

Life Test Case Study for Heater Cartridge Reliability



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Standard Disclaimer

This presentation is intended as a general outline of the life test work done on heater cartridges at the Santa Clara Site of Agilent Technologies in 2008.

There are many very interesting topics related to this work that are considered company confidential.

All confidential topics have been removed from this presentation.

The Story, The Dilemma

June 2007: A new technique was developed that would solve many customer problems.

Time to market, time to market, time to market.

August 2007: The design team moves out of the investigation phase into the lab prototype phase and discovers an issue with derating.

- To take full advantage of the new technique, the heater cartridge must be able to run at temperatures up to 800C.
- In general, heater cartridge technology has problems with long-term operation at temperatures above 650C.

February 2008: Reliability Engineering is asked to consult with the R&D team and to construct a life test plan.

Reliability Engineering, First Things First

Since the design team was still in the lab proto phase, it seemed reasonable to look at alternative technologies.

Several technologies with good reliability at 800C were identified.

However there were issues with form factor that precluded using the available “off the shelf” components.

The alternative technologies also had issues with cost and second source availability.

Reliability Engineering, First Things First



Various ceramic fiber heaters. These are specified to 1100C.

Pictures courtesy of Tempco's website (www.tempco.com)

(This slide added post presentation – to address questions on alternate technology. You need to read the rest of the presentation to put this answer in perspective.)

Question: What is different about the ceramic fiber heaters that allow them to go higher than the cartridge heaters.

