Overview of the Whelen automated PCB line.

Whelen Engineering, Two Years Later

If you know anything about this unusual (and extremely private) company, you probably read it right here at I-Connect007. Whelan Engineering's truly unique PCB manufacturing operation is the result of a company initiative to bring their PCB needs back into the States—and do so at a cost savings. It has been quite a success, largely due to the efforts of brainchild Alex Stepinski, now VP–PCB at Whelen. The company is still in the thick of manufacture, including an expansion of the PCB facility.

We published our first article on Whelen in the October 2015 issue of *The PCB Magazine*. Then, we published Alex's "how-to" paper that he presented at IPC's Spring meeting and conference in June 2016. By reading that article carefully, you can learn a great deal about automating your process using off-the-shelf items.

This time I had the privilege to accompany Happy Holden (with I-Connect007 colleagues Jonathan Zinski and Bryson Matties) to visit Whelen's PCB operation in the far reaches of New Hampshire.

Patty Goldman: Alex, it's good to be here at Whelen to see your process firsthand. It's been two years since I-Connect007 last visited when you were just getting started. Now we're interested in an update on this, the most automated PCB factory in North America. How's it going, and how are things running?

Figure 1: Happy Holden (left) and Alex Stepinski discuss Whelen's process in detail.

Alex Stepinski: The process has stabilized since the last conversation, and it's very predictable now from a quality perspective. From a labor perspective, we have consistent schedules and predictable labor and delivery schedules; we have predictable quality at this point. It's a robust process, and it essentially runs itself, the control plan that's in place.

Goldman: How was the startup?

Stepinski: The startup was challenging from a couple of perspectives. One was the inkjet technology and the second was reliance on smaller suppliers to deliver on a consistent basis. We had some late deliveries on things as well.

Goldman: Once everything was installed, did it take a few months to get everything smoothed out?

Stepinski: It was a few months to balance in the chemistries for recycling. The recycling was the biggest challenge there, because we kind of went out on our own in developing things. We didn't have all of the equipment configured from the beginning; we couldn't find any supplier that could give us full systems for recycling, even though we looked diligently. Everybody had only half measures; nothing was complete.

We bought a lot of half measures and connected the dots to make a system, and this required a lot of research, data collection, adjustments, improvements, and updates, to get to the closed-loop efficient system. A closed-loop inefficient system was how we started, and a closed-loop efficient system was where we ended up.

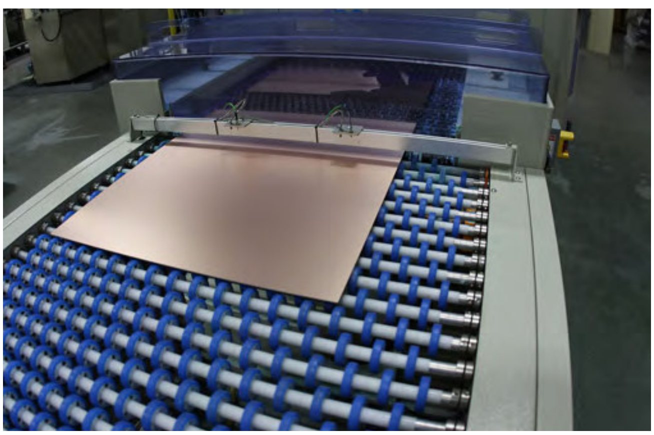

Figure 2: IPS conveyor line.

Happy Holden: I have a couple questions on the inkjet printing. Both the innerlayer imaging and outer layer imaging utilize the same etch and strip equipment in the line but in a different order—for outer layers you strip and etch. I asked you earlier about this and you indicated that the innerlayers and outer layers aren't interspersed, they're run batch-wise. It's a manual intervention in terms of bypassing one process because it's been turned off and using another one. That's done manually. I assume then that there's an accumulator there?

Stepinski: Yes.

Holden: So if you're running innerlayers, you can still run outer layers, and the outer layers go into the accumulators while it's processing innerlayers, and then once you're finished with innerlayers it takes the outers out of the accumulator and runs on. It's probably a quick switchover between innerlayers and outer layers, but it's not done automatically. It's done manually since they're all inline. The other question about the accumulators was, are they also for the fact that all the conveyors don't run at the same speed? Is that why there's an accumulator for that optimal process?

