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In Support of Cutler Insulator Failure Investigation

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SPAWAR
Systems Center
San Diego

SSC San Diego
San Diego, CA 92152-5001

SSC SAN DIEGO
San Diego, California 92152-5001

F. D. Unetic, CAPT, USN
Commanding Officer

C. A. Keeney
Executive Director

ADMINISTRATIVE INFORMATION

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Released by
J. W. Rockway
Technical Staff

Under authority of
S. D. Russell, Head
Electromagnetics & Advanced
Technology Division

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EXECUTIVE SUMMARY

The Naval Radio Transmitting Station, Cutler, Maine, has experienced four insulator failures in the last decade. All are believed to be the result of lightning strikes to the antenna. The insulators that failed are fiberglass-belted safety core insulators that had been installed in the late 1990s. An investigation into these failures was undertaken in order to understand the cause of the failure and the implications to other sites having the same type of insulator. At the same time, the Navy has initiated a procurement program to replace the safety core insulators at Cutler with fail-safe insulators. The first array insulators will be replaced in the summer of 2007 and the second in the summer of 2009. The cost of this replacement is significant.

The safety core insulators were tested at VLF voltage prior to their installation at Cutler, but they were not tested with impulses. All flashovers in the VLF tests occurred in the air between the corona rings. As a part of the investigation, impulse tests were done at Hydro Quebec; the tests showed that flashover occurred along the surface of the insulator when the voltage rises very fast (high dV/dt). Flashover along the surface is believed to be the primary cause of damage to the safety core insulators. Our conjecture is that making the design such that the flashover takes place in the air will protect the insulator.

We used a scale model insulator to investigate the flashover phenomenon using an impulse generator owned by the Navy. The objective was to see if different corona ring configurations could keep flashover away from the insulator body. Two series of tests were performed at the Edgar Beauchamp High Voltage Test Facility (EBHVTF). The first test, during June 2005, was a validation and calibration of the Hipotronics® IG-600 Impulse Generator (IG) that had been in storage since 1995. The second test, during September 2005, tested scale models of the Cutler insulator with several different corona ring configurations, including a model of the one current at Cutler.

The IG was successfully activated and generated impulses up to 1.2 MV with peak times as short as 0.6 µs and up to 20-kAmp peak currents. The glaze on a small safety core insulator was melted at these current levels. Flashovers along the surface initiated from the region around the triple point at the ground end of the insulator body when that area was not well shielded. One tentative conclusion is that symmetrical grading is required on both ends of the insulator to protect the insulator body from high dV/dt impulses.

The scale model tests were performed with several corona ring configurations, including the unsymmetrical one installed at Cutler. These tests showed that the flashover path can be kept away from the insulator body by bringing corona rings closer together, although this reduces the VLF withstand voltage of the insulator. Symmetrical corona ring configurations with spacing up to 2/3 of the total insulator length always flashed in the air. Non-symmetrical configurations having the small (Cutler) corona ring at the ground end flashed along the insulator surface at high values of dV/dt. The surface flashovers seemed to initiate from the triple point at the ground end of the insulator body and terminated on the high-voltage end corona ring when that triple point was well shielded.

A limited set of configurations was tested. The test results were promising, indicating these insulators can be protected from lightning-induced impulse flashovers with the appropriate corona ring configurations.

Replacing or modifying the corona rings on the existing insulators would be much less expensive than replacing the insulators. It is too late to affect the 2007 insulator replacement. However, this fix could be developed and tested in time to impact the second phase, scheduled for 2009. Following replacement of the insulators in the first array, there will be enough safety core insulators to double insulate the second array. If it can be shown that the use of modified rings and/or double insulating

would enable the safety core insulators to operate reliably at Cutler, then the second procurement could be avoided at considerable savings to the Navy. Therefore, it is recommended that the U.S. Navy pursue design and testing of a modified corona ring assembly for the Cutler safety core insulator assembly that will significantly increase the surface flashover threshold, thereby enabling reliable operation at Cutler with the existing insulators.

A limited literature search was performed and the results indicated that surface flashover for long gaps is not well understood at this time, and there is no complete theory that can be applied as a basis for the corona ring design. Thus, the design approach must be empirical. Scale modeling is a good way to sort through configurations, but the final design must be tested at full scale.

