Development of High Temperature FPE Capacitor and Manufacturing Capability

DE-FC26-06NT42949

TECHNOLOGY STATUS ASSESSMENT

Hamilton Sundstrand, Dearborn, Steiner and Brady

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1.0 Introduction

Under NETL project DE-FC26-06NT42949, Hamilton Sundstrand, Dearborn Electronics, Inc., Brady Worldwide, Inc., and SteinerFilm, Inc. are developing a controlled, systematic, design of experiments to optimize the manufacturing and testing process for fluorene isophthalate terephalate, or Fluorene Polyester (FPE) capacitors, which is an existing, high temperature, capacitor technology utilized in the aerospace industry, and to develop commercially available, reliable, and affordable 250 C (482 F) rated capacitors. These processes include film casting, film metallization, final capacitor assembly, as well as, a complete definition/documentation of the testing that must occur throughout the supply chain. The objective of the project is a mature supply chain for reliable, 250C film capacitors by 2009-2010.

2.0 Current State of the Technology

2.1 Summary of Background of Industry/ Sector

The aerospace, drilling and other industries currently use ceramic, film and electrolytic capacitors. In particular, parts of the aerospace industry prefer metallized film capacitors (figure 2.1-1) for power conditioning, filtering and energy storage in applications ~ 5kw and larger applications. Typical aerospace temperature ratings are 125C components used in 110c max conditions. Deep well drilling equipment and next generation aerospace equipment required components with 200C + ratings.

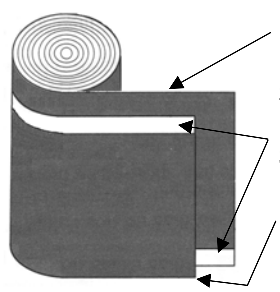


Figure 2.1-1 Typical Metallized Film Capacitor

Metallized film capacitors have the ability to "clear" small defects, have high reliabilities, have a long useful life, and fail in a controlled and manageable fashion at the end of life. Alternatively, ceramic capacitors have hard failure modes, and are susceptible to vibration and thermal cycling environments. Electrolytic capacitors have difficulties with "dry-out", a short life, and low reliabilities at elevated temperatures. Because of this, the aerospace industry has focused on metallized film capacitor as the most viable high temperature capacitor solution.

2.2 Technologies Currently Used

Standard Military (Established Reliability), as well as, State-of-the-art, 125C (257 F) capacitors are shown in Table 2A.

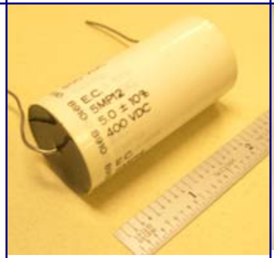
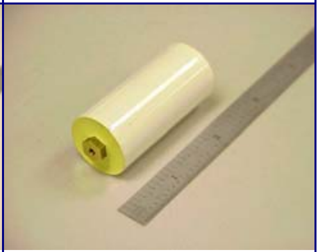
	Standard MiL	**HS - Baseline**	**Recent R&D**
Capacitor Ratings	**5uF**, 400Vdc, 125C	**30 uF**, 400Vdc, 125C	**30 uF**, 400Vdc, 125C
Dimensions (Length : Dia)	2.27 : 1.09	3.125 : 1.125 in	2.75 : 1.0 in
Volume	2.12 in^3	3.11 in^3	2.16 in^3
Energy Density	2.35 uF / in^3	12.7 uF / in^3	13.8 uF / in^3
Environment	Non-Hermetic	Hermetic	Environmentally-Sealed
			

Table 1A: State-of-the-art Low Temperature Capacitor Technology

Various film types are available today such as polycarbonate (PC), polyetherimide and Kapton. Kapton film capacitors are known to be used today in deep well drilling applications. But fluorene isophthalate terephalate (or Fluorene Polyester - FPE) is seen as the only feasible near term option to 250C capacitors, as concluded by the Air Force laboratories. Other films have temperature limitations and/or would result in much larger and expensive devices due to less-favorable electrical characteristics (FPE dielectric constant is 3.4 vs. PC at 3.0 for the same film thickness; and FPE breakdown voltage is 12 V/mil compared to 8kv/mil for PC). A polycarbonate (PC) capacitor theoretically equivalent to the 200C FPE unit developed with the Air Force would have ~ 4 times the volume of the FPE part. (FPE at 3.4 has a higher dielectric constant than PC at 3.0. For the same film thickness, this results in 13% increases capacitance.

