HOW TO MORE ACCURATELY PREDICT THE FIELD RELIABILITY OF AUTOMOTIVE POWER ELECTRONICS

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M E C H A N I C A L A N A L Y S I S

W H I T E P A P E R

INTRODUCTION

If your company makes planes, trains, automobiles, medical devices, computers, and communication systems, or you are a large electronic device supplier, the reliability of your products in the field is crucial to your business success. The growing market for electric and hybrid vehicles is increasing the pressure on life-time performance of the devices that power them. Estimating the actual field reliability before the product ships is difficult for two reasons. First, test data on the reliability of the individual parts is limited, and second, the experiments needed to subject a sufficient number of parts to accelerated testing are time-consuming and costly. This situation has hampered the introduction of new electronic devices, power units, and PCBs, and is slowing the adoption of new technologies such as wide-band gap devices, for example, silicon carbide (SiC).

On top of this, we have discovered an inability to extrapolate lab-based test data to the field because thermal models are unable to predict junction temperature rise during operation across a drive cycle with good enough accuracy. In this paper, we take a closer look at these problems and how two recent innovations from Mentor Graphics can help to solve them.

ESTIMATING FIELD LIFETIME OF AUTOMOTIVE POWER ELECTRONICS

Let's take a look at the process used for field lifetime estimation. The definition of field lifetime depends on how the product is used. In the case of a car, reliability is normally assessed against a standardized drive cycle, such as the U.S. Environmental Protection Agency's Urban Dynamometer Driving Schedule, which is translated into a power versus time profile for the electric powertrain and is also used to create a profile for individual components such as IGBTs. Then, a junction temperature profile versus time is created with a simulation model that uses the power versus time profile.

The magnitude and number of the temperature swings this changing power profile produces are then counted. The greater the magnitude of the temperature swing, the greater the effect on lifetime. The magnitude of the predicted temperature change can also be used to define the target temperature changes for active power cycling experiments that are used to measure failure rates in the lab.

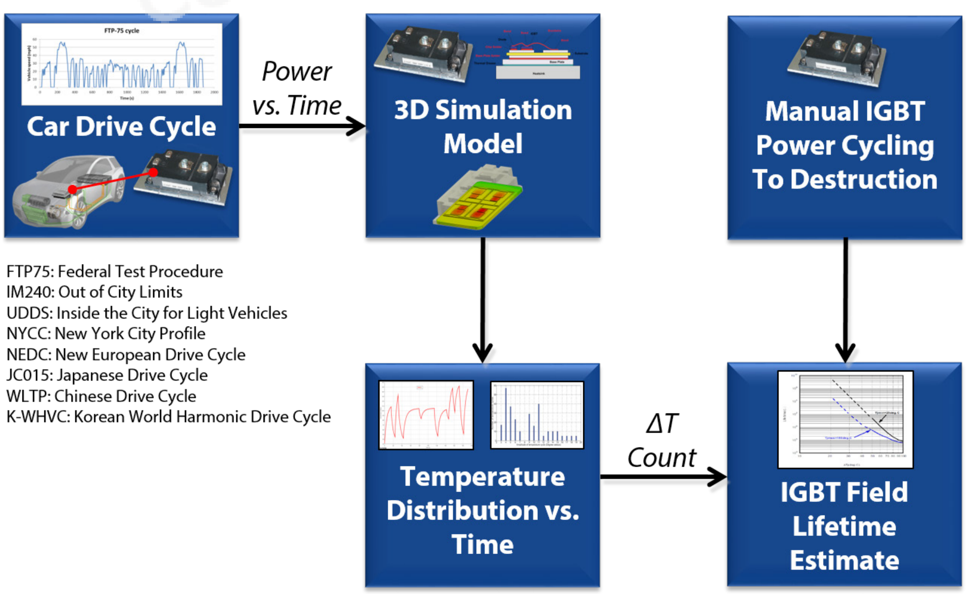

Figure 1: The traditional process for IGBT field lifetime estimation.