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BACKGROUND

Four lightning-induced insulator failures have occurred at the U.S. Navy's Cutler, Maine, VLF station since the installation of safety core insulators there in 1995. The insulators provide electrical isolation and tensile strength in the halyard that supports the corners of the 12 diamond-shaped panels, which are suspended from 26 towers. Thousands of insulators of this type are in operation at locations all over the world, including several other U.S. Navy sites, where they have operated with extraordinarily high reliability. The estimated mean time between failure (for these insulators is on the order of thousands of years [1]. The work described in this report is part of an effort to understand the failure mechanism at Cutler and implications regarding potential failures at the other U.S. Navy sites.

The strength member of the safety core insulators is a fiberglass belt wrapped around pins in the end fittings. Porcelain tubes cover the belt between the end fittings. The porcelain tubes and end fittings form a sealed chamber that is filled with transformer oil, which acts as a high-voltage dielectric to protect the belt from breakdown. The end-caps are designed to provide an air pocket that allows the oil to expand and contract with temperature variations. In U.S. Navy installations, one end-cap is physically located higher than the other end-cap. The upper end-cap is designed to keep the air pocket inside, above the fiberglass belt, at all tilt angles for that installation.

Tests of safety core insulators were done at the Navy's VLF/LF High Voltage Test Facility in Forestport, New York, during the 1980s at the time of the first consideration of their use. These tests showed that the insulators could be effectively used for the Navy's applications. However, tests on an upside-down insulator revealed that the fiberglass belt could be carbon tracked from end to end, effectively shorting out the insulator, if (1) the air bubble extended beyond the end-cap, exposing the belt to air in the high field region beyond the end-cap, and (2) enough voltage was applied. This type of failure has occurred in installations where improper installation has resulted in the wrong end-cap being up, or improper articulation of the insulator end connections put torque on the insulator body causing the seals to fail and the oil to leak out, in both cases exposing the belt to air in the high field region beyond the end-cap.

Other tests were conducted at the Navy's Edgar Beauchamp High Voltage Test Facility (EBHVTF) in Dixon, California, the successor to the facility in Forestport. These tests, which were part of the Cutler insulator failure investigation, showed that once tracking has been initiated on the carbon belt, the RF voltage can continue to drive the track across the belt, including the part under oil [2]. The results verified that even if the RF voltage is too low to initiate the belt burning in the area exposed to air, the initial burn can be initiated by lightning with subsequent completion of the track driven by the RF voltage.

The first two failures at Cutler were the result of a design flaw. The analysis following the first failure showed that the upper end-caps were not large enough to fully contain the air bubble at the shallow suspension angles for Cutler installation. A project was immediately initiated to replace the end-caps with one that did fully contain the air bubble. This was done by cycling the insulators through the factory several at a time and took about 2 years to complete. In the meantime, the second insulator failed. Both of these failures were electrical only, in that the fiberglass belt tracked but the insulator remained intact otherwise. At the time of these two failures, Cutler was operating in single array mode due to painting of the other array, and the insulator electrical failure took the station completely down.

The third failure involved an insulator with a modified end-cap. It failed electrically at the time of a lightning hit. However, both arrays were active at the time. Following the electrical failure, the

array with the damaged insulator was grounded at the feed-point, and transmissions continued on the other array. This resulted in induced current flowing through the damaged insulator, burning of the fiberglass belt, and structural failure within a few hours.

When the insulator failed, the large corona ring on the halyard end of the insulator swung into the supporting tower, resulting in considerable damage. The immediate short-term fix involved removing the large corona rings from all the insulators. Also, a pressure relief diaphragm was installed in each insulator that would not allow the internal pressure to get high enough to cause the insulator to explode. The standard operating procedures (SOPs) at Cutler have been modified so that in the event of another insulator failure the transmitter will be brought completely down until the panel containing that insulator can be isolated and lowered to the ground. At the same time, the decision was made to replace all the insulators at Cutler with strings of fail-safe insulators. That project is underway and installation is planned for Summer 2007 for the first array and 2009 for the second array.

