HDD Technology: History of the '747' Curve

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***Abstract:-* This short document tells the story behind the '747' curve. This is a test devised at IBM in the 1970's and used to evaluate recording systems for Hard Disk Drives (HDD). It is still widely used throughout the industry. The test plots off-track capability vs. adjacent-track 'squeeze'. The plotted results form a curve that resembles the front end of a 747 airplane.**

Key Words:- HDD-testing, 747, areal-density, off-track, squeeze, error-rate, IBM

It is truly remarkable that HDD technology continues to 'scale' to ever higher capacities in support of the world's insatiable demand for ever more massive and inexpensive data storage. Today, Western Digital is at the forefront in meeting this demand with solutions in both hard disk, solid state and even cloud data systems. Western Digital's legacy leans heavily on its IBM hard disk drive heritage which dates back to the 1950's. We all know that the HDD itself is over 60 years old and that it remains the primary and most cost-effective mass data storage medium in the cloud. Rock-on HDD!

As we all know, HDD's incredible data density is enabled by scaling the entire recording subsystem including head-widths, media film structures and magnetic spacing, coupled with highly complex system integration algorithms enabling seamless performance across a wide range of operating conditions. Since the inception of disk drives, the magnetic track-width has shrunk from about .13mm down to < .00005mm, a factor of over 2500x! In addition, down-track bit spacing has scaled from 0.02mm (1.2kbpi) to less than .000013mm (>2000kbpi), another factor of over 1500! Couple that with the associated dramatic miniaturization of the HDD and you have the wonderfully challenging industry we work in!

40 Years and Still Going Strong!

One of the principal tools used by magnetic recording technologists is entering its 5th decade of existence: the venerable '747' curve which shows the relationship between on-track error rate, off-track read capability, track and bit spacings. The 747 curve has been used for decades by recording physicists and engineers in **all** HDD companies, but its public origins trace to a paper presented by Earl Cunningham and Dean Palmer from IBM at the 1988 Joint Intermag/MMM (Magnetism and Magnetic Materials) Conference[1]. In fact, the '747 test' had already been in existence as an IBM trade secret since 1978 but was only discussed publically a decade later.

So what is a '747 curve' anyhow?

As we all know, HDD's store data in concentric tracks of data fields interspersed with critical servo and timing information to keep the head on the correct track at any point in time. Let's focus on the data portion for this discussion. As tracks are forced ever-closer together, they naturally begin to interfere with one another. One can take the limit to its extreme where an encroaching track fully overlaps (and obliterates) the data track… that is not good! HDD engineers understand these relationships and it is a testament to their engineering prowess that disk drives continue to grow. Back in 1978, this was a novel concept and IBM engineers were trying to find good ways to test their heads and media.

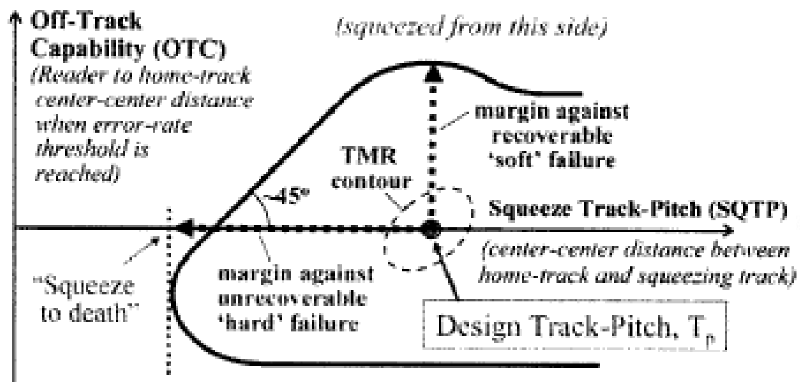
Earl Cunningham is no longer with us, but recently Dean Palmer reflected on the genesis of the '747 test'. *"(…) I wanted to let you how things got started with the 747 test. I had just changed jobs in 1977, going from a post-doc in experimental nuclear physics at the University of Minnesota, to a fulltime job with IBM in Rochester, Minnesota. IBM was augmenting its disk drive business in San Jose (which worked with high end machines) by starting up a development lab in Rochester to look into smaller disk drives. I was assigned to bring up the testing facilities (precision test stands) in Rochester so we could measure the progress of our component development.*