Stepinski: It's actually not because of speed. The speeds have all been balanced. The accumulators are going from a continuous process to a batch process; that's where we have accumulators. Not for speed, because the average speed coming out of the batch processes matches the continuous processes. It's just that they can't take them at the same rate, the same interval. For instance, an inkjet machine will probably deliver two panels at about the same time, and then there'll be a two-minute delay, and then it takes the next two. It's not doing one every minute.

Holden: But if you had a change in thickness of the copper from one product line to another, you'd have to slow down the horizontal plater,

Figure 3: Strip-etch-strip line.

and then wouldn't all the other machines have the wrong immersion time?

Stepinski: But that's the slowest line so it doesn't really matter.

Holden: If you had a spec that called for twice as much copper, that machine would have to be even slower. Do you have the flexibility of changing the current density or the pulse rate to keep the conveyor the same speed and double the amount of copper? Or, do you have to actually reduce the conveyor speed, changing the immersion time?

Stepinski: It depends on how much copper.

Holden: Everything tied together means everything has to be balanced. One reason why processes are separated is because you might say for maximum throughput, the conveyors run at different speeds, and so you have isolated conveyorized processes, with manual loads and unloads.

Stepinski: Relative to that, the individual loaders/unloaders, when a panel enters then, and they all automatically center the panels, because you get drift going through horizontal equipment. Every time we go through a loader/unloader, we center and then we change the speed immediately after centering to get the panel out. That deals with the speed changes.

We can deal with speed changes at that level as well so we don't burn out on the material. We're entering the load/unload station, at the speed of the preceding line, stopping, centering, and then exiting at next line speed. The gaps are managed accordingly. The speed of the etcher is almost one-to-one with the speed of the plater; we've matched that. If the plater runs at one meter a minute, the etcher runs at one meter a minute. If the plater runs at half a meter a meter a minute, the etcher runs at half a meter a minute. Remember, we're panel plating, so if the plater is running at half a meter a minute, it's putting on twice as much copper. Then the etcher runs slower and it matches. It's all matched and balanced.

Holden: This is an unusual line in that it's panel-plated plus patterned tin. It's not a conventional panel plate line; it's kind of a panel/pattern hybrid.

Stepinski: That was the lowest-cost solution I could come up with.

Goldman: Meaning lowest cost to do the panel.

Stepinski: Yes.

Holden: I'm surprised that the companies that sell inkjet printing for solder mask haven't come out with a plating or etch resist machine or mask. Yours are adapted with this wax-based ink. Where did you start on that inkjet printing for resist and for pattern plating? They're not really even available now, so you made an obvious choice to custom engineer that level of inkjet printing. You're not ink formulators, so...

Stepinski: No, Dow formulated the ink. We tested it here and validated that it worked before we bought the equipment. When the machine showed up, we optimized the preceding and follow-up processes to handle it. There were a few uncertainties in designing the process. I planned it very quickly, so I had to compensate for the uncertainties. We have a preclean in front of the line, and it turns out that

Figure 4: Horizontal pulse plater.

is an unnecessary process, it's non-value added. It was originally designed as a subtractive etch process. We were able to modulate the plating recipes to pulse the right amount of roughness on at the last anodes, and we were able to eliminate the subtractive etch with the roughness or stripping process after inkjet so it would in effect strip it and do tin plating and handle surface treatment because we're plating it in. Even though it's there, we're not using it. I didn't know we'd be able to get that good.

Holden: Is anyone else using a horizontal pulse plater to improve the resist adhesion?

Stepinski: It was recommended to us by Atotech. They said they had a handful of accounts that had been able to achieve it. What we had to do was do the DOE to see what roughness worked best with the inkjet ink. The inkjet ink has extremely good adhesion, and you can't make it too rough. The product is so thin that when it hits the surface, it penetrates every crack, every nook and cranny in the crystal structure, unlike a dry film, which is extremely viscous, and you have to push it in.

Holden: Is that UV-cured or thermally cured?

Stepinski: This is a UV-cured product. It gets a dose of 900 millijoules.

Holden: And that machine has a built-in AOI. Is there anything else built-in?

Stepinski: No, that's basically it. It's the AOI, and cure and coating.

Holden: And the pinless lamination saves a lot of process steps. Since you're not using pins, you don't have the messy caul-plates to deal with.

Stepinski: Or maintenance program, yes.

Holden: It's an optical alignment, and then kind of a welding of the layers together.

Goldman: How well does that work?

