Designing a Long-Life, Page-wide Print-head

Stephen Conner (2), Lisa Underwood (1), Minal Shah (2), Thom Sabo (1), Clayton Holstun (1), Brian Canfield (2), Curt Voss (2)
1 Hewlett-Packard Company, 16399 W. Bernardo Drive, San Diego, California, 92127 USA.
2 Hewlett-Packard Company, 1070 NE Circle Blvd., Corvallis, Oregon, 97330 USA.

Abstract

This paper discusses three key concepts we used to develop a pagewide printhead designed for a long service life. First we analyzed the product goals as well as past products' strengths and weaknesses. This resulted in a product reliability specifications and an initial identification of which areas needed reliability improvements.

Then we introduce the concept of Discovery Testing. This technique stresses the system, subsystems and components to higher levels of stress than what would be experienced in a typical customer environment. This allows for rapid discovery of design weakness with fewer parts and in less time.

Finally, following the Discovery Testing phase, a classic build-test-fix cycle was followed. Weaknesses identified in the Analyze and Discover phases are eliminated or improved through design or assembly changes.

To help make this process more tangible, the paper deals with four case studies of actual problems we discovered and took to resolution.

Analyze Phase

As laid out in the paper *Transformation of Thermal Ink-Jet Product Reliability Strategy [1]*, the development of our PageWide printhead started with the Analyze phase. In this phase, the customer use and environmental requirements were analyzed. The capability of previous products were reviewed and the weaknesses and strengths were documented. The potential failure modes for the new product requirements were accounted for and tracked in a Failure Modes and Effects Analysis (FMEA). The customer needs, the projected capability of our printheads, and financials are reviewed together to set reliability specifications in the form of a statistically based "reliability budget". In the early phase of a program it is important to get this budget in place, even if failure rate estimates have to be made. Those estimates can be refined as the program continues.

The risks of the product and gaps of information highlighted in these two tools were then addressed in the next phase of the development, Discovery Testing.

Discovery Testing Phase

The relationship between a product and a failure modes can either be characterized, demonstrated or simply identified and eliminated.

Because the intended life of these modules is multiple years or many thousands of prints, failure modes cannot be identified by simply testing at the usage stress (Figure 1.) HP used the common industry practice of overstressing designs to discover weaknesses in the designs or expose issues with the assembly methods of the given design (Figure 2.).

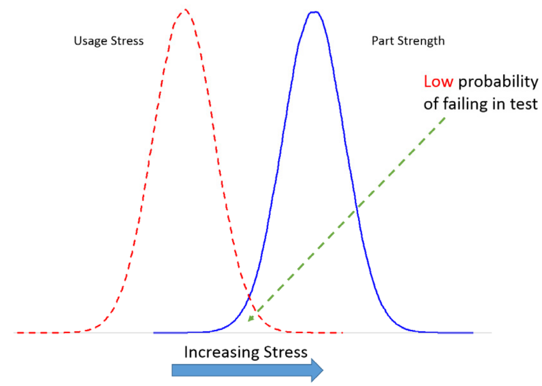

Figure 1. Low probability of finding a failure when testing at the usage stress level.

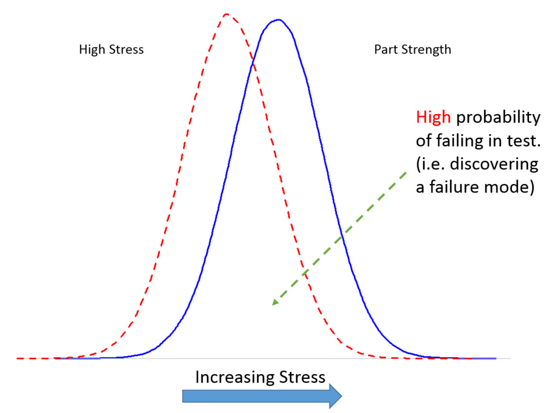

Figure 2. Higher probability of finding a failure when testing at a high stress level.