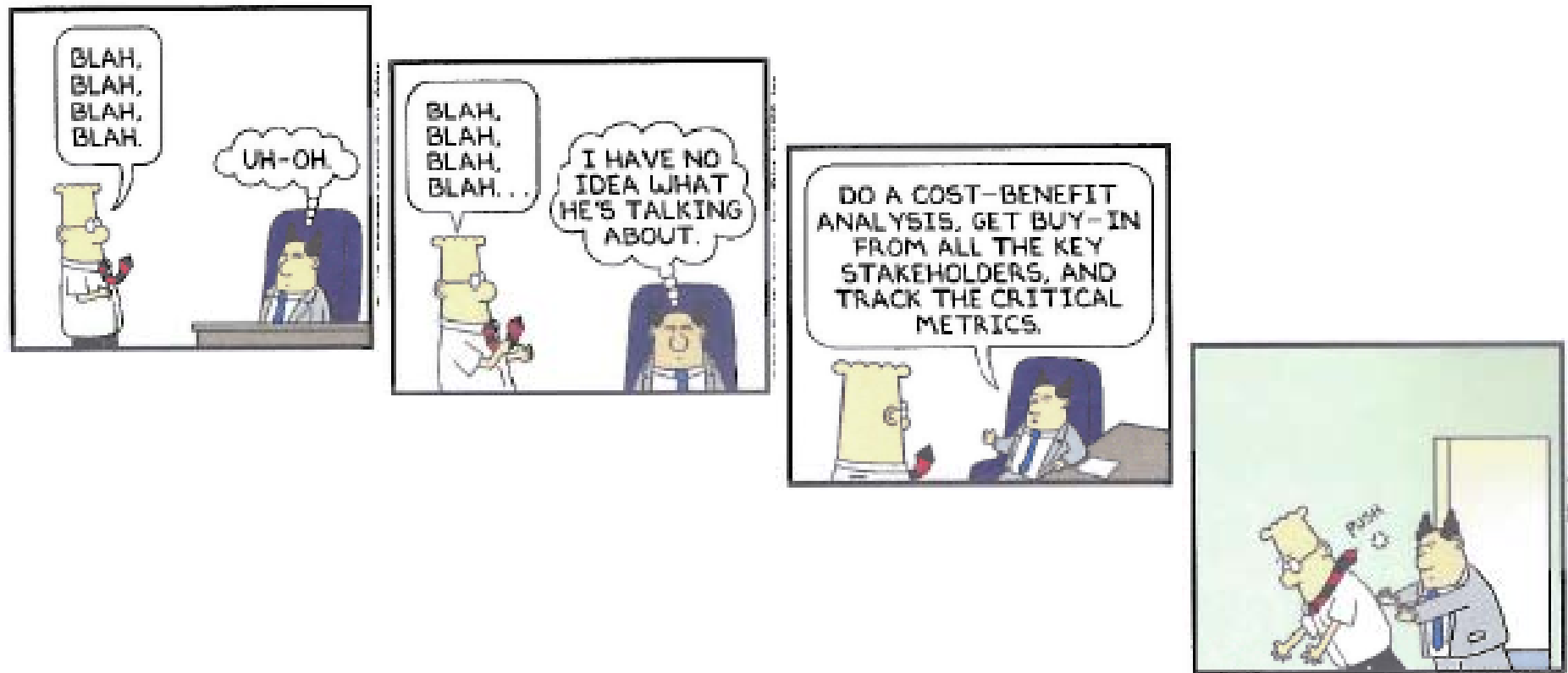
Answer: Three things

- 1) Only the heating element is exposed to high temperature. There is no need to bring in nickel or copper based power wires as is done for the manufacturing process of the heater cartridge. The center conductors in the heater cartridge are the high risk parts.
- 2) The ceramic form factors are physically larger and can accommodate having coiled heater elements throughout the structure. Since there are no linear wire forms along the length of an expanding cartridge, matching the temperature coefficient of expansion of the materials is much less important. The coiled heater elements simply expand and contract with very little induced fatigue (think of a coil form like a slinky) .
- 3) Since the heater forms are physically larger, the thickness of the heater wire is less of design constraint. The heater wire can survive many years of oxide formation because it is thicker and can afford to lose some conductor cross section without risk of current crowding and burn out.

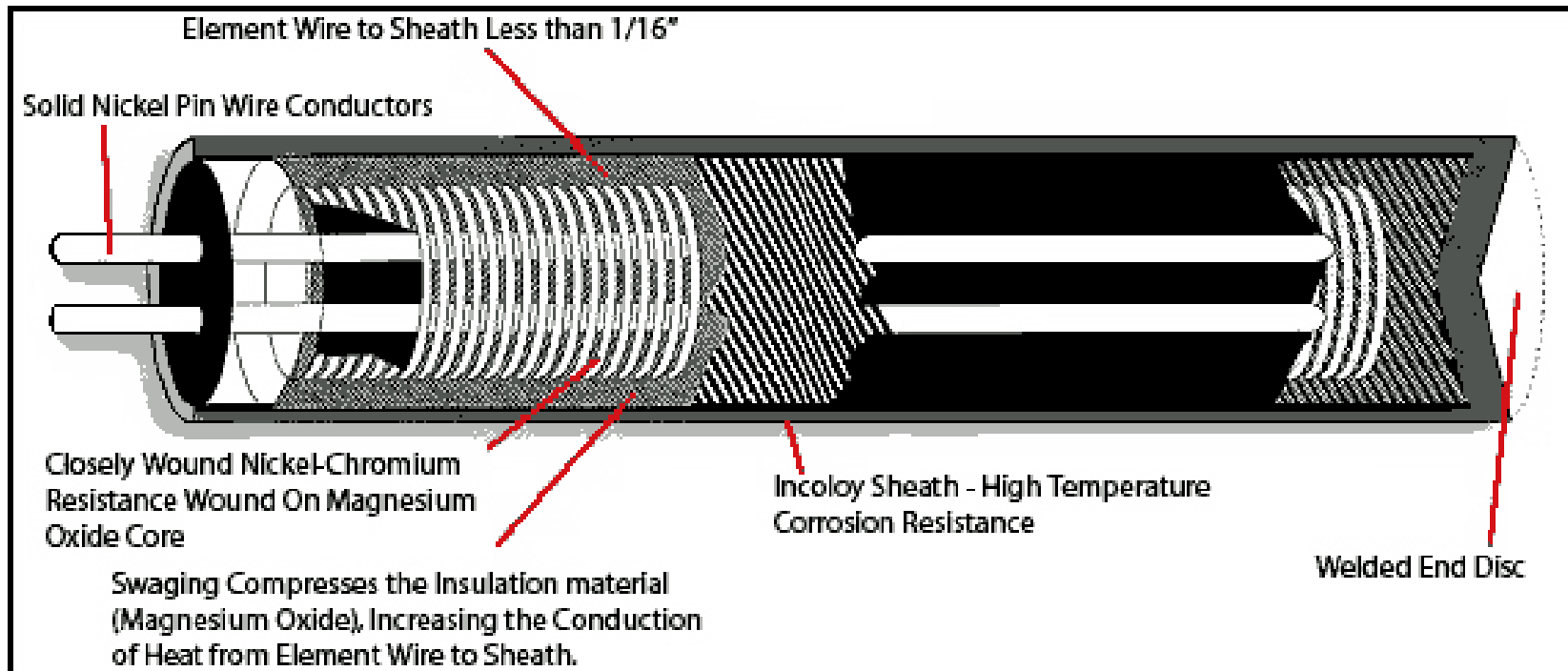
The Mold is Cast

In April 2008, a critical decision was made:

The project development would proceed using heater cartridge technology.