Stepinski: For our technology, it's fine.

Holden: I noticed the rotary oxygen plasma etch replaces all the permanganate desmear. Does that have sufficient throughput?

Stepinski: Yes.

Goldman: The rotary plasma etch, though, that's really a batch process. How automated can you make that? Somebody has to load and unload right?

Stepinski: Yes, and the plasma machine is a limiting factor with higher volume. You're not going to get 100 plasma machines by a chemical desmear line. For us, the rotary plasma machine makes sense.

Holden: Because of the high level of automation and the minimum of any kind of delay, there's an elimination, a lot of outer layer and innerlayer pre-etch, acids, and things like that that people have because panels are sitting around.

Stepinski: Fingerprints.

Holden: Those all have to be eliminated. If it's not touched by people then there's no chance. Plus, your equipment is really designed under the concept of a microclimate. The building is not specifically climate-controlled because there's a microclimate inside of the process area and it can be kept extra clean and conditioned. Also, you have a concept of no fume scrubbers. I think one time you wrote that, wherever possible, you've elevated the temperature to facilitate evaporation, which is one of the ways of recycling the chemicals.

Stepinski: Yes, thermal energy instead of chemical energy.

Goldman: Is the copper that you produce from etching usable in your copper plating process?

Stepinski: Yes. It's been qualified but we don't put it in there right now. The concern is that in the theoretical world, it works fine. The concern is that someday, somebody is going to put in some copper that still has some ammonia on it or something like that, on fifth shift or something like this. I have this nightmare—this nightmare that has never happened to us, but it pops into my head in the middle of the night. We get paid 95% of the anode price anyway, so we're covering the cost basically. For 5% more, I avoid a lot of potential risk. But it has been certified by Atotech to be reused. They don't do that lightly.

Goldman: It's an insurance policy.

Holden: The conductive polymer that replaces electroless copper—what are the trade-offs between the two?

Figure 5: Horizontal conductive polymer process.

Stepinski: Electroless copper is more expensive to maintain and analyze in a conventional factory. It's also an environmental liability. We've done a lot of work to develop countermeasures so it's not an environmental liability in our factory.

Goldman: How has it been working in the line? Has it been 100% reliable? Right now, I know you're mostly doing single- and double-sided.

Stepinski: The conductive polymer is working fine. It's a no-brainer. I don't know of any issues. We do a low percentage of multilayer but have had no issues. It's an extremely reliable process.

Holden: What is the mechanism of the conductive polymer?

Stepinski: The conductive polymer mechanism is putting down the permanganate, and the conductive polymer is an acid permanganate. You're actually precipitating manganese dioxide onto the dielectric surface, and then the conductive polymer absorbs onto it and gets conductive enough to galvanically plate it up.

Goldman: Because you're going right to panel plating in the acid copper, with just a few rinse steps. I suppose that helps.

Stepinski: Yes, and the conductive polymer itself has a pH of 1.9. The whole line is acidic permanganate polymer and galvanic copper. The conditioner on the front of the line is alkaline; it's just a wetting step. The only limitation with the conductive polymer process is that on more exotic materials it doesn't absorb as well. In those cases, you're in the electroless arena.

Goldman: You mean anything beyond FR-4? Like polyimide or flex?

Stepinski: No, we were able to do polyimide. We have flex and it's not been a problem. As long as there is no acrylic through the process. If you expose acrylic in the hole wall it will chew up the acrylic because of the high temperature of the acid permanganate which is at 90°C (the first step of the conductive polymer process).

Goldman: Other than acrylic, what specialized materials can you not run through?

Stepinski: There are a few where you have lower deposition rates that you have to run it through multiple passes. Some of the Megtron materials for instance are a little more challenging. Those materials may leach out as well.

Holden: One of the questions I had was about the maximum lot size or order size.

Stepinski: We have up to 1,000 panel lots right now. Minimum lot size is one.

Goldman: Of course, because you can automatically change…

Stepinski: Yes, it's pretty automatic.

Goldman: Put that part number in or whatever and everything changes down the line as necessary.

Stepinski: As long as it's part of the same kind of family of product, yes. If it's a different product family then no, we have to intervene a little bit, just mainly changing some things. For instance, if you go from double-sided to multilayer, there are a couple of slight changes. If you go from double-sided to single-sided, there are some changes. We have one recipe for IPC-6012 Type 1, one for Type 2, one for Type 3.

