

# **Overcoming Logistic, Economic and Technical Challenges to Implementing Functional Test in High Mix / High Volume Production Environments**

Craig T. Pynn  
SiFO Technologies  
Concord, California

## **Abstract**

Functional circuit test (FCT) of circuit boards and end products in a high volume (>1000 units per day) production environment presents challenging technical, logistic and cost obstacles that are usually more complex than those encountered at the inspection (automated optical inspection) and the manufacturing process test step (in-circuit test).

FCT “logistic challenges” are even more significant when there is a variety (high mix) of different circuit types to be tested. It is not uncommon for production lines to routinely have fifty or more active board types, each with a difficult-to-forecast production schedule that must respond to varying customer demand.

The exigencies of high volume production—not to mention the economics—preclude the typical “one-off” functional testers or “product-minus-one” found in many production environments. A “universal test system” is required. However, most “universal testers” are typically large and expensive, where (1) cycle times may be several times longer than the line takt rate, and (2) complex fixturing and UUT connection requirements that are difficult to modify in line further impede throughput.

Developing and maintaining revision control of application test programs for FCT is a further complicating factor in a high product mix environment. The difficulty of developing a practical FCT system to be used in the production line is exacerbated when the tests must include accurate and repeatable measurement of “outlier” electrical parameters such as very low or very high voltages and currents, and/or low level and/or very high frequency RF signals.

We have developed a standardized FCT system architecture, combined with fixturing/UUT interconnection solutions designed for the rigors of a high-mix, high volume production environment, significantly reducing total cost compared to typical custom-designed FCT systems. We have also developed algorithmic programming techniques that have proven useful to minimize overall UUT test time.

We will describe how this architectural and procedural approach meets FCT technical, logistic and economic goals by studying the actual functional test of a high-mix, high volume AC driver product, which has more than 50 distinct variations, built in a volume exceeding one million units per year.

The robustness of our technical test solution will be further illustrated by describing test requirements that included voltage measurements of up to 1200V and current measurements up to 40A.

## **Introduction**

Functional test, whether of a circuit board, module or the complete product is the all-important quality gate between the OEM and its electronic manufacturing services (EMS) provider, more commonly called a contract manufacturer (CM). Although it is the contract manufacturer that conducts the actual test on its manufacturing floor, it is the OEM that defines and certifies the criteria that must be met in order and for the circuit boards, modules or finished products to “pass” over the crucial boundary of acceptable performance and quality (and ultimately payment for) to transfer the product from the CM back to the OEM. Boards, modules or completed products that fail functional test are stuck in the CM’s inventory until they can be diagnosed and repaired.

While the words “functional test” have many meanings, and functional test as practiced in electronics manufacturing today has multitudinous variations and “add-ons” such as ISP chip programming, for our purposes here we simply mean the test or sequence of tests performed following assembly in order to ascertain whether or not the individual unit-under-test (UUT) meets agreed upon electrical and mechanical performance specifications within agreed-upon tolerance limits. In short, does the UUT “work?” To the author’s knowledge, no OEM has ever been willing to accept any product or module without first performing some form of functional test, which varies from simply powering up the UUT to a full gamut of complex parametric tests.

## **The Problem**

Most of today’s electronic products are built in high volume manufacturing environments often located thousands of miles distant from the OEM’s engineers, who have designed and created the product. As product life cycles continue to shrink from years to months, and as product model variations multiply, implementing competent and productive functional test in a high rate-of-change environment that demands ever faster new product introduction (NPI) cycles on a manufacturing floor

that may be thousands of miles distant has become increasingly challenging. A typical design-to-manufacturing flow is for the product to be designed by the OEM, who builds a prototype locally and then uses a test bench to perform what we'll call engineering or design verification test. As shown in Figure 1, following design and engineering verification test, the product enters the NPI phase. During NPI, the OEM and contract manufacturer work together to release the product into full volume manufacturing. NPI usually includes product functional test development and debug. Once NPI is complete, the CM assumes responsibility for product build and manufacturing test, until the product passes the agreed-upon "quality gate" and then is accepted by the OEM. Functional circuit test (FCT) is almost always the agreed-upon product quality gate. While FCT tester itself is located on the contract manufacturer's floor, it invariably has been developed and certified by the OEM. Only after the UUT has passed the quality gate will the OEM take ownership of the product.