The fourth failure occurred in conjunction with a rare, very large, lightning strike (100-kAmp peak current [3]), which shattered the porcelain tube and heavily tracked the fiberglass belt but left the belt intact structurally (Figure 1).

Figure 1. Cutler safety core insulator failure #4.

The pressure relief diaphragm was intact following the fourth failure. That fact and other analysis reported by Zueck [4] indicated the porcelain was shattered from the outside, by either thermal stress or the shock wave from the high-current lightning bolt.

No failures have occurred in an array that was not actively transmitting during a lightning storm. For that reason, another SOP was initiated following failure 4 to have the transmitter turned off during lightning storms. These are rare summertime occurrences at Cutler (1–3 per year). Since that SOP was initiated, there have been no failures.

IMPULSE TESTS AT HYDRO QUEBEC

As a part of the effort to understand the Cutler insulator failure mechanisms, a set of impulse tests was done at Hydro Quebec using their large 10-MV lightning voltage simulator [5]. Discussions with the Hydro Quebec engineers indicated that the location of the flashover path is related to the absolute slope of the voltage waveform triggering the flashover. The greater the value of dV/dt, the more likely the flashover path would be along the surface of the insulator and/or penetrate into the insides of the insulator. High dV/dt impulses with flashover on the surface are believed to be the cause of the second two failures at Cutler [6].

The Hydro Quebec tests were performed on both the safety core insulator by itself and with the two large corona rings that had been left in place at Cutler from the original long string of fail-safe insulators. For these tests, the porcelain tube of the safety core insulator was replaced with a plastic see-through tube. The test report [5] contains pictures of every flashover for these tests. Figure 2 shows one of these pictures for the safety core insulator by itself.

Careful analysis of the test data in the report, especially examination of the pictures, revealed that there was a dV/dt threshold below which flashover occurred in the air and above which the flashover occurred along the surface of the insulator. The threshold for the insulator tested was about 7 MV/μs (7×10^{12} volts/second). Figure 2 shows the flashover for a voltage waveform with a magnitude of dV/dt above the threshold.

In Figure 2, note that the streamers in the air from ring-to-ring have not quite made connection, while the flashover path down the surface of the insulator has been completed. Also, note that the surface flashover path appears to terminate at the porcelain metal interface of the smaller corona ring (upper end). Lightning simulators of the type used at Hydro Quebec simulate the full threat voltage waveform that might be generated by a lightning strike, but they do not provide the full threat current. Consequently, the flashovers along the surface did not cause any damage inside or outside the insulator.

Figure 2. Cutler safety core test at Hydro Quebec.

CUTLER CONFIGURATION ANALYSIS

Theoretical analysis of the waveform that would appear across the Cutler insulator from a nearby lightning strike showed that the dV/dt is a linear function of the peak current in the lightning strike [7]. Analysis of lightning strike data in the region around Cutler for a 5-year period indicates the median strike peak current is about 20 kAmps [3]. The lightning strikes correlated with the insulator failures are about that level, except for the fourth failure, in which the lightning strike was much larger. A 20-kAmp strike near the insulator at Cutler gives an estimated value for dV/dt of 9 MV/µs, well above the value needed to flashover on the surface.

NAVY IMPULSE GENERATOR

The EBHVTF has an impulse lightning tester that is rated at 600 kV peak. The Hipotronics IG-600 Impulse Generator (IG) was purchased by the Navy Facilities Engineering Service Center around 1989. It was unboxed, cleaned, reassembled, and readied for use in the "barn" at Dixon. Figure 3 shows the impulse generator in the background. The red vertical tubes in the foreground contain a capacitor load and resistive voltage divider.

The IG is a six-section Marx generator. Each stage has a capacitor that can be charged to 100 kV DC, but under normal operations is limited to a maximum charging voltage to 80 kV DC. The IG has a selection of resistors that can be installed in various combinations to produce impulse waves of desired front (rise) and tail (decay) rates. We started with front resistors of about 15 ohms (25 ‖ 50) and tail resistors of about 150 ohms (200 ‖ 450), which provided a standard pulse of 1.2 x 50 µs. Later, we changed the front resistors to about 7 ohms (25 ‖ 10), which produced a rise time of about 0.8 µs. Finally, we installed shorting bars for the front resistors, which produced a rise time of about 0.6 µs. This is the fastest pulse this generator can produce.