What is a heater cartridge?



Picture courtesy of the ThermalCorp web site (www.thermalcorp.com)

The Agilent heater cartridge included two additional center wires for a K-type welded thermocouple.

Contacting the Experts

There are several well known companies who have been making heater cartridges for years. Just to name a few:

- Chromalox (formerly Ogden)
- Watlow
- Omega

Several days were spent calling these companies and finding out as much as possible concerning failure modes and mechanisms.

Identified Failure Mechanisms

After collecting notes from six heater cartridge OEMs, a Pareto of potential failure mechanisms was established.

For heater cartridges being run over their temperature spec:

Highest Frequency

Damage to the insulation on the cartridge leads

Mechanical failure of the thermocouple junction

Oxidation and burn out of heater element

Lowest Frequency

Fatigue related wire failure

Mechanism 1: Damage to the Insulation on the Cartridge Leads

The cartridge leads are by far the most vulnerable part of the cartridge design.

For a cartridge rated to go to 650C, the lead insulation is typically only rated to 450C!!

If you want good heater life at high temperatures then you absolutely have to protect the cartridge leads.

Resulting Modes

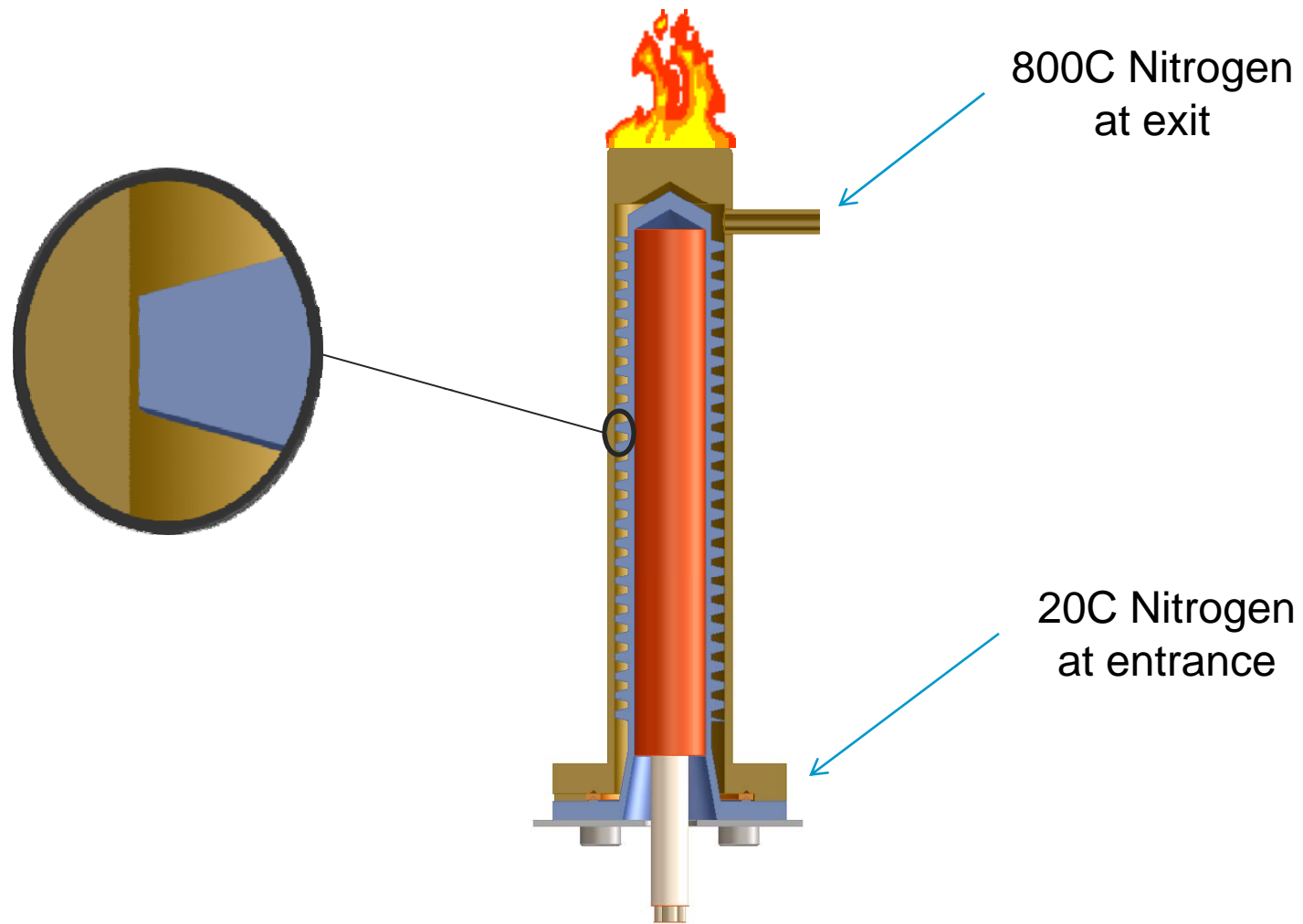
The lead insulation eventually breaks down and results in a short circuit.