**Figure 1: A typical OEM-to-CM product flow**

However, that the demands associated with implementing what we call functional circuit test (FCT) as the final quality gate for the CM-to-OEM handoff are more onerous and complex than those encountered at the inspection and the manufacturing process test (in-circuit test) steps. As a result, functional test too often becomes a bottleneck—both during the NPI and volume production phases. The objective of this paper is to examine the roots of the bottleneck problem and to examine by example how these bottlenecks can be eliminated and even avoided altogether.

**FCT challenges**

A major reason for functional test bottlenecks is that design verification usually occurs in the development lab where tests are designed and applied by skilled engineers who understand every nuance of the product design. This is typically an informal test setup that includes a variety of manually programmed instruments selected for maximum flexibility. Functional circuit test, on the other hand will be used for high volume testing on the manufacturing floor requiring maximum throughput, performed by operators who are not engineers. These realities require thoughtful design that considers the very different environment in which FCT occurs.

The question becomes, then, how do we engineer and implement competent functional circuit test that meets the OEM's specs developed on their test bench while still being capable of implementation in the always too short NPI timeframe, and then being maintained and even upgraded in the high volume production environment without having to fly the OEM's design engineers to the manufacturing site and requiring them to set up camp for several weeks to get things right? As it turns out, the challenges inherent in transforming the test bench into a high throughput functional circuit tester are fairly common across virtually every type of electronics product, from simple power supply modules to complex handheld devices such as smart phones and tablets. There are three "challenge categories"—technical, logistic and cost—whose implications we need to consider in the transformation from test bench to full-fledged functional circuit tester.

The first challenge, quite naturally, is defining exactly what technical requirements must be met in order for the tester to be appropriately equipped for the functional test requirements at hand. But beyond simply ensuring the tester can execute the functional test suite to the required test specs, there are other technical criteria that must be met. For example, a truism of functional test is that the accuracy of the measurement to be made must be greater than the resolution required to distinguish "pass" from "fail." Further, many functional tests occur at low voltages, high currents, and/or high (usually RF) frequencies. Performing milliohm measurements or detecting and measuring RF, while typically straightforward in the lab, can present almost intractable challenges on the production floor where there are high levels of ambient noise, unreliable connection methods and a host of other environmental issues that simply do not occur in the lab.

**Table 1: From test bench to production floor: Technical challenges**

TECHNICAL PARAMETER	CHALLENGE
<i>Measurement Accuracy/Repeatability</i>	Especially for "outliers" such as low and high voltages and currents, and high frequency (RF).
<i>Human interface tests</i>	In high volumes functional circuit test requires automated means to test human interfaces such as displays and keypads.

Achieving repeatable, noise-free measurements that lie within acceptable tolerances is a non-trivial test engineering task. Also, many products being tested have human interfaces such as push buttons, switches and displays. While some of these may be simple for the operator to perform and verify, there are questions of the effect of operator variability and fatigue on reliability and repeatability—all ending up in a “judgment call.” For example, judging display readouts may be simple, but what about display brightness? In most high volume environments these tasks will need to be automated, requiring sometimes highly clever engineering solutions.

The second category is “logistic challenges,” which includes factors that tend to be unique to performing often complex and/or low signal level tests on the production floor. Frequently, these are often are not considered at all at the engineering verification test stage performed back in the lab. Wherever high volume assembly is occurring, test throughput —the total amount of time required for test, usually measured in seconds per unit tested—becomes a dominating factor. The higher the throughput, that is, the faster the overall test, the better, because test throughput that is substantially slower than the line rate means multiple testers are required, something every person involved in design and manufacturing wishes to avoid, (except perhaps the tester vendor...) wishes to avoid. Four elements affect overall throughput: the time to connect the unit, module or board under test to the tester, time, test time, diagnosis time if there’s a test failure and disconnect time. The functional circuit test designer must always consider strategies to reduce total test execution time, diagnostic time (although diagnosis of failed UUTs will frequently be performed off line) and UUT connection and disconnection (sometimes called handling time). Achieving reliable and repeatable connect and disconnect time is in itself almost an art form, especially for assembled modules such as those found in automotive electronics that may have cable harnesses and multiple connectors.