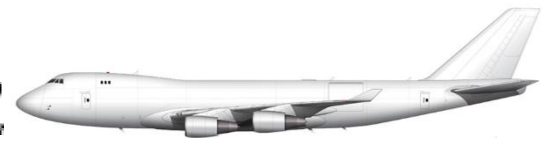
Another fellow was working with me, Earl Cunningham, who had the advantage of working in the flexible media group and therefore understood more or less what was going on with the magnetics. So together we started making tests to evaluate the components that San Jose sent us. We eventually happened onto the combination of written old information tracks, write under-track and write-adjacent track that we thought would give us information about the degradation in performance we could expect as we moved these tracks around. We knew that the tracks would move around in real drives due to a host of reasons and we wanted to see how robust the system was to various offsets.

We were interested in the result that happened when the adjacent track was moved toward the centerline of the track of interest. Instead of monotonically reducing the off-track capability of the read back, at some point it actually <u>increased</u> the off-track capability. But after continued movement toward the center of the track, the decrease started and there was a linear reduction in the off-track capability. The resulting curve for both positive and negative off-track capabilities resembled the front of a 747 airplane and I believe that I suggested that.

Unfortunately, IBM would not let us publish this test or the results so it was not widely discussed for some time. If you look at the attached Technical Report 07.1123$_2$ dated 1989, on the last page it states that the 747 test was mentioned in IBM internal memos in 1978 and in 1981. That is when we were using it.

Another attachment, Technical Report, TR 07.821, was the text book that Terry McDaniel and I wrote and used to teach a class at Rochester for many years. It has the 747 test outlined in one of the later chapters. And finally, the third attachment is a published paper from 2008 that *modifies the 747 test to be based on Data-Block Failure-Rate instead of bit error rate. But it does have a reference at the back [1] to Earl's and my model at the Vancouver Intermag Conference, 1988. That would have been long after it was first used in Rochester."*





How does this test stay useful?

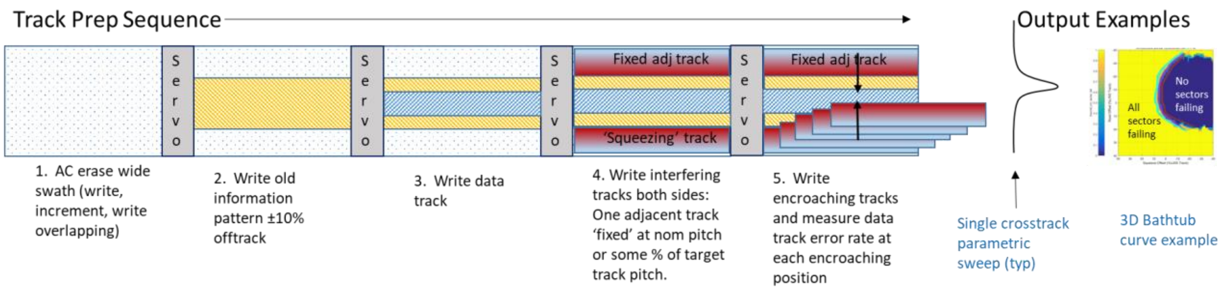
As with any test that has a long history, the 747 test has evolved over the years to keep up with various HDD technology evolutions. In 1998[3], the test was revisited by Beach and Bonyhard to reflect the emerging use of MR (magneto-resistive read) heads in the industry and attempted to derive an empirical model for the behavior of the many variables at play in the recording system including track pitch, write width, reader sensitivity and a host of other system noise sources.

In 2008 the 747 test was revised again by Jin, et al.[3] to reflect current methodology, modifying the original bit-error rate to a more useful Sector-Error Rate (SER). Sometimes, the inverse of SER is used, termed Sector Failure Rate or SFR, but the results are otherwise identical. This was an important modification and kept the test itself useful as the industry moved to PRML detection and then to LDPC error correction methods where a data sector is either recovered perfectly or the entire sector fails catastrophically.