- A shorted thermocouple lead to ground often results in a run-away zone.
- A shorted AC line to ground often results in blown fuses.
- A shorted AC line to thermocouple line always results in damaged PCAs

Mitigation

In this application, we are using the cartridge to heat nitrogen gas. By choosing to start the circulation loop at the leaded end of the cartridge, we can use the cool nitrogen gas to our advantage. The in-coming nitrogen keeps the leads below 450C even when the cartridge control point is at 800C.

Life Test: What exactly were we testing?



Mechanism 2: Mechanical failure of the thermocouple junction

K-type thermocouple leads are used as the control point sensor in these cartridges.

This type of thermocouple uses alloys of nickel-chromium and nickel-aluminum.

Spot welding these wires together usually produces a mechanically robust junction.

However at very high temperatures, the junction tends to embrittle and crack along the contact faces of the spot weld.

Resulting Mode

The thermocouple output eventually becomes intermittent.

Mitigation

The heater cartridge OEM recommended using a larger bead at the junction to ensure a smooth transition from one wire type to the other.

Tungsten Inert Gas (TIG) welding was used to produce a larger junction bead to give a gradual alloy transition.



Mechanism 3: Oxidation and burn out of the NiChrome heater wire

The wires in the cartridge are encased in a swaged and hardened magnesium oxide (MgO) insulation.

To get to the wire, oxygen must enter at the leaded end of the cartridge and then diffuse through the hardened MgO insulation.

The small amount of oxygen that reaches the NiChrome forms a layer of oxide.

Each thermal cycle of the cartridge causes some of this oxide layer to cleave off due to differences in the thermal coefficient of expansion (wire versus wire oxide).

This exposes fresh NiChrome wire and the process repeats with the next thermal cycle.

Eventually areas of the NiChrome wire are so thin that current crowding results in burn out.

Resulting Mode

The NiChrome wire becomes an electrical open. The heater no longer heats.

Mitigation

Not much can be done to seal the cartridge against oxygen.

Not much can be done about thermal cycling. The cartridge temperature can be turned up or down, on or off, at the customer's discretion.

However since the life of the NiChrome wire is directly related to its thickness we can delay this failure mode by using a thicker wire.

One way to get a thicker wire is to specify a higher wattage cartridge than required.

Over specifying the wattage gives more margin for the NiChrome wire but has an over-all size penalty for the cartridge.

Mechanism 4: Fatigue Related Embrittlement.

When a heater cartridge is run at extreme temperatures, the four wires at the center of the cartridge will experience fatigue.

The number and magnitude (peak to peak swing) of the thermal cycles determine how fast the fatigue accumulates.

The high temperature exposure tends to change the ductility of the wire.

At the same time, the wires are being subjected to tension and compression within the confines of both the hardened MgO insulation and the steel jacket of the cartridge.

This results in changes to the microstructure of the wire – primarily grain growth. The wire loses ductility and eventually becomes embrittled.

Resulting Mode

The four center wires eventually fracture resulting in either an open thermocouple (no reading) or an open power circuit (heater no longer heats)

Mitigation

Not much can be done about thermal cycling. The cartridge temperature can be turned up or down, on or off, at the customer's discretion.

Although 650C is the typical working limit for heater cartridge technology, some manufacturers offer modified cartridges specified to the mid 700C range.

These cartridges increase the diameter of the thermocouple and power wires in order to increase life.

The OEMs could not offer any life test data to support their claim that thicker wires are less susceptible to fatigue than thinner wires.

Life Test: What were the deliverables?

Deliverable 1

At the end of life test, the project's reliability goal (90% reliability or better at 1 year) should have associated confidence estimates spanning an 18 month "normal use" period.

Deliverable 2

At the end of the test, the failure modes and mechanisms should be ranked in Pareto order according to their frequency.

