Next Generation 200°C Film Capacitors Enable Optimized Power Conversion Solutions for Harsh Environments

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Abstract

The temperature limitations of traditional DC link capacitors prevent full optimization of power dense inverter systems for aggressive operating environments such as down-hole drilling and aerospace electrification. W. L. Gore & Associates has developed a self-healing PTFE-based dielectric and partnered with Advanced Conversion to provide DC link film capacitors capable of reliable operation up to 200°C. This paper presents validation testing results for "wrap and fill" style capacitors that meet and exceed requirements for down-hole drilling applications. Initial prototype evaluation of an Advanced Conversion DC link test kit using the high temperature film is also provided.

1 Introduction

Traditional DC link capacitors are temperature limited and require cooling when operating in harsh environments such as down-hole drilling and aerospace. Additional cooling for the capacitors is not a desirable system level trade when trying to achieve optimal power density using wide bandgap switching elements. W. L. Gore & Associates has developed a next generation self-healing PTFE-based dielectric film and partnered with Advanced Conversion to provide DC link capacitors capable of reliable operation up to 200°C without de-rating. This capacitor technology shifts the existing temperature design limit and enables a new paradigm of system level optimization for demanding power conversion applications.

A "wrap and fill" style capacitor with various capacitance options is now in production and we have multiple customers qualifying parts for down-hole applications. Energized thermal cycling data is presented for discrete capacitors to validate life subject to full rated voltage from -40°C to +200°C. Initial evaluation of the high temperature film in an Advanced Conversion DC link test kit is also provided.

1.1 Gore High Temperature Film

Conventional high temperature capacitor dielectrics have been limited in high temperature capability, with PTFE having the greatest temperature handling [1]; however, these materials have limited reliability and energy density due to either 1) their inability to be metalized and thus must be used in film-foil configurations or 2) limited high temperature clearing capability. W. L. Gore & Associates have developed a proprietary next generation PTFE-based dielectric capacitor film that can be readily metallized to enable operation up to 200°C without these traditional limitations. This film has excellent dielectric strength as shown in Fig. 1 and exhibits very good self-healing properties comparable to metallized polypropylene [2].

This film has previously been targeted for 400V DC capacitors, and it can be run at rated voltage up to 200°C WITHOUT de-rating required, which is a significant milestone. However, this work will show that with design optimization of downstream manufacturing, 600V DC continuous operation can also be achieved.

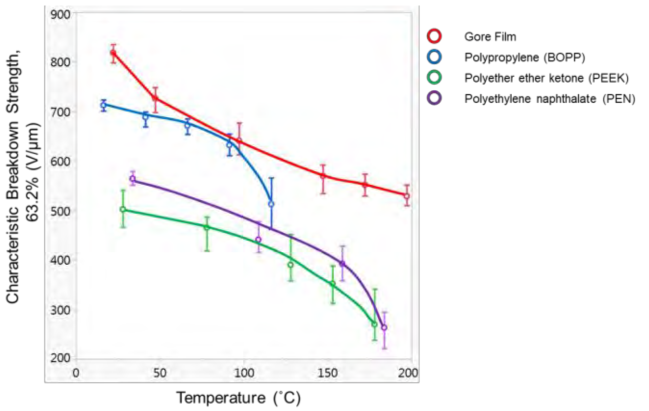

Fig. 1 Characteristic breakdown strength of various film capacitor dielectrics over temperature.

2 Test Protocol

2.1 Test Samples

Two variants of life testing samples were fabricated for evaluation using 4um W. L. Gore & Associates PTFE-based film. The first was the Advanced Conversion 8031G025-24-1, which is a commercially available 25uF capacitor rated at 400V DC as shown in Fig. 2. A total of 14 samples were tested, and data is presented in section 3.1. The second variant was a 50uF capacitor rated at 600V DC, which was an early prototype of the Advanced Conversion 8041G050 part series. These parts use the same 4um Gore film, but incorporate an optimized metallization scheme for higher voltage stress. A total of 6 prototypes were tested, and data is presented in section 3.2. The life test samples are comprised of metalized film windings that are end sprayed. Terminal connections are made using high temperature insulated wires welded to each face of the capacitor. A "wrap and fill" approach with high temperature tape and epoxy is used to seal the ends of the capacitor and provide mechanical support for the lead wires.