**Table 2: From test bench to production floor: Logistic challenges**

LOGISTIC PARAMETER	CHALLENGE
<i>Test cycle time</i>	Functional test (including handling & connection) is often slower than line rate, requiring multiple testers
<i>Unit Under Test interconnection</i>	Multiple connections, cable harnesses, etc. further impede throughput.
<i>Fixture reliability</i>	High current measurement degrades fixture-to-UUT connection, resulting in inconsistent measurements

Other logistic issues for the tester designer to consider include situations where the unit under test must be placed into a container, such antennas or Helmholtz cages required to isolate RF signals from surrounding stray signals. The test designer must even consider issues such as whether the units to be tested arrive via conveyer or on trays in carts.

Finally, overhanging everything else is the question of cost. Engineering and even manufacturing management generally views test as a cost center, a “necessary evil,” and rarely as adding product value. The arguments for test as a value-add activity are grist for a different paper. Suffice to say, the overwhelming objective is to minimize test cost. In-circuit test, and to a lesser extent, automated optical inspection have done a creditable job of reducing manufacturing test cost. In fact, as we will see, there are circuit board test situations where adding in-circuit test ahead of functional circuit test can further reduce total test cost. There’s no question that functional test can be one of the most costly steps in the entire manufacturing and test process. Each and every product type being tested possesses unique test requirements, and as we’ve seen, many of them can be difficult to measure reliably.

**Table 3: From test bench to production floor: Cost challenges**

COST PARAMETER	CHALLENGE
<i>FCT is more complex than in-circuit test</i>	Wide variety of technical requirements; more challenging measurements.
<i>FCT tends to be inflexible</i>	Inherently unique test plans require “one off” engineering design and debug each time.

Above all, of all the elements in an electronics production line, functional circuit test is usually the least replicable from production line to production line, or even across a single product type or model. Even when the functional circuit tester is a simple “product minus one” tester where the board being tested is inserted in the final product and checked to see if the product still operates, every functional test—and therefore the tester and the test application set for the UUT—tends to be a “one off” design. That means significant levels of expensive engineering and re-engineering design and test debug each time a new product model is introduced into production. It’s important to remember that this re-engineering with each new product type exacts cost on two fronts: real cost in the form of time and materials and opportunity cost in the form of possibly delaying the new product introduction cycle, since the product cannot be ramped into full production until its functional test software and hardware is fully debugged and certified by both the contract manufacturer and OEM as constituting the acceptable product quality gate.

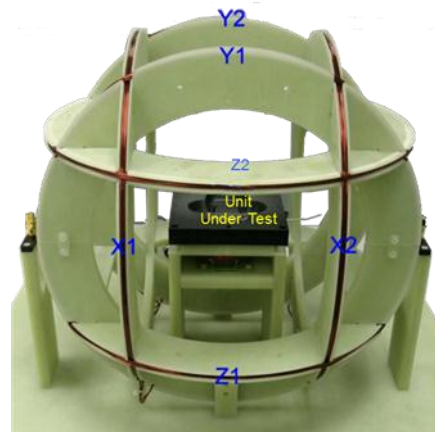
For many years automatic test equipment vendors have attempted to design and market general purpose functional testers that meet technical and logistic challenges, while simultaneously satisfying cost requirements. They have been generally successful in mission critical “cost is no object” situations such as military and aerospace test—and in some telecommunications test where extensive sets of highly complex parameters must be measured. But for consumer electronics, and to a lesser extent, automotive electronics, ATE vendors have not successfully marketed product functional test products over the long run. This forces the OEM itself to become the test equipment designer and vendor.