Goldman: Interesting. You have different recipes and that's part of the programming.

Stepinski: Yeah, within our thickness limits.

Holden: Is the front-end tooling done here?

Stepinski: It's actually done in New York state for the most part. I have a tooling team in New York state of former employees of mine from another fabricator. They've been trained over here, the designs get sent over there, and they do all the tooling and send them over.

Holden: I was thinking, since there's no artwork, are there any new files required here that haven't been a conventional part of tooling? We've had direct imaging for a while.

Stepinski: Not really, no.

Holden: Once you start utilizing any kind of direct imaging, you have those artwork files. We've always had drill/router files, and we've always had electrical test files. There are no changes in the files between an inkjet printer and, say, the laser direct imaging.

Stepinski: There's one more step in between for the inkjet, but it's just a quick software step that's automated.

Goldman: You also said that there are files for drill rout, files for solder, files for direct imaging, even the tacking. If that's automated, there have to be files for that too, right?

Stepinski: Yes.

Holden: Is there a file for AOI?

Stepinski: Yes. It's all CAD reference.

Goldman: I want to ask about yields. Has there been a ramp-up? What are you seeing yieldwise? I think this is something the readers would be interested in.

Stepinski: The yields have been solid—in the high 90s. We've had some issues with the inkjet from time to time but we've captured all those and corrected them. When we have rework it's a very, very small amount. What we would have more than anything would be downtime. We capture these things quickly and the downtime is the big risk.

Goldman: Do those captures happen automatically? If there is a problem, is there something that stops things?

Stepinski: Yes, but there's a little gap sometimes. For direct defects, you can capture them at the machine; it's for interactive problems where you have some subtle issue with the ink or something like that. That turns into a plating problem, and it takes a little longer, and then you have some panels to work on. So far everything is correctable.

Holden: Does the WIP system currently read barcodes?

Stepinski: In the current system, when we release a job to the floor, we print stickers. We don't have travelers here; stickers are coming out of a sticker printer with barcodes on them, and it tells the person at drill how many are in the stack, what material type it is, and then they build the stack and put the sticker on the stack. The drill machine reads the sticker, and then it drills the material codes into the frame.

Holden: How many additional readers are throughout the system?

Stepinski: We have six total—in process, input, and things like that. The part-specific data is at AOI at each imaging step. Then, right at the end, as we build the board, we make another barcode. If you look at finished boards you'll see there's a barcode made by a solder mask and legend, in combination. That gets read by the score machine and the router.

Goldman: Nobody programs anything in; each machine reads the barcode and knows what to do.

Stepinski: Yes, it's a paperless factory.

Holden: What happens if something breaks?

Stepinski: It's like at any other factory. If something breaks, the first thing that happens is that the panels in the previous step get offloaded to the loader/unloader, and when that one fills up it goes to the next loader/unloader. It stops feeding and it cascades all the way back.

Goldman: It must be difficult then, because you lose that advantage of things not sitting.

Stepinski: Usually we can recover very quickly when we have a downtime issue. At a regular shop, what happens is it just gets shoved in the corner somewhere, and then at the production meeting, someone gets notified that there's a big problem. Things don't resolve themselves automatically. Usually, someone's got to push to make sure someone shows up to fix it, or changes somebody's priority to go fix it.

Here, there are different line segments and I think we have seven total line segments broken up, and for each segment, all the critical alarms go into a big megaphone that we make. Whelen makes the megaphones—an emergency warning megaphone. You can have it sound like a British police car, a U.S. fire truck, or whatever. All these sirens. We have seven different sounds, and we've all memorized the sounds. You hear that sound, everybody in the factory goes there. That's how we've functioned, and it's the same way in the new process.

Goldman: I presume you have some sort of preventive maintenance schedule so that doesn't happen very often.

Stepinski: Yes, we have a very detailed preventative maintenance schedule. But, it's not just for breaking that we have sirens. If someone has to change a filter, we get notified as well. If the resist strip drum needs to have the resist taken out of it, the alarms go off too. All these things are what we call critical issues that require labor. The equipment is considered fully autonomous, and when an alarm goes off, that means it needs some labor. Because then your process is more predictable, you've got less downtime, and your customers are happier. We can afford to do things that way, which is great.

Holden: You selected copper ammonium sulfate etchant over the traditional ammonium chloride. Was that specific or simply because that was what was recommended?