A prototype integrated DC link test kit incorporating Gore High Temperature Film was also constructed for evaluation. This part is based on a standard Advanced Conversion design that is optimized for use with the Infineon HybridPACK Drive™ module. Data for this test kit using conventional polypropylene film has been provided previously [3-4] and initial results using the W. L. Gore & Associates PTFE-based film are presented in section 5.

Fig. 2 Photograph of a PTFE-based film 400Vdc capacitor used for life testing.

2.2 Test Parameter Selection

For down-hole applications the primary reliability test leveraged to gain confidence of design robustness is elevated temperature and voltage life testing. However, unlike many other industries it is typical to also combine thermal cycling into the same test, increasing the stress on the component as it experiences a dynamic temperature profile while under voltage. This approach was selected to demonstrate the capability of these parts to meet the temperature and voltage requirements for down-hole applications.

One compromise of the selected approach is a reduced ability to use the collected data for power law and Arrhenius modeling of expected lifetime. This is due to the introduction of multiple stress factors and failure modes beyond clearing (self-healing) events. However, the combined stress factors provide a more realistic dataset for challenging environmental conditions while also being very time and sample efficient by combining two tests into one.

For demonstration purposes, the thermal cycles should have a relevant effective duration at elevated temperature and rated voltage. This will stress the parts similarly to the fixed temperature DC endurance test commonly used to characterize capacitors. The target duration at elevated temperature is often double the desired life of the component. In some cases, durations as low as one times the desired life are used with the temperature elevated 10-15ºC beyond the use temperature. Down-hole life targets for high temperature applications are typically in the 100's of hours [5], so we selected an aggressive target of 1000 hours at elevated temperature.

Down-hole testing requirements typically specify an upper temperature of 175ºC. Since the Advanced Conversion capacitors are rated at 200ºC, that temperature was selected as the upper limit for this testing to push beyond the industry standard. A minimum temperature of -40ºC is typical for capacitor testing, and we decided to use the same lower limit. To apply the maximum stress to the capacitor samples, we elected to apply rated voltage over the full temperature range. The test protocol is summarized as follows:

1) Thermal cycle from negative 40ºC to positive 200ºC with 5°C per minute ramp rate between temperature limits
2) 10 hours dwell at high temperature and 2 hours dwell at cold temperature
3) Rated voltage applied during the entire test
4) Total of 100 cycles.

Note that the testing was performed in compliance with JEDEC standard JESD22-A104E condition M modified [6].

2.3 Test Setup

Testing was completed at W.L. Gore & Associates using a Sun EC12 environmental chamber to control ambient air temperature and a Matsusada power supply to apply DC voltage. Temperatures were verified with thermocouples at the beginning and periodically throughout the test. Note that a nitrogen gas purge was used to create an inert environment in the chamber. A picture of the samples in the chamber is provided in Fig. 3.

Samples were removed intermittently from the chamber for evaluation, with a roughly logarithmic schedule. This approach allowed for more frequent testing initially to detect any early shifts with less frequent later internals to reduce the number of interruptions. Evaluation included capacitance and equivalent series resistance (ESR) measurements made with an Agilent E4980A LCR meter and insulation resistance (IR) testing done with a Keithley 6514b electrometer.

3 Life Test Data

The following sections show the life data collected over 100 cycles completed as part of testing. Samples experienced a total of 1280 hours of voltage and temperature exposure, with 1000 of those

