a compatible drive. And, also, the other thing we did was we didn't guess the track pitch correctly. So, we had to shift that.

Gardner: The track pitch or the track placement or both?

Dee: Probably a bit of both, yes. And the width.

Gardner: Yeah, you have a half-inch tape and you have 18 tracks. But exactly where the tracks are, guard bands and the width of the element…

Dee: We'd come up with our own set of numbers for that. IBM's drive was slightly different. So, we had to be compatible. So, we shifted the dimensions.

Gardner: My understanding, from early conversations, it was pretty close.

Dee: Oh, yes, it was pretty close. In fact, so close that, I think it was the Christmas break of '85, StorageTek was still trying to decide whether they could buy this head. Didn't want to manufacture it. It'd been buying tape heads from other manufacturers for its whole lifespan. And, of course, they couldn't buy them from IBM. So, one Christmas we came in. I came in with another engineer and, during the break, when no one was there, and he was pretty skillful in removing, aligning tape heads and tape paths and things. So, we took the IBM head out of the IBM drive, put our prototype head, one of the ones that actually worked, okay? Had 18 channels working. Put that in and aligned it according to the same measurements he'd made from the IBM head. And we plugged it in, because it turns out the connectors were the same. That was another bit of serendipity, okay? The connectors were the same. So, we just plug it straight in…

Gardner: Really?

Dee: **It** ran the diagnostics and the error statistics. And it matched the IBM numbers with the IBM head in there even though it wasn't an exact clone. The MR head was different, had different resistance and different biasing scheme and so forth. And the write head was two turns, but it had a different back structure in terms of the ferrite. It was more efficient. The IBM head used to run on 190 milliamps, if I remember rightly, and ours ran on 150, 160 milliamps. So, our head ran with the wrong current, but it still wrote just fine. And took the data, wrote the report, put the report on the director's desk. So, when he came in, January the 3rd, he would read that. And that's what made the decision for StorageTek to set up a manufacturing line to make thin film MR tape heads.

Gardner: Was it more than system or subsystem diagnostics? You also do analog-type measurements, resolution, things like that?

Dee: No. At the time, the only thing we had time to do was to really run data and look at the error rate counts. But it ended up that recording channel with that tape, the chrome dioxide tape, had a lot of margin. We ran the write current way out of the write current, past the peak. But it still wrote fine. And I'm sure that the read signals might've been a little distorted, but it was a peak detecting channel. And as long as it was in the timing window, didn't matter if it was a funny-looking wave form. As long as it was above the threshold within the timing window, then it would deliver the correct data.

Gardner: At that time, was the head tape interface design the same as IBM?

Dee: Actually, it wasn't. I think originally the design we had had straight crosscuts in the ferrite surface to scoop the air off, and IBM came out with parallel slots so that it would lighten the contact pressure. Because it turns out chrome dioxide tape was the next best thing to sandpaper, in my opinion.

Gardner: <chuckles>

Dee: **O**kay, for scraping over heads and wearing them out. So, I'm sure IBM made it such that it wasn't pushing down quite so hard on the surface to extend the head life. And it didn't take much -- I mean, even IBM's contour, the wear pattern was a wavy line right across the head. Down where the elements were, where the slot was, in front of it, it would wear. And in between, where the air would run, it didn't wear. So, it was a compromise contour over performance versus head life.
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Gardner: So in spite of a more efficient write element and a slightly different head tape interference, the head, from the lab, read and wrote in an IBM drive to the standards of the IBM diagnostics?

Dee: Yes, that's correct.

Gardner: That's pretty impressive.

Dee: Yeah.

Gardner: So in looking back, in your mind, comparing the two heads, walk me through a comparison. Which features you think were better perhaps in the IBM design and better in your design?

Dee: Well, I'm very biased here…

Gardner: Of course.

Dee: I think we were better in our MR head design. The biasing technique we use, it was called offset in the gap. So, there's two magnetic pieces that form the gap. And the MR element wasn't in the middle. It was off to one side. So, when the sense current runs through the MR element, there's a magnetic field that couples to it and provides you the bias field the MR head needs to linearize it. In the IBM head, they did a little bit of that but they ran 2,000 angstroms of titanium as a shunt beside it to draw some of the current so that the current delivered the field you wanted. However, if you shunt it, the word shunting, you shunt the signal to it. So, the output was lower, and there was this huge 2,000 angstroms of titanium next to the MR element that actually wasn't necessary. So, it wasn't in our design. We didn't think to put it in because…

Gardner: Never put it in.

Dee: No. You could get the bias field you want just by offsetting it more. Now, the bad thing about the offset, if you want a negative thing, I'll have to think of something negative, okay, is that, when the tape runs in this direction, the wafer looks different than when it's running that direction. It goes sort of-- it goes lopsided. It's a phase shift, and the channel has to deal with that. So that could be perceived to be a problem. Because in the IBM design, that was less so because it was nearer the center of the gap. So that's a design detail.

Gardner: We'll probably return to it. But at this point, I understand you are the lexicographer for the tape recording axioms? You have three of them?

Dee: Oh, yes. Yes, I came up with what I call the three axioms of storage devices, not just tapes.

Gardner: Understood.

Dee: I gave an invited talk at the NSIC Annual Meeting in Monterey many years ago. And it became clear to me, over time, that there were three things that governed everything in storage devices. Axiom number one was that the media is the problem, okay? It causes all your problems and it determines what you can or cannot record, densities, speeds, feeds, everything. Axiom number two is the head is the messenger. It's telling you what the media's doing wrong or right. And axiom number three is the channel has to understand the messages, and they have to stop whining about that. Because they're always shooting the messenger. When the channel guy looks at his signals, he always blames the head. The first thing they do, they change the head out. But 9 times out of 10, it's the media is the problem.

Gardner: I interrupted you there because you talked about the channel having to deal with a phase shift. And that brought out the axioms

Dee: In that case, the messenger could speak with a forked tongue because of that offset. Because sometimes the tape drive would read backwards. That 3480 and StorageTek's 4480 would be asked to read backwards, okay?

Gardner: Which brings me back to that this first head now being put in the IBM drive. It was a read-backwards head, meaning it had a read element with write elements on either side.

Dee: No.

Gardner: No?

Dee: It would read the tape that was already written backwards. So, you'd write the tape this direction and read it, read while write. And then, at some other time, it stops and it wants to read something back.

Gardner: Reads backwards.

Dee: It reads the data in reverse order. It's not writing. It's just reading. But even though our head had this asymmetry, the channel has enough margin that it could absorb that.

Gardner: That was the point I was getting at. The IBM channel could deal with your head which had the different asymmetry. Now, the STC channel was then designed to deal with the asymmetry too?

Dee: Yes. I think it had two different settings, the forward read or reverse read.

Gardner: So you mentioned four turns versus two turns. But in the production head, you went to two turns.

Dee: Two turns.

Gardner: That was an engineering decision or a management decision?

Dee: No. I think, at the time, that was a management decision. They wanted it to be compatible with IBM, and they thought the head might be more compatible if it was two turns. It turns out it made no difference at all. Especially our two-turn head, as I mentioned, was much more efficient than the IBM design because of the way the coils were laid out. So, the write current in our head was 30 percent lower than theirs anyway. So even though it ran in a tape drive, the optimum write current would be different in the 4480.

Gardner: With four turns, the current would've been reduced by another factor of two.

Dee: Yes, which we thought was a good idea. The head displacement was different, and the amount of power required out of the tape drive would've been lower. And I think the, like I said, I think the rise time was sufficient to give the recording characteristics correct.

Gardner: You mentioned transverse versus longitudinal slots. Either one better, different? Does it matter?

Dee: At the time, with nickel zinc ferrite as the base for the head, the magnetic pieces, I think the slots across the head wouldn't have survived very long. The corners would've worn off and it would've started to fly. So essentially the 4480 head came out with exactly the same contour as on the IBM head.

Gardner: And probably the right decision.

Dee: Yes. There was one change we wanted to make. But, again, that was turned down because actually it was too late in the manufacturing cycle. On the edge of the tapes, there was two slots in the same direction of the tape where the tape used to droop into these slots. That was to cover the problem of debris accumulation on the tape edges. And there was two slots, each side, and the piece of ferrite in the middle. That used to wear off. So, track 1 and track 18 used to wear down and then the head would fail. We came up with another idea where you had one slot, put more ferrite out there, take the inner slot out and then track 1 and 18 didn't wear out. But that was never introduced.

Gardner: How long did it take then from the time you got the 3480 head until you then had a head you felt was suitable for a Storage Technology tape drive?

Dee: **…**I can't remember. I don't remember when the 4480 actually came out, tell you the truth, whether it was '86 or '87. You know what? Sorry.

Dee: But the head was the technology gating item clearly. Without that, there was no tape drive for StorageTek if we didn't actually make it.

Gardner: The production design was actually done in a different group than yours and you guys went on to the next generation?

Dee: No, we actually took the head design and processing. The groups were blended for a while. The R&D group and the advanced manufacturing group were blended for a while. And then, when everything was final, we went back to R&D again to do the next head.

Gardner: For what it's worth, IBM announced it's 3480 in March of '84 with general availability in the first quarter of 1985.

