HIGH VOLTAGE METALLIZED POLYESTER FILM CAPACITORS IN EXTREME COLD OPERATIONAL ENVIRONMENTS

Ron Anderson
ASC
American ShiZuki Corporation
Ogallala, NE (308) 284-3611

ABSTRACT

High voltage metallized polyester capacitors operating under severe environmental conditions provide superior reliability. The conditions include: high voltage stresses for 20,000 hours at temperature extremes of 85 degree/C to -190 degree/C (90 degree Kelvin). Greater than 520,000 hour MTBF is exhibited by the test results.

INTRODUCTION

The reliability of dry wrap and filled constructed, high voltage, metallized polyester capacitors is much greater than expected. High voltages exceeding rated, temperatures of 85 degree/C, and operation in a liquefied gas such as argon or nitrogen at -190 degree/C (90 degree Kelvin) for times of 20,000 hours represent harsh operating conditions. This presentation provides the results of evaluations at those severe conditions. The capacitors demonstrated that they are capable of reliable operation in conditions beyond their typical specification limits.

The liquid argon environment results are from Stanford University's new Linear Collider project. The capacitor application, high voltage D.C. blocking, is part of the Lead (Pb)/liquid Argon (Ar) calorimeter. The calorimeter measures the electromagnetic and hadronic particle energies which occur as the electron (e-) and positron (e+) beams collide head on.

HISTORY

High voltage metallized polyester capacitors in a non-impregnated, dry wrap and fill construction were developed and introduced in the early 1970's. They had several advantages over the existing metal enclosed, high voltage paper and film capacitors.

1. Relative small size compared to the larger impregnated paper/film hermetically sealed capacitors.

2. No leaking impregnant on adjacent components nor the detrimental effects on reliability from such leakage.

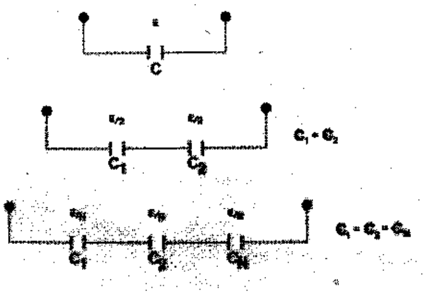
3. Improved reliability provided by metallized construction and self healing characteristics.

4. More versatile size configurations with the wrap and fill construction.

5. Non-metallic, non-conductive encasement requiring less insulation in the application.

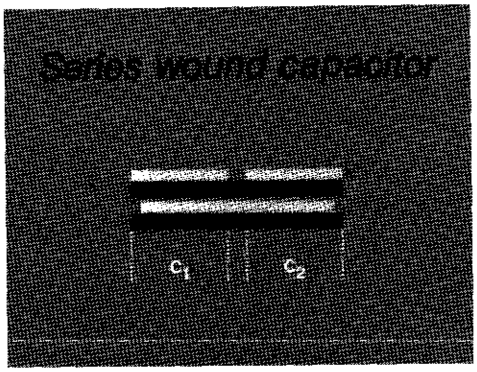
HIGH VOLTAGE SERIES CONCEPT

The concept of the high voltage series dry film capacitor was accomplished prior to their introduction by using several individual capacitors connected in a series configuration. The metallized series multi-section construction provides the same effect; that is, two 0.1 MFD, 600 VDC rated capacitors connected in series can be rated at 1200VDC, but will be 0.05 MFD. Each additional capacitor connected in series will provide an additional 600 VDC rating, but further reduces the total capacitance.



Doing this with discrete individual capacitors is not volumetrically efficient because of the encasement and connection space for each capacitor. Additionally, unless the capacitance values are matched closely, the voltage divided across each individual discrete capacitor may overstress one of the parts and possibly cause premature breakdown.

The high voltage metallized series multiple-section capacitor accomplishes this voltage division internally and packages all sections within one wrap and fill encasement. The patterned dielectrics used in the series construction assures uniform capacitance values and equal division of the voltage.

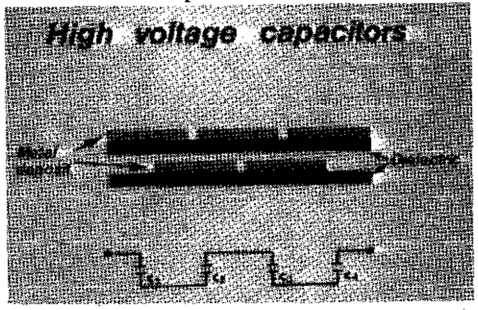


This series construction technique allows thinner dielectric thickness because the rated voltage is equally divided over several sections. In turn the required margins between the opposite conductive plates can be smaller providing additional size reduction. The length of the capacitor (width of the series dielectric) is one of the limiting factors, in that the more sections (capacitors in series), the longer in overall length.