Let's review a few of the 747 tests currently in use:

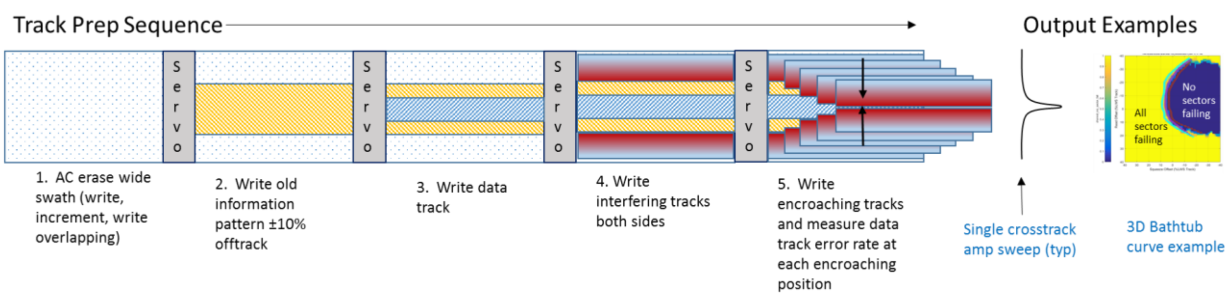
1) The original 747 test was produced by squeezing from only one side with the assumption that one adjacent track is nominally positioned or positioned at some fixed percentage of the design track pitch. This test was widely used from inception to the late 1990's.

The single-sided 747-test:



2) When track pitch (and associated Track Mis-Registration or TMR) increased to the point that most tracks were squeezed, it was recognized that the 747 test had to adapt to better represent expected drive operating conditions. A variant of the 747 test was then developed that squeezes tracks in from both sides (double-sided squeeze). This test typically writes full tracks at each squeeze position and measures the effects of this squeeze on the test track. For each squeeze position, a full rewrite and reread is required, so this test is the most time consuming of all the 747 variant tests.

The double-sided 747-test:



3) As most recording technologists will attest, many variants of the above test have been developed. Some modifications include those intended to improve the accuracy of the output in the presence of special types of noise or interference. Other modifications are tuned to reduce the measurement test time and yet others are tuned to deliver a matrix of outputs, thereby delivering not only the 747 related metrics, but other important system level measurements.

4) Sometimes these measurements are made in the field and results compared to the factory test results to ensure data integrity over time

There are myriad ways that the 747-test can be utilized and, in fact, new tests based on this tried and true measurement method are still being designed. As new recording methods such as Shingled Magnetic Recording (SMR) or Interleaved Magnetic Recording (IMR) begin delivering to the industry, we can confidently say that the 747-test will once again be utilized and perhaps further modified to stay current. Stay tuned to technical publications like IEEE Transmags for related papers.

What does the future hold for the 747 test?

As you can see, the 747 curve has evolved over the years from its origins at IBM in 1978, its first publication in 1988, its modification for MR heads in 1998 and a further modification for newer channel technologies in 2008. The HDD industry owes a collective debt of gratitude to the 747 inventors and the test itself. We see it continuing to be a primary analytical method as the HDD business migrates to energy-assisted writing technologies (MAMR and HAMR), and with these technologies, the test may ultimately see 50 years of use!

References:

[1] E.A. Cunningham and D.C. Palmer. “A model for the prediction of disk file performance from basic component capabilities”, paper JE-3, MMM conference, 1988

[2] E.A. Cunningham and D.C. Palmer. “Characterization and Derivation of the 747 Curve – A guide to Track Pitch Selection”, IBM technical report #TR 07.1123, November 1989

[3] R.S. Beach and P.I. Bonyhard. “An Offtrack Capability Model Including Noise, IEEE TransMag, Vol 34, No 4, July 1998

[4] Z. Jin, M. Salo and R. Wood. “ Areal-Density Capability of a Magnetic Recording System Using a ‘747’ Test Based Only on Data-Block Failure-Rate”, IEEE TransMag, Vol 44, No 11, November 2008