Dee: Oh, wow, that was quicker than I remembered.

Gardner: Well, sometime announcements of availability don't occur. But that was the official announcement and the stated availability date, first quarter '85.

Dee: So this head was the first head that StorageTek had ever manufactured from raw material onsite here on the Louisville campus.

Gardner: Prior to that, Storage Technology had purchased heads.

Dee: Yes.

Gardner: Why didn't they purchase this one?

Dee: Well, they used to buy heads from Applied Magnetics and Nortronics. Used to make the big 9-track, coil winding-type heads. And it turns out that those two companies couldn't come up with a thin film-compatible head in the time frame that was needed. A couple of them came and gave us presentations about designs and they were different -- I wouldn't say they were alien to us but they were completely different, not a ferrite head with two turns of gold in between, a very simple design. They were the complicated, more plated, thin-film, disk-type heads, which had multiple layers and multiple thick permalloy magnetic pole pieces, which unfortunately didn't respond fast enough to the 45-nanosecond write equalization pulses you need to get through to the tape in that product. And one of the principles that drove us in the design originally was, because we had to have so many channels all working in one process, the processing had to be kept simple. Like all thin film or integrated-circuit work, the more you touch the part there's a probability of getting it wrong or having an error. You could have 99.99 percent product correct, every step. But you multiple that together, and you get a lot of yield dropped. You have to have all 18 working all the time, every step. So, the processing that we had on the write head only involved one photolithographic mask, okay, to do the whole write head, okay? The companies that were proposing what they were going to do had about 10 photolithographic steps, okay?

Gardner: Okay.

Dee: And we had one. That one photolithographic step defined the coil, plated it and then you evaporate the coil through it and lift off your photoresist and the write head thin film was finished. And on the magnetoresistive head, there's only two steps, one for the MR device and one for the overlay, the copper-gold overlay, on the back leads. So, in other words, three masks to make an 18-channel read-write head.

Gardner: Or three masks per channel.

Dee: No. You do all 18 at the same time. So, in other words, the mask had 18 images which you put down whack and then exposed it and done in one go. And the write-read head only had two masks, and the write head had one. Then you have an 18-channel read-write head finished in the cleanroom. So, the yield was pretty good, okay? These other designs, the yield was terrible. AMC sent us some prototypes back in '84-ish time frame. Only one channel would work. And we said, well, that's not quite good enough, we need 18. So, the processing went down to building eight, where the thin film disk heads were being made to utilize the cleanroom down there. So that was in I guess late '85-ish to do that. So, of course, that was after StorageTek had gone Chapter 11, which made life interesting.

Gardner: So, at this point, we've finished talking about the 3480 class of heads, which Storage Technology produced a different head but was fully compatible in several ways, in your opinion, a better design. And so now, at this point, the group moves on to the next generation of heads?

Dee: Yeah, that product was shipping. So, the R&D group thought about what was going to come next as tape capacities have been doubling every time. The next doubling, it was fairly straightforward to double number of tracks. Because if you do that, you can use the same tape and you can use the same channel, you can use the same cards, everything and just produce another tape drive at twice the capacity, okay?

Gardner: Well, to use your term, the message from the head may be a little different because the areal density's now gone up by at least a factor two.

Dee: The areal density, yes.

However, as you know, the track widths at that time are very large from what we're used to now and even shortly after that. But clearly the requirement from the channel group was that the output from the read head had to be the same. Even though the reader was going to go down at least a factor or two and probably a bit more to allow for mis-tracking. Because it was write wide, read narrow in a sense. If you're going to halve the writer width, then the reader had to go down a factor and probably a bit more. Went down a factor of three almost I think. But the output had to be the same, okay?

Gardner: That sounds like an impossible task.

Dee: Well, unless you know what you're doing, okay? So, when you do an MR head, you know that the output is proportional so the change in resistance and the MR ratio for a permalloy element is about two or three percent. So, if you want the same output, the ratio of the change in resistance over the resistance is still going to be two or three percent. So, the way to get the change in the resistance to be the same, you just have to raise the resistance of the element or make the resistance of the element the same as it used to be. So for the wide reader if it was 30 ohms you had to made the narrow reader 30 ohms, and to do that you just reduce the width and the thickness of the element, and that's what we did.

Gardner: Pure scaling.

Dee: That's all we did, just scaled it and got exactly the same output, the 4480 head with a third of the track width, and the read/write group said that it was a miracle as you just said, but it really wasn't. It was just scaling and you can keep scaling our heads for a bit more than that probably, as disk drives demonstrated in the '90s, but again it was a full differential bias, differential read, and differential sense, and it was exactly the same as the 4480 head, only scaled down. So in other words, I really didn't have to do much which is why we got it out fairly quickly, and the write head was the same. Again, two turns or so on a ferrite base. The only difference between the 36 channel head and the 4480 head was the 4480 head had one module which was all write and one that was all reads, and for the 36 track to go, say you want to read and write in both directions, you interleave them. So there was a writer and a reader, a writer and a reader. So in each module there was 18 writes and 18 reads side by side interleaved. So you first did the write process and then you came back and did the read process. So what we did is we essentially did the same process, thin film process that was on the 4480 interleaved on the same substrate, and then once you've done that you just cut two of these modules and turn one over to face the other, and there's a reader downstream from this writer and a reader downstream from that writer. So you can do both directions, and we got that head out, the prototype out fairly quickly and tested it and it worked just the same as a 4480 head pretty much, and put the report on the director's desk that we'd done this 36 channel head to double the capacity of the tape, and just by a miracle of fortuitous, the very next day IBM announced their 36 channel drive and it was to be this doubling track density, two-direction tape motion that was compatible with this 36 track head that we'd developed. Again, the only difference was the reader width wasn't the same as the IBM's head. When it eventually came out we saw it, and the track pitch wasn't quite exactly half of something. They'd shifted it over a little bit and we didn't know why but we had to be compatible, so we moved ours.

Dee: So that head really, even though it seemed more difficult to do and everything, the people in the clean room, in the R&D clean room did a great job in merging those two things. There was one photo-lithography expert, Marybelle Blakesley, a lady who was an expert in dual layer photo-resistant process, which we used a lot in the write head process, and she was the one. There was the original design of the write head and this interleave design, and by that time StorageTek had invested in an R&D clean room for us. So we had our own space. So we were able to work independently of the manufacturing line or vice versa. They were able to work independent of us because, you know, if you try and do R&D on the manufacturing line, all of the manufacturing engineers don't like it because you're disrupting their processes. So that period of time when we had our own clean room enabled to really pretty fast 36 track development, and beyond that we even developed a 72 and a 144 in parallel with that and we offered it to StorageTek saying "Well, you can do a 72 on a 144 track, okay, with the same design on chrome tape," but they were in the mode at the time of being IBM compatible. So if IBM wasn't going to do a 72 track tape on chrome then StorageTek wasn't..

Gardner: And would this be the same concept of just smaller by scaling more

Dee: Yes. The tape industry wasn't using track following servo at the time. The concept there which was upped from the head group to suggest to the companies that you take two 36 channel heads and offset them to get you 72, to scale the widths of all the channels. Just stick two heads in. That was turned down because that would cost twice as much apparently.

Gardner: At least for the head part of the drive.

Dee: Yes. Right. So, and the same sort of idea for 144s or you have what we call a bang-bang head where it had two positions. No servo. You just move it on an actuator up or down against stops, and that was the concept then. But none of those transpired, primarily because IBM never went to a 72 or one lower, 144 fall.

Gardner: And as for yours, you could tell management was not willing or interested in pursuing OEM opportunities

Dee: I guess not at the time, and later they did by the way, but as a result there was a lull in products, StorageTek tape products between the 36 and whatever came out next, which we'll talk about if you like. There seemed to be a long gap, several years of not knowing what to do next. I mean we came up with the 72 and 144. You can do this next. You can do this next, you know, but that never transpired. And then the concept came up. I don't know who suggested it, excuse me, who suggested it from the tape group. It wasn't me but it was to be a dual tape drive that wasn't compatible with IBM, and that was what was called the Eagle drive then and came out as the 9840, and the 9840 was a totally different tape drive thing compared to what had come before in terms of the IBM compatibility direction. It was a two reel tape with a center load head, a cartridge as opposed to a tape reel that pulled down and spooled up on another reel. Both reels were in the cartridge. It was a cartridge drive, a separate tape spool tape drive.

Gardner: Mm-hm.

Dee: And this was to speed up the access time to data. In other words, you didn't have as far down the tape to run.

Gardner: Half the distance?

Dee: Well, it's be about a quarter. I mean, oh yes at least half because you're in the middle.

Gardner: Right.

Dee: You start in the middle and that's where you put your directories or your startup files, is in the middle, and then you either go that way or that way to find the data. It was called Fast Access Tape, which at the time it was faster.

Dee: And that concept came up. I'm not quite sure who it was. They come to the head group. We needed to make a head for that. Now it had to read and write in both directions and do a lot more tracks to get the capacity up, which is where track following servo started at StorageTek on tapes.

Gardner: So you did the head? You did the head?

Dee: Yes. It was 18 channels. It wrote down 18 tracks at a time. But then it stepped over n times to I think f 144 tracks on tape and it's follow on was 288, and then it's follow on was 576. This is in the sequence of tape drives.

