# Comparative Evaluation and Analysis of the 2008 Toyota Lexus, Camry and 2004 Prius DC Link Capacitor Assembly vs. the SBE Power Ring DC Link Capacitor

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***Abstract*—US Department of Energy, Oak Ridge National Laboratories (ORNL) and SBE, Inc. report test results comparing the Toyota Lexus, Camry, Prius (both new and end of life) and Kemet capacitors with the SBE Power Ring. While exact comparisons are difficult because of size, shape and terminal configurations the SBE capacitors showed from 4 to 8 times lower temperature rise than the others tested and with substantial volumetric reduction as well.**

***Keywords-Capacitor, Inverter, Reliability, DC Link, Temperature, Automotive, Toyota***

## I. INTRODUCTION

The DC link capacitor (also referred to as a DC bus capacitor) is a critical component in voltage source power converters/inverters found in EV or HEV drive systems. The challenge is to provide this capacitor with high power density, low temperature rise, and high reliability at low cost. This capacitor has several functions independent of the motor type used [induction, brush DC, brushless DC, or switched reluctance]. The capacitor functions as a local low ESR/ESL DC source to minimize semiconductor switch turn-off transients, supply [on a cycle by cycle basis] short term current into the inverter/converter, and to reduce as necessary voltage/current ripple and EMI seen by the DC source. The capacitor current will create internal heating, the extent of which depends on the capacitor winding and termination design. As EV power requirements increase, the DC link capacitor is required to carry increasingly higher current. This will increase capacitor dissipation and temperature rise. It is useful to document a comparative evaluation between DC Link capacitors used in previous and current Toyota HEVs, and competing DC link capacitors from Kemet and SBE. The test was to determine if capacitors are available for DC link applications that offer higher power density and significantly lower temperature rise than those currently in use. Test results will enable design freedom to investigate optimal capacitor performance trade-offs that involve increased switching speeds, lower capacitance, smaller physical size, lower weight, lower cost, and potential for increased reliability and/or less complex lower cost system level thermal management.

## II. TEST DESCRIPTION

DC link capacitors were obtained and all were evaluated for temperature rise (Trise) at 200ARMS, 5KHz. Tested examples consisted of those used in Toyota hybrid vehicles [Prius, Camry, and Lexus], one from Kemet/Arcotronics, and 2 from SBE. Computerized Tomography (CT) scans were obtained for the Toyota and Kemet capacitors to non-destructively gather as much internal construction data as possible. The CT scans had limited resolution, particularly with respect to relatively thin copper internal interconnects, but they were sufficient to choose logical thermocouple locations and to reduce the possibility of short circuits during their installation. Thermocouple locations chosen for the SBE capacitors were based on simulated internal temperature profiles. One thermocouple was located at the predicted hot spot to better obtain worst case Trise.

The testing was performed at ORNL, National Transportation Research Center (NTRC) facility in Knoxville TN by ORNL-NTRC staff who also compiled the data. Although 20KHz testing would have better predicted behavior in current to next generation vehicles [1], the NTRC test current source was limited to 5KHz if 200ARMS was to be sourced to all capacitors tested.

Providing high frequency high current to capacitors for testing is an interesting challenge. For a 3 phase inverter, it is difficult to obtain accurate values for capacitor current as it consists of a wide spectrum that extends from the fundamental variable output frequency to several harmonics above the switch frequency. While one can argue that Trise measurements made while the capacitor is installed in an operating inverter are most representative of performance, it is impossible to do this for the widely varying physical size, shape, and terminal configurations of the tested capacitors. The most practical way to compare capacitor current carrying capability is sine wave testing. Fig. 1 shows the schematic of the NTRC test fixture used.

The ESPEC temperature chamber was set at 25°C to provide a relatively stable and constant temperature environment. Two large cables were brought through the chamber access port, ending in large connection blocks. Short 3" leads of #4AWG connected these blocks to the capacitor under test [Fig. 2]. The current through the capacitor is sourced by paralleled amplifiers and step-down transformers as shown in Fig. 1.

The parasitic impedance of the paralleled transformers limits the amount of current that can be sourced by the power amplifier stack [Fig. 3]. At 200ARMS the test frequency was limited by this impedance to 5KHz. Capacitor thermocouples were monitored via the Keithly Data Acquisition system and data entered into Excel spreadsheet for analysis.