Stepinski: This process came from a European company that built a number of these types of machines. They relocated to China, and we purchased from them. As received, the equipment was not what you see today. There were a lot more peripherals, and we did a lot of development work on the tool, and arrived at the current process. As received it did not have fume recycling, and the rinse recycling wasn't effective. We

Figure 6: One of seven Whelen-made sirens used to alert employees that a process needs manual attention.

added fume recycling and rinse recycling to the system, and made it a totally closed loop; there's no connection to the scrubber or anything.

Holden: Is that etchant made of basic chemicals or is it proprietary?

Stepinski: No, we mix it. It came with proprietary chemicals, and we now use our own formulation. We run 75 grams per liter copper and two grams per liter ammonium phosphate, with a pH around 8.6. The galvanic process liberates ammonium and oxygen, which we then reintroduce into the system with the Venturi to regenerate it. One of the keys to the system is the etching goes through a cascade mechanism and gets the Venturi action, and it sits through that, it goes through this cascade for about four minutes. In that time, we're able to regenerate all the copper one (Cu^{+}) to copper two (Cu^{++}), and then return it to the etchant, to the spray bars.

We never spray with any copper one; it's always regenerated. The etch rate is much more consistent in this case. We're not doing any reaction in the chamber itself. It's in a hermetically sealed offline tank, and we do not reintroduce the etchant until all the copper one is gone, because the copper one is a poison and changes the etch rate. Our etch rate is always the same.

Goldman: You basically have the same bath in there that you've had from the very beginning. But you must have some dragout?

Stepinski: No, the dragout is all returned to the etcher.

Holden: If you do a mass balance, and you're introducing copper from copper foil, you have to take copper out somewhere.

Goldman: I was thinking of just a solution dragout at the end, but with the rinsing…

Stepinski: One of the differences with our system is that with a typical ammonium etch system they run a much higher copper content. This causes other problems; now the solution is at the saturation limit. When you introduce a little bit of water in there, you cause a lot of problems, you start making sludge. The fun thing about our process is we run at a little less than half the normal concentration. We've adjusted the other components to balance that. Etch factors are good; we're 5:1 plus for etch factors.

Because the salt content is so low—we manage the total salt content—we say the maximum total salt content is 200 grams/liter. That's everything, anions, cations, everything—we can take a water hose and just put it right into the etcher. Our rinses cascade back into the etcher.

Holden: Your first rinse is probably the replenisher, isn't it?

Stepinski: No, we just have a cascade rinse. In fact, it doesn't go back into the etcher directly; the rinse cascade goes into a little holding tank, which gets metered into the galvanic cell where we have a very high ammonia content, and that's able to absorb it all. That's how we balance. The air fumes are balanced, the negative pressure that we generate from the Venturi above the solution level, we connected the front of the entry to that. So, we're able to locally remove the fumes from the atmosphere right around the machine. You don't smell any ammonia fumes even though we walked by the etcher and it was fully on, everything was on. You don't really smell anything.

There's enough suction there just from the Venturi, which isn't even connected, nothing's connected to a fume scrubber. It's just local pressure. We have a local under-pressure, and we have over-pressure in other areas to compensate. Everything balances.

Holden: That's the one process I don't find in North America, this ammonium sulfate one. But also this one is tied up in a very rigorous closed-loop system, and that is highly unusual.

Goldman: How long did it take you to get that to balance?

Stepinski: Six months. It was one of the longest items, because the process was brought to us by a supplier, and we relied on the supplier a lot initially to get it set up, and then when it didn't meet my expectations we had to go and really dig into it ourselves. We changed everything and ended up where we are now. Half the equipment is not even there anymore. It was highly overengineered and overcomplicated, and simple is the way to go.

Holden: That's one area I'd like to look at, the chemical dosing or chemical control stations.

Stepinski: Yeah, you can't even really see it. It's so simple. You can see it, but there's nothing much to see. We have a specific gravity controller on the galvanic cell, and one on what we call the complexer, with the cascade inside, which oxidizes. This is all specific gravity based, but it's just a huge, long tube.

Holden: Most of them are controlled by specific gravity, which you could really throw away because the specific gravity controllers are absolutely terrible.

Stepinski: Terrible. I agree. We made all our own specific gravity controllers. We just use a densitometer. We put a pressure transducer on the bottom of a tall pipe. The taller the pipe, the more sensitive it is.