For Example:

=======

ASC's 10,000 volt X675HV capacitors are 3.875" long and have five capacitor sections in series.



RELIABILITY ANALYSIS

Since these high voltage metallized capacitors are voltage stressed two to three times greater than the typical DC capacitors, there was some question of their reliability. To examine that, a Hi-Voltage Test program was conducted. The test program's duration was initially 10,000 hours (extended for a total of 20,000 hours).

One-hundred-eighty (180) capacitors were tested. This included eighteen (18) samples of the ten (10) different design variations which included all six voltage ratings and series section configurations. The test sample breakdown was as follows:

18 Samples - X675HV	.68	MFD	2,000VDC
18 Samples - X675HV	.33	MFD	4,000VDC
18 Samples - X675HV	.01	MFD	6,000VDC
18 Samples - X675HV	.022	MFD	6,000VDC
18 Samples - X675HV	.15	MFD	6,000VDC
18 Samples - X675HV	.033	MFD	8,000VDC
18 Samples - X675HV	.10	MFD	8,000VDC
18 Samples - X675HV	.022	MFD	10,000VDC
18 Samples - X675HV	.047	MFD	10,000VDC
18 Samples - X675HV	.033	MFD	16,000VDC

Each group of 18 samples were voltage stressed as follows:

6 Pieces at 75% of the 25 degree/C Rated Voltage
6 Pieces at 100% of the 25 degree/C Rated Voltage
6 Pieces at 125% of the 25 degree/C Rated Voltage

The test was conducted at 85 degree/C, the maximum rated temperature for the X675HV capacitor. The X675HV is rated up to 65 degree/C at full rated voltage and derated by 25% at 85 degree/C. So at the 85 degree/C test temperature, the voltage stress was increased beyond the 75%, 100%, and 125% levels. The test samples were actually stressed at 100%, 133%, and 166% respectfully, of the 85 degree/C voltage rating. For simplicity sake, the 25 degree/C rated voltage stress levels of 75%, 100%, and 125% will be utilized in the remainder of the presentation.

Capacitance and Dissipation Factor were measured each 1,000 hours and Insulation Resistance was measured each 2,000 hours during the first 10,000 hours and then at 15,000 and 20,000 hours. All capacitors were monitored for shorts the entire 20,000 hours.

After 10,000 hours, there were no catastrophic failures at either the 75% or 100% conditions. The Mean Time Between Failure (MTBF) at a 90% confidence level was greater than 260,000 hours. Thirteen (13) shorts occurred at the 125% condition which indicated a 26,648 hour MTBF. The parametric effects on the capacitors were insignificant for Insulation Resistance and Dissipation Factor. The average Capacitance Change was less than 1.0% negative for the 75% and 100% conditions. However, significant changes occurred at the 125% stress level with an average capacitance change of -34% change. The -34% change indicated massive conductive plate erosion and loss.

After 20,000 hours, there were no catastrophic failures at either the 75% or 100% conditions. Therefore, the MTBF (90% confidence) was greater than 520,000 hours. At no time during the test was any degradation in either Insulation Resistance or Dissipation Factor experienced. If the failure definition is expanded to include capacitance change beyond 10%, the MTBF's became:

75% Voltage Stress Level: >520,000Hours
100% Voltage Stress Level: >250,000Hours

and if capacitance change is further reduced to not beyond 5%, the MTBF's became:

75% Voltage Stress Level: >520,000Hours
100% Voltage Stress Level: >60,000Hours

The average capacitance changes after 20,000 hours were -.7% for 75% and -3.5% for 100% stress level.

EXTREME COLD APPLICATION

In late 1985, Stanford University contacted us concerning a high voltage (5,000 VDC) blocking capacitor application. What made their application unique was that the capacitors had to operate immersed in a liquid argon environment at -190 degree/C (90 degree Kelvin). The application was an upgrading of the two mile long accelerator at Stanford Linear Accelerator Center (SLAC) in Palo Alto, California. The capacitors were to be used in the Lead (Pb)/liquid Argon (Ar) calorimeter section of the detector in the new Stanford Linear Collider (SLD).

Since the normal low temperature capability of plastic film capacitors is specified at -55 or -65 degree/C, the capacitor's performance capability and reliability at -190 degree/C was in question.