The first issue with the current situation (shown in Figure 1) is that the models used to predict the temperature changes over the drive cycle are not sufficiently accurate. A model based on the as-designed geometric data and material properties can appear to be quite accurate when compared to the temperature vs. time profile that results from the part being switched from a powered on condition to powered off, as can the resulting structure function. Yet, in fact, the model may produce a temperature rise that is wrong by more than 20% or more when subjected to a short power pulse (Figure 2).

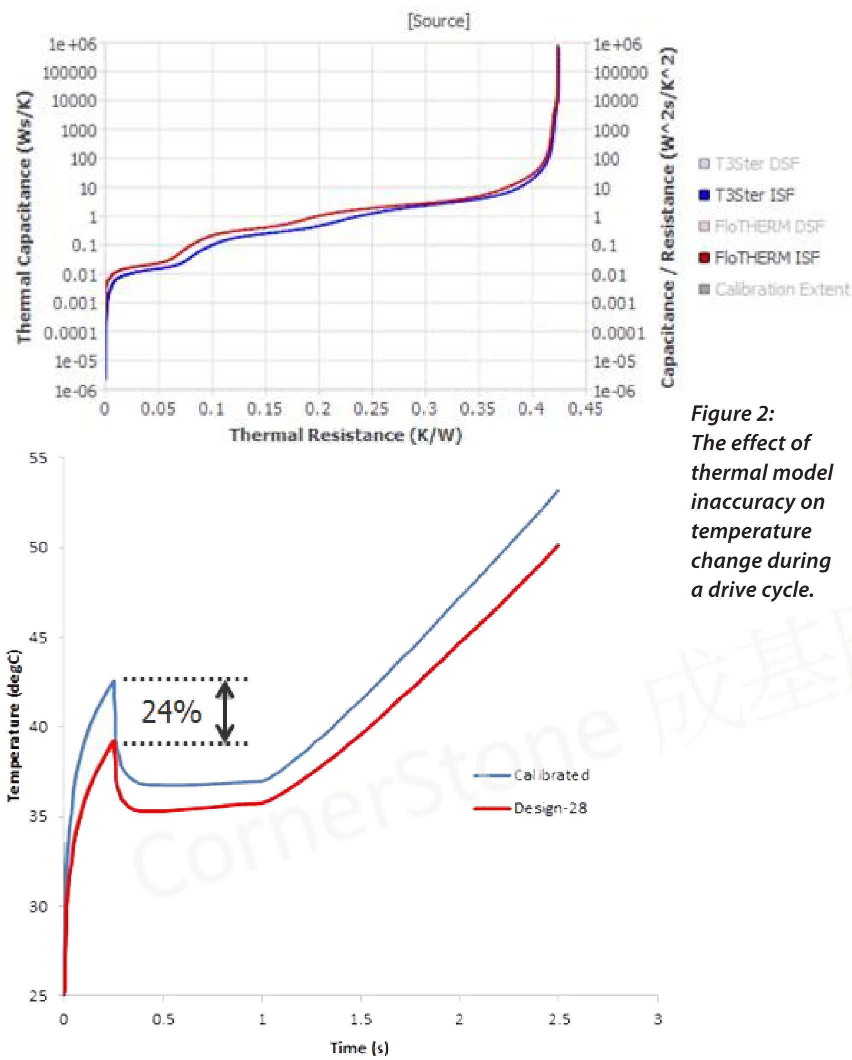

Figure 2: The effect of thermal model inaccuracy on temperature change during a drive cycle.

This is important for two reasons.

1. Predicting the wrong temperature rise in the application can have a big effect on the predicted reliability. With the trend toward higher operating temperatures supported by SiC devices, where the temperature can change by as much as 140 °C, under-predicting the temperature rise by 20% will result in an over-estimation of lifetime by more than 60%.

2. Compounding this, the predicted junction temperature swings in the application are often used to plan the lifetime tests, which affect the ability to extrapolate data from the lab to the field. Inaccurate simulation can result in a poor choice of test conditions.

The lifetime tests are lengthy, and they involve a lot of manual effort, which means they are costly. For these reasons, plus the limited availability of testing facilities, too often, too few parts are tested to get statistically reliable set of lifetime data from the tests.