To move from concept to example, we’ll examine a variety of actual applications that have addressed the technical, logistic and cost challenges. Out of these solutions we can see a test architecture and test strategy approach emerge that meets these challenges in a realistic and cost effective manner, while also meeting the strenuous environmental and productivity requirements of test on a high volume, high mix production floor.

### Meeting the technical challenges

First, let’s examine how some fairly rigorous technical challenges were met in testing an object that is doubtless in the pockets of many here today: an automotive remote entry key fob. The test spec was straightforward in concept but challenging to execute in a production environment. The spec called for performing an RF calibration process by measuring its field strength in the X, Y and Z dimensions. This is a critical measurement because the key needs to reliably determine its relative location with respect to the vehicle. For example, the key needs to know it’s inside the vehicle before the engine ignition can occur. Other basic tests were required, as well: door lock/ unlock, alarm function and so forth. Finally, the test spec called for physical actuation of the key fob’s buttons. So, the functional circuit test designer needed to design a test fixture that would simultaneously allow measurement of the key fob’s RF signal in three dimensions while also actuating the buttons.

The OEM’s original test specification called for a single Helmholtz coil and a mechanism that sequentially positioned the key in three axes. This mechanism would likely have been complicated, slow, maintenance-intensive—and expensive. The solution devised and engineered by the functional test system designers was to build a three-dimensional calibrator with 3 orthogonal Helmholtz coils. During calibration, a signal generator connected to the coils provides specified test frequency and amplitude for each test step. The mechanical disadvantages of physically moving the key through 3 axes were eliminated. Moreover this designed allowed the key fob to be placed inside the coil structure, while still allowing room for a mechanical actuator for each of the buttons.



**Figure 2: The 3D Helmholtz coil developed to measure 3D RF field strength**

The functional test system designers developed a test system that included two programmable instruments, a spectrum analyzer and function generator, as well as an in-house designed mux for signal switching. The unit under test (UUT) is placed on a tray in the center of the 3D calibrator. A coupling antenna, positioned near the unit under test, receives the RF signal emitted from the UUT, which is decoded by the test computer. Commands are transmitted to the unit under test via a command antenna. A top press plate with mechanical fingers depresses each button of the UUT, simulating a human user to verify proper operation. The test flow begins with identification and authentication, followed by a sensitivity test and 3-axis calibration using the Helmholtz coils. Other tests such as bit width testing occur at this step, too. The push button test and an overall functional and output power test follow, ending with a battery test.

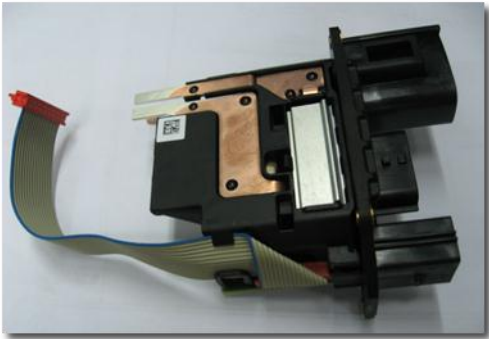
**Table 4: Technical challenges—lessons learned**

Tester and fixture design needs to creatively consider production floor environmental realities.
Using existing standard test system architecture avoided the need to engineer from “the ground up,” allowing engineers to focus on the Helmholtz coil design.
Likewise, standardized test routines were adapted to specific tests for the RKE.

So, what were the key lessons that we learned in this case with significant technical testing challenges? First, the overall tester design, especially where the tester meets the unit under test needs to consider realistic production floor realities such as accomplished here by eliminating the complexities of mechanical movement by designing a 3D Helmholtz coil to calibrate the key fob. Using a standard product functional test architecture and adapting standardized test routines to fit the specifics of this test flow also eliminated the need to reinvent the wheel, greatly developing engineering design time and cost.