2.3 Benefits/Inadequacies of Current Technologies

FPE was originally developed by 3M in the mid-1980s, but was not viable for traditional aerospace requirements until ~2000, when Brady Corporation began successfully producing thin gauges of the film (5 microns and below) supplied by Ferrania. Shortly thereafter, Hamilton Sundstrand, Dearborn Electronics, SteinerFilm, Brady Corporation, and Ferrania partnered with the Air Force Research Laboratories (AFRL) to produce the prototype 250V, 16uF, 200C capacitors -- but in very limited quantities in a research environment. Various other metallized film FPE capacitors were manufactured for testing and evaluation at Hamilton Sundstrand, NASA, DOD and DOE-Sandia. Recent Sandia experiments were performed in early 2006.

The FPE technology is proven to provide needed electrical characteristics at >200 C But clearly work is required on the manufacturing processes to ensure reliable affordable high temp capacitors by 2009 – 2010. The small batches or FPE film to date have shown many problems with stripping and metallization processes and machines at Steiner. Brady has begun basic experimentation with fillers to reduce the stickiness" of the very thin film. But many batches need to be manufactured to find the optimum filler/film for Steiner use without sacrificing the needed electrical properties. Also, early attempts showed that there is need to optimize and standardize the capacitor manufacturing approach at Dearborn. In summary, the overall "supply chain" is many steps away from a commercial product:

- FPE/filler: Brady needs to develop a consistent FPE formula with fillers that allow easy processing at Steiner without penalizing electrical characteristics of the film
- "Web handling": Steiner needs to iterate with Brady and make changes to machinery set ups to allow for good, consistent handling of the thin film
- Metallization: Steiner needs to develop a consistent standard for metallization of the film
- Capacitor: Dearborn needs to develop a standard capacitor assembly that will result in a reliable, affordable item.

The NETL activity will systematically solve each of the current problems resulting in an optimized supply chain at the end of the project.

3.0 Development Strategies

Hamilton Sundstrand's technical approach to the HTHP Drilling Program is to provide a controlled, systematic, design of experiments to optimize the entire FPE capacitor manufacturing and testing processes. These processes include film casting, film metallization, final capacitor assembly, as well as a complete definition / documentation of the testing that must occur throughout the supply chain. To accomplish this, Hamilton Sundstrand will orchestrate four production size batches of FPE capacitors through the complete supply chain. Each of the four batches has a specific purpose with only one variable being changed throughout the entire manufacturing process.

Batch 1—FPE/filler handling and metallization experiments

The objective of Batch 1 is to evaluate six different FPE constructions for "web-handling" (on Steiner's rollers/machines) and final capacitor assembly properties, including but not limited to, dielectric withstand voltage (DWV) and elevated temperature characteristics. The variations among these six variants shall include filler types, filler particle size, and filler concentration levels. The candidates that prove to be the easiest to strip and metallize at Steiner will then be sent to Dearborn for capacitor manufacture and test. Dearborn Electronics shall manufacture 50, 4uF capacitors from the successfully delivered variations of FPE film. The 30 capacitors with the highest Insulation Resistance (IR) and DWV shall be tested at 25C, 200C, and 250C for electrical properties and shall go through 500 hours of elevated temperature testing (250 hours at 200C and 250 hours at 250C). The results of these tests shall be combined with web-handling assessment from SteinerFilm and fed back to Brady Corporation for each of the six FPE constructions being investigated.

