Reliability of Lead-Free Printed Circuit Boards

by **ROBERT TARZWELL AND KEN BAHL**

The assembly process for existing tin/lead solder was almost at the limit of the PCB technology's ability to withstand the assembly temperature and time without experiencing via reliability problems. Most aspects of the PCB such as the traces, solder mask, white marking, laminate and plating are relatively reliable. They rarely fail in use. However, the copper barrel in the vias and holes are the primary failure mode regarding long-term operational failures. We know from years of trial and error that any small change in the process or design of the board might result in dangerous opens and board failures in the field. Small changes includes items such as:

- The more assembly cycles that a circuit experiences, the less reliable the product will be in the field.
- The hotter or longer the assembly cycles are, the less reliable the product will be.
- The thicker the laminates, the less reliable, by a considerable factor.
- The lower the T/g, the less reliable the board.
- The copper ductility of the plating bath, greatly affects the reliability.
- The copper plating thickness, if too thin, will drastically lower reliability.
- The cure and selection of the prepreg in multilayers plays a big role in future life cycles.
- Drilling quality affects hole-plating quality and therefore reduces the life in the field.
- The controversy: to remove or leave the unused pads° in a multilayer, may affect reliability.
- The de-smear process is critical to reduced via cracking.
- Any small pinhole in the copper wall is concern for reliability.
- The expansion rate of the z-axis is critical.
- A high number of thermal cycles over 100°C delta caused reduced operational life.

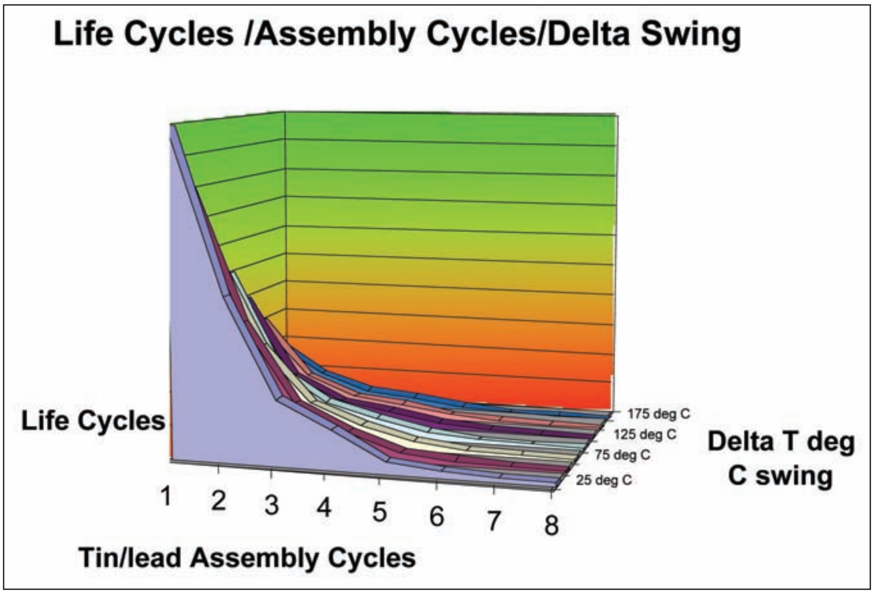

Figure 1. Life cycles, assembly cycles, delta swings.

I have suspected for years that the normal PCB was very close to falling off the reliability edge, simply due to the large number of seemingly unrelated factors which would cause terminal failure of the vias by copper cracking. The existing copper plated via was anything but bullet proof. The wide range and sensitivity of the copper via cracking problem suggested the vias were close to breaking and all they needed was a small push. I proved the theory correct by finding, and eventually fixing, the underlining stress problem which caused the via cracking. The new high reliability technology ensured that the manufactured vias were so strong that most of the previous problems no longer affected long-term reliability. The large number of small factors which previously compromised the via reliability were reduced to almost no effect. The simple fact that so many controversial papers and discussions were based on whether something as trivial as leaving or removing the inner-layer pads would affect the board and its ultimate reliability related to its fragility. The industry was spending a great amount of time and effort engineering around many factors that are so small and minor that they should not cause any effect. However, they can create reliability issues, either singly or in combination, when we use our existing plating methods.