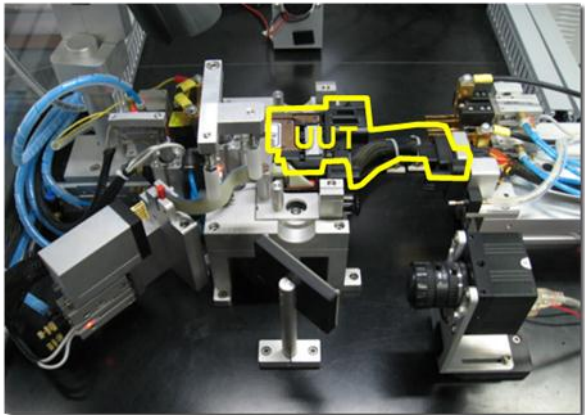
**Meeting logistic challenges**

Now we turn to a different example that illustrates the need to consider productivity and logistics issues, in short, how do we ensure the highest throughput and the most reliable and repeatable test environment? In this case the assignment was to perform a full functional test to a power module that was part of an automotive engine control unit. We face three distinct requirements, each of which if not executed properly could affect both productivity and reliability of the test. First, as shown in Figure 3, the module had an unusual shape and required connection at three different locations in order to be tested. Second, there was the requirement for repeatable measurement of an extremely low value resistance, 510 milliohms. Third, we needed to measure a very high current, 30 amps, albeit at a relatively low voltage.



**Figure 3: The ECU power module UUT**

The most significant implication of the unusual shape of the UUT and its three connectors is that the amount of time required to manually connect and disconnect the module to the test equipment could become unacceptably long, even impeding overall product throughput. And at first glance these two resistance and current measurements might seem to better fit into the technical challenges category just discussed. However, actually making the measurements was not the major issue, but reliably making the low resistance and current measurements on each and every UUT—hundreds per day—in a repeatable fashion place the challenge both firmly in the logistics camp. Let’s examine all three problem areas in turn. Preliminary testing showed that it could take up to 30 seconds to place the module on the tester and connect the three connection points on the power module manually and about 15 seconds to disconnect it manually, adding 45 seconds to the overall test time for each UUT. Since the actual test itself took only a few seconds, this additional time was unacceptable at anticipated production volumes. The solution was engineering a pneumatically actuated quick connect and disconnect probes that connected the entire UUT in far faster than a manual approach. Total fixture activation / deactivation time is now under 3 seconds.



**Figure 4: A quick connect/disconnect test fixture that minimizes set-up and disconnect time**

Measuring low value resistance and capacitance, while straightforward in the lab, can be extremely challenging in the high volume production environment. The reason is not that a single measurement to the UUT is inherently complicated; it's that one measurement can be made repeatable over thousands of module. Neither the tester nor the fixture apparatus should introduce measurement variability. A four-wire measurement to the exact point on the ECU where the measurement is occurring usually eliminates the problem, and this approach was used here. However, in this particular module there was inherent variability in the contact resistance of the ECU's own connector, which led to measurement inconsistency. The solution was, in a word, blunt. Higher force pneumatics in the fixture applied greater pressure to the module's contact fingers. As further "reliability insurance," the mating contact finger style in the fixture was enlarged in order to touch the entire surface area of the module contact. This two-pronged approach resulted in eliminating module-to-module variability in the required half-ohm measurement.

The third challenge was measuring 30 amps. This test step required considering two aspects. Because of the high current involved, the first considerations was operator safety. A major advantage of a pneumatically operated test fixture is that safety interlock to ensure the operator's hands are nowhere near the UUT when it is activated. The second consideration was measurement repeatability. As with the low resistance measurement, at these current and low voltages, and increase of just a few milliohm in fixture-to-UUT contact resistance could skew the measurement. The main problem here was that 30 amps flowing through the fixture contactor many hundreds of time a day in production shortened its operational life to just a few days. (This degradation also exacerbated the contact resistance variability problem.) The solution again was to apply greater pneumatic force, enlarge the fixture contact to cover as much area as possible and plated it with gold to prolong its life. Also, since electrical parameters change over time, it's important to perform calibration at regular intervals. For the ECU test a "calibration block" built in the same shape as the UUT was constructed and placed in the test fixture. An LCR meter was used to measure system and fixture resistance. These data were then stored in the test program to serve as the "bias reference value" when actual testing was occurring. In this way, accurate UUT testing was possible even as residual values in the test fixture changed over time.