Since ASC (formerly TRW Capacitors) was not equipped to conduct such cold testing, Stanford began several test programs to examine the X675HV's extreme cold operational capability. Their target failure rate was less than 1% after five years operation at 5,000 VDC. The five year operation was defined as 30,000 hours (250 days, 24 hours/day for 5 years). It involved six high voltage ramp cycles per operating day from 0V to 5,000 VDC (7,500 ramps over the lifetime) and five thermal cycles from 25 degree/C to -190 degree/C per year (25 thermal cycles over the lifetime).

The desired MTBF was 3,000,000 hours. Our 20,000 hour Reliability Analysis at 85 degree/C if extended out to 30,000 hours would exhibit a 780,000 hour MTBF for the 75% voltage level. Therefore, the 75% voltage level for the standard X675HV 6,000 VDC rated capacitor would be 4,500 VDC. Eventhough Stanford was specifying a 5,000 VDC, the actual operating voltage was to be 3,000 VDC to 4,000 VDC (50% to 66% of 25 degree/C rated voltage). That would provide additional reliability so long as the 85 degree/C testing matched with what occurred at the -190 degree/C cold operation.

SLAC TESTING

To determine the X675HV's cold temperature operational capability, SLAC conducted several evaluation tests. The largest consisted of the following 995 test samples. These parts were standard off the shelf X675HV capacitors without any special testing or conditioning.

48 Samples	.0015 MFD	6,000 VDC	X675HV
145 Samples	.010 MFD	6,000 VDC	X675HV
802 Samples	.015 MFD	6,000 VDC	X675HV

The .0015 and .010 MFD samples had capacitance measured and recorded before and after test, while the .015 MFD samples were read only after.

The 995 capacitors were mounted on Printed Circuit (P.C.) boards with a 40 megohm resistor in series and tested as follows:

1. 48 Hour Burn-In at Room Temperature:

   48 hours at 5,000 VDC (+250/-0V) at 25 degree/C. One .010 MFD device displayed high leakage (2 megohms IR) initially, all other parts passed the burn-in.

2. 600 Hour Steady-State Life Test at -190 Degree/C:

   The P.C. boards were cooled to -190 degree/C at a rate of less than 5 degree/C per hour in a helium environment. After 48 hours, the helium was replaced with liquid nitrogen (LN2). Following stabilization at -190 degree/C (3 hours), the capacitors were charged up to 5,000 VDC over a one-half hour period.

As the voltage reached 4,000 VDC; arcing, discharging, or self healing (clearing) of the capacitors was noted. This condition continued for about 24 hours, but practically ceased after 48 hours at 5,000 VDC in the LN2. Only four arcs were observed between the 100 to 600 hours of the test for all 995 capacitors.

Even though the Life Test was designated as a Steady-State Test, approximately each 24 hours the voltage was reduced from the 5,000 VDC down to 3,000 VDC. After which, the voltage was increased up to 5,150 VDC and immediately back to the 5,000 VDC (Steady-State Voltage).

During and at the completion of the 600 hours, the current draw (a few micro-amps) remained about the same. Therefore; indicating no shorted capacitors.

3. <u>One Thermal Cycle (25 Degree/C to -190 Degree/C):</u>

After the 600 hours Steady-State testing, the vessel was warmed up to 25 degree/C in 16 hours, then recooled to -190 degree/C (LN2) within 20 hours. This simulated one thermal cycle.

4. <u>Hi-Voltage Ramp Testing at -190 Degree/C:</u>

Following the one thermal cycle, the P.C. boards were ramp voltage tested at four different ramp cycle times. The ramp test voltage configuration was 4,500 VDC to 350 VDC and back to 4,500 VDC. The number of cycles and ramp time periods in minutes were as follows:

			Time (Minutes) Periods		
Test Con-fig.	Number of Cycles	Total Cycle Time Period	Ramp Down 4500V to 350V	Ramp Up 350V to 4500V	Hold Voltage at 4500V
1	280	14.3	5.0	4.3	5.0
2	1200	11.3	5.0	4.3	2.0
3	1200	6.0	2.0	2.0	2.0
4	2300	5.0	2.0	2.0	1.0

4980 Cycles x 995 Units = 4.955 Million Unit-Ramps

No abnormalities were noted during the ramp testing to indicate any failures. Upon completion, the devices were warmed up to room temperature and checked. No electrical or visual/mechanical failures were found.

If the voltage ramps during the Steady-State life test are included, nearly 4.98 million unit-voltage ramps were accomplished with no failures at -190 degree/C in the LN2 environment.