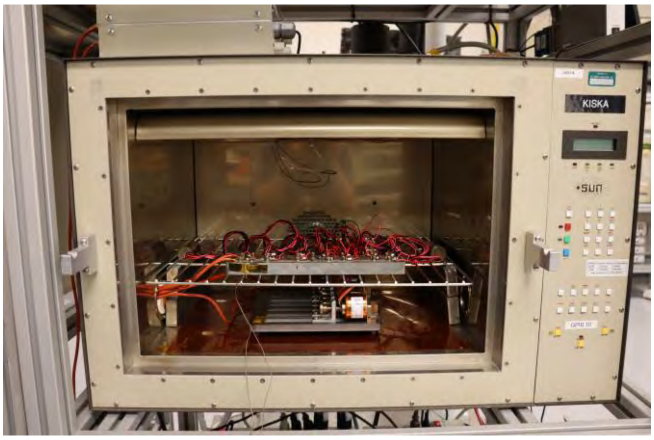

Fig. 3 Image of test setup with 25uF capacitors located on the top rack and 50uF capacitors located on the bottom of the chamber. Thermocouples are shown attached to the left side of each fixture.

hours at the elevated temperature setpoint. Note that some of the samples are continuing to run beyond the initial 100 cycles and that data will be reported in a future paper.

3.1 25uF 400V Data

Capacitance and ESR changes for these samples are presented as a function of cycling in Fig. 4 and Fig. 5, respectively. The average 1kHz capacitance change after 100 cycles was -1.0 percent and the average 1kHz ESR change was 16.6 percent.

These results are very encouraging and clearly demonstrate that this capacitor design can operate at 200ºC. Of the 14 samples tested, one of the 25uF parts was noteworthy for having divergent behavior of the ESR compared to the other samples. This part was torn down for evaluation as discussed in section 4.1.

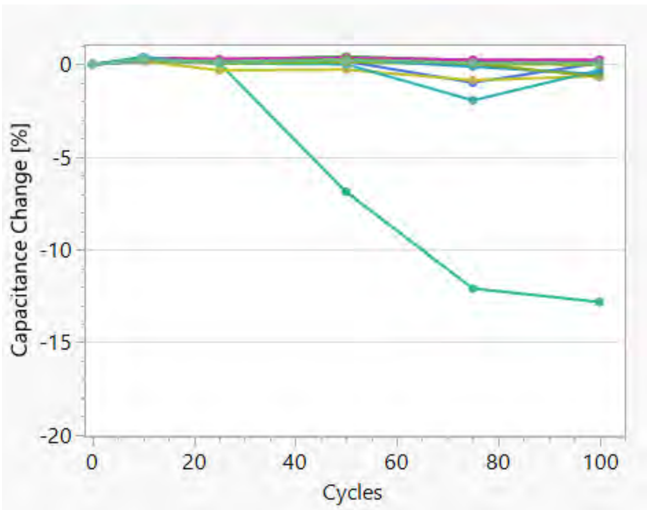

Fig. 4 Capacitance change vs cycle count, 400V samples.

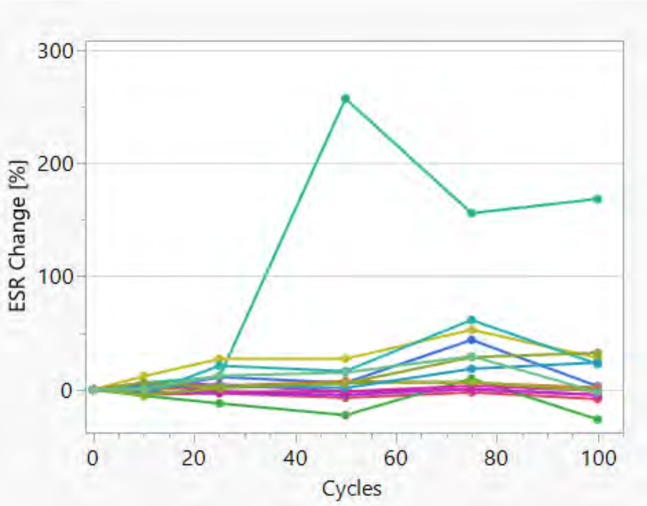

Fig. 5 1kHz ESR vs cycle count, 400V samples.