Figure 3. Hipotronics Impulse Generator.

The charging voltage is indicated by a meter in the IG control console. The maximum pulse voltage is normally the charging voltage multiplied by the number of stages, in this case six. However, when the shorting bars are installed, the circuit overshoots, resulting in a higher peak voltage.

The impulse voltage is measured using the capacitive voltage divider, the tall red tube in the foreground of Figure 3. The division ratio is 300:1. The divider output is connected to one channel of a digital storage oscilloscope through a string of attenuators.

The impulse current is measured using a shunt resistor connected to the ground leg of the test object. The shunt resistance is 0.01 ohms, giving an output of 0.01 volts per ampere. The output of this shunt is connected to the second channel of the scope, also through a string of attenuators. A small leakage current was observed for pulses that did not flash over the test object, but a strong signal was observed when the test object did flash over.

IMPULSE WAVEFORMS

In Figures 4 through 6, the voltage waveform is displayed as the top trace and the current waveform is displayed as the lower trace.

Standard Resistor Set

At impulses without flashover, the voltage appears as a textbook double exponential with a 1.2-µs rise time. When the voltage is just above the level required for flashover, flashover occurs well after the voltage peak as indicated by the voltage waveform being chopped to zero at the same time as the current waveform started. As the voltage is increased, the delay to flashover reduced so that the voltage was chopped earlier.

Reduced Front Resistors

With front resistors reduced to 7 ohms per stage, the impulse had a faster rise time, about 0.8 µs. Its behavior was essentially the same.

Shorting Bars for Front Resistance

With shorting bars in place of front resistors, the voltage wave displayed decaying oscillation. The rise time was about 0.6 µs. Note that in Figure 4 that flashover has not occurred and the current shown is leakage current.
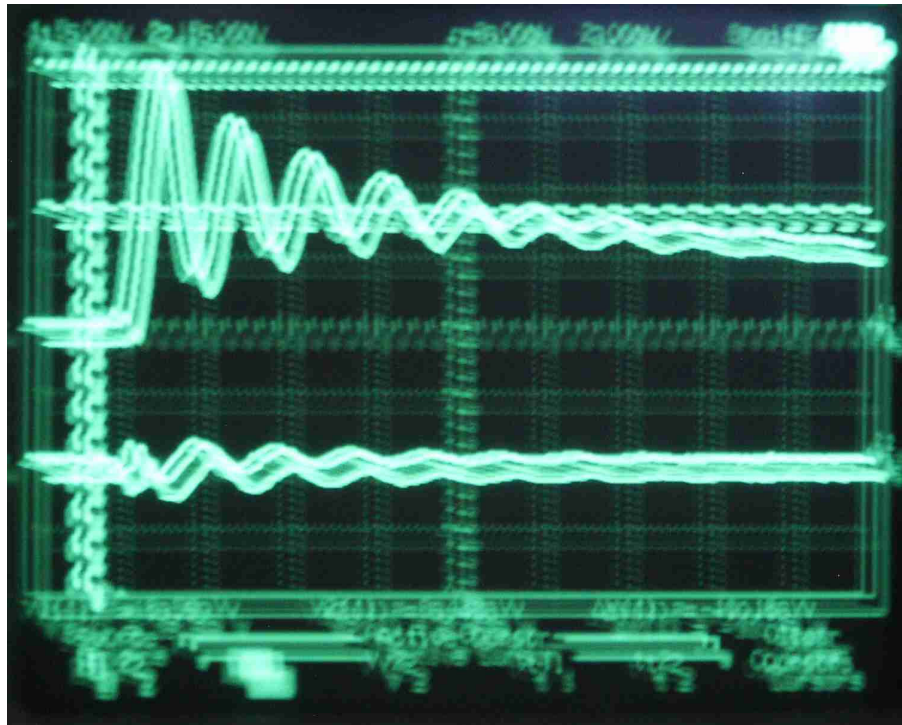
Figure 4. V and I with shorting bars for the front resistor, V below flashover. Flashover has not occurred.