Dependable field lifetime estimates are hampered by the fidelity of the simulation models used, as well as the quantity and quality of test data (Figure 3).

The engineers in Mentor Graphics Mechanical Analysis Division have developed the following unique, discrete solutions to address these issues, which, when used together, can ensure the highest fidelity estimation of field lifetime for power electronic devices.

AUTOMATED MODEL CALIBRATION PROVIDES MORE ACCURATE RESULTS

First, the simulation model is calibrated with measurement data from the Mentor Graphics T3Ster transient thermal characterization and measurement system. The T3Ster equipment captures the transient response of a semiconductor package without using thermocouples, based on the JEDEC Electrical Test Method, JESD 51-1 [1].

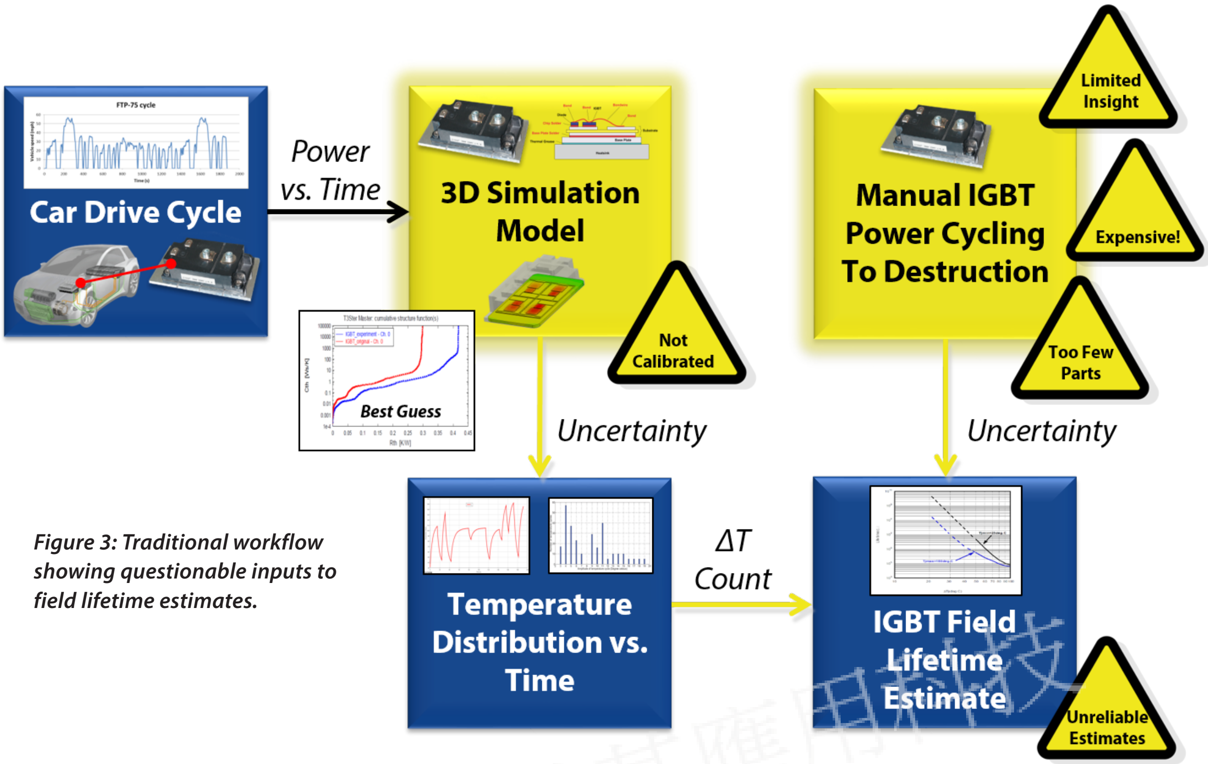

Figure 3: Traditional workflow showing questionable inputs to field lifetime estimates.