Gardner: Sure.

Dee: So on the same cartridge, and the tape in there was different. It wasn't chrome dioxide anymore. It was metal particle tape, and the cartridges and the tapes were made by 3M, or Imation because Imation started about then, didn't it? It came out of 3M.

Gardner: Yeah. You didn't date the 9480.

Dee: It was the mid-90s.

Gardner: Mid-90s?
[Editor's note: According to STC's 1999 10k availability of the 9480 was announced in December 1988 with first reported revenue in 1999.]

Dee: Yes, the 9840, and it was a central load cartridge for high capacity. I think it was the first one came out at 20 gigabytes, which doesn't sound like a lot now but anyway, it was a lot then. Okay? Twenty gigabytes and there was 144 tracks on tape, and the head designed for that was interesting. Because you had to read and write in both directions, we went to an 18 channel write head, a 3 bump head with 3 modules. We had a write head and a read head in the middle and a write head, and they're all in the same line. So you could write this way and read or write that way and read. Read after write in both directions, and the write head design was thin film and..

Gardner: That's a process change for your guys.

Dee: Yeah. We went to thin film because with metal particle tape, the coercivity is much higher. You could not use ferrites. You had to use a higher magnetic moment pole piece.

Gardner: And you're still making these heads here in Colorado. You're not outsourcing them from a third party.

Dee: Correct. So, we developed in this period where there's this gap, in that period we developed various pole processes for tapes. We use plated permalloy. No good. Conductivity of the metal was too high. Couldn't get fast pulses through it and it wore away easily. It was too soft. So we chose cobalt zirconium tantalum alloy, a sputtered pole piece and made a thin film head. It looks just like a disk head only with a cobalt zirconium tantalum material pole pieces. It's an amorphous material, harder, and it has high moment to write on metal particle tapes. So because the coercivity of the media was considerably higher than chrome dioxide. You have a question?

Gardner: No. I'm just following your numbers though. The module was an 18 head.

Dee: Yes. Each module is 18 channels.

Gardner: So when you double the capacity you go from 144 to 288. Your module width shrinks.

Dee: Nope. It's the same.

Gardner: Same?

Dee: The only difference is you have more servo channels. So you can halve the pitch as the head moves across it.

Gardner: Halve the pitch. So you double the elements in the module?

Dee: Double the number of servo reading elements. It's still 18 channels.

Gardner: Yeah.

Dee: They're narrower now and they move across twice as many times to double the number of tracks, and you keep doing that again.

Gardner: But you have a limited one half inch width for all of the tracks.

Dee: Yes.

Dee: The pitch changes. Yes. The pitch is halved.

Gardner: If the module remains the same size since the tracks are now half the width, you got twice as many elements in that module and aligning the modules, three modules becomes a challenge.

Dee: Yes. The alignment of the three modules was a challenge because you go in both directions.

Gardner: Right.

Dee: Now you can't use azimuth angle to align them because when you put one on track the other one comes..

Gardner: It's off track, right?

Dee: Right, yeah. So it's a compromise there.

Gardner: So is it still separately modules and you solved the alignment problem?

Dee: Yes.

Gardner: Or are you still not that fat?

Dee: No. We're still not-- I mean it's still fairly wide tracks, even the 500 on the tape.

Gardner: Yeah. I mean it's a thousandth-- it's you're talking about a mil.

Dee: Yes.

Gardner: And you can-- but then if you want alignment within 1/20 of the pitch?

Dee: Yes. You can do that.

Gardner: You know, you're talking a 20th of a mil. That's getting pretty small

Dee: Yes, the alignment gadgetry got sophisticated. The mechanical guys who worked that out didn't obviously..

Gardner: But you did in fact solve that problem?

Dee: Yes.

Gardner: And then keeping them aligned though for temperature and humidity is another potential challenge.

Dee: You glue them together good.

Gardner: I beg your pardon?

Dee: You glue them together really well.

Gardner: <laughs> Okay. That just seems everything's made of rubber.

Dee: Oh, no. Well, we used some sort of concrete. I can't remember what it was but it seemed to work, do the job.

Gardner: Really? Okay.

Dee: Yes. It worked but the other thing about that head was I know we switched from ferrites to a cobalt zirconium tantalum on the write head. The read head was very different, and this is where the read/write group really got me-- well it didn't get me annoyed but we couldn't have the center tapped device anymore because the reader was too narrow. In fact, the width of the reader was now the width of the center tap almost [ph?]. Okay? So you had to go to a single ended-- what we called single ended device, which was basically a stripe with two wires hanging on them, two leads, and unfortunately the feed through was terrible because you did read while write. When you got 18 write heads turned on, every read head sees those write currents and fields from that head, even though you have a shield in there. We put a shield in between, which had to be mechanically stable. It couldn't be copper or anything. It was too soft. We used just regular brass I think was sufficient, but still there was enough leakage across the head surface. The signal noise ratio was terrible when you're writing. So, the question was how to solve that and that was a head problem. Well, I'd never admit anything would be a head problem, but anyway, so one design that had been proposed in the literature and various things was a dual stripe MR reader. I don't know whether you've heard of that. It's where you have-- instead of having one stripe you have two on top of each other, okay, with them joined at one side for the center lead and the other two leads you sense differentially, which means now the feed through signal went through the loop that was made by the read head circuit. One was in one direction. One was in the other. It was non-inductive, winding essentially. So the feed through was eliminated with this design. However, making 18 or 36 of these in a row with 100% yield with films on top of each other only 500 angstroms apart proved to be difficult. In fact, I'm pretty much sure that's why nobody ever used this design. Okay? It was because of getting it to work. In fact, the gentleman in the corner office, the director, worked for IBM and he liked the dual stripe type design but he said it could never be made, never be manufactured. They tried and failed and said "No, it never could be done." And so, we had to push back hard on that opinion, say "Well that was 10, 15 years ago. The equipment's better now. The photo-lithography's better now. We need to give it a go." Alright? So we did. And so, we prototyped dual stripe readers with 18 or 20 of them in a row because there were servo readers, too. Outside the 18 there was pairs of servo readers to read an amplitude based servo system, and of course the first prototypes we made all shorted out, just as predicted by the guy in the corner office. Okay? But then as you know, like a lot of things, a miracle happens, right? There was one guy in the manufacturing line, the clean room. I'll have to remember his name because he deserves all the credit. He had a Ph.D. I tried to recruit him into the R&D group because he was really good, but taking him off the manufacturing line was probably a bad idea. He came up with a process to clean the first layer, because the problem was we did this lift-up process and you get these whiskers around the periphery of the photo-resist. So when you put the second layer on top they used to short through, short circuit. He came up with a process to eliminate all those whiskers. It was a process called Snow Clean. You know how you bead blast things in a machine shop to clean them up with glass or sand to clean all the stuff off when you've welded it or soldered it or something? Well he used a similar idea at a thin film level, and he used snow or small water crystals to blast the whole substrate, and it would knock all these whiskers off but not affect the base films. Put the next layer on top, worked like a champ, 100% yield. In fact, we had better yield on readers than write heads. That thin film cobalt zirconium tantalum process was more difficult than the dual stripe read process in the end. It was because of that one process change that that guy made. I really wish I knew his name because he left the company in the end.

Gardner: Keep thinking about it and we'll add it in.

Dee: Yes, right because without that life would've been a lot different. Okay, but then because the dual stripe worked we sent that head to the read/write group for evaluation and they fell in love with the damn thing, right, because the signal noise ratio was fantastic now because it eliminated all excess noise input into the read channel. So, and it was a dual stripe reader which means it could differentially detect and sense and eliminate second harmonic distortion, and all the other good things that you like about differential bias and sense, and the other thing that I liked about it, all the thermal asperities went away because a thermal asperity on a tape comes across, as you know, it's like a hot match striking over the head and it raises the temperature of the MR element and you get a pulse on the MR signal, which typically unlocked the phase lock loops in the read channel. However, it hit these two. They were so close together it hit them simultaneously and they were subtracted. I mean it was like-- well they fell in love with the heads in the end. Okay? The head group could do no wrong after that, but that was pretty good.

Gardner: I think at least one disk drive company did dual stripe.

Dee: It was on a floppy disk drive I think.

Gardner: No. I think somebody other than IBM did it but then they all went to GMR.

Dee: Right.

Gardner: As opposed to the dual stripe

Dee: Yes. They went to GMR very quickly.

Gardner: Yes but I think there was at least one company did AMR.
[Editor's note: Some early Seagate drives were shipped with dual element MR read heads based upon a design originated at HP][3]

Dee: Right, but I think we even shifted to two readers and a writer because the yield was so good on the read in the end, and each read had 18 data channels and 4 servo channels. So that's 22. So that's 44 readers in one head. So to get yield on 44 tracks, 44-- I mean process the pieces. We can do-- and on that case I think, that's right, we still used ferrite shields for that device, for the reader because it was separate from the writer. It was the write process was independent from the read process. You know, like disks gets and you put a reader on a write, one process mustn't kill the other one, and in this case keeping them separate made it easier to perfect the read design or the write design independently. So that head was a real challenge and it was interesting.
[1:10:00>
It came out in the end and the 9480 was fairly successful I believe, and because of its central load tape drive, fast access, and it was used pervasively in the banking industry for check imaging, I think was the main use for it. So when you clicked on your bank statement it would go find the tape and load it in the tape library and you didn't have to wait very long. Not the case now. Everything's on probably disk or solid state disk now.