As the charging voltage is increased, the first flashovers occur well after the voltage peak. Figure 5 shows an example of the voltage and current waveforms for that condition. The large peak in the current waveform at the same time that the voltage waveform is cut off is the evidence of flashover. The current rings down as an exponentially damped sine wave.
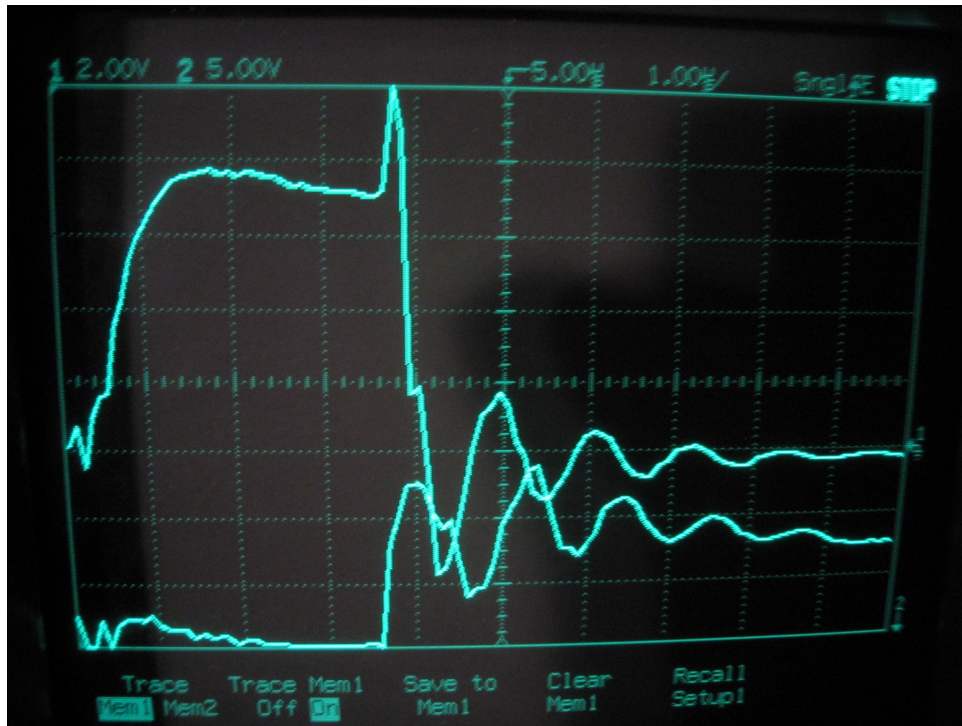
Figure 5. V and I with shorting bars for the front resistor, V just above flashover. Flashover occurs well after voltage peak.

As the charging voltage is raised further, dV/dt increases and flashover occurs earlier in the pulse so that the current peak and voltage drop move to the left. At sufficiently high dV/dt, flashover occurs on the leading edge of the voltage waveform before it reaches the maximum peak. An example of this is shown in Figure 6.
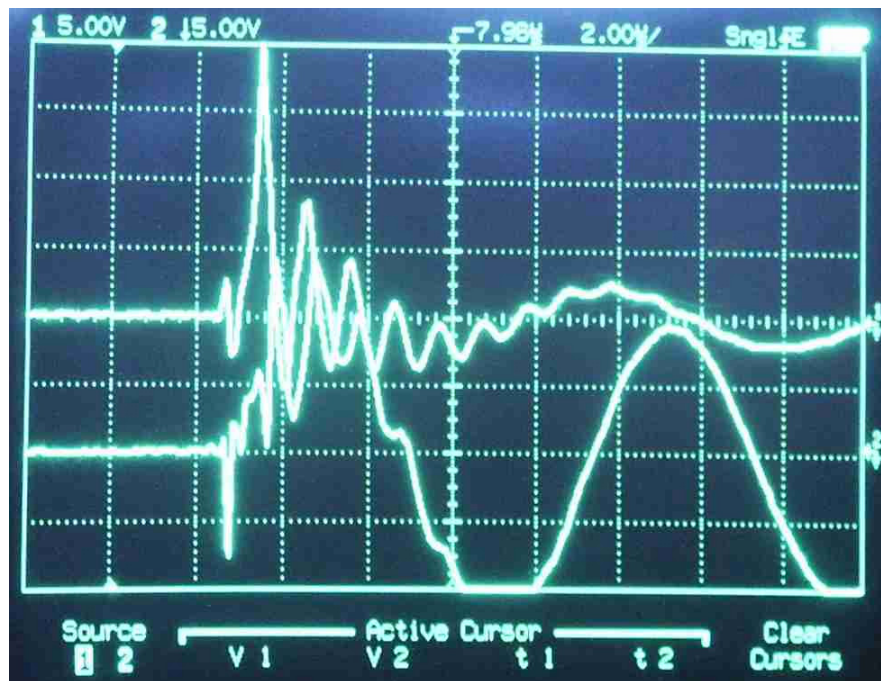
Figure 6. V and I with shorting bars for the front resistor, voltage well above flashover. Flashover occurs on leading edge of pulse.