With the new high reliability via plating technology, the vias are so strong that they are unaffected by most factors. The T/g of the material is no longer a concern as the vias do not crack with repeated thermal cycles. Reliability does not now relate to the T/g value, the new copper plating is so strong that the drilling quality does not directly

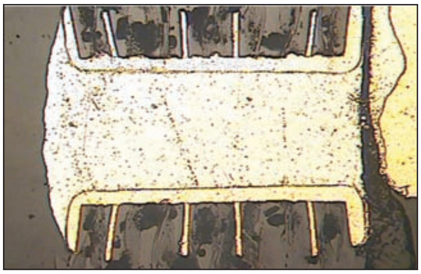

Figure 2. Picture of the extreme angle the pads can endure with the expansion force of the laminate.

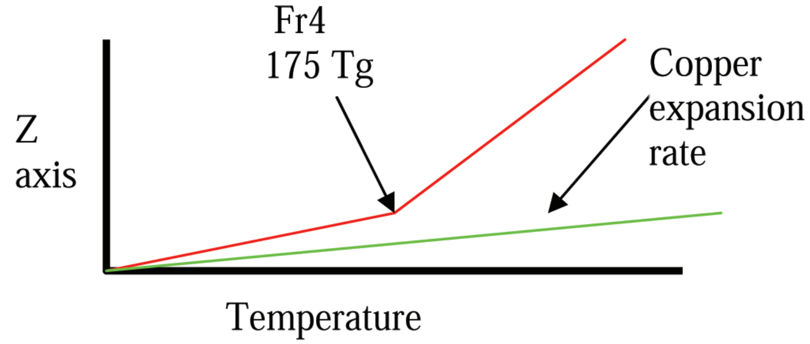

Figure 3. Differential expansion rates between laminate and copper.

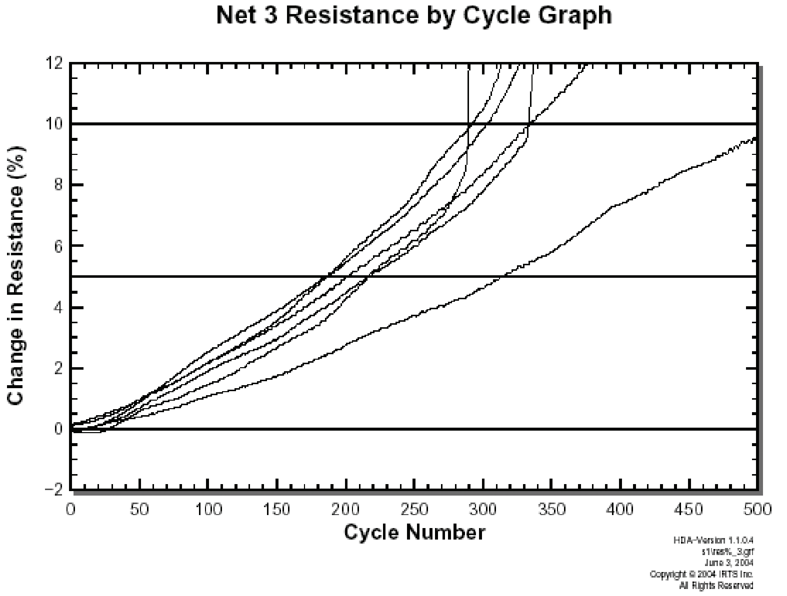

Figure 4. Normal Tg 175 HATS testing results of only 250 to 450 cycles.

cause cracking. The new plating process provides a hole wall that is stronger than the z-axis expansion forces, e- modules (Young's modules) of any laminate. The copper ductility is also no longer a controlling factor of long-term reliability. Simply put, the new higher reliability via is so robust that I have yet to crack one in many hundreds of thermal tests, solder shock tests, long thermal cycles at very high temperatures or very low temperatures. The new via looks and operates the same as a regular via, only vastly stronger. Looking at both normal and new technologies you would not be able to see the difference.

The effect of the new lead-free assembly solder cycles and higher temperatures will be at a reduced reliability due to early via cracking in the hole. Tests have shown the old FR-4 laminate 175 T/g is not suitable for lead-free applications. This mandates the use of new laminate with the required testing and proving period before we are really sure of its reliability. Additionally, testing has confirmed early copper via cracking with the hotter, longer, lead-free solder assembly cycle. The extra lead-free temperature causes damage to the copper barrel and subsequently, a lower number of thermal operation cycling will be experienced before copper via cracking. We are experiencing a 10-20 percent lower thermal operational cycle life per lead-free assembly cycle in laboratory testing compared to only five percent with old tin/lead assembly cycles.