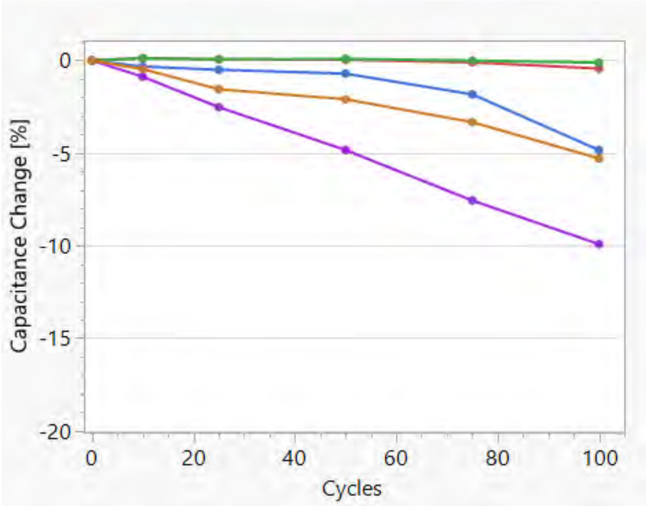

Fig. 7 Capacitance change vs cycle count, 600V samples.

Insulation resistance measurements showed minimal change over the course of the test (see Fig. 6). This data validates that the dielectric material maintained strong insulation performance and that all parts exhibit a fail-open failure mode despite the elevated temperature environment. Similarly, the packaging materials are not showing any electrical degradation.

3.2 50uF 600V Data

Capacitance and ESR changes over cycling are shown in Fig. 7 and Fig. 8 respectively for the 50uF capacitors tested at 600V. The average 1kHz capacitance change after 100 cycles was -4.1 percent. ESR performance was mixed, with some samples showing strong performance even with the higher voltage stress. This is very promising for these early prototypes and the driving factor for the ESR change is addressable with further development as will be discussed in the next section. Insulation resistance tests for the 50uF parts run at 600V showed minimal change over the course of the test similar to the 400V samples. The IR data is presented in Fig. 9. Further discussion of the results is provided in section 4.2.

4 Life Test Discussion

The capacitor samples have demonstrated the capability to meet or exceed the end-of-life requirements for down-hole tools. A typical threshold for capacitance would be 20 percent loss. The typical end-of-life criteria for ESR would be a 100-300 per cent increase depending on the specific application. Note that both criteria would apply to the

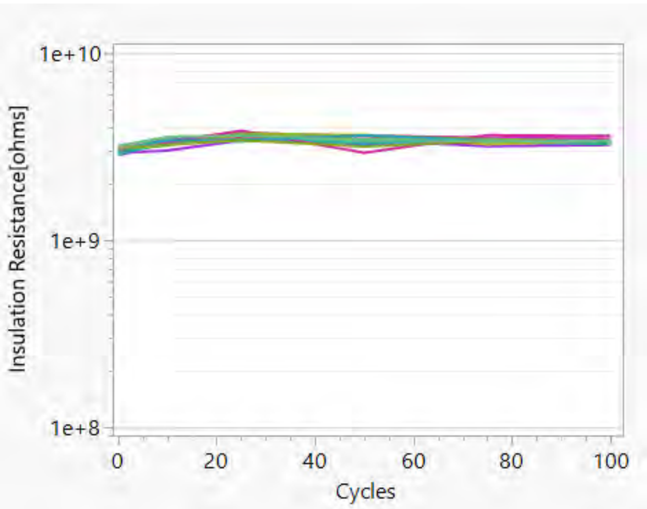

Fig. 6 Insulation Resistance (IR) data for 25uF samples tested at 400V.

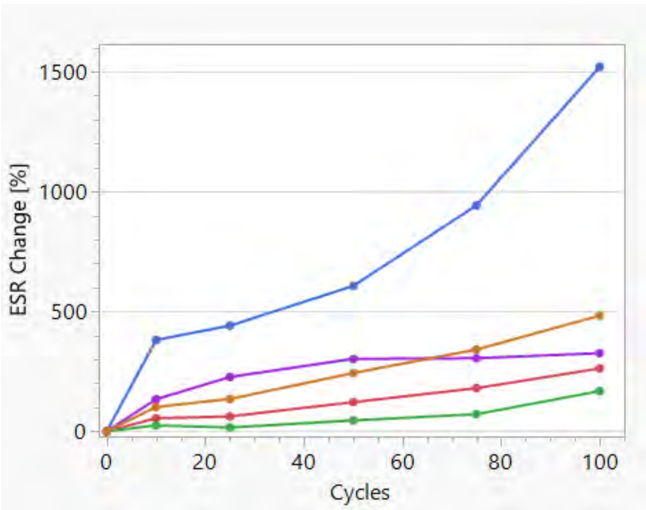

Fig. 8 1kHz ESR vs cycle count, 600V samples.