Life Test: What were the constraints

Constraint 1

The hardware needed to simulate system operation would not be available until June 2008.

Scheduled product release was late September 2008.

Only 4 months to complete the life test.

Constraint 2

Due to budget constraints, only 2 life test set ups would be built.

Life Test: The Plan

Life Test Plan

A PC based automated test program would cycle the heater cartridges. Focus on simulating customer work day cycles as well as weekend cycles.

Front load the shortest duration tests and run 24/7.

Change the test plan based on feedback from the earlier phases.

Three phases were planned

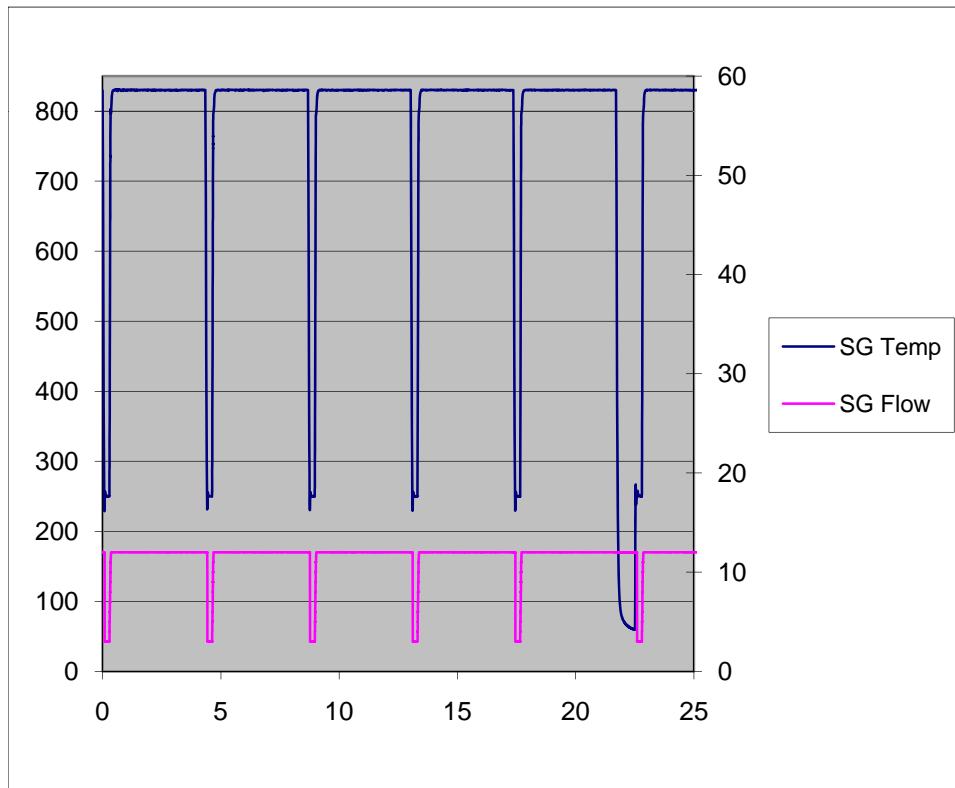
Phase 1: Lots of cycles. Short dwells at both low and high temp.

Phase 2: Increase high temperature dwell time.
Increase transition slew rate

Phase 3: Increase high temperature dwell further.
Increase maximum temperature.