The applied stresses used to "discover" a failure mode can be anything. It could be temperature, humidity, cycle rate, voltage, force, altitude or others. Choosing the appropriate stresses should be guided by first principles of the materials of the design as well prior knowledge of previous products. A key to successful discovery level testing is making sure that stress is not excessive. Meaning that the level of stress does not induce a failure mode that wouldn't occur at the use conditions. For instance, if a wiping system is designed to operate with 2 pounds of applied force, you might choose to test with 4 pounds of force to look for excessive die wear. But you would not use 20 pounds of force which could cause die cracking. Or, you would not test your plastic parts at a temperature that would actually melt the plastic if melting is not something the part would ever do under the harshest of customer use conditions. Good failure analysis after testing is very useful in making sure failure modes are realistic and not just a result of the high level of stress.

After a failure mode is discovered the engineering team is left with four choices:

1. Do nothing,
2. Demonstrate robustness of the design to the failure mode at the specified reliability,
3. Characterize the failure mode so that the failure distribution curve is estimated or,
4. Eliminate the failure mode through better design.

All four choices can be valid options to take depending on the specific situation. In fact, all four choices were made at different times during the development of the PageWide printhead. One may choose to not address the failure mode revealed in discovery testing for several reasons. The failure mode may be known to only occur at accelerated stress levels or, via prior knowledge, it is known that the rate of failure at the use condition will be well below specification. Both demonstrating and characterizing failure modes can be expensive (due to part costs and test equipment usage) and they can take a significant amount of time to complete. Only a few critical failure modes should be characterized to this extent when test time is long or test cost is high.[2] While the information gained from demonstration and characterization testing is useful for estimating failure times, eliminating the failure mode, is the only choice that actually improves the reliability of the product. Elimination of the failure mode is the transition from the discovery phase to the Build–Test–Fix phase.

Build – Test – Fix

The classic approach to resolving engineering problems is the build – test – fix cycle, where one builds parts, puts them into tests which puts them under stresses, and then analyses the results to come up with a fix. This cycle is repeated as often as necessary to find a solution that passes one's discovery level testing. If a solution is not available that passes discovery level testing in the allotted development time, engineering teams tend to fall back on characterization stress levels to determine the actual customer impact.

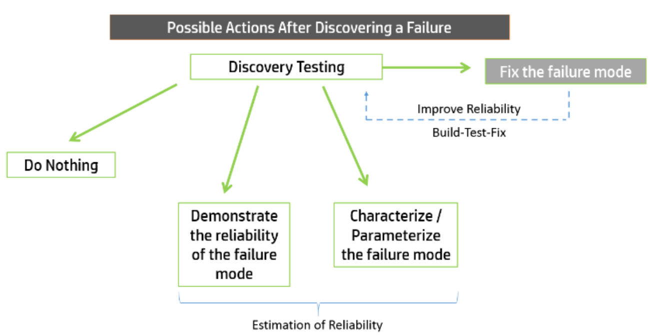

Figure 3. The Build-Test-Fix cycle improves reliability.

Paper Jam Example

One failure mode that came out of both our "analyze" and "discovery phases" was print head damage due to paper jams. With any printing system there is a risk of a paper jam which can cause physical damage to the print heads. It was no different with this print system.

Paper jams of a real print system at customer use rates and conditions are infrequent. It would take too much of the development schedule to wait for enough jams to happen, analyze their impact and then make any necessary design changes. Because of this, overstress techniques were employed to discover and understand the susceptibility of the printhead to paper jam damage in a timely fashion. HP created a testing process that would repeatedly cause the type of paper jams known to cause damage to the print heads in past products. With this process we were able to induce paper jams in a test bed quickly enough to see what parts of the PageWide printhead were damaged and how.

Discovery level testing is not able to accurately predict how many real paper jams the printheads could survive, but was very good at allowing us to rapidly test a variety of designs to see which one was most robust to paper jams. These designs needed to protect the printhead from paper jams, allow the printhead to be wiped clean with the servicing sled and maintain the desired printhead to paper spacing. Multiple iterations of printheads were designed, fabricated and tested before the final design of the PageWide XL printhead was implemented.