Gardner: I think today you are correct, but everything's still backed up to tape.

Dee: Mm-hm, probably.

Gardner: No, it's just when you start talking petabytes there's simply nothing that compares in cost Some small amounts are stored in on line storage. Tape still the archival application.

Dee: Yes, the ultimate backup.

Gardner: The ultimate backup. I mean the near backup may in fact be on the disk array but when you want to put something in Iron Mountain so it'll be there forever, you put it on tape. Is that right?

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[3] See: "Magnetoresistive (Mr) Heads And The Earliest Mr Head-Based Disk Drives: Sawmill And Corsair," C Bajorek, Computer History Museum, Mountain View, CA

Dee: Yes.

Gardner: Put it away.

Dee: Yes. So the 9840 series of tape drives went from double capacity and so forth, two three iterations. I think it stopped at 576 tracks.

Gardner: Okay. That's through at least two iterations.

Dee: I think two or three iterations in it.
[Editor's note: The 9480D, the fourth generation of the 9480 family was announced in early 2008][4]

Gardner: Tape has for many, many years featured down level compatibility.

Dee: Right.

Gardner: That's sort of the mantra in the tape, that the new drive should read at least one and I guess today two at most.

Dee: Right, reading down. Yes.

Gardner: You can read the previous generation and maybe one more.

Dee: Right.

Gardner: But beyond that you would need a special system or some intermediate device. Is that the case here?

Dee: Well yeah. The latest one could read the first.

Gardner: Read the first one.

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[4] [Editor's note] The 9480D, the fourth generation of the 9480 family was announced in early 2008. Source: A review of Storage Technology websites from the Internet Archives shows first mention in March 2008, see https://web.archive.org/web/20080306010657/http://www.sun.com:80/storagetek/products.jsp

Dee: Yeah

Gardner: Of course that, as you pointed out, made it somewhat easier to predict what the next generation product would be.

Dee: Mm-hm.

Gardner: Just multiply its..

Dee: Sorry. This product was not IBM compatible.

Gardner: No, but your..

Dee: I don't think so.

Gardner: Your next generation 144..

Dee: Yes.

Gardner: ...would be a 288.

Dee: Yes.

Gardner: Chances are.

Dee: Mm-hm.

Gardner: And then the next one beyond that would be a 576 if I can-- if I can multiply by..

Dee: Yes, and then I think-- I'm not quite sure what the last product of the sequence was but because the media changed to get the higher areal density, that had to put a set of redundant readers in to read back to the first generation because the new readers just..

Gardner: Actually you see that every once in a while where there's a hybrid which has two sets of heads, one for the latest generation and one for the older stuff.

Dee: Right.

Gardner: So now it's through the mid-90s; you're still at StorageTek and you're still working on heads?

Dee: Yes, StorageTek.

Gardner: At some point you became a Storage Technology fellow.

Dee: Yes. Actually that was-- I have it in the newspaper there, around 1994. I was recognized primarily for the fact that the tape head technology ended up being the key technology to enable StorageTek to [be in the market.]

Gardner: The key messenger, to use your term.

Dee: Yes. In this case head technology -- because we bought the media. We didn't make media, right? And tape drives, we had lots of mechanical engineers that did great tape drives, you know, but that little piece in the middle, the magnetism and the thin film design was a key enabler for the company I think.

Gardner: But as a general rule the media you bought came from an IBM standard or a digital standard for DLT or QIC. But when you went out to do this metal particle tape, the 9840, in a cartridge which I presume was your design, how did you work that media out?

Dee: Well, we went to 3M or no, Imation.

Gardner: Same thing by them.

Dee: Imation. Yes. Imation. And so, we wanted to make this cartridge and they produced a metal particle tape already for LTO-1 I think, the original LTOs. We said "Okay, we want the metal particle media in this cartridge." they got sole rights to manufacture the cartridge for us, with StorageTek logos on it.

Gardner: So it was a standard tape that they were making for some other application.

Dee: I think so. Yeah. I think so. Yeah.

Gardner: And the mechanics of the cartridge was your design but you gave it to them with an exclusive license.

Dee: I think the mechanical people at StorageTek designed the cartridge but I think the two groups, the Imation group and that group worked together pretty well to come up with a manufacturable one that was, but it was this dual reel with a window and a door on it, with a little mechanism when you plugged it in, it opened the door and so forth.

Gardner: Any idea why dual reel instead of single.

Dee: Fast access. That was all.

Gardner: So just to get in the middle?

Dee: Yep. Lower capacity because you get less tape in it.

Gardner: Interesting. Okay.

Dee: And it was the same. It was the same shape and size as the original 3480 cartridge the square.

Gardner: The square?

Dee: Yeah, for there are two reels in it.

Gardner: Interesting.

Dee: Okay? And that was so it would fit in all tape libraries that were already out there. Okay? Rather than having to have a different tape library.

Gardner: Sure.

Dee: ...or different racks or different something. So it was inside the same cartridge but it was two reels in it just to get fast access. A lot less of capacity because you get less tape in it, which also sped it up by the way. So you had less tape and then you put it in the middle of the tape. So you're about factor four in access time improvement, and that was attractive to people to that were more interested in access time than [capacity].

Gardner: And don't want a disk drive.

Dee: Right. Yes. The disk drives at the time still weren't a dominate force as they are now.

Gardner: They were like maybe one or two gigabytes at that point in time.

Dee: Right. And this was a 20 gig.

Gardner: Early '90s.

Dee: Yes. Right. It was a competitor then in that sense.

Gardner: And reasonably successful.

Dee: Yes, I think so.

Gardner: So as a fellow, did your job change?

Dee: A little bit. The notoriety sat with me very well but I tend to be in hideaway in this little lab, you see, for years and years and years, right, and now suddenly I'm put on stage sometimes, which is kind of interesting. But no, yes. The one thing that StorageTek wanted-- there was another fellow also. The one fellow was Art Rudeseal and then I was the second one in the company and then I think there was some other that followed, but one thing that StorageTek encouraged, or the middle management did anyway, was for the fellow to do something new. I was lead out on a rope, you know? A bit of cash, bit of money. Go do something innovative that's not necessarily mainstream. So I said "Okay. I can anticipate that tape heads are going to have to have GMR in them someday. So why don't you go and buy me a sputtering system that can do GMR heads?"

Gardner: A quarter million dollars?

Dee: At least. So they said "Okay." So I went and bought one. We bought it from Nordiko. That was who was making them at the time, and I hired another engineer who wasn't frightened of really thin films. I was kind of scared of five nanometer films or less, but they're fractions of a nanometer. Okay? So I was a little bit scared of that in the sense that unfamiliar territory in terms of scale. So we hired a guy name Brad Engel out of the University of Arizona where he worked in the optical. The funny thing was with him is he was also started out being a low temperature physicist and ended up in a completely different discipline, but he was very good at these ultra-thin films. And so, we bought this sputtering system and sent him off, said "Go make GMR films." So we made the first spin valves at StorageTek with a tape head in mind. So that went on for a while because it turns out tape didn't really need spin valves for some time. You remember I said number one is that the media's the problem. There wasn't the media to support the areal density where you needed a spin valve, but I thought that it would take a long time for the group and StorageTek to get a spin valve functioning with a fledgling one or two people on the side, but we did and of course eventually they use them and they're using them now. So, but it did but it took a few years to get there. So that's one thing that happened.

Gardner: Mm-hm.

Dee: I was allowed to explore a bit more rather than product in mind.

Gardner: So you're still involved on a product side but you had this separate budget and separate group that you could experiment with?

Dee: Yes, a little bit. Yes. It wasn't very big but it was enough to get it going.

Gardner: And you picked GMR spin valve..

Dee: Right. As the thing that we would need one day. And eventually that came about and all tape heads now have spin valve readers in them. They're not TMR or anything. They're straight spin valves. So, still. So that was one change.

Gardner: Has tape encountered the writing problem yet?

Dee: What do you mean the writing problem?

Gardner: Well the disk folks are pushing the point where they can't get enough flux density at the business end of the head to magnetize the particles with a strong enough coercivity that they'd like to have to keep the bits from reversing. The disk drive guys are fighting this whole trilemma every day now.

Dee: Right. Well they have been for some time.

Gardner: For about 10 years.

Dee: Right. Yes. That's what I said, some time. Yes. Well no, tape still uses particles, not thin films with grains.

Gardner: Not domains over film, right?

Dee: Right. And yes, the particles are small enough to have the same problem, the superparamagnetic problem.

Gardner: They are?

Dee: Yes. They push that. They've been pushing that for about five years, but not in the sense of it's a problem. They just make sure they don't have any of those small particles that small.

Gardner: But you can still generate enough field in the heads to-- if you can get a particle that'll work, writing is not the problem.

Dee: Right.

Gardner: The physical chemistry of creating that particle is the problem.

Dee: Yes. That's where they're at.