## III. THERMOCOUPLE PLACEMENT

CT images were obtained from North Star Imaging [www.4nsi.com] to non-destructively determine internal construction of the capacitors to be tested. This enabled thermocouple locations to be chosen that would investigate Trise, including predicted locations where Trise would be the highest. 1/16" holes were drilled to place thermocouples within the capacitor assemblies, within the capacitor wound element in some cases. Note that metallized capacitor electrodes are of high enough resistance that such drilling does not measurably increase the losses. [Placement of thermocouples within capacitor elements may compromise the capacitors for future operation under bias in an application.] Fig. 4 shows one of the CT scans showing thermocouple locations. Thermocouples were installed as shown in Fig. 4. #8 was to sense the terminal temperature. #9 was to sense the highest expected temperature within a capacitor element.

#10 and 11 were to sense the temperature profile as one moved away from the terminals, with #12 and 13 sensing at the top [filled surface] and bottom [metal casing]. Although the CT images were essential for thermocouple placement, they had limited resolution and for this capacitor did not show the internal copper coplanar layers above and below the wound sections. In spite of careful examination of the CT scans for this part, drilling for insertion of thermocouples #9, #10, and #11 caused short circuits in the top coplanar layer. Careful investigation with a sharp new 1/8" carbide drill showed the presence of the coplanar layers separated by a film sheet, and allowed the shorts to be cleared to withstand 40VDC, fully functional for the Trise test which proceeded without incident. The investigation and repairs to this capacitor left it "cosmetically challenged", so a layer of silicone was added to the top surface [Fig. 5].

CT scans of the rest of the Toyota and the Kemet capacitors were similarly examined and thermocouples installed at locations that were expected to best explore internal temperature rise.

The Camry and Prius capacitor assemblies contained more than one capacitor. Only the DC link section [majority of the assembly volume] was tested in each case.

Because the SBE capacitors were equipped with 8 terminal pairs, connection was made via coplanar bus assemblies similar to what would typically be used in a 3 phase inverter application.