5. <u>Post-Test Electrical & Predicted Reliability Results:</u>

The average capacitance changes were .1% and .3% on the .0015 and .010 MFD capacitors respectfully. The .015 MFD capacitors were measured only after test. The capacitance distribution exhibited a mean capacitance of .0148 MFD with a sigma of 1.27%. The highest capacitance value was .01582 MFD indicating that no capacitors experienced an internal short between sections which in this capacitor would cause a nominal capacitance of .030 MFD (two section device).

With no failures occurring in the 995 piece sample during the 5,000 VDC test for nearly 600,000-unit hours, a 261,000 hours MTBF (90% Confidence Level) was indicated. This matched with our 20,000 hour 85 degree/C life test MTBF (250,000 hours) for the 100% stress level considering capacitance changes beyond 10% as a failure.

6. <u>Additional Tests & Approval:</u>

Following this large scale test, an additional 200 pieces of a .022 MFD X675HV 6,000 VDC capacitor were tested at 5,000 VDC and in LN2 at -190 degree/C. It was initially the highest capacitance value anticipated, but a .028 MFD ended up being the maximum cap value used.

Besides these preceding life tests, a pressurized (50 PSI) LN2 life test was run. This was conducted to assure that the pressure caused by the weight of the liquid argon at the bottom of the vessel did not effect the capacitor or reliability. Additionally, a chemical compatibility test was conducted to assure that the capacitor encasement materials and liquid argon did not cause some undesired effects. The capacitors passed both tests with acceptable results, and the X675HV capacitor was approved for the -190 degree/C (90 degree Kelvin) 5,000 V.D.C. blocking calorimeter application.

<u>SLAC RECEIVING INSPECTION TESTING</u>

Once the new detector production was funded, the construction began. In mid-1986, SLAC ordered 110,000 standard 6,000 VDC X675HV capacitors. Six capacitance values were ordered ranging from .0047 MFD up to .028 MFD. Delivery was made in four shipments.

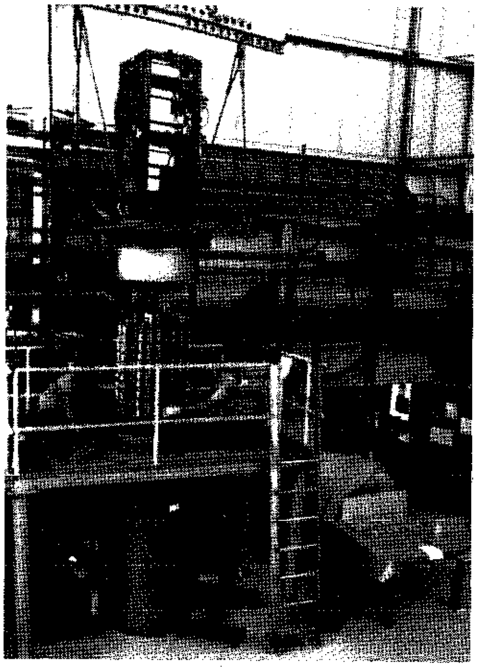
Each shipment was inspected and tested by SLAC upon receipt. A random sample of 1,000 capacitors was pulled proportionally from all six capacitance values. The capacitors were burned-in with a ramping voltage from 0 to 5,000 VDC and back to 0V. The initial 48 hours was at room temperature followed by a second 48 hours, while the temperature was thermal cycled from room temperature to -190 degree/C and returned to room temperature. After the burn-in testing, the 1,000 piece sample was cold life tested in LN2 (-190 degree/C) at 5,000 VDC for 720 hours (30 days). This cold life testing provided (720,000 unit x 4 shipments), 2.88 million-unit hours of additional testing at 5,000 VDC and -190 degree/C.

All four shipments were found acceptable to SLAC's criteria and were released for P.C. board assembly.

SLAC PRODUCTION TESTING

Following the P.C. board assembly, each board was conditioned as follows:

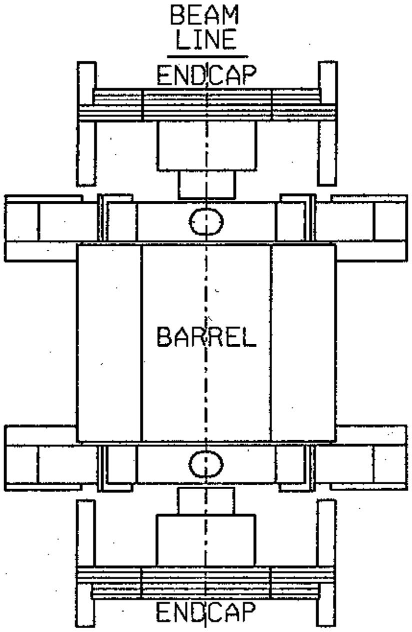
1. Burn-in at 25 degree/C for 48 hours at 4,500 VDC.
2. Burn-in in LN2 (-190 degree/C) for 48 hours at 4,500 VDC.