The T3Ster system measures the voltage drop across a temperature-sensitive parameter (TSP) of the device, such as a diode, between two powering conditions. The voltage is related to device temperature through a K-factor calibration of the TSP. Because thermocouples are not required, T3Ster provides a highly repeatable measurement that accurately captures small temperature differences (0.01 °C), between the source and the environment. The T3Ster system captures transient response of the device under test with a 1 µs measurement resolution in time.

Additionally, the T3Ster technology outputs a structure function that describes the thermal resistances and thermal capacitances along the heat-flow path. This can be mapped to physical objects within the package structure to determine issues with manufacturing processes and to identify locations of thermal degradation [2–6]. As the industry gold standard for thermal response measurements, a model calibrated against T3Ster measurement data offers the most accuracy for replicating the internal thermal gradients within an IC package with respect to time.

By mimicking this power step change in a simulation tool such as the Mentor Graphics FloTHERM CFD simulation software, the simulated transient response can be compared to the measured transient response. This is usually done by comparing measured and modeled structure function curves. Any deviation between the two indicates that some aspect of the simulation model is incorrect, and it must be corrected before the results can be trusted. Traditionally, this removal of deviations (or model calibration) was done manually, involving many model changes and a high level of experience to achieve a reasonable match. Often the experience of the practitioner was insufficient, or the time pressures of the thermal design cycle influenced how good the "best model found" was, forcing the use of a somewhat deficient model in practice.

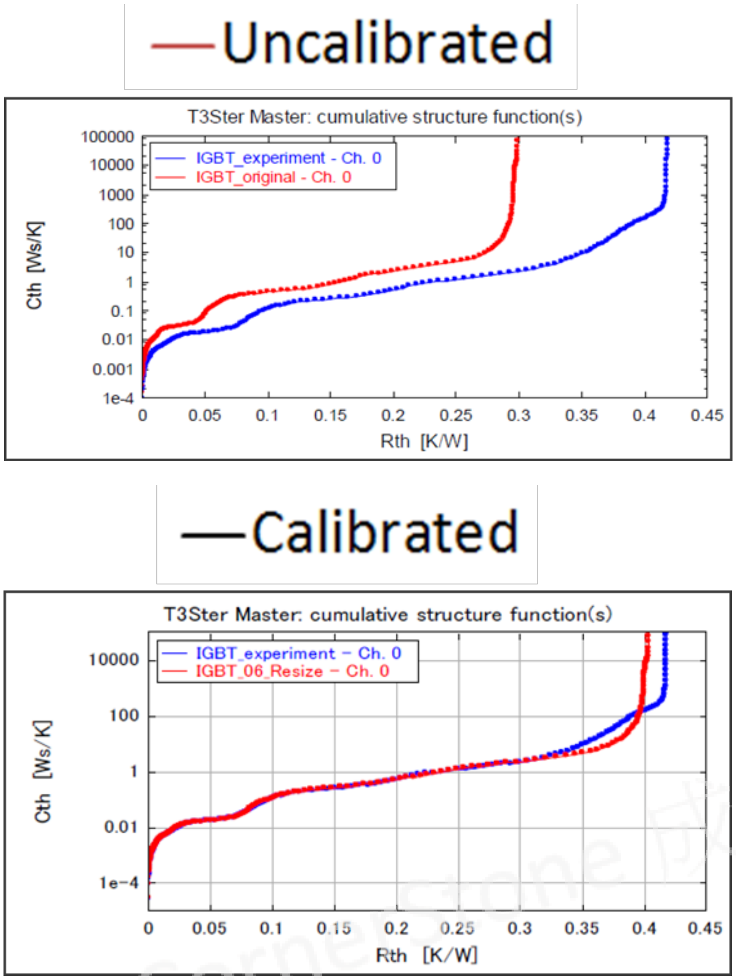

Figure 4: Uncalibrated model (top) vs. calibrated model (bottom). The differences above 0.3 K/W are outside of the package body and so were not calibrated.