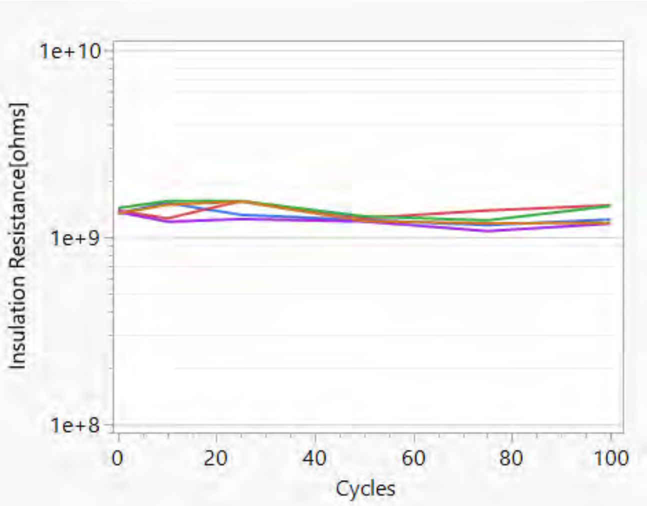

Fig. 9 Insulation resistance (IR) data for the 50uF samples tested at 600V.

typical down-hole life of 100's of hours. Further discussion on the specific 25uF 400V and 50uF 600V results is provided in the following sections.

4.1 25uF 400V Parts

The 25uF capacitor samples have clearly illustrated the ability to meet end-of-life targets as described above at a higher temperature and longer test time than typical industry requirements. Our test is specifically 200ºC and 1000 hours versus the traditional 175ºC and 100's of hours. However, one part did show a higher ESR increase and capacitance loss than the other samples.

The high ESR part was evaluated at different frequencies to give some insight into the possible reasons for this behavior. As described by Brown [7], such testing is particularly useful relative to disconnection between the film edges and end spray. Capacitance and ESR data at different frequencies are shown for this part in Fig. 10.

The capacitance curve marked "ESR Defect" is very interesting in that it shows the capacitance drop with frequency. Loss of edge connections will force the current to flow through the film metallization in the winding direction to reach the "active area" of disconnected turns. At higher frequencies, this is hampered by the inductance of winding direction path and the capacitance drops. The "Typical Response" ESR curve is dominated by the capacitor leads and is quite stable over the tested frequency range. The "ESR Defect" ESR curve is dominated by end disconnections in the winding and is inversely proportional to frequency.

While 1kHz is more realistic for typical switching frequencies, lower frequency measurements can provide useful insight. In particular, the impact

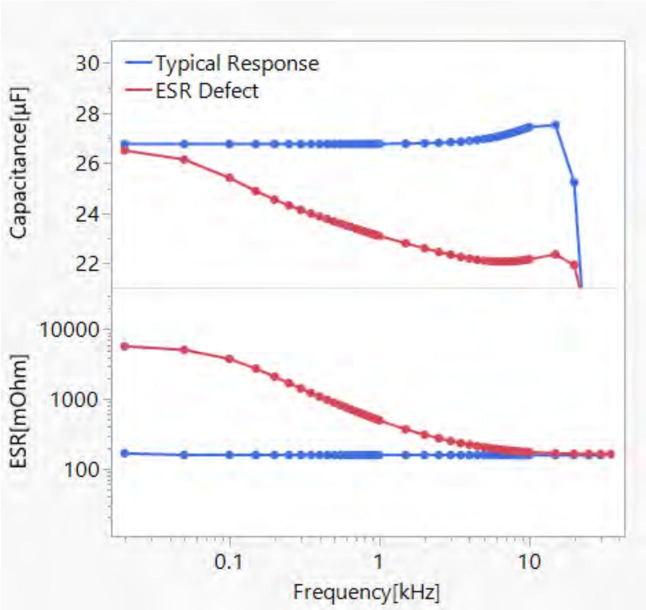

Fig. 10 Comparison of capacitance and ESR data for defective capacitor vs typical response in 400V testing.