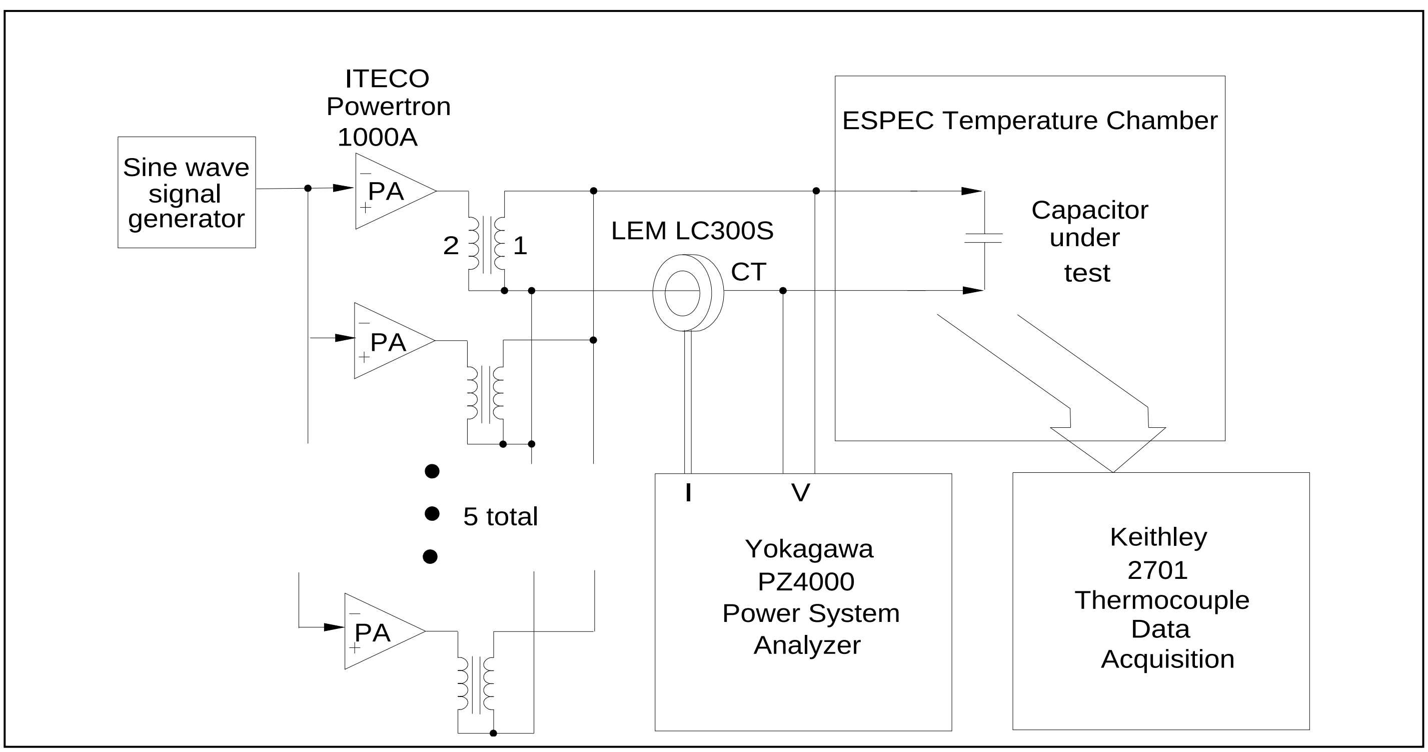


Figure 1. NTRC capacitor current source and data acquisition schematic

Figure 2. An example of capacitor under test

Figure 3. The amplifier stack at ORNL – NTRC

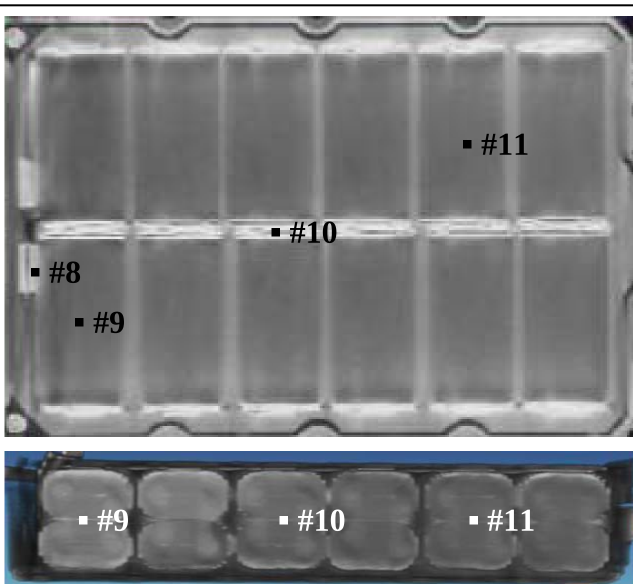


Figure 4. Scans of thermocouple locations

Figure 5. Toyota capacitor with addition of silicone layer

Figure 6. SBE 500µF DC link - 700D349

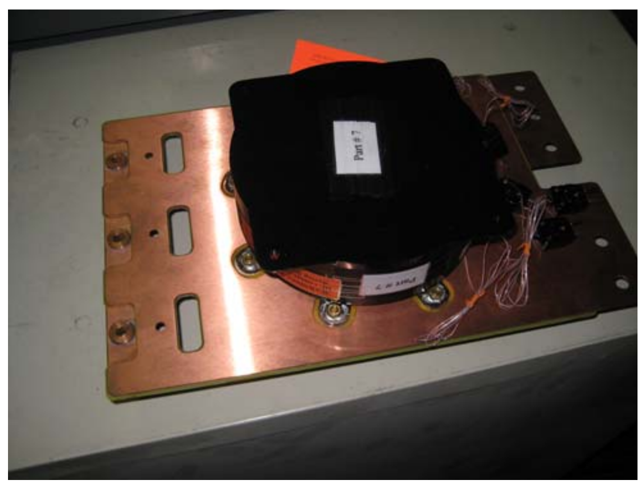

Figure 7. SBE 500µF DC link - 700D349 - installed on bus plate

Dimensions of these assemblies [not counting the tabs used for connection to the test apparatus] are: 700D349 bus 210mm X 295mm & 700D348 bus 311mm X 337mm. There were no thermocouples attached to these bus assemblies, although thermocouples were attached to the terminal assembly within the capacitor to determine terminal heating as was done for the other capacitors tested.