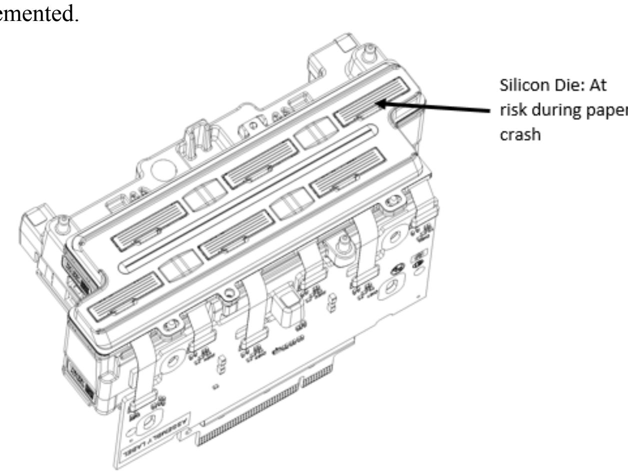

Figure 4. Picture of PageWide XL printhead.

Electronics Life Example

Thermal Inkjet printing results in a stressful environment for electrical components in a printhead. The printhead is exposed to heat, moisture, chemicals from the ink, electrical current, and mechanical contact. The printhead needs to be robust to these stresses for long periods of time.

To make sure the PageWide XL printhead has a design that is robust to the stresses in the system, we again did our testing using the discovery level testing technique. We reviewed the known stressors of temperature, relative humidity, and time with electrical charge applied, and then designed tests to increase the stress level to see what parts of the design were the weakest. Temperature is a known stressor for increasing the rate of chemical reactions. But one can only increase the temperature so far without invalidating the results. If the temperature is raised to a level that creates a failure mode that could never be seen at the use condition, then we have gone beyond the foolish limit/excessive overstress and the data is worthless. So care must be taken to know the properties of the materials under test (like glass transition temperatures), and to design the test to be as fast as possible without compromising the integrity of the test.

Likewise, increased relative humidity has been known to cause faster corrosion, and thus is good stress factor for this type of testing. One must be careful to maintain a non-condensing environment, as having liquid water sitting on a printed circuit board or other electronics could be considered an excessive overstress (unless one expects the electronics in their printing system to see liquid water, in which case, it would be part of the discovery level testing).

An additional stressor is the length of time and level of the electric charge applied to the electronics. Minimizing test time without creating unrealistic failure modes was again a difficult challenge. Running Discovery level testing with these stresses enabled us to find failure modes quickly, even though they may not occur for many years at the customer use condition. Finding these failures allowed us to tune our raw materials, alter our design and improve our manufacturing process resulting in a more robust design to the stresses put on to the pen electronics by temperature, humidity, and usage.

Shipping Fluid Example

Transporting a printhead from the manufacturing site to the end customer is obviously necessary. However, the distribution channel is filled with a large number of shocks and vibrations of varying size. Additionally the module must endure temperature extremes and large changes in altitude. Whether on a truck, train, boat, or plane, the module needs to be able to withstand all these stresses.

The shipping channel, though necessary, does not provide any inherent benefit to the customer. However, during transportation, the module can be damaged or the quality degraded. The module can ingest air, ink can degrade parts of the printhead, or the pigment in the ink can settle. All of these potential failure modes can reduce the life of the module.

In the Analyze phase, the team knew from past products that pigment settling and the interactions of the ink with the other materials could be a significant issue. Not only can these issues cause significant failures in the printhead, but the test time is long and test cost can be quite high. Some failure mechanisms can be accelerated through stresses like temperature and some cannot. The Team had learned from past programs that pigmented inks, like the ones used in PageWide XL printer, can possibly have shipping and storage issues that can take years to manifest with no way to accelerate them. This makes finding and fixing these failure modes not feasible within the schedule of the program. Instead, it was decided to eliminate the potential failures completely. Instead of shipping ink inside the printheads, a benign "shipping fluid" was created for transportation. This removed the risk of shipping with ink, reduced the cost of testing and verification, and put the program ahead of schedule in this area of the design.

However, in the Discovery phase of testing air ingestion was discovered. Print-heads were being tested at vibration levels used for qualifying ruggedized or military level products. Mechanically and electrically, the printheads performed well, but it was discovered that the printheads were ingesting air through the nozzles. Excessive air can reduce the overall life of the printhead, so the printhead went through a few iterations of the Build-Test-Fix cycle. Eventually, the final design solution was the shipping fluid for the PageWide XL printhead being altered to make air ingestion much less likely to occur even at high levels of vibration.