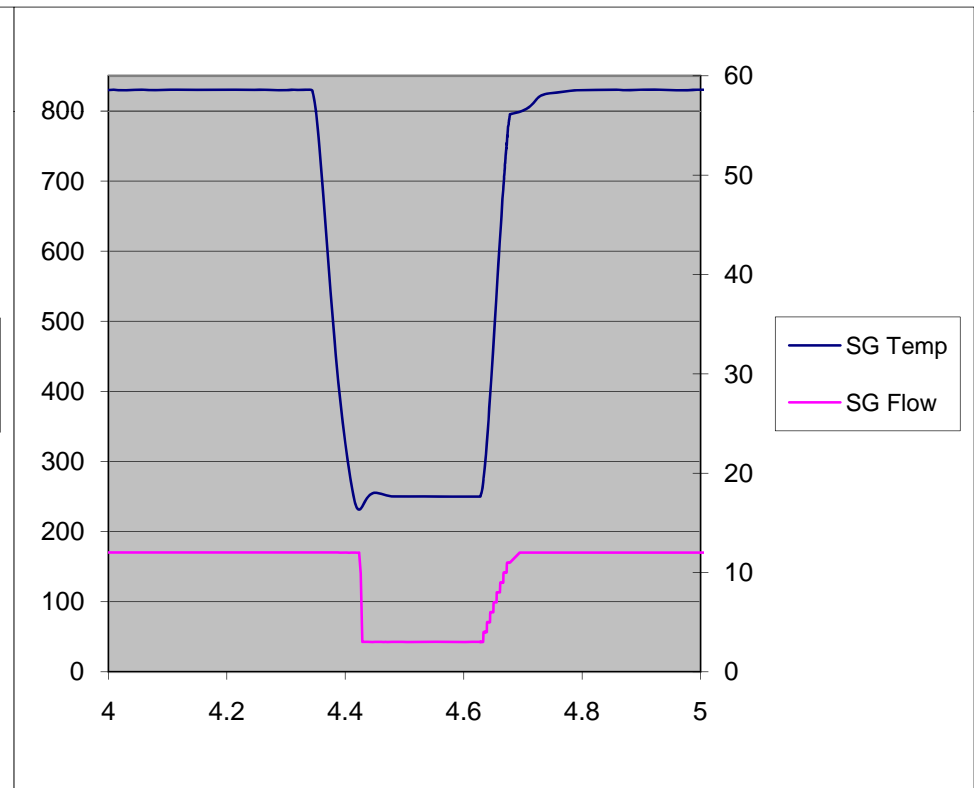
Simulated “Normal” Customer Use

Weekly profile
including weekend.
(C, L/min, hours)



Work Day Profile.

Note maximum rate of change
for both transitions
(C, L/min, hours)



Acceleration Factors?

Acceleration factors exist for each of the 4 failure modes. But as in so many other cases, the actual acceleration is highly dependant on the particular design and application.

For example: We can look up the NiChrome oxide formation rate in free air at a given temperature. But we don't know much oxygen is actually getting through the hardened MgO insulation.

For example: We can look up the general rates of fatigue related embrittlement (work hardening) for the 4 center wires. But given that the cartridge sees a temperature gradient ranging from a few hundred degrees C to 800C, FMEA simulations would be needed to estimate the actual stress profile on the wires.



Maximizing Utilization Rate (Time Compression)

To maximize the utilization rate, the weekly “normal use” profile was divided into discrete operations and assigned stress levels on a scale of 10. Duration of this activity was also assigned per the “normal use” customer use profile.

Some examples are shown in the table below:

Activity	Stress Level	Duration
Transition from “stand-by cool” to 800C	6	3 minutes
Dwell at 800C	5	8 hours
Dwell at “over night stand-by” cool	1	16 hours
Dwell at “weekend” cool	0	48 hours

(This slide added post presentation to answer questions on time conversion rate)

A level 5 implies 100% utilization – intended use mode, acceleration factor =1.

A level 0 implies that the activity is not utilizing the heater cartridge. The rank zero activity has no effect on heater life.

Any level above 5 implies some mechanism is in play which is beyond the intended use mode. For example, thermal shock comes into play during the temperature transitions.

In this case, the normal use stress levels ranged from 1 to 6 on a scale of 10. In assigning this scale, we purposely left some headspace at the top in the event that we found one of the assigned levels was incorrect and needed to be increased.

The assigned acceleration multipliers for increased stress levels are often well above this scale (example: 2.5X for a stress based acceleration equates to 250% utilization rate.)

Stress Level	Utilization Rate
10	200%
9	180%
8	160%
7	140%
6	120%
5	100%
4	80%
3	60%
2	40%
1	20%
0	0%

Maximizing Utilization Rate (cont)

To increase utilization rate, the profile was modified to increase the percentage of the high stress activities.

Activity	Stress Level	Duration
Transition from “stand-by cool” to 800C	6	3 minutes
Dwell at 800C	5	2 hours
Dwell at “over night stand-by” cool	1	15 minutes
Dwell at “weekend” cool	0	15 minutes

In the example above, we have increased the percentage of the level 6 activity by decreasing the duration of level 5, level 1 and level 0 activities.

Conservative Use of Acceleration Factors

Where accelerations factors were applied, typically only a fraction of what was believed to be the potential acceleration was used.

Activity	Stress Level	Duration
Transition from “stand-by cool” to 800C	7	2 minutes
Dwell at 800C	4	8 hours
Dwell at “over night stand-by” cool	1	16 hours
Dwell at “weekend” cool	0	48 hours

In the example above, the rate of change on the transition has increased. The duration has changed from 3 minutes to 2 minutes and the stress level increased from 6 to 7. R&D believes the actual increase in stress to be much higher.