TABLE I. CAPACITOR DESCRIPTIONS

| | *Source* | *Voltage Rating* | *DC Link Capacitance* | *Approximate Dimensions* | *Volume ($cm^3$)* | *Surface Area ($cm^2$)* |
|---|---|---|---|---|---|---|
| 1 | Camry | 750 | 2629 | 245mm L<br>178mm W<br>73mm H | 3300 | 1535 |
| 2 | Lexus | 750 | 2098 | 254mm L<br>171mm W<br>51mm H | 2215 | 1302 |
| 3 | Prius | 600 | 1130 | 222mm L<br>184mm W<br>41mm H | 1675 | 1150 |
| 4 | Kemet | 750 | 2600 | 254mm L<br>171mm W<br>51mm H | 2215 | 1302 |
| 5 | SBE | 600 | 500 | 159mm D<br>48mm H | 953 | 637 |
| 6 | SBE | 600 | 1000 | 215mm D<br>48mm H | 1743 | 1050 |

## IV. SBE CAPACITOR TEMPERATURE PROFILE

Since the capacitor is symmetrical around the radial center line and axial center plane, the simulation complexity can be substantially simplified as shown; this shows 1/4 of the capacitor with the core at left, with simulation of top half from axial center. The inner copper terminal plate and inner surface of mandrel are set at 75° C ambient in this simulation.

The simulation was run for a slightly larger volume capacitor running at 300ARMS showing a 2°C Trise near the inner ID. Since the core in the tested examples was NOT tied to a fixed temperature, the most likely hot spot was predicted to be towards the axial center near the core [Fig. 8] [2]. A thermocouple was located at this location at the axial center within each of the SBE capacitors. Thermocouples were also placed at the axial center under location of the terminal attachment to the capacitor winding. Simulations are limited by accuracy of materials parameters, thermal input as a function of location, and thermal boundary conditions.

The above simulation input used published values for specific heat and thermal conductivity for polypropylene, actual loss variation with axial position [based on current and metallization resistance], and anisotropic heat flow based on metallization contribution to thermal conductivity in the axial direction. SBIR Phase II funded research at SBE is ongoing to obtain better values for the anisotropic thermal conductivity of biaxially oriented PP film. Of particular interest is the substantially anisotropic thermal conductivity in axial and radial directions that is being determined for the tested SBE capacitors designed for high ripple current applications.

### A. *Test results:*

Although the detailed temperature data for all the capacitors tested is interesting and relevant, space does not permit presenting this information for all the capacitors tested. Fig. 9 shows data for the Lexus capacitor that is typical and provides insight to general behavior of the others. The Toyota and Kemet capacitors all have terminals with relatively small cross section. Experience has shown such terminals to be a significant source of heating, hence the thermocouple locations within the capacitor assembly next to one terminal. One can see this high temperature sensed by thermocouple #8, Fig. 9. The oscillation on this curve is due to periodic temperature variation within the chamber.

It is IMPORTANT TO NOTE that the leads connecting the current source to the capacitor are a significant contributor to the observed terminal temperature rise shown on Fig. 10! No effort was made during this testing to mitigate this effect, as there would be the same amount of heat added to each capacitor during the testing. One can make the argument that a larger capacitor will be cooled more by the temperature chamber [more surface area] and that appeared to be the case. The Camry capacitor [See Fig. 11] was the largest capacitor of all those tested, and of the Toyota and Kemet capacitors had the lowest terminal temperature. It should also be noted that the Camry capacitor had the largest terminal cross section area of the non-SBE group.