Gardner: It's a nice place to be.

Dee: Right. That's true. By the same token, the moment thickness products of the magnetic layer on the tapes is such that you need spin valves and have needed them for the last couple of generations to get to the higher areal density. Lots more tracks. There's thousands of tracks, two, three, four, five thousand tracks on a half inch tape, and hundreds of thousands of bits per inch, linear. Otherwise you can't get five terabytes on a cartridge, but yes. So that's all true. That's the transition they made and to get the signal noise ratio with particles in a binder technology, the particles have to be small. And so, they clearly have experimented with tapes where the particles have had thermal problems, in R&D anyway. So we don't use those tapes. We use the ones that are stable. So, end of story. What happens next, if there is another next in tape, is a more interesting issue. Again, the media's the problem here. What's the media going to look like if you want to up the areal density some more from where they are today?

Gardner: But it sounds like the messenger technology, to use your term, the head technology and even the channel technology are more readily available than the media. The problem is the media today.

Dee: Yes, and that's because of the disk drive industry in terms of areal density, and that is ahead of tape and always has been, for a long time anyway. It's been ahead of tape. Maybe it wasn't originally in the beginning but it is now and has been for some time. So yes, the spin valves, we don’t use spin valves anymore in disks, right?

Gardner: I'm sorry?

Dee: They don't use spin valves anymore in disk drives.

Gardner: Well I think the industry is adopting the term spin valve to talk about all of the MR heads. A TMR, tunnel magnetic-resistance, head is a spin valve in today's terminology.

Dee: Of sorts. It's not GMR then.

Gardner: Right. the disk drive folks today I think use the term spin valve to apply to all sorts of magneto-resistive heads.

Dee: Oh, okay.

Gardner: Technically you might say spin valve really only applied to GMR.

Dee: Well we don't use TMR in tape at the moment, although it was always considered it could be a good fit.

Gardner: And I think actually tape channels today are very, very much like disk drive channels.

Dee: Oh yes.

Gardner: They're just state-of-the-art digital channels. Just you've got 18 running in parallel instead of one.

Dee: Correct.

Gardner: Which is a different set of problems.

Dee: When I first worked in tape drives that always fascinated me that a tape drive when it lacks the data it reads it back immediately and checks to see whether it's correct on the fly, right? So it's running down there at hundreds of megabytes a second doing a read-back check immediately before it gets spooled up on the take up. So you know the data's correct before it even gets spooled up, and it does it all on the fly in the electronics and does it really fast clearly. I mean you've got 18 channels, each channel running at-- don't know how many megahertz and it crosschecking all the data and checking the error correction codes and all that stuff to make sure it's correct and it..

Gardner: Disk drives don’t do that at all.

Dee: No, and if tape isn't correct it stops, backs up, and writes it again or it just writes it again on the fly. It doesn't even bother with the backup, backing the tape up. It just keeps on going and then writes it again. Okay? There's a little bit of capacity overhead required for that but that's budgeted in.

Gardner: No, that's from the disk side, it's-- disk drives really have always gotten away without doing a read back check of any form.

Dee: But tape drives always do it. Always do it.

Gardner: About this time you leave StorageTek?

Dee: Well, Sun Microsystems purchased StorageTek in 2005 and I became a Sun Fellow because actually I was promoted to Senior Fellow at StorageTek a few years before that. So I became a Sun Fellow by grandfathering in as the companies merged. I didn't work in the head group much anymore. I worked on actually storage systems. Nothing had changed when I was became a StorageTek and Sun Fellows. I was given a lot more presentations and things and doing a lot less actual work, in my opinion in terms of the technical stuff. There was an expectation level that had changed, that this is what you did now. You didn’t do this technical stuff anymore.

Gardner: Did you have a lab and a budget and other people?

Dee: No. No. That went away.

Gardner: You were just by yourself?

Dee: Yes, essentially and I kept proposing to the company sort of the various things that they could be working on or doing, different storage device designs or concepts, none of which panned out or were taken up, and but I found myself at a certain level of expectation where I really wasn't doing much. It was kind of disappointing and that's when I ended up leaving, is because it turns out Sun Microsystems, when one company buys another, okay, historically the old company tends to disappear. The people, they eventually go. They're either laid off, leave, or whatever and that's what happened over the next two or three years at Sun Microsystems and I was one of the ones that [laid off][5], and as soon as that happened the phone rang. It was Quantum. They said "I hear you're not there anymore. Come work here." And so, I went to work at Quantum.

Gardner: This would be in '96?

Dee: No, 2008.

Gardner: 2008. So you were-- the acquisition of Sun was 2005.

Dee: Right.

Gardner: I was off by a decade. It happens to me more lately.

Dee: Yes. Well after 9840 there came the T10000 drive which was terabyte. I did a lot of promotion of terabyte tape in the industry. I talked at NSIC, mass storage system conference, did a lot more of this going and giving talk things and gradually a lot less of actually doing the head work. I guess that happens, right, to a lot of people. It happened to me, too. So, and in the end-- well T10000, I worked on that which was the terabyte drive, but after that it changed and I did more and more of this.

Gardner: So let's pause there for a second and we'll talk about your head activity on the T10000.

Dee: Yes. I promoted the idea of terabyte tape because after the last iteration of 9840 which was got up to I think in the end, 200 gigabytes, I said "Well let's do a terabyte tape," and most people said "That's five

[5] [Editor's note] Sun Microsystems plans to lay off 212 people in Broomfield and Louisville by the end of September 1982. Source: Denver Post, July 10, 1982.

X. There's no way you can do that.- you know the tolerances were so tight. And servo was up to its stops and everything in that tape drive. I said "Well, no. You just got to get the right media and the head technology's probably there. There's already GMR in the wings over there. Okay? See, over there? See?" And then so I started working on doing a terabyte tape and I think I need to be checked on this but was StorageTek the first to come out with a terabyte tape?

Gardner: Was it? I don't know.

Dee: It was close I'm pretty sure. No, I think when the LTO 4 came out it was 800 gigs (uncompressed) and StorageTek was a terabyte[6], and that was a pretty good-- and that was a different concept of tape drive also. I think it had two heads in it. Two heads. One wrote the top half of the tape. One handled the bottom like this, and all channels running at the same time. So the data wasn't actually all physically located like it always used to be, straight across the tape. It was downstream a bit, but logically and timing wise it was buffered and it was fine.

Gardner: It didn’t matter, and it was servoed?

Dee: Yep. Went to timing based servo on that one. Went away from the amplitude based servo. Run out of head room there. And so, went to timing based servo. So you get more of it and it turns out you do get more resolution in timing based servo, just like the IBM guy said. So that was true and that's what T10000 went to that. The media was originally metal particle I think and now the subsequent tape drives that have been done in the last five years or so, of course I haven't worked there so I don't really know. I think it's barium ferrite media. So but anyway so, cut a long story short, I went to-- I left Sun and was immediately hired by Quantum. Wasn't sure I wanted to work there because of the work they wanted me to do. They wanted me to be a tribologist. Can you imagine?

Gardner: After all these years in magnetism to now move to tribology, but I have to say my experience is that a senior guy in an area like heads probably knows a fair good bit about tribology, having experienced the wear and all the problems the tape does to tape heads.

Dee: I always had this story. I always had this thing that I said "The tape heads are fine until you run tape over them." Okay?

Gardner: Right. Then the message gets distorted. Yes.

[6] [Editor’s note] If not first at 1 TB the T10000 was certainly early. StorageTek announced general availability of the T10000 at 500 GB in April 2006 and a second generation T10000B in 2008 at 1 TB. LTO-4 is 800 GB and LTO-5 at 1.5 TB shipped in 2010.

Dee: Right because then normally the tape does all sorts of things to the head. It deposits rubbish all over it. It wears it away. You can imagine. It's two rubbing surfaces and I mean..

Gardner: If they are in fact rubbing. Sometimes they fly.

Dee: Oh, they pretty much been pretty hard contact now for the last 20 years. There's no way you can get the spacing low enough without hard contact because of the surface roughness and so forth over a particular base media system.

Gardner: Well, the disk drives still don't touch the disk.

Dee: I understand. It's a little, tiny thing. This is a big thing, so big is different. It's different.

Dee: So no, I became a tribologist. Kicking and screaming "No, I don't want to do it," and then-- but and I worked on it for about a year or so because Quantum was doing R&D for LTO, heads and media was the name of the game in terms of how the two talked to each other. So I got also involved in the recording physics as well, as well as the tribology.

Gardner: Mm-hm.

Dee: Started tribology, still did tribology but I saw some great techs. There's one gal there who's really good, Huong Yah Chen, a Chinese lady, did all my testing for me. She did all the testing. She did tape drives, tapes. I said these heads, these tapes, this humidity, this speed, this whatever. She'd go off, run the tests in the chambers, collate the data, take the photographs, micrographs, the SEMs, you name it, AFM profiles, collate the data and give it to me. It was fantastic. It really was and I could make an evaluation of, you know, and I did my data analysis on that. So the drudgery of tribology, Hong Yah Chen took the drudgery a bit, all the testing because it fairly laborious.

Gardner: Now Quantum at that time and to this day doesn't make anything.