(This slide added post presentation to answer questions on time conversion rate)

There were several questions on the net acceleration (maximizing high utilization activities X stress accelerations) .

Reviewing the data, the time compression due to maximizing high utilization activities was a little over 2X.

The stress accelerations in the third phase were in the 4X to 5X for some of the longer dwell activities. The estimate for one activity got into the 9X range due to a combination of increased stresses (and suspected interactions).

The net acceleration for the Phase 3 work was over 10X.

Adding Up Time?

Since all 3 phases of testing referenced back to the “normal use” customer profile, there was a strong lobby effort to convince the reliability engineer that the simulated time from each of the three phases could simply be added together.

The basis of ALT is the use of constant stress over time.

It is not intended to be a “Step Stress” test.

The bottom line:

A few of the longest life data points moved through multiple phases and the phase times were added. (Mea Culpa)

Life Test: The Results

Phase 1: Lots of cycles. Short dwells at both low and high temp.
No failures. 6 units tested.

Phase 2: Increase high temperature dwell time.
Increase transition slew rate
No failures. 4 units tested

Phase 3: Increase high temperature dwell further.
Increase maximum temperature.
2 failures. 4 units tested.

Life Test: Pareto of failures

1) Damage to the insulation on the cartridge leads

Only 1 failure observed. Mitigation worked.

2) Mechanical failure of the thermocouple junction

No failures observed. Mitigation worked.

3) Oxidation and burn out of heater element

No failures observed. Mitigation worked.

Life Test: Pareto of failures

4) Fatigue related wire failure

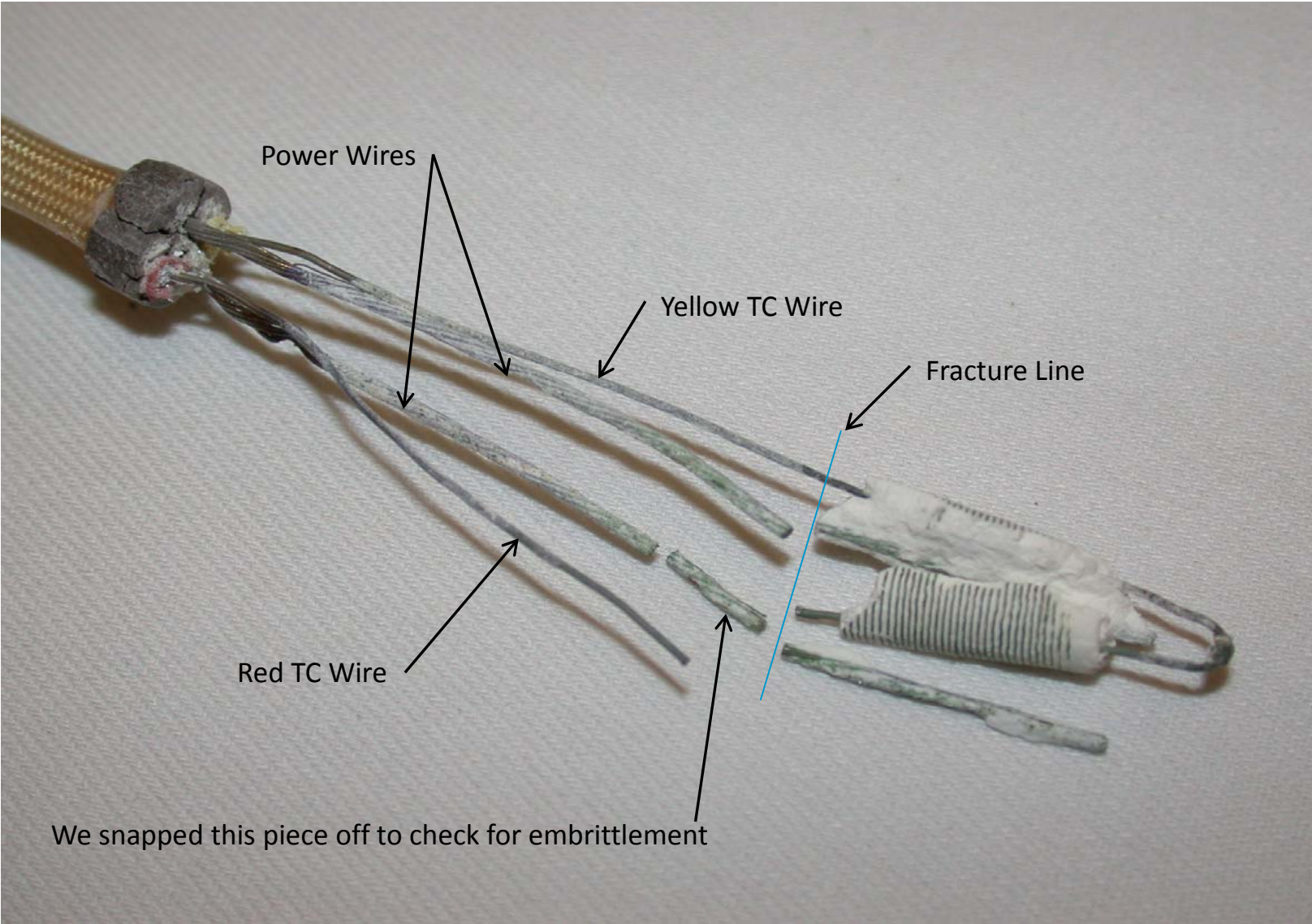
Recall that while this was the lowest ranked failure during the investigation phase, it was also the one with the weakest mitigation.