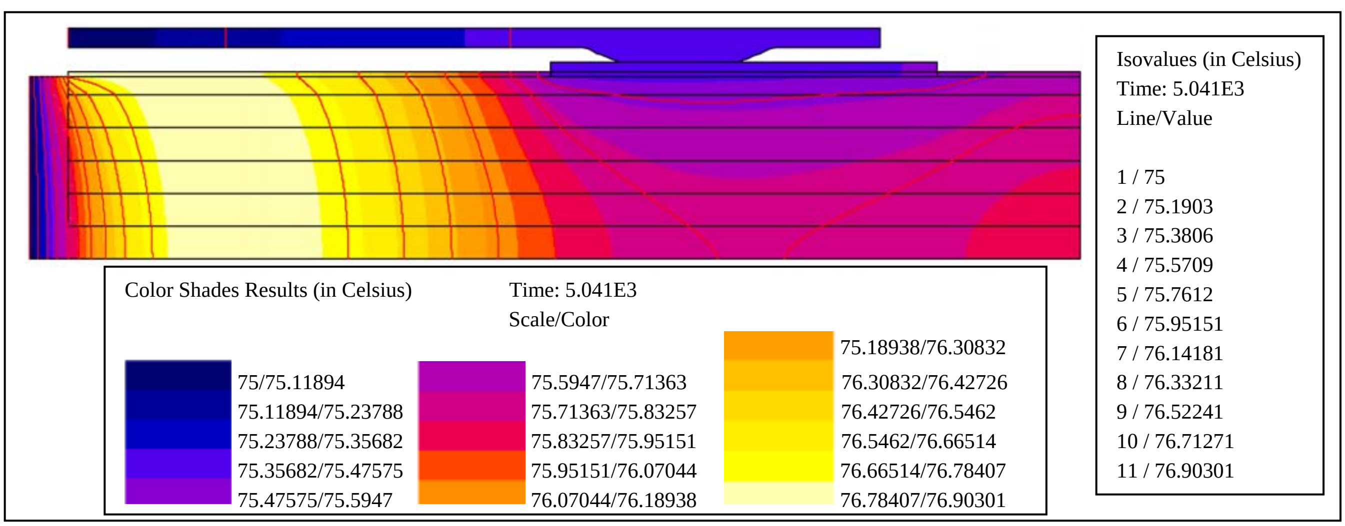


Figure 8. 5000 second simulation temperature profile indicating predicted hot spot