With five assembly/repair, lead-free cycles, a typical electronic circuit may not even survive the assembly process with 10-20 percent reduction in operational life per assembly cycle, if there is any problems with in the board. In the lab, we can relate operational life survival time to length and temperature of the assembly cycle. The hotter or longer the soldering time, the more it stresses the copper vias. Any stress put on the copper via during soldering creates small cracks and fissures within the barrel, at interconnects and along the pad/hole interface. The expansion forces (Young's modules) of the laminate stretch the barrel from the middle outward. The expanding laminate causes the via pads to angle upward in the direction of the expansion. The repeated bending of the copper pad hole interface, as well as the stretching, causes the copper to start to separate.

After three solder cycles, you may not be able to see the micro cracks with cross sections. Only by measuring the resistance of a string of vias, such as the measurements used by IST and IRTS HATS testers, will you see a small increase in the resistance as the copper stretches and cracks. If the multiple soldering cycle damages the copper via enough, it will fail prematurely during operational use. Each tin/lead solder cycle is equivalent to lowering the number of operational cycles at 150°C delta swing by approx-

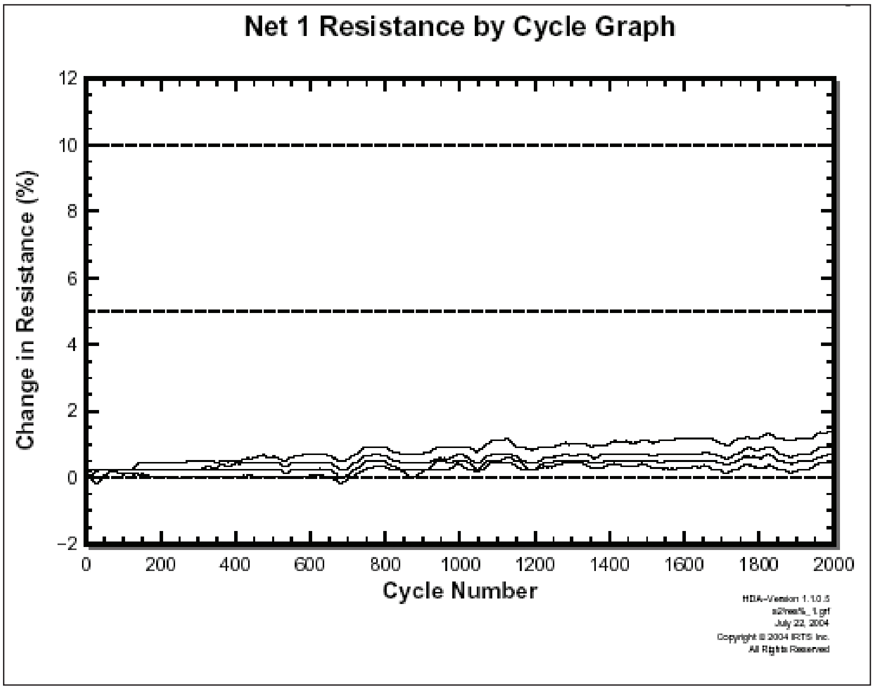

Figure 5. Extended life cycling with high reliability technology no change over 2000 cycles.

imately 100. A lead-free solder cycle that is hotter and longer, will lower the operational life by more than 150 operational thermal cycles. A typical PCB only survives 250-600 thermal cycles in the 150°C delta range. As the operational temperature swing decreases, the stress exerted on the copper barrel each cycle is less, therefore, surviving longer.

A PCB can survive thousands of 40°C temperature operational swings. There are no hard, fast, real numbers on delta temperature swings and operational life survival because so many small changes to the design and manufacturing procedures affects the overall survival of the board. The same theory exists with assembly solder cycles and the effect they have on operational survival; each assembly cycle reduces the operational life.