**Table 5: FCT Logistics challenges—lessons learned**

The production floor is not the test lab, and requires far more attention to designing for the realities of the production environment such as operator safety
Tester throughput is highly affected by fixture connection methodology.
Rugged design and materials are mandatory, especially for the fixture.
Don't forget to design the tester and test fixture for ease of maintenance.
Include a regular calibration plan.

There are two prevailing realities on the high volume production floor. First, the production floor is a much harsher environment than the comparatively pristine test lab. It's an electrically and often acoustically noisy environment. Test and assembly operators under pressure to keep product flowing will hurry and are apt to be less careful when handling UUTs. Test equipment operators are usually not test engineers; they are focused only on getting the product on, pressing the start button and getting the product off the tester. The test protocol and tester design need to consider this reality. Second,

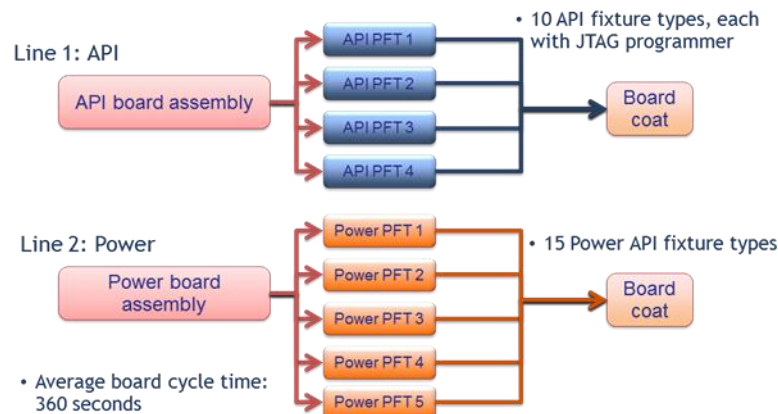


throughput is king. Procedures that wouldn't even be considered in the development lab, such as connecting and disconnecting the unit being tested can bring line productivity to a virtual standstill if every single step in the test process is not evaluated for its suitability in high volume production. There's much more to the production test sequence than just the electrical stimulus and measurement. Third, in this harsh production environment, the tester and especially the test fixture must be over-designed and over-engineered to withstand what could be hundreds of thousands of actuations. Not just ruggedness needs to be considered, but ease of maintenance as well.

### Meeting cost challenges

Finally we turn to perhaps the greatest challenge of all: testing cost. No matter how hard test equipment vendors attempt to persuade their customers that test adds economic value to the product, most manufacturing managers—and many test managers—believe just the opposite. Test equals cost. Anyway test can be minimized, while still meeting quality gate requirements, test cost can be reduced.

In our illustration of a generally applicable approach to reducing test cost, we turn to a set of boards used in personal transportation products such as electric wheelchairs. The board “family” consisted of a controller board (“API”) and a “power” board, each with numerous variations such that each board type required its own individual fixture. Worse, each functional tester was difficult to modify in order to adapt to new board types as they came along. Production volume was high and tester throughput was slow, meaning the inevitable outcome was a requirement for multiple test systems—anathema to all production managers. So, the upshot was that while a test strategy was in place, it was slow, expensive and inflexible. In this case there were two production lines. The API board had ten distinct variations, each requiring its own test fixture. The power board had fifteen variations. Each board type required its own test fixture, making a total of twenty-five fixtures, each costing upwards of a thousand dollars. Adding to the overall fixture cost was the fact that each API board contained a serial flash ISP chip that had to be programmed using a JTAG ISP programmer mounted inside each API test fixture, raising test cost even more.