of clearing can be better understood at a measurement frequency of 20Hz. The average capacitance change for the 25uF parts after 100 cycles at 20Hz is positive 0.2 percent. This is counter intuitive at first but note that Fig. 4 shows a 0.3 percent increase in capacitance at 1kHz after 10 cycles. There is clearly a "conditioning" effect of the test parameters. Taking this into account, the average capacitance drop measured at 20Hz is only 0.1 percent over the remainder of the test. The point to understand is that this indicates very little clearing activity.

Subsequent teardown of the ESR Defect part confirmed the theory that the issue resulted from film to end spray disconnection. The end connection is highly dependent on extension control and other process parameters. Significant improvements have been made as the production line is maturing and we expect even better performance is possible going forward.

4.2 50uF 600V Parts

The 50uF samples were anticipated to show more ESR increase over life testing given the new design and higher voltage stress. The results are quite encouraging, with all samples meeting the 20% capacitance loss requirement for end-of-life. Furthermore, three of the parts remained within the 100-300 percent ESR over the test full duration, which shows it is possible.

The higher ESR samples were removed from the test after 100 cycles and torn down. These parts show some evidence of end connection loss, which we expect to mitigate going forward with our improved manufacturing process. As discussed in the previous section, low frequency measurements at 20Hz provided some useful insight into capacitance loss due to clearing. The average capacitance loss at 20Hz was found to be 1.5 percent, which shows a larger impact of clearing than the 400V parts.

It should be emphasized that the voltage capability demonstrated by the 600V design is a significant increase. The impact of voltage stress on the life of a dielectric increases nonlinearly and is typically modeled using the following power law equation $(V_1/V_2)^n$ where V_1/V_2 is the ratio of voltages to compare and n is the power law coefficient which is experimentally determined. Using a typical power law coefficient for BOPP of 10 for example, an increase in voltage from 400V to 600V would result in approximately 57 times faster aging. The minimal shift in capacitance observed for the 600V samples over our testing validates the capability of the new high voltage metallization design.

This performance results from reduced clearing size, which is an indicator of lower clearing energy. A visual comparison of clearing activity between the 400V and 600V samples tested is presented in Fig. 11. The reduced clearing size for the 600V film metallization design results in less capacitance lost from each clearing event. Additionally, the lower energy clears are less damaging to the surrounding area. Although the film is designed to enable successful operation at 600V, another benefit of this design is increased lifetime at lower voltages.

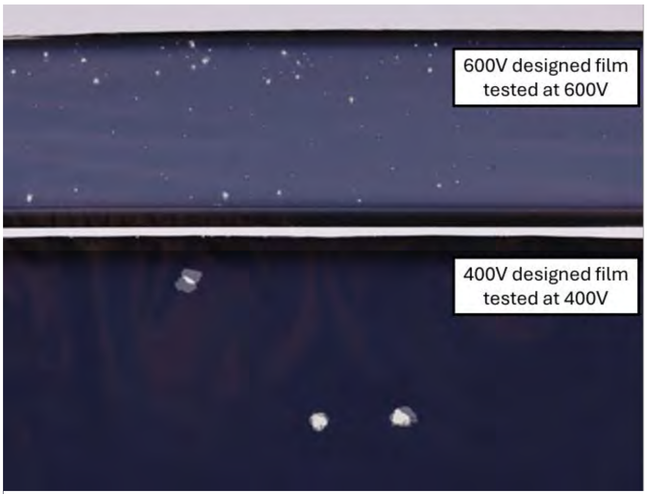

Fig. 11 Comparison of clearing sizes for 600V designed film (top) and 400V designed film (bottom). Note the 600V design film is narrower than the 400V designed film.