Holden: That's the differential pressure (DP) method. Most of the guys that sell these things with the chemical use a hydrometer or something like that, and if you break a beam or close a microswitch…

Stepinski: Any turbulence causes a lot of problems.

Holden: Yeah, they bounce around and things like that. It's better if you have a totally sealed one where that center mass never changes but you can change the calibration. It's an interesting set of equations and debate between remembering what Archimedes' principle really says. Most of them work off the changing volume, and that is the displaced mass can change, because it floats up and down, but if it's totally immersed then that mass isn't going to change. Or it works off a little titanium chain, and as it goes up and down, it changes the weight rather than changing the volume. There's a radiation-based densitometer and there's differential pressure-based specific gravity controllers. Are there any other etchers or pre-etches in the line?

Stepinski: The only pre-etches are associated with final finish, so HASL pre-clean or ENIG pre-clean, and then we have an alternative oxide process we use prior to solder mask, which also does double duty as our multilayer treatment.

Goldman: I was going to say, your innerlayers must get some oxide treatment.

Stepinski: We have one process for both.

Goldman: In the very beginning, you've got copper coming in. You have to clean that. Is that a microetch up there on your laminate copper?

Stepinski: No, we deburr it—mechanical deburr right now for double-sided products. For cores, we don't clean it; we go straight into inkjet.

Holden: The inkjet has much better adhesion. Although, changing current density or pulsing in the panel plate for the inkjet, how is that compared with the innerlayer inkjet?

Stepinski: The unannealed grain structure and annealed grain structure are very different things. We're going with an unannealed copper on all the electroplated stuff, because we're going too fast, we're not giving it time to anneal. It's a very different grain structure than what we get out of a box that's fully annealed. The crystal structure is very different.

Holden: In one of your talks, you said the process time is 105 minutes from load to unload.

Stepinski: The whole factory takes four and a half hours to go around, but it is 105 minutes to get from plate through etch.

Holden: I have been comaparing 105 minutes to the typical four weeks, which is the conventional way with all the queues and the movements and things like that.

Goldman: I think the conventional way, plate through etch, from the beginning of a design, taking a panel, putting it in at the very beginning of the core drill to the exit, completed parts, is four and a half hours. That's what you should compare to your four weeks. Although, some companies have a special prototype line or area and prototype engineers whose job it is to speed fast-turn jobs through shop. Comparing single-sided versus the double-sided, the single-sided turnaround must be shorter.

Stepinski: Not much. You just don't have to drill and you don't plate it. If you measure the cycle time starting at plate, all you're getting rid of is plating steps, and that saves an hour total. It's three and a half hours I guess, something like that.

Goldman: If a designer comes to you with a prototype design and plops it on there, in less than half a day he's got his board to test. That's pretty good.

Holden: You could have a lot size of one, so you could do one panel, which would be the prototype if he wants one or two boards.

Goldman: Or, if he's not here, he zaps over all the information, and you could have his panel on his desk the following morning at the latest if he's not local.

Stepinski: Sure, and we've done that.

Holden: One of the global strategic goals we had

Figure 7: Schmoll Maschinen drill machines.

at HP was from bill of materials and schematic to an assembled, tested prototype in five working days. In other words, we'd take two days to design the board, two days to fabricate the board, and one day to assemble and test it. You give us a schematic and a bill of materials, and five days later we'll hand you a finished, assembled prototype. We got down to five and a half days, versus 12 or 16 weeks for everybody else.

That comes through a lot of automation and a lot of standardization. Somebody was telling me, "It takes three weeks to get a solder paste stencil." I said, "We don't use solder paste stencils. We apply the solder while the board is still in the panel form, clean it, and then calendar it, and the solder paste is on the board when we ship it to the assembly guy. They don't do any solder pasting, they just apply flux and put down the part."

Goldman: Of course, now you can inkjet that solder paste, and the stencil guys ought to be worried.

Holden: One of the things that we found, even 40 years ago, when HP was doing 150 GHz test equipment was that we would monitor not just the thickness but the dielectric constant of incoming laminate.

Stepinski: That is the only thing that we're not checking, but we probably will down the road.

Holden: Well, Alex, our time is up. Thank you for all the time you have spent with us. Thanks for the update and for answering our questions about your most intriguing facility.

Goldman: Yes, it has been a pleasure and a privilege to visit Whelen. **PCB**