Resistor Life Example

Pagewide printing systems are particularly susceptible to nozzles which do not fire, since multiple pass print modes are not possible. Our printer employees a sophisticated mechanism to detect missing nozzles and we use special techniques to compensate for them once they have been detected. This works very well for the typical types of single nozzle defects that arise from particle contamination. But some failure modes engage physics that allow a defect at one nozzle to grow into adjacent nozzles, and the compensation system will eventually break down.

To deal with this, we designed a Discovery Level method of testing which continues to fire a resistor for some duration even after we have detected that it has failed. Various test procedures were developed to probe this sensitivity. A consequence of this is the actual definition of "failure" of a multi-die module evolved, and caused us to rework our mathematical treatment of failure rate data to transform die level data into a prediction of module level failure rates.

Once this was accomplished it became clear that we had a marginal reliability situation for nozzle life. This in turn forced us to go back to the underlying design and make changes to improve the module level robustness to the multiple nozzle failure mode.

Conclusions

Creating a functioning PageWide XL printhead is extremely challenging. Making it highly reliable is even more difficult. Following the Analyze, Discovery Test, and Built-Test-Fix path enabled us to utilize past knowledge, find new failure modes, and design out weaknesses all while keeping costs relatively low and staying on schedule.

References

[1] S.A. Conner, P.E.Watts., "Transformation of Thermal Ink Jet Product Reliability Strategy", *Reliability and Maintainability Symposium, (Jan) 2012.*

[2] S.A. Conner, "Deciding When Reliability Demonstration Is Best For the Bottom Line", Reliability and Maintainability Symposium, (Jan) 2014.

Author Biography

Brian Canfield is a Master Technologist with 30 years' experience developing Thermal InkJet products for Hewlett Packard. He leads efforts to develop products and technologies more effectively to deliver high value, reliability, and robustness with reduced budgets. Key strategies include Shift Left, Feed Forward, and Discovery Level testing.

Steve Conner received a Bachelor's of Science Degree in Chemical Engineering from the University of Massachusetts in 1991. He received a Master's degree in Manufacturing Engineering jointly from Oregon State University and Portland State University in 1999. Steve has worked in industry for the past 24 years. For 23 years he has been working in the ink-jet development organization of Hewlett-Packard. During the past 13 years his focus has been on ink-jet product reliability.

Clayton Holstun received a Bachelor's of Science Degree in Mechanical Engineering from Washington University in 1980. He has been involved in the design of pen-based, liquid electrophotography, and thermal ink jet printing machines for Hewlett-Packard since then. He has performed system development, integration, and testing on HP's first office pagewide product, and on the current technical graphics machine.

Thom Sabo received a Bachelor's Degree in Education from Arizona State University in 1974. He spent 10 years teaching before returning to ASU and earning a Mechanical Engineering degree in 1986. Thom started his engineering career as a thermodynamics specialist working for 8 years on satellite launch vehicles with General Dynamics. Thom has spent the last 22 years developing reliable HP inkjet printers. Thom also earned an MBA from National University in 1991.

Lisa Underwood received a Bachelor's of Science Degree in Chemical Engineering from the University of Colorado Boulder in 1997. She received an MBA from University of Colorado, Colorado Springs in 2002. Lisa has worked in industry for the past 16 years, developing specialty media for inkjet and LaserJet printing and most recently writing systems for HP inkjet printers.

Minal Shah received Bachelor of Engineering in Metallurgy and Masters of Engineering in Materials Technology from India. She received another Masters and PhD degree in Materials Science from Oregon State University in 2008. For a short while, she was a product engineer and has been an R&D reliability engineer working on different aspects of PageWide technology at Hewlett Packard for the past 6 years .

Curtis Voss is a research and product development engineer at HP's inkjet facility in Corvallis, Oregon. He has worked in a variety of areas including the fabrication of microelectronics, thermal and piezo inkjet MEMS devices. He currently develops system level printer tests with the HP PageWide Technology. In his spare time he races sailboats and gardens.