No data supported thicker wires holding up better to cyclic fatigue.

Almost exclusively, the failure mode involved an open thermocouple. However sometimes heaters would show both thermocouple failure and heater wire failure simultaneously.

Every autopsy showed the same morphology. The wires were embrittled. In the area of highest mechanical stress, these wires could be snapped like rods of glass.

Heater Cartridge Reliability – Failure Analysis



The Red Wire (Alumel) Breaks first

An interesting observation was that the red thermocouple wire was always broken.

Sometimes it was the only wire broken. Sometimes it was broken along with one of the other three wires.

A little research brought up a twenty page paper on why this happens:

A Case of Embrittlement of Sheathed Alumel
Thermoelements in LMFBR Fuel Pin Simulators
(McElroy, Leslie, Clark. March, 1974)

Oak Ridge National Laboratory
Operated by Union Carbide Corp
For the US Atomic Energy Commission

Presenting the Data, Lessons Learned about Format

I presented some results using a standard Weibull plot with confidence bounds. After the meeting, I was asked to “simplify” the results.

Consider the audience.

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Presenting the Data, Lessons Learned about Format

People who are unfamiliar with reliability data tend to have a stronger reaction to low reliability numbers than to low confidence numbers.

In one presentation, I formatted the data with confidence held at 80%. In that case the demonstrated 1 year reliability as 37%.

The group's reaction was not favorable. They interpreted this as "we have high confidence that the reliability is low".

-- which was not the message I was trying to get across.

However a few weeks later I presented more or less the same data but this time started with a 90% reliability goal. Confidence numbers were presented for various time periods (3 months, 6 months, 9 months....)

This seemed to go over very well. The group interpreted this as "We don't have good confidence in our reliability goal because we don't yet have enough data".

-- which was the correct message.

Using the Beta Distribution

Several software packages and reliability websites offer confidence limit calculators.

However typing individual numbers into a calculator and then reentering the result into Excel became too tedious with rapidly increasing field population.

Eventually, a formula was programmed directly into Excel to calculate confidence level based on:

- 1) Reliability goal
- 2) Population
- 3) Number of successes.

$$Y = 1 - \sum_{i=0}^{n-r} \frac{(n+1)!}{i!(n+1-i)!} (P_L)^{n+1-i} (1-P_L)^i$$

Formula courtesy of CRE Primer, M. O. Locks

Statistical Results (not for website archive)

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“Best Guess” is based on the observed level of wire embrittlement (i.e. based on physics of failure). Failed cartridges as well as 6 and 12 month functional cartridges were dissected to get these data points.

Comment Added Post Presentation

Question from audience: Why is the “inferred” confidence curve is well beyond the envelope of the empirical confidence curves. The empirical confidence curves are low due to insufficient sample size and insufficient test time. If I could test more units for more time then I believe the empirical curves would begin to approximate the inferred curve.

My belief is that the real field data should fall somewhere between the upper bound of the empirical confidence lines and the inferred “physics of failure” line. We will need at least another 12 months of field data to know how the story ends.

Statistical Results (not for website archive)

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Conclusions and Future Work

Life test deliverables were met. The mitigations applied to 3 of the targeted failure mechanisms appear to be working

For the fourth mechanism (wire fatigue), we have enough information from life test that a DOE could be designed and implemented within a few weeks.

Per Marketing, holding 90% reliability along the “Best Guess” confidence curve would put this product well ahead of similar competing products.

The 90% reliability / confidence plot will be updated with field data every 3 months until 2011.