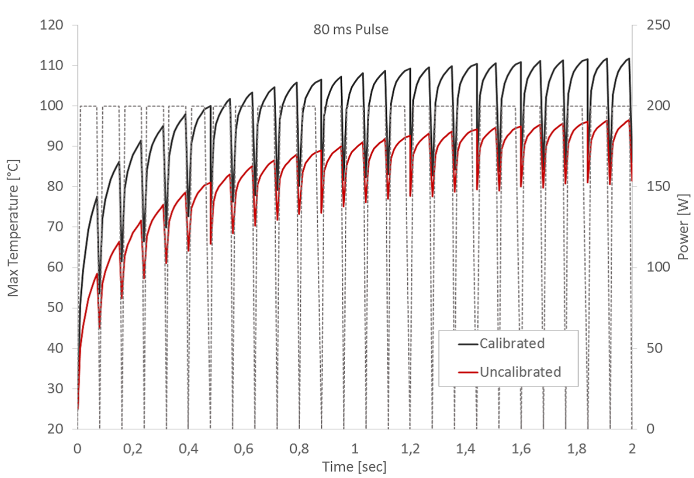

Figure 5: Comparison of uncalibrated and calibrated thermal model response to a 200-W, 80-ms pulse power profile.

This model calibration is automated within the Command Center module in the latest release of FloTHERM, Version 11.1. FloTHERM directly reads in a structure function generated by the T3Ster system from the measured transient response of an actual part to a step change in power. It is automatically compared to the equivalent structure function created from the simulation results. Model modifications are automatically made to the simulation model until a high-quality match is found. Thus, the calibration process is reduced to identifying the dimensions or material properties that are difficult to measure or have some degree of uncertainty.

Subjectivity of the calibration is eliminated because the comparison of the structure-function curves is formalized mathematically. The previous requirement to decide how the model should be changed is completely replaced with an optimization routine that automatically drives the simulated results toward matching the empirical curve. High-quality simulation models that match the industry gold standard for transient thermal measurements are now easily created within the time pressures associated with electronic design (Figures 4–6).

This calibrated model, used as part of a system-level simulation, accurately predicts junction temperature rise; as a result, it can also be used to guide the experimental design for active power cycling reliability tests on power electronics components used in the automotive drive-train.

The automation of these tests was enabled by the release of the Mentor Graphics Power Tester 1500A in 2014, which eliminated the need for manual intervention and the removal and remounting of parts to conduct laboratory testing. The Power Tester 1500A provided unprecedented insight into cause-and-effect among the competing damage mechanisms by combining the measurement of changes in electrical parameters with automated structure-function generation during cycling to identify changes in the thermal stack. The original system could only test 3 parts at a time, which has now been extended to 12. However, this still falls short of the volume of parts that need to be tested to produce dependable, accelerated-test lifetime results for the automotive industry supply chain.

SCALABLE, AUTOMATED HIGH-VOLUME TESTING TO ACCURATELY PREDICT LIFETIME RELIABILITY

After automated model calibration, the second solution offered by Mentor Graphics is the Power Tester 600A, released in May 2016, which provides maximum flexibility and is intended for use with parts that are mounted on an external cooling system such as a cold plate or direct liquid cooling. The Power Tester 600A is designed to operate at a high voltage under load current, 48 V, so that multiple parts can be tested in series. It has 16 measurement channels, and the system is able to test devices that operate at as high as 3 V DC drop per part when under load. Each Power Tester 600A can be controlled separately using its own touch-screen computer. Alternatively, as many as eight systems can be connected together and controlled from a single centralized computer, allowing up to 128 parts to be tested concurrently as a single centrally controlled experiment. This exceeds the current requirement that most automotive OEMs place on their Tier 1 suppliers to test a minimum of 77 parts [8].