5 DC Link Testing

Wound capacitor sections using Gore High Temperature Film were built into a standard Advanced Conversion 700A245 test kit (260uF at 700V) fitted with thermocouples for comparison to the known baseline of polypropylene. The windings are “surfaced mounted” onto an optimized bus structure that provides an inductance of 8nH connecting to an Infineon HybridPACK Drive™ module [3-4].

The instrumented prototype DC link was tested at 150Arms and 10kHz to look at the temperature rise and thermal time constant at the winding hotspot. Note that this initial experiment was performed at room temperature to provide a comparison with conventional polypropylene. The normalized temperature rise over time for polypropylene and the PFTE-based film are compared in Fig. 12. The high temperature film has a time constant of approximately 37 minutes, which is even longer than polypropylene (approximately 28 minutes). This property is very important in the context of a “mission profile” where the worst-case temperature of thermal equilibrium will not be achieved during short high-current operating intervals. As such, the enhanced current rating enabled by the high temperature film can be even further exploited. The temperature rise of the PFTE-based film indicates that there are no unexpected loss mechanisms and the material has a decent thermal conductivity for removal of heat comparable to polypropylene.

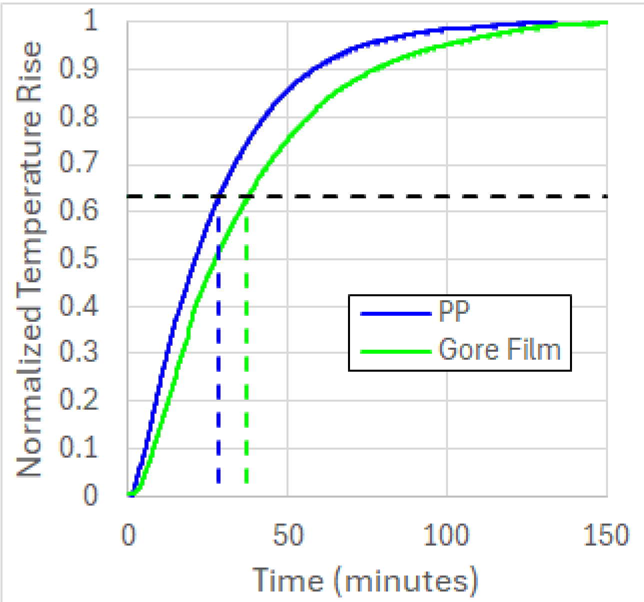

Fig 12 Comparison of thermal time constants for PP and Gore film (dashed lines show 1/e point).

6 Conclusion

W. L. Gore & Associates has developed and commercialized a PTFE-based capacitor film with excellent self-healing properties capable of operating at 200°C with rated voltage applied. Advanced Conversion has utilized this film to create 400V and 600V standard products lines of “wrap-and-fill” style parts. Representative samples from both series have been subjected to a very aggressive life test of 100 thermal cycles between -40°C and 200°C with rated voltage applied. These test parameters provided an effective duration of 1000 hours at 200°C which is more aggressive than the common drilling industry test at 175°C for 100’s of hours.

Both the 400V and 600V parts show it is possible to meet (or exceed) typical end-of-life requirements of 20 percent capacitance loss and 100-300 percent ESR increase. Some of the samples exhibited larger ESR changes and these were removed from the test and torn down. These parts were found to have end connection issues, which have been addressed with manufacturing process improvements. The remaining samples are currently running additional cycles pushing out toward 2000 hours at 200°C.

Finally, a complete DC Link test kit has been fabricated with the PTFE-based film and compared with polypropylene. The W. L. Gore & Associates film does not show any unexpected loss mechanisms or thermal issues and has a longer thermal time constant than polypropylene. This looks very promising for aerospace applications but will require additional development of high-temperature packaging.

A self-healing film capacitor solution has been demonstrated to enable optimized power conversion solutions for harsh environments up to 200°C for aerospace and down-hole applications.

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