Dee: Correct, as far as I know. Someone else makes it and they put their sticker on it, their label on front.

Gardner: Yeah I know but somehow the research you were doing had to relate back somehow to the people who then designed the drives that would be made for Quantum.

Dee: Yeah. There was a joint development agreement between Quantum and Hewlett-Packard.

Gardner: So you were doing essentially the head research..

Dee: Yeah.

Gardner: ...to support the designs that were then going to be implemented.

Dee: Yes. And so, I did the tribology there and also got involved in the recording physics and some of the head design issues. If things didn't work quite right I was able to give my input, given my background.

Gardner: This should be some LTO generation?

Dee: Six.

Gardner: Six?

Dee: It started out five.

Gardner: Five translate to six?

Dee: To six and then also seven.

Gardner: Okay.

Dee: So three iterations were in the works. I was also on the media group committee thing for LTO. We talked at length when I was in Tucson about the structure of the LTO Consortium.

Dee: Okay.

Gardner: Which Quantum I guess joined late.

Dee: Yes.

Gardner: But was a full member by the time you joined it.

Dee: Yes. So I was on the media committee. So there was someone from Hewlett-Packard, someone from IBM, and me and we did the media decisions I guess about what the media was going to look like for the LTO-7. Then we'd get samples from the media providers which were by this time going to be 100% from Japan. So it was Sony, Fuji, Maxell, TDK, and Imation initially but they dropped out I think.

Gardner: Today there are only two.

Dee: And that is?

Gardner: Sony and Fuji.

Dee: Sony and Fuji and they're probably arguing about various things, too. Anyway, that's what I was saying, Maxwell and TDK went. That's..

Gardner: So you would do the evaluation research and then you would comment on the specifications being produced by the LTO Consortium.

Dee: Right. We gave the feedback to the media vendors, head suppliers and also the development group at HP. So, and I was kind of because of my experience in pretty much everything there, I have a finger in all those pies, the tribology tribe, the recording physics pie, and the head pie, and the media pie. So, I did a lot more work there than I had envisioned in my mind, which was good. It was good for me because like I said, the latter years in Sun, I got pushed into this role was essentially giving presentations and things. It wasn't a very interesting job in that sense, you know? The Quantum job was better. I was back in the lab again.

Gardner: How did that as a person who had taken his theoretical concepts, proven them as technology, taken them to production, now you're sitting here sort of on the side still doing the research but you've got to convince the IBM guy and the other members of the consortium. You can't reveal your trade secrets but you've got to somehow cause them to evolve standards and specifications that would work. How did that work for you?

Dee: Well, actually I was fairly comfortable with it because you get to the point where you've been doing it long enough that it becomes second nature, a lot of it, which is why I came up with the three axioms. I said "This industry's governed by this," and as soon as you realize that you know what to do now because all of the media vendors knew I'd said this, and they always said they understand. The media is the problem. And so, whenever we didn't like something we said it was the media, and it was true. There was this trade-off going on between some of the media characteristics and how well the head could handle it. This was the tribology thing, and of course you have to figure out how to solve that head tape interface because now, in like LTO-6 and 7 the spacing between the magnetic portion of the media and the magnetic portion of the head had to be 20 nanometers or less. Now for a disk drive that may sound pretty big still, but this is a piece of gooey media, flexible media scrapping over a head, and that 20 nanometers has to be there for the life of the head which has to be many years, not 10 minutes. Okay? And quite often there were head media combinations that only lasted 20 minutes before that spacing went from 20 to 40, and then all bets are off. No-- couldn't resolve the bits anymore because of the spacing loss. So no, it's-- the tribology thing, it was a big deal. It still is I think, although fortunately I don't work on that anymore because it's not an exact science. It's a combination. It's physics, chemistry, electrochemistry, and so forth. It's all of these things happening all the time. There's ions going everywhere, moving around, chemicals oozing out of the tapes, and there's all these materials in the head. There's a spin valve in there, right? Spin valves. You know what's in there. There's cooper. There's cobalt. There's all-- you think of an element, it's in there probably and then you want it not to erode away by 10 nanometers over years and in an environment like this or on a ship trucking up and down the Japanese coast, right?

Gardner: Yeah, or in Hong Kong where the humidity is high.

Dee: Yeah. These aren't necessarily in nice, controlled data centers. A lot of them are but not necessarily. So that, the tribology issue, and it turns out that we came up with a solution in the late LTO, and you can look at the patents on that. There's a solution to that we came up with, and I haven't worked at Quantum in over-- I left there in.

Gardner: Can you summarize the patent?

Dee: Yes. Because the-- it ended up that we twigged or at least I twigged that there's so many materials involved, so many-- five different tapes, vendors, different compositions and proprietary goo, and a lot of times in history people have tried to put coating on a head to hide all this, but it typically it wears off and typically the coating has always been some sort of ceramic or diamond-like carbon or something that isn't diamond. Okay? I think that's more of a marketing thing I think than a real thing, and because of the electrochemistry and because the MR ions are biased and you've got these chemical cells functioning, we worked a lot with Fred Spada at CMRR because he's an electrochemistry type dude. That was his main reason for the cause of the erosion in tape heads. It's because you've got voltages everywhere and you've got all this chemistry, that you get all these ions running around and it's this electrolyte soup that's flowing over the head all the time. So, the thing to do is to try and get rid of all that. So the concept was to put a metal over the head. So you make it-- you make the potential uniform. So there were no potentials now to drive the electrochemistry, and the one material I researched that I thought would work great was titanium, and the thing that put me off on some people originally was that titanium is a very volatile metal and they said "We don't want volatile things on the head group, on the head surface," which is why people were using ceramics and oxides and zirconium oxides and so forth to cover it, but it turns out that titanium, as you know, is an exceedingly reactive metal. It oxides almost immediately once you've produced it, and that oxide, that native oxide is absolutely bulletproof. It's a bit on the same lines of disk drive TMR heads that use magnesium which they oxidize. They put down a fraction of a nanometer of magnesium and the oxidize it to form the tunnel barrier. It's the same concept and the titanium is a thicker coating and I noticed that we've used titanium in the past to clean up sputtering systems because it grabs all the oxygen out of the residual gas because it's that reactive, but that TiO_2 layer is absolutely-- I wouldn't say it's hard. It's tough, and toughness is what you want in a tribology situation. You want it to be hard but its Young's modulus not to be too bad. In other words it has to be a little bit springy so when an impact comes it goes back. It doesn't break off. If it's hard and brittle it breaks off, but if it just comes back a little bit.

Dee: Another anecdote is years ago I broke my leg and they put titanium metal bars in it, and the reason the use titanium is because of this oxide layer that's on it and it doesn't interact with the body chemistry. It's that the titanium metal is underneath. It's strong but it's that oxide coating that protects it from the body chemistry, and the same with submarines doing that, titanium hulls because they don't rot in the ocean as well as not being able to be detected by magnetometers. And so, I looked up how the oxide forms, looked up some papers on that and it turns out it forms approximately a three to four nanometer oxide layer in approximately 30 minutes. If you do a thin film, take it out of the sputtering system, just leave it in the lab, 30 minutes later it forms a three to four nanometer oxide layer. I said "Three or four nanometers? That's about right." So here's what we did. I did an experiment where I did probably 10 nanometers of titanium on the head and I just said "Do that and send me the head. Don't do anything else." So I did the head. I left it in the lab and it oxidized. I didn't know whether it was going on. I got the head, ran tape over this thing, and it ran for hours and hours and hours and didn't change, weeks and weeks and weeks and didn't change. So I proposed to Quantum and HP that we put titanium on the heads and they said "Richard, you can't do that. It'll short all the MR heads out." Okay? I said "I know that. That's part of the solution, to short everything out." "But you won't have any read signal." Okay. What we do is we hide the MR elements before we put the titanium down. The heads I'd made I didn't bother, shorted all the MR ions out. We know that. Okay? And so, yeah, to cut the long story short, in the end we put down four nanometers of silicon nitride over the whole head and then five or six nanometers of titanium which then oxides down to four nanometers. It leaves another nanometer or two of titanium under it for a total of about 10, which is half the 20, but it never changes. So every LTO-6 head now has that on it.

Gardner: So it sounds like from a technology point of view, at least in terms of tribology you're pretty well running up against some fundamental limits.

Dee: Yes.

Gardner: You make a four nanometer and you make a two. Maybe can you make a one?

Dee: Well, the thing about the titanium was that it made this four nanometer layer automatically. You didn't do anything. Now, if you try to sputter titanium dioxide, it don't work. You had to grow it natively.

Gardner: Right.

Dee: It was a much more-- and we had it tested. We took it to Rocky Mountain Labs over here and did XPS and low angle x-rays, you know, spectra and so forth, and it was 99% TIO-2 on the surface. No TIO and no TI, and the other things that was-- it was marketing maybe. Sometimes I do marketing. I said "It's self-healing. Each one comes off. The titanium just re-oxidizes again and fills itself in." I'm not quite sure whether that was true but conceptually.

Gardner: And it was your colleagues idea to short it all out. Then you came up with the titanium as at least one material that does a very good job of that.

Dee: Well, no. I don’t know whether it was a colleague or anything. It just sort of happened. Okay, well if we electrically short everything out then the electrochemistry goes away.