Samples were prepared and subjected to simulated lead-free and tin lead solder assembly cycles. After each group was prepared, they were then thermally cycled to simulate operational life. Standard control samples were used to ensure consistency in the testing. The standard control samples showed a typical three assembly cycles equated to seven high temperature shock tests with limited failures which would be considered normal. The lead-free samples at the higher and longer assembly cycle showed a shorter operational stress thermal life of two to three cycles before cracking of the vias appeared. The two to three stress cycles would relate to a seriously reduced operational life.

In fact, there are a myriad of small and large items which all affect how long a circuit board will survive. The biggest, of course, is the environment in which it is designed to live. Humidity, temperature, high and low cycling, exposure to sun or environmental chemicals all shorten the operational life of a product.

Then came the requirement to get greener: the specific change is Japan/Europe RoHS specifications of no lead. The old tin/lead, low melting point, easy wetting and long understandable reliability is now replaced with the worst type of knowledge: that of the unknown.

To understand the unknown, we need to look, experiment, and think of methods to light the darkness ahead. The requirement to remove lead from the assembly process and product has created many problems. The one, which I specifically examined, is long-term reliability of high temperature assembly cycles on printed circuit boards.

To understand the relationship between PCB laminate and temperature and high reliability, you must first understand the variables of the chemical formulas and how they affect the laminates' ability to withstand temperature and time at temperature. For the last twenty years, the PCB industry has tried to balance a higher T/g (the temperature at which the laminate becomes soft and plastic like) with cost and reliability. As the T/g rose, so did reliability in long term measurements. The plated via/hole experienced less stress because the laminate expanded less in the z-axis during assembly.

The new lead-free solders, such as the most popular Sn Cu Ag , melt and reflow at 30°C to 40°C higher temperature. This extra temperature is enough to destroy or delaminate most normal Dicey-based 175 T/g, FR-4 laminate before it gets off the wave solder machine.

To understand the mechanism that will delaminate a T/g 175, FR-4, you need to look at the Td of the laminate. As you heat up laminate, it starts to decompose. The chemical matrix that holds the epoxy together is failing. When enough of the epoxy decomposes, it can no longer hold the glass fibers and layers together. The expanding forces of heat and water turning to steam will force the layers apart.

The typical 175 T/g laminate that we have used and understood for years, is now a instant dead dinosaur and it was not a meteorite that killed it, but the 245°C assembly temperature of lead-free. The Td of a laminate is now one of the most important factors in surviving the switch to lead-free. When I talk to design and product engineers, they seem to have a problem understanding that you cannot just specify a higher T/g and life will be happy again. When the laminate chemists used Dicey to improve the T/g, they lowered the Td (thermal decomposition) of the laminate.

The lower Td was not really important when we dealt only with tin/lead solders because the laminate never reached a high enough temperature to start to decompose. The rate of decomposition of 175 T/g FR-4 increases quickly with the time above 220°C.

Therefore, we have a dilemma. We need

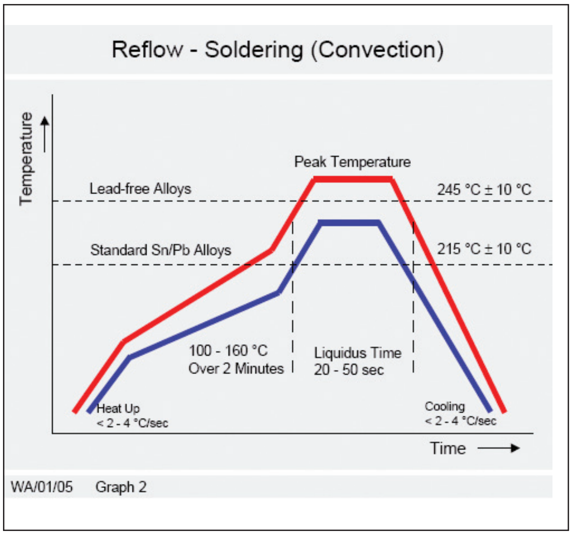

Figure 6. (Chart courtesy of Isola USA).