P.C. BOARD BURN-IN

Throughout all of the testing SLAC conducted, the capacitors were exhibiting typically a .2% failure rate. The failure mode was primarily low Insulation Resistance (below 50,000 megohms at 5,000 VDC). This 50,000 megohm requirement at 5,000 VDC was over the entire temperature range, down to -190 degree/C. Insulation Resistance on Hi-voltage capacitors typically is measured at 500 VDC electrification and at room temperature conditions. ASC's X675HV catalog limit is 25,000 megohms at 500 VDC after 2 minutes electrification at 25 degree/C. This demonstrates the excellent operating performance of the X675HV beyond catalog limits.

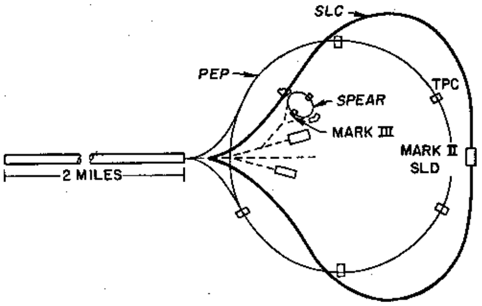
After the P.C. boards were conditioned and passed SLAC's post test criteria, they were ready for assembly into the calorimeter segmentation stacks. There is a total of 288 segments that form the barrel around the electron beam's collision point. 48 segments around the barrel complete the 360 degrees. The barrel's inside diameter is about twelve feet and has two rows of stacked segments around the circumference with an outside diameter of about eighteen feet. These 96 stacked segments are three deep (total barrel length about twenty feet), for the total 288 segments [(48 x 2 = 96) x 3 = 288]. Besides the calorimeter barrel, there are two endplates or caps on each end of the twenty foot barrel. It consists of sixteen pie-shaped stacked segments which are two layers deep for a total of sixty- four pie-shaped segments for both ends.



Once the segments were assembled, each of them were conditioned as follows:

1. Burn-in at 25 degree/C for 48 hours at 4,000 VDC.
2. Burn-in in LN2 (-190 degree/C) for 48 hours at 4,000 VDC.

Additionally, just prior to each stacked segment being assembled into the detector and collider on site, the segments were burned-in twice at room temperature and at 3,000 VDC for 24 hours. Both of these were conducted in a dry nitrogen environment to avoid high voltage corona. Both stacked segments (the outer and then the inner) of each row were assembled into the detector at one time because of the mechanical and electrical connections.



SLD COLLIDER'S STATUS

The assembly of the Lead/liquid Argon calorimeter in the SLD detector has been underway since late 1986. Installation of the calorimeter in the collider hall began in mid-1987 and is due to be completed and operational in early 1989. The estimated cost for the Detector is $53 million dollars and is being funded by U.S. Dept. of Energy (DOE), National Science Foundation (NSF), and additional funds from Britain, Canada, and Italy.

The Collider is to study the collisions of electrons (e-) and positrons (e+) at energies up to 100 GeV (50 GeV each beam). 100 GeV is 100 billion electron volts. To give you an idea of the magnitude of 100 GeV, the typical X-ray machine we use in the component industry has 50 KeV (50,000 electron volts). Therefore, 100 GeV is 2 millions times more powerful.

The new Detector along with the two mile long linear accelerator is used in the study of particle physics. The accelerator simultaneously accelerates electrons (e-) and positrons (e+) up to 50 GeV down the two miles. Then each beam is separated and looped around a one kilometer diameter circle. Each beam is 1 by 1-1/2 microns in size and is aligned to collide head-on into each other at the center of the loop in the center-of-mass of the SLD Detector.

SLAC IN PALO ALTO SHOWING THE 2 MI. ACCELERATOR, 1 KM. LOOP, AND SLD DETECTOR

CONCLUSION

All the testing completed by SLAC in liquid nitrogen (LN2) at temperatures of -190 degree/C (90 degree Kelvin), exhibit that plastic film capacitors can operate at much lower temperatures than ever expected. Additionally, the SLAC testing exhibited that our previous high voltage reliability results at 85 degree/C still do apply, even at very cold temperatures.

ACKNOWLEDGEMENT

The author and ASC wish to sincerely thank Dr. Rafe Schindler of SLAC and the Stanford University for their assistance in this presentation by providing the evaluation and SLD Detector information.