Gardner: Right.

Dee: That's almost obvious, right? But the reason nobody had come up with it before, so we were shorting everything out, including the read signals. Well I said "Okay. We'll solve that problem later."

Gardner: Fix the first problem, deal with the next one.

Dee: Yeah, and then we ran the heads for six months, almost a year, the same head that we first did it on and it still ran with the same SNR. Okay? So, it was like a miracle almost - there's four or five patents been issued by Quantum on that.

Gardner: This was at Quantum. Quantum's a member of the LTO Consortium.

Dee: Mm-hm.

Gardner: They then contributed the patents to the consortium?

Dee: No idea.

Gardner: So you just don't know how Fuji and Sony worked with Quantum and the LTO Corporation to allow those patents to be used by them in producing..

Dee: I don't know anything about that. The consortium and how it really worked, I really didn't get into. You know, I was the tribologist in the background.

Gardner: It's an interesting, as an outside observer, -- the LTO concept was to set standards and specifications but not tell people how to do the job.

Dee: You just had to be compatible with it.

Gardner: Just be compatible.

Dee: And across the table.

Gardner: Well, so there's spec that it's got to last six months with this abrasive material. If it doesn't you don't work, but if the only solution known is this particular patented material, how does that work?

Dee: Well, I don't know whether it's the only solution but it's the solution..

Gardner: It's a solution.

Dee: ...we came up with and it seemed to work great. And I think it's still working.

Gardner: Yeah. Well, in conception-- well, it sort of depends upon how broadly you can write the claim. I'm assuming Quantum has good patent attorneys, they would claim any metal that self-oxidizes.

Dee: Mm-hm.

Gardner: You could write a claim that says coated with a conductor that self-oxidizes, having previously insulated the MR without specifying materials at all.

Dee: Right.

Gardner: With dimensions that are on the order of four nanometers.

Dee: I'm pretty sure there are some claims like that.

Gardner: Which are pretty board.

Dee: And then the subsequent claims might claim everything else, most of the periodic table.

Gardner: So if Quantum got broad claims such that, you know, maybe come up with it some other way, but absent that they sort of have to use your patent.

Dee: Well, the issue is IBM makes tape heads but they probably-- I don't think they put titanium on theirs. So, maybe they have a different solution or maybe they replace heads more often. We don't know that either.

Gardner: Back to the days when IBM had a service engineer at every large tape account, changing heads every day on the nine tracks.

Dee: I remember that.

Gardner: We've come a long way, haven't we?

Dee: Yes, we have.

Gardner: You mentioned I believe STC. You did a design for Aspen?

Dee: Yes.

Gardner: Have we talked about that?

Dee: No, don't think so. It was-- I don't-- when StorageTek acquired Aspen Peripherals they were producing a 4480 compatible type drive and they had an AMC head in it. This is now 10 years on. At AMC you had actually managed to make something, but it was a thin film write head with bulk permalloy poles, and that was their design, and also the read head, the MR read head was the same as-- similar to StorageTek's only it was biased on the other side of the gap. Okay?

Gardner: Okay.

Dee: So, the question was, okay StorageTek buys Aspen Peripherals and Peripherals makes a tape drive. They're buying tape heads from this company. StorageTek makes tape heads, makes the same tape heads. They're compatible with that same tape. So why don't we put StorageTek heads on this drive? Okay? Well, the answer is what? What's it cost? These people were charging X dollars and we could manufacturing it for half that. So we had to make a tape head that would plug-in to that drive. Now remember this -- our tape head was a nickel zinc ferrite, two turn writer. There's was a thin film permalloy head with about five or six turns in it, like a disk head but very thick permalloy poles. Our head would transmit 45 nanosecond pulses with a 2 nanosecond rise time. This head would only transmit a pulse that was about 150 nanoseconds long and the rise time was about 40 nanoseconds because of the metal pole pieces. You just couldn't get a fast pulse through it. So they had to adapt their channel in order to write the tape properly to accommodate the fact that the head didn't respond to fast pulses. So we had to come up with a head without changing the tape drive now.

<laughter>

Dee: Okay? That would run off the same current as them with the same pulse train. So I said "Okay. We'll go and do that," and so in the end we ended up with a nickel zinc ferrite based head with five turns in it to get the write current of the same. Now the inductance was up so it responded a little slower, nowhere near as slow as the permalloy head, and then we demonstrated it in the Aspen tape drive in a similar manner that we did the IBM one years ago, and we put it in a tape drive and it functioned, had very similar error rates and everything, and we had to modify the read head so that the element was on the other side of the gap. So the phase shifting was the other way around. Okay? So, in our opinion it was a poorer choice because you're biasing off the glued on closure. There was more tolerance in that gap than there was using the thin films as your guiding one, but be that as it may, we made the head that way round. And so, everything worked fine and then we went to management and said "What do you want to do? We can make this head for half the price that they're paying for the AMC head," and they said "Okay. Let's make it." So what that meant was more volume was going through the head shop, which helped, as you know. You've got to amortize all that infrastructure, all those sputtering systems..

Gardner: Clean rooms.

Dee: Clean rooms. The more heads you can put through it the cheaper they get. And so, that helps. And so, that's the decision they made, and in the end, so all the heads were made at StorageTek for the Aspen drive after that.

Gardner: And I presume we're talking hundreds of dollars to buy a head.

Dee: Do you know what? My memory recalls that they were paying $1,700 a head.

Gardner: $1,700 a head.

Dee: From AMC and we could make it for $800. They'd estimated it would be about $800, and the reason they're that expensive is because the volumes were still low compared to what you see with disk drives today where there's millions a week.

Gardner: Yeah.

Dee: Okay. These are real-- we're talking pretty low volumes.

Gardner: A single head, a single element, right?

Dee: Well, I'll tell you another anecdote. There was a StorageTek fellow. New CEO comes in, wants to talk to me, right, and one of the things he wanted from us is he wanted a tape drive with a lower unit manufacturing cost. Okay? "Okay, Richard, can you come up with a [lower cost drive]-- our tape drives cost way too much to build." All right? And I said "Well, how much do you want it to cost?" He said "$500," unit manufacturing cost for a 18 channel, whatever it is tape drive. I said "You get the tape head for that." Okay? That's all you'd get is the head with $500. He's saying "Why's that," in his head. Volume. "If you can sell a million tape drives," I said "Then you can have the head for $50." Okay? I million in a year. They're only selling 25,000 a year or something or whatever. I can't remember what it was. And that's what was really funny I said he wanted, I said "Well, you'll get the head for that but nothing else." You can sell the head but it won't be a storage device.

Gardner: I assume that was Ryle Poppa.

Dee: No. [I don’t recall his name.]

Gardner: And then since [leaving] Quantum [in 2013] you've been consulting?

Dee: A little bit, not much.

Gardner: Did you move to California for Quantum or you stayed out here?

Dee: Oh, no. No. Quantum had an office in Boulder. I didn't have to move house or anything. It was a little bit closer than StorageTek.

Gardner: Okay.

Dee: So, and then they closed the building down in Boulder because it was on the CU campus actually. They were leasing a building and they'd leased it for many years, and then CU wanted it back. So it was turning all the lessees out of this building. And so, they opened up an office in Louisville, over there behind Home Depot, and which is even closer. So, that was sort of where they went at that time.

Gardner: Alright. So it's been a very interesting afternoon. You've been in the tape technology business. Actually I take it some subsystem work at Quantum.

Dee: A little bit. Yeah, really recording physics.

Gardner: Okay.

Dee: In terms of how the gaps interact with the tapes in terms of resolution and spacing loss and frequency diagrams and so forth that channel guys like.

Gardner: So like any senior technologist your purview is a lot wider than your specialty.

Dee: Yes and I think that's part of the reason that I was successful in the early years and in the mid-years too, is because I had a good grasp on the mechanical side, the electrical side, the magnetic side, and the media side, and the channel side a little bit. I knew what they wanted. I spent a lot of times talking to the channel guys. So I had a broad view to enable to be successful in the head area.

Gardner: So taking that broad view, looking back what do you think were the biggest accomplishments of the tape industry, the 35 years that you've been involved? You can rank them one through three, and then looking forward what do you think are the biggest challenges to the tape industry as it goes forward for the next 10 or 20 years?

Dee: Okay. Well I think the sort of the biggest advances there, and I'm still going to harp on the fact that the media's the problem, okay, but the media changes were important. I know you mentioned it offline before but I mean they were big changes.

Gardner: From iron oxide to barium ferrite?

Dee: Well, all the way through.

Gardner: To barium, to cobalt chrome to..

Dee: Yeah, to metal particle. They solved the metal particle problem. Remember when it first came out it used to oxidize and degrade. They fixed that by coating the particles with something, Yttrium or something or an oxide or something. I can't remember what it is now, and the metal particle tape enabled a more rapid move up the areal density curve. So that was important. The MR heads were there and you could scale those. We talked about that. You can do that and that happened. So that was straightforward. Another transition was once the coercivity started going up and the areal density started going up, the shift from the heads from ferrite based to thin film, full thin film based. That had to happen. There are lots of people or companies wanted piggyback thin film read/write heads like disk heads in tape drives a lot earlier than they needed to be there. But eventually we got there out of necessity because of the areal density growth. And so, that was a big transition. Remember that gap in between the chrome tape drives and the metal particle drives? We shifted from ferrite based because of the lower coercivity to cobalt zirconium tantalum based write heads and then eventually the spin valves when you got the lower moment media like barium ferrite, and being able to scale that coating down on the media was really I think impressive. Have you ever been to Japan and seen the coaters at Sony or Fuji Film?