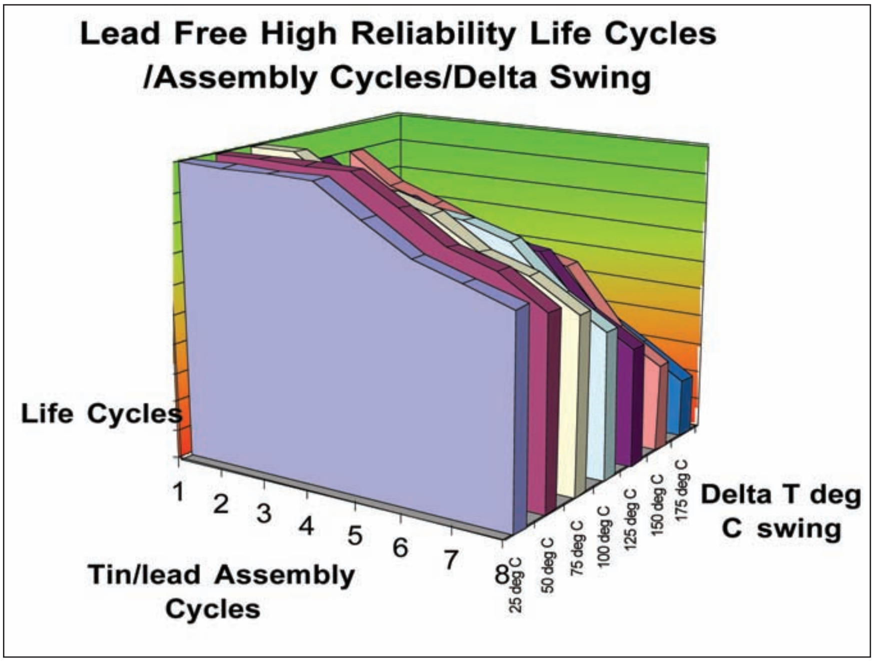

Figure 7. Lead-free, high reliability life cycles, assembly cycles, delta swing.

the higher T/g for long-term via/hole reliability but we need a higher Td to survive the longer, hotter assembly cycles of lead-free.

We must look at different laminates to create a long-term, reliable, lead-free PCB. After an extensive search, it appears that a few good alternatives are available. I chose to test and experiment with Isola 410 and mem 1755. I studied the proposed assembly temperature profile to compare with the thermal decomposition properties of the two test laminates. The lead-free cycle was 30 to 40 seconds longer, with a 15 to 20 second longer dwell time above the 175 T/g point, with a maximum temperature of 250 to 290 °C. The new lead-free assembly profile is longer and hotter by a significant amount, enough to warrant concern of delamination by vapor pressure created by moisture. The lead-free assembly profile is also hot enough to present a potential problem with copper via/hole cracking in products in the operational field. As the temperature rises above the T/g, the expansion rate of the laminate increases to a point where via copper cracking over time is a major concern. The Td of the two new laminates is high enough (360°C) to prevent delamination but that is not the only factor we must be concerned with.

The mem1755, which is a Phenolic based epoxy product, is significantly different than what we have been using, so further study is needed to ensure reliability of the product over time.

To ensure reliability after the hotter lead-free assembly cycle, the laminate must possess a few other parameters such as low CTE and good CAF resistance and have low moisture absorbance numbers. When 1755 laminate is compared to other lead-free laminates, it showed one of the lowest moisture absorbance numbers at 0.25 percent. The CTE ratings for 1755 were also one of the lowest of all the laminates studied at 12 ppm. The CAF test shows very good resistance with prolonged cycles, proving it a good possibility for lead-free applications. The Isola 410 laminate also had ratings that were sufficient for proper lead-free use.

Thermal tests were initiated to ensure passing the higher temperature requirement. Both passed a recommended lead-free T288 test, at greater than 6 minutes at 288°C. However, when I studied the assembly temperature profiles, the T288 test may not be long enough.

The T288 test is one single solder float time based test, where a real assembly profile will be 2 to 4 such cycles, totaling 15 minutes above 175°C, ramping up to a maximum of 260°C temperature. Therefore, it is important to test the laminates in a real world experiment, as similar to assembly cycles as I could duplicate in the lab. I used multiple solder float test at 288°C, with 60 second floats which represents approximately the same rise and cooling cycle of a wave solder machine. After each solder float, one sample was cross-sectioned and viewed with a 200x microscope for cracking in the vias. After 4 to 5 cycles, some of the sections showed severe cracking, whereas the single T288 six-minute float did not. Obviously, the number of cycles influences the creation of cracks, not just the time above T/g. Each cycle stresses the copper in the hole by expanding it a little bit farther each time.