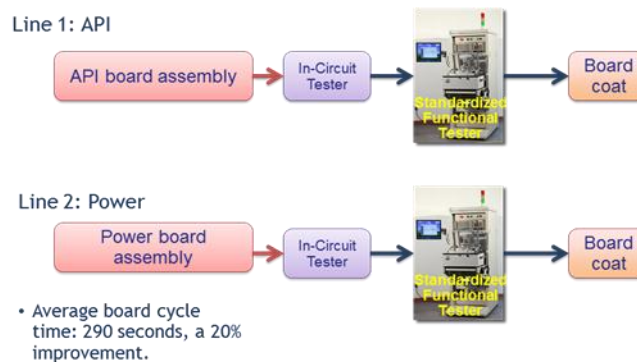


**Figure 5: Original API & Power test strategy**

Production volumes were sufficiently high such that four functional circuit testers operating in parallel at the end of the assembly line were required to test the API boards coming off the line. And another five functional testers were required to test the power boards coming off the second production line. The average total test time (including handling) was 360 seconds—six minutes.

Numerous fixtures, multiple testers, long test times, inflexible testers. Each of these represented a distinct opportunity to reduce test cost.

The biggest cost reduction leverage came from eliminating the separate test platforms and moving to a general-purpose platform. In addition to offering the needed flexibility to accommodate future versions of both the API and power boards without having to alter the test platform itself, the designers were able to incorporate a single JTAG ISP programmer into the test system itself, eliminating the requirement—and cost—of individual programming dongles in the ten API fixtures. Next, the designers turned to the test fixtures and evaluated the commonality and differences among the various API and Power board types, and were able to reduce substantially the total number of test fixtures required.



**Figure 6: Revised API & Power test strategy**

Finally, the overall test strategy was evaluated in detail, test by test. Based on an analysis of the boards’ fault spectrum—the distribution of failure types across all the boards—a new test strategy was adopted. Before, boards went directly from the manufacturing line to the functional tester. But the analysis revealed that a traditional in-circuit tester placed ahead of the functional tester more easily and inexpensively detected faults such as solder shorts and wrong components. As a result the test strategy was changed to add in-circuit test.

A new test strategy—in-circuit, followed by a simplified functional test performed on a general production test platform—was adopted. The fixture count for each board type was substantially reduced. The new general-purpose test platform meant every board variation could be tested on the same system, eliminating the need to “tweak” each tester to the specific test requirements of each board type. Perhaps most significantly, the new test strategy, together with improvements in ISP programming resulted in a 20 percent reduction of total board cycle time: from 6 minutes to less than five minutes per board. While adding in the in-circuit test step to increase overall test productivity may appear counter-intuitive, the key is that each tester is doing the task it performs best: in-circuit for board assembly, component, and solder faults; functional test for board operation and programming.

**Table 6: FCT Cost challenges—lessons learned**

Standardizing on a “universal tester” with flexible architecture and standardized test algorithms reduces FCT capital cost.
Re-use of proven software components reduces re-engineering costs.
Standardizing core fixture design reduces tooling cost.
Evaluating the fault spectrum leads to optimal test strategy and increased productivity.

There are several non-intuitive steps in the area of test cost challenges that led to a reduction in test cost and a 20 percent improvement in overall productivity. Standardized tester architecture reduces initial engineering costs. Perhaps even more importantly it substantially reduces re-engineering costs when a new board type or test requirement is added. That the generalized test will deal with both existing and future board models and variations eliminates the need for multiple, slightly different test platforms, as was previously required.

Standardization applies to test software as well, allowing reuse of test algorithms. As it does standardizing on a core fixture design to cover multiple board versions. Finally, and perhaps most counter-intuitively, re-evaluating the overall test strategy by analyzing the fault spectrum—what tends to fail—can lead to significant cost savings.

## Conclusion

So, what have we learned? First, that functional test takes on a dizzying array of different—and challenging—technical requirements. Engineering creativity and a willingness to think outside the proverbial box is needed to meet these challenges. Second, there must be awareness that the realities of the production environment are quite different than those of the development lab. Throughput and environmental ruggedness are mandatory. But perhaps the most valuable lesson is that standardization in as many areas as possible—tester architecture, fixture interface and the fixtures themselves, the test software—is the most rational and ultimately, cost effective approach to functional circuit test. This means sometimes operating counter-intuitively such as adding in an additional test step or being willing to accept the higher price of a standardized test platform over the frequently illusory cost savings of multiple smaller custom-built testers. In the end, achieving a technically competent, logistically capable, cost-effective purpose-built functional test strategy follows a standardized path.