Batch 2: Web-Handling Optimization

The objective of Batch 2 shall be to optimize the casting process of FPE film on the Brady Corporation's production casting equipment, based on the experience from Batch 1. As many as six different FPE constructions shall be examined. Dearborn Electronics shall manufacture 50, 4uF capacitors from the successfully delivered variations of FPE film as in Batch 1. The results of these tests shall be combined with web-handling assessment from SteinerFilm and fed back to Brady Corporation for each of the six FPE constructions being investigated. The web-handling properties and the high temperature capacitor properties, including but not limited to, DWV and elevated temperature characteristics of the final capacitor assembly, are the desired optimization metrics.

Batch 3: Metallization Optimization

The objective of Batch 3 shall be to optimize the metallization process at SteinerFilm. SteinerFilm shall alter the metallization process variables, to optimize its process for FPE high temperature capacitors. As many as 12 various metallization configurations are anticipated. Dearborn Electronics shall manufacture 75, 4uF capacitors from as many as 12 various metallization configurations while maintaining a constant and pre-defined capacitor manufacturing process. The 50 capacitors with the highest insulation resistance (IR) and DWV from each of the different metallization experiments shall be tested at 25C, 200C, and

250C for electrical properties. These capacitors shall also go through 500 hours of elevated temperature testing (250 hours at 200C and 250 hours at 250C). Dearborn Electronics shall use the remaining capacitors (approximate qty 300) to perform end connection experiments and final package assembly experiments.

Batch 4: Capacitor Manufacturing Optimization

There are two objectives for Batch 4. First, the capacitor manufacturing process at Dearborn Electronics shall be optimized. Second, 900 production quality high temperature FPE capacitors shall be manufactured. Dearborn Electronics shall use 15 of the 30lbs of consistently manufactured and metallized FPE to optimize the capacitor manufacturing process. Final capacitor properties, including but not limited to, DWV, IR and elevated temperature characteristics, shall be the metrics to be optimized. Winding tension, initial clearing procedures, temperature pre-conditioning (bake-out), clearing at elevated and cycling temperatures, pulse clearing, step clearing, and other proprietary capacitor manufacturing processes shall be the variables under examination. The 600 capacitors with the highest IR from each of the capacitor manufacturing experiments shall be tested at 25C, 200C, and 250C for electrical properties. These capacitors shall also go through 500 hours of elevated temperature testing (250 hours at 200C and 250 hours at 250C). Dearborn Electronics shall use the remaining 15lbs of FPE and the results of the end connection and packaging experiments of Batch 1, 2 and 3 to manufacture 900 "production" quality, high temperature capacitors.

4.0 Future

The primary barriers to the use of FPE capacitors today in the oil/gas and other industries are maturity of the technology and product cost. Theoretically, 250C FPE capacitors could be produced today. But the process time would be long and the production yield s would be very low, resulting in impractical costs.

The result of this NETL activity will be a mature supply chain for 250C FPE film capacitors and the launch of new products in Dearborn's commercial catalog. Each of the four phases, or batches, will optimize the processes for a consistent product:

- FPE/filler: the best FPE/filler formula will be standardized by Brady after the batch 1 and 2 development activities. Minor variations will be made as needed during the batch 3 and 4 metallization and capacitor efforts.
- "Web handling": after iteration with Brady on filler and FPE options, SteinerFilm will have the most efficient methods of handling the FPE film on their machines
- Metallization: With a FPE film standard now available, Steiner will optimize the metallization process for both process efficiency and electrical performance characteristics.
- Capacitor: Finally, after 4 phases of learning, Dearborn will begin producing prototypes of production-quality capacitors during phase 4.

Technology transfer and commercialization of high temperature FPE capacitors will begin during the latter portion of phase 4. Dearborn and Brady will publicize their work through communications and technical paper submission with appropriate technical and industry groups, i.e. the Capacitor and Resistor Technology Symposium (CARTS), PowerSystems World, and the Applied Power Electronics Conference (APEC).

Dearborn plans to introduce FPE capacitors to its product line in the 2009-2010 timeframe after the success of the NETL project. High temperature capacitors are a key enabler to high temperature power electronics, allowing their use in the deep well, aerospace and other high technology industries.