Gardner: No I haven't. You have. Tell us about it.

Dee: It's amazing. They have these jumbo rolls of the substrate material, which is polyethylene nappthalate or PET.

Gardner: It used to be 24 inches. Now they're 48 inches or above now.

Dee: Yeah. They're four-foot jumbos and they weight about a ton. Okay? Four feet wide, and they run it through the coating machine, and this is what's most impressive is that it goes through the coating machine at 10 meters per second. Now remember the latest tapes the substrate is only 4 microns thick. So this film four feet wide, four microns thick running at 10 meters a second through a coating machine, and it puts down an underlayer, okay, and on top of that it puts a less than 100 nanometer thick magnetic layer that contains data particles and wear particles and everything else to plus or minus a nanometer. Okay? And it goes through a dryer. If it gets oriented it goes through a magnetic field and it gets spooled up, and that's going at 10 meters a second and it doesn't break. Can you imagine if something happened to that machine? It's unraveled itself. You've got a ton of material spinning at-- I don't know what the RPM is but watching it, it's like mind-boggling. You've got to get out the way in case it breaks, you know? But to get that scale, you know, what is it? I think the coating thickness is down to about 60 nanometers.

Okay? Over a four foot wide running at 10 meters a second with thickness control is pretty amazing, and it's not that they invented that. I think they've been doing it for so long that it's an evolutionary process improvement thing, you know, because they were coating originally at hundred microns thick and then it was 50 microns thick and then it was so-and-so, and then it went to two layers and so forth and you put one layer down. Then it has to be dried and calendered. Calendering is like putting it through a ringer to flatten it all out. You get all the bumps off and that's really impressive to see that, see that running, and that is why tape is so economic, the scale, the sheer scale of it. They can make millions and millions of miles in tape in an afternoon run, you know? Which is why tapes are cost-effective in that sense because even as the tape drives are expensive you run a lot of tapes through them. So it amortizes itself. So, I think the media progression has got to be it. I won't say that the tape head is-- also because of the sheer yielding problem of the multiple channels, there's 64 devices in a 9840-2 head, 64 magnetic things to get a yield of 100 percent. Okay? In a disk drive you only have one or two things to get that yield. Alright?

Gardner: They just replace each one or two of several if it's bad.

Dee: You have to get all 64 elements correct. So the yield on each element has to be high -- I don't know how many nines you have to get to before you get, but so that's pretty impressive too to do that.

Gardner: So what do you think of the challenges now looking forward?

Dee: I'm going to say it again, the media.

Gardner: The media.

Dee: Because the particles in a binder have been so successful it's hard to think how you can make a disk thin film-like media stand up to the rigors of scrapping it over a tape head because you have to scrape the air off to get it down, to get the spacing to-- right now I don't know what the spacing is in LTO-7. I think, but I was working with 20 nanometers as a number. It might be 10 now -- the coating on the head is already 10. So there's no flying like there is in a disk drive. You are in hard contact and as you know, pure metals, if they're oxides it's different like the titanium thing worked, but that's not magnetic so that won't work. But I think it's going to be tough to come up with a media to keep the areal density progression moving rather than it just stagnating. Has the areal density curve in disk drives stopped or is it still going?

Gardner: Well that's a subject of debate.

Dee: Because the capacity of disk drives is still going up but I know how they do that. They put more disks in the package.

Gardner: So I track disk drive areal density pretty closely. And right now it's sort of a learning curve, improvement 15% a year at best.

Dee: Mm-hm.

Gardner: They have a distribution of domain size and making it narrower [has been lately the way progress has been made].

Dee: I was asking a guy years ago. I was says "How are you making the areal density gains," and he said "Particle size distribution in the media."

Gardner: Right.

Dee: So that's all they can do.

Gardner: That's all they can do because you can't push it much smaller.

Dee: Yeah.

Gardner: So the density is increasing but it's at such a low rate compared to doubling every two years or 18 months. So what we see is the new drives are coming out every-- so to double the areal density takes 1.15 raise to the 5th or 6th or 7th power. -- you see a doubling areal density every five to seven years now.

Dee: Right.

Gardner: It's still improving but not as fast as it used to because the industry is up against some real hard physical barriers, and it sounds like tape is too.

Dee: If they want to stay with the particle in a binder thing then they're already at the particle size. The, you know, they're getting to a point where if we go any smaller we're going to suffer the same problems.

Gardner: Are the metal particles that small?

Dee: No, barium ferrite particle.

Gardner: Barium ferrite. So they have to go to metal particle.

Dee: No. They went to barium ferrite because the moment was a little lower because remember it's a demagnetizing effect. That's the problem. You can do one of two things. You can raise the coercivity with a higher moment or you can just lower the moment so the reverse field is not as high, the demag field is not as high, and that's what barium ferrite essentially did, and the issue with barium ferrite of course was when you make particles they're in little plates shaped. They're not some little ellipsoids or circles or spheres rather but they're little plates and they tend to stack up like poker chips and then now they look like a bigger particle. So the solution to that was not to orient them. So randomize them and they don't stack, and I think the barium ferrite media they use now is randomized. It's not oriented media, and all that gives you is a different pole shape, which means the channel guys have to come up with something to figure that out, which they do, and I'd like to give the channel guys some credit. I know we bang up. I've been bashing them and I've bashed them a lot in the last 30 years but the channels have done a lot to contribute to the areal density gain, whereas you can have the same density on the tape and then depending on your channel and how you look at it, you can get one bit per transition, two bits per transition, or three bits per transition. So you get more bits, data bits for a similar magnetic recording. I've always said that the ones and zeroes that come off a tape or a disk are in the imagination of the channel engineer.

Gardner: Right.

Dee: Okay? Because as the head delivers it is an analog signal. It's a wiggly line on a scope. Somehow you've got to interpret that in ones and zeroes, and you can do it in many different ways. So now, there was peak detection and then partial response. It goes on and on, right, in various different ways. So every aspect of the recording system had to make gains.

it's not just the media. Well, that's the key. The heads can take it especially. The devices, the disk drive because of its areal density has been leading. I think like leading with the spin valves and so forth and the tape has followed a bit, but the multi-channel nature of tape heads is the real challenge, and the fact you went from nine track heads to-- it was the 9840 head. There were 64 devices in it to put down 576 tracks. That was again another move, and track following servo, if you look at some of the charts on some of the papers that have been written of areal density growth in tape, if you look at the slope of the areal density growth from the '50s through to 1992, it's one slope, and then after 1992 it's a steeper slope, and that transition is track following servo, and I've been giving the heads and media and channels a lot of credit, but the track following servo is what made the transition.

Gardner: See, I would argue that then what that shows is there was a technology the change in slope shows the key technology breakthrough with track following servo and the heads and media could then scale with just engineering.

Dee: There you go. Right.

Gardner: Until it will bend over, that's happened to disk drives.

Dee: Yeah.

Gardner: In my view, not necessarily agreed to by everybody but it was the change to thin film sputtered metal [media bent the hard disk drive curve].

Dee: Yeah, media.

Gardner: Media and thereafter the line took off and now it's folding back over.

Dee: Right.

Gardner: So we need another breakthrough, or maybe none's coming.

Dee: Yeah. It's interesting because although track following servo is not a new concept it was implemented That was the key. That's what changed in the early 1990s in tape technology. It was implemented and that changed the slope -- but it was on flexible media, right? I mean tape's like wet noodle, right, when compared to disk drive media. And so, it flops around. It moves around over the head and if you can follow it, your track density suddenly takes a leap and that last year coincided with the transition from chrome dioxide particle to a metal particle as well.

Gardner: So in your view, if I can summarize, tape is pretty much up against a similar problem as disk or flash except that if it can figure out a way to abandon particle in binder and move to a smaller domain then it could start scaling again. But otherwise.

Dee: It's all to do with signal to noise ratio, how many particles can you get in a bit?

Gardner: Disk drives are down to about seven. Can't go below one. Seven domains in a bit.

Dee: Right. Mm-hm.

Gardner: Maybe nine. You know, it's that sort of number.

Dee: Yeah, but that's what happens is when the signal to noise ratio decreases because of that. That's where the channels guys have to come in to handle the lower SNR.

Gardner: True but there's a limit. [We joke that] at some point you don't need any domains. You just put a white noise generator and correct it, right?

Dee: Yes. Okay.

Gardner: Not a practical product.

Dee: No.

Gardner: Anything you'd like to say in conclusion?

Dee: Not really. I think my move to Colorado to work in this industry clearly was a good one, I mean in terms of a career move.

Gardner: Okay.

Dee: So that was definitely true. You know, we came here and we did well. We raised three children. We live okay. The industry worked for us, you know? So that's good.

Gardner: Okay.

END OF THE INTERVIEW