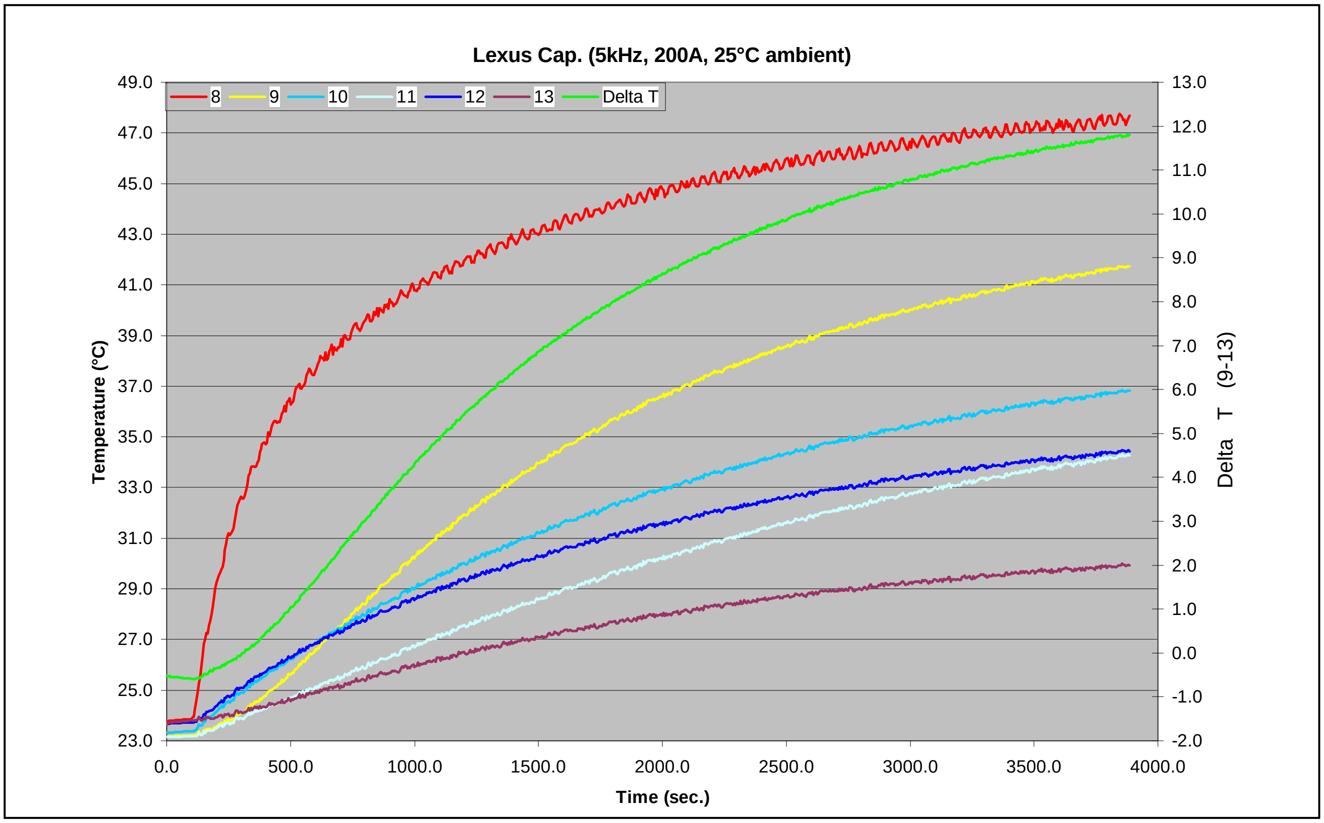


Figure 9. Temperature data for Lexus capacitor, thermocouples #8 - #13

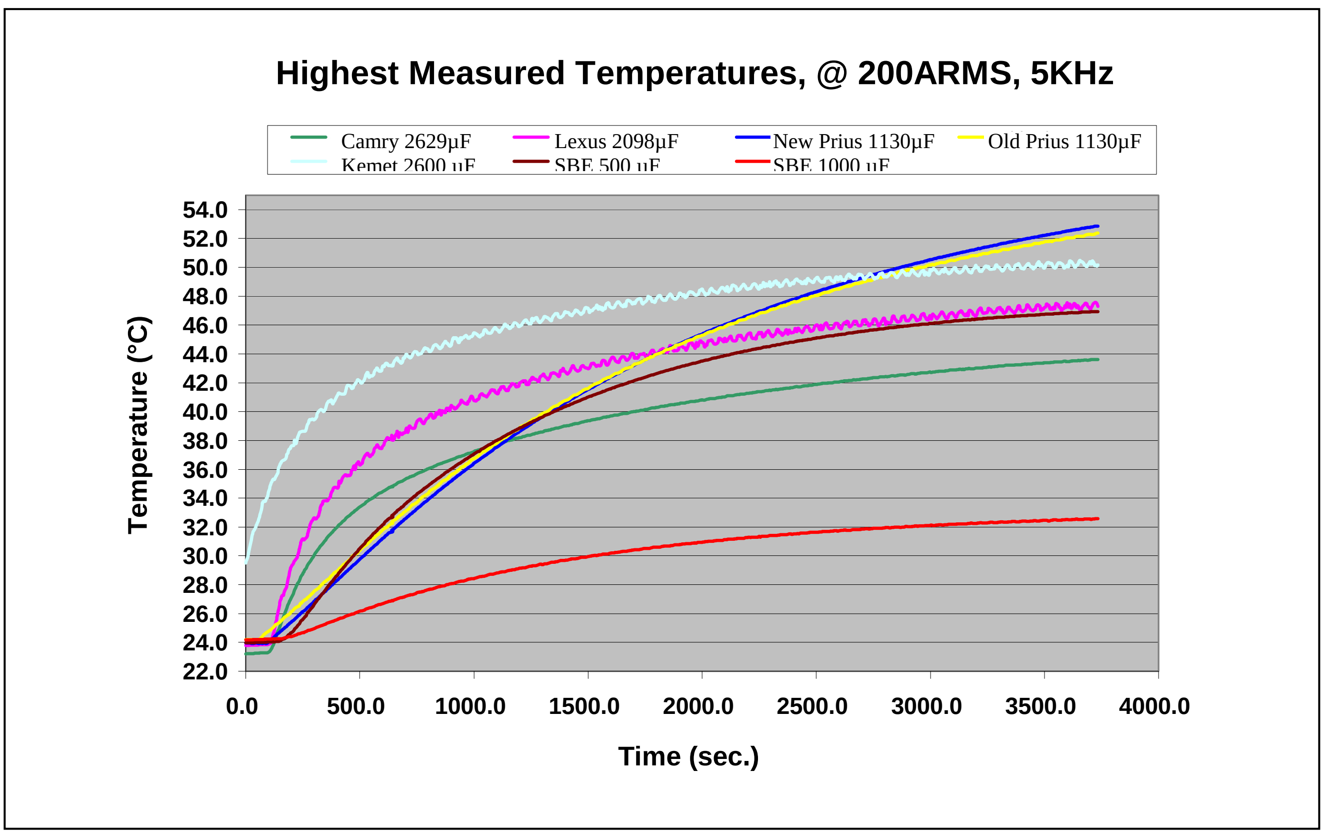


Figure 10. Measured highest temperature of tested capacitors

As shown in Fig. 10, the maximum overall temperature of each capacitor includes factors such as total dissipation of the capacitor, the interconnect to it, and the ability of the environment [chamber with near constant T forced air cooling] to remove the heat. This is proportional to the surface area of the entire capacitor structure. The total surface area of the SBE capacitors is nearly tripled as a result of the surface area of the copper bus assembly to which those capacitors are necessarily connected, with capacitor internal heat removed via the multiple terminal pairs. One could argue that made the test unfair, on the other hand it could be as well argued it shows the thermal advantage that a coplanar bus can add to the electrical advantages of such an interconnect system. The 1000µF SBE capacitor showed very low overall temperature rise compared with others tested. This is the result of the low internal losses and of the bus structure acting as a heat sink for test system conduction and interconnect losses. The overall temperature rise for the 500µF SBE capacitor was higher as a result of higher capacitor element losses, higher current density in the internal interconnect, and a smaller coplaner bus assembly. Given its physically small size and low capacitance value it exhibited performance comparable to the much larger Toyota and Kemet capacitors. Fig. 10 data shows that power converter designers should seriously evaluate conduction losses in all terminals, buses, and system interconnects, with infrared thermal imaging used to determine interconnect heat sources. This would best be done from a system “cold start”.

Capacitor internal Temperature rise shown in Fig. 11 was determined from the coolest location on the capacitor case and the hottest location measured within each capacitor. Note that the internal Trise measurements are independent of the highest measured temperatures shown in Fig 10. It can be seen that if one wanted equilibrium results, there would be a long wait involved, however each capacitor was tested for approximately the same time and is entirely useful to compare the capacitors tested. Data was time truncated for graphing to better compare the behavior of all capacitors. An interesting discovery from the SBE capacitor data [not shown due to space constraints] was that the hottest location measured was at the capacitor axial center under the connection to the terminal assembly rather than at the anticipated core location highlighted by the simulation; true for both the SBE capacitors. As part of the SBIR Phase II DoE funded research being done at SBE, carefully measured materials parameters [specific heat, anisotropic thermal conductivity, and metallization TCR] will result in improved models for capacitor thermal behavior. The multiple terminal design [the capacitor as a distributed element] is shown to reduce terminal Trise. There are also mechanical and electrical advantages to using distributed terminals not addressed in this paper. Other capacitors tested were designed as traditional 2 terminal capacitors just made larger for the application and are not optimized for these characteristics.