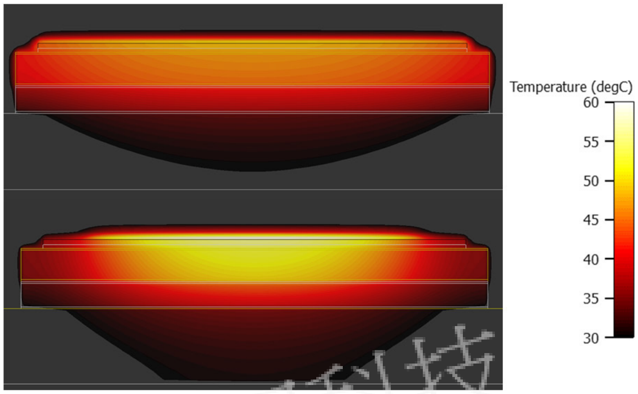

Figure 6: Temperature differences between uncalibrated model (top) and calibrated model (bottom).

By using multiple systems, a statistically significant sample size can be tested for different powering conditions to generate the lifetime curves for different junction temperature swings within a few days or weeks, depending on the testing conditions. The testing is auto-mated, so there is no need for operator intervention during the testing other than to remove or replace failed parts, greatly reducing the testing time. The system can operate 24x7 unattended, which minimizes the cost per part tested. Figure 7 illustrates how combining automated model calibration with the Power Tester 600A improves the overall workflow for testing and estimating lifetime reliability.

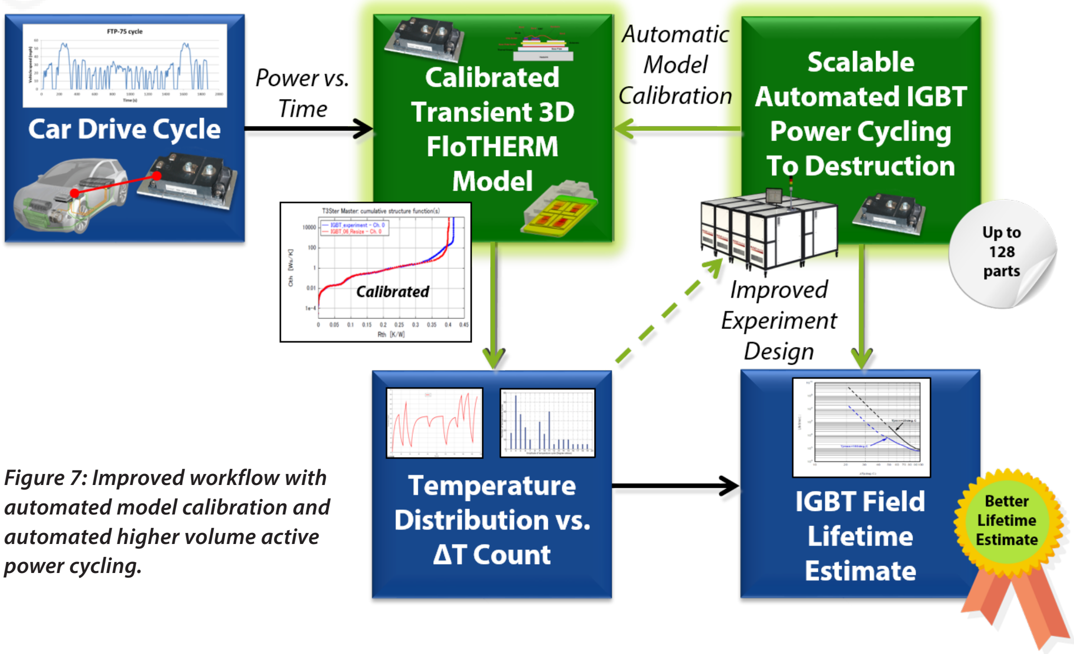

Figure 7: Improved workflow with automated model calibration and automated higher volume active power cycling.

CONCLUSION

Field reliability estimation is greatly improved by using a calibrated thermal model that can provide greater than 99% accuracy for simulations of junction temperature rise versus time. Such accurate models can ensure that active power cycling measurements are correctly defined. The addition of automated, high-volume active power cycling drastically reduces the testing time and cost per part, making it possible to test a higher number of parts cost-effectively, which increases the statistical validity of the lifetime curves and further improves field reliability estimates.

For more details on the Power Tester 600A, go to www.mentor.com/powertester-600a.

ACKNOWLEDGEMENTS

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