As I tested the various laminates and simulated lead-free assembly cycles. I realized that the long-term reliability of the new lead-free assembly system with the new laminate was not as good as we need. In fact, what I found concerns me. Many companies will be fighting reliability problems over time when they can just simply use a higher T/g or Td

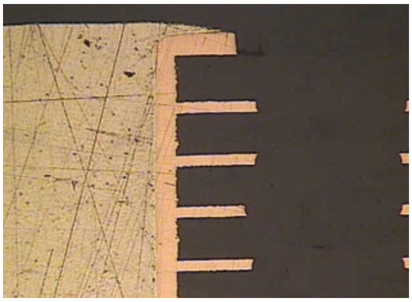

Figure 8. Photo of high reliability via hole after 3 preconditioning cycles, 2000 thermal cycles from -45 to 145°C and ten 10-second solder stress tests at 550°C.

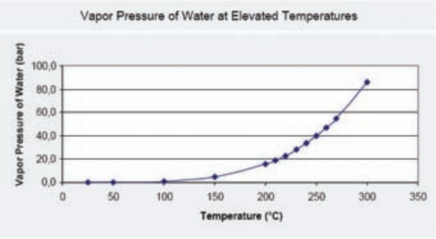

Figure 9. Chart courtesy of Isola USA assembly temperatures.

material to solve their lead-free problems.

My company allowed me the time to play in the lab for a while and see if I could come up with a more reliable via. Anytime I need to fix something large, I find it useful to look for cracks in the armor. After a considerable time looking in old, rusty PCB armor, I stumbled upon a different approach to plating copper vias.

A simple answer is to make the copper in the vias stronger. I found a stress problem in the vias/holes which limits the life in thermal cycling situations, either short extreme ones like assembly solder cycles or smaller multiple cycles like we experience when the product is used outside for mother nature to take pot shots at or under the hood of an automobile. The FR4 laminate expands with only so much pressure and can be controlled by a stronger via. If we manufacture the copper via strong enough to resist the laminates' limited expansion push, we will have limited cracking of the copper because it's not being stretched or bent. By eliminating the copper stress in the holes, we found the in operational thermal cycling reliability exploded straight up. The new technology immediately showed great promise by passing a very extreme solder float test of 30 cycles at 288°C, with no sign of cracking in the vias or holes. The samples were tested by IRTS HATS testing service for long-term reliability. They called after two weeks and said they wanted their machine back. After 2000 cycles, the high reliability coupon samples were still going strong with less than two percent resistance change on most nets. Ten percent resistance change is considered a net failure point. Typically, 200 to 400 cycles on a HATS machine is considered a pass. What the HATS testing did was prove the new technology would dramatically improve the reliability of any laminate with any T/g. It appeared I had indeed found a better mousetrap.

Further investigating of the lead-free situation revealed a potential problem with vapor pressure at the higher temperature of lead-free. As the temperature rises, the pressure rises faster from the moisture absorbed by the laminate converting to steam. Between a 210°C normal tin lead cycle and a 250°C lead-free assembly cycle, the vapor pressure is double. At the same time, the laminate is less able to withstand the pressure. The pressure generated by the steam will delaminate the board which is softened by the higher assembly temperatures.

It is therefore important to use high Td laminate with a low (<0.3) percent moisture absorption to limit the mount of moisture in the board as well as an increased strength above 240°C. It would be advisable to bake any lead-free boards prior to assembly to remove as much moisture as possible.

In conclusion, if you are switching to lead-free assembly practices, you need to be aware of the required change in laminate. Designers must be concerned with the number of assembly cycles and try to design the components to minimize the number of times the board is subjected to the higher, longer, lead-free assembly solder cycles. You need to be aware of potential reliability problems if your product will experience temperature cycles in operational use of greater than 50°C.

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Robert Tarzwell is presently working with Sierra Proto Express (San Jose, CA) to introduce new bleeding edge, advanced circuit technology like lead-free, high reliable electronics, heat sinking technology and ultra fine lines to the world. Since selling his company in 2000, Robert has disseminated PCB high-tech to many companies as a consultant, and wrote ten books on PCBs and car racing. He has three patent-pending applications in fine lines, high reliability and outer space PCBs. He is currently semi-retired in the Bahamas, spending his free time writing books, working on antique cars and deep sea fishing.

Ken Bahl

Ken Bahl is the President of Sierra Proto Express.