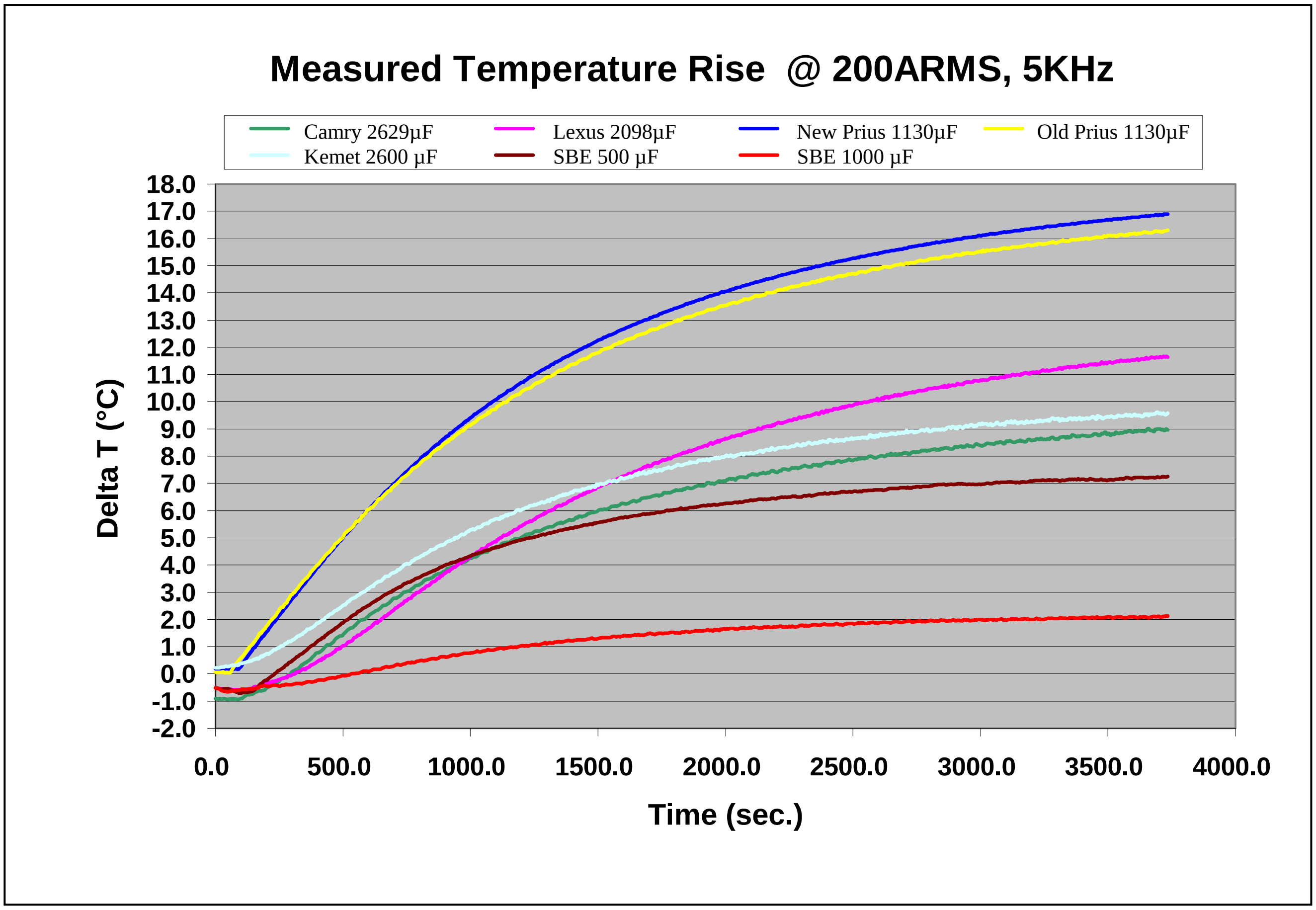


Figure 11. Measured internal temperature rise of the tested capacitors

## V. Summary of Results

Test results clearly show the design evolution within the Toyota hybrid designs. The Lexus capacitor is substantially smaller physically, yet with only a small Trise increase over the capacitor used in the Camry. As expected, the Prius capacitor had the highest Trise. Also notable is that the capacitor from the 160,000 mile Prius exhibited no performance degradation. The Kemet capacitor performance was similar to that of the Toyota Lexus capacitor, but with higher capacitance and ~2.5°C lower Trise. This is because of the higher percentage of internal capacitor assembly volume that is active as a capacitor. It does not use conventionally wound capacitor elements.

The Trise of the SBE capacitors was substantially lower than any of the Toyota or Kemet designs. This is especially relevant as the SBE capacitor design could allow power conversion systems with lower cost, volume, and weight without sacrificing current carrying capability. The lower Trise would result in higher system reliability and the possibility of different cooling options.

## VI. On-going and Future Research

SBE test capability will be enhanced to operate at ~20KHz to achieve data at a more relevant frequency. This will allow examination of the tendency for capacitance nearest the terminals to carry more than its share of the total current [current hogging]. The conductors carrying the current into the test chamber will be water cooled to minimize conduction losses from heating the capacitors as was the case for the test results described in this paper. The goal is to better measure Trise based on actual capacitor losses and to better represent the expected system environment. Additional capacitors from other vendors will be evaluated, with electrical and thermal behavior obtained.

## Acknowledgment

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## References

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