INITIAL TEST – JUNE 2005

The primary objective of the initial test was to activate the IG and determine its capability. The results are described above (Navy Impulse Generator). Following that, tests were performed on a small safety core insulator and a preliminary scale model of a Cutler insulator. A brief description of the testing with the safety core insulator is given in this section. A more detailed description of the pulser and the initial tests is contained in the test plan [8] and quick-look report [9].

TEST OBJECTS

The test object was an Austin A-S3003S "safety core" insulator in three configurations:

- with two large rings (Figure 7)
- with only the top ring (Figure 8)
- with small rings

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Figure 7. Austin A-S3003S safety core insulator with two large rings.

TWO LARGE RINGS

This configuration (Figure 7) was hit with a series of pulses starting with a charging voltage of 10 kV/stage and ending with 80 kV/stage. When there was no flashover, the peak voltage reached more than six times the charging voltage due to the circuit ringing. No flashover was observed for charging voltages up to 30 kV/stage (~200 kV peak).

At 35 kV charging voltage per stage, the insulator flashed over on roughly half the pulses. At 40 kV and above, the insulator flashed over on every pulse. All flashovers were ring-to-ring.

BOTTOM RING REMOVED

We removed the bottom ring from the insulator to see if the flashover path would then move to the surface of the insulator (Figure 8).

Figure 8. Insulator with bottom ring removed.

This configuration was hit with pulses starting with 10 kV/stage charging voltage and ending with 80 kV/stage. At 30 kV/stage (~ 200 kV peak), the insulator flashed over on roughly half the pulses, and it flashed over consistently at 35 kV/stage (~ 230 kV peak). When the voltage reached 50 kV/stage (~ 333 kV peak) and above, the flashover appeared to be along the insulator's surface.

The time to flashover was 960 ns at 50 kV, and decreased as the voltage was raised. At 80 kV/stage, the time to flashover was 360 ns.

Peak voltages and currents were recorded from the oscilloscope trace. The highest peak voltage recorded was about 800 kV. This exceeds the expected maximum of 80 kV/stage x 6 = 480 kV because of the oscillations in the circuit. The oscillations occur because the front resistance was reduced to zero by using the shorting bars.

The corresponding peak current recorded was 16 kA.

After shutting down and grounding the apparatus, we inspected and found the flat area near the lower end casting and a fingertip-sized area on the tip of each rain shed where the porcelain's glaze appeared to have melted and re-solidified. This is shown as slightly lighter-colored brown areas on the right-hand side of the bottom sheds shown in Figure 9.

Figure 9. Insulator showing damage to glaze.

We installed two smaller rings on the insulator and ran impulse tests at 50, 60, and 70 kV/stage. All flashovers appeared to be ring-to-ring.

REVERSED POLARITY

We reversed polarity of the IG, and ran a series of impulses on the insulator with small rings, starting at 10 kV/stage and ending at 80 kV/stage. The behavior was essentially no different from that at positive polarity. The insulator always flashed over at 40 kV/stage and above.

BASIS FOR SCALE MODEL TESTING

The basis of scale model testing of impulse flashover involves the concept of the velocity of propagation of the arc across the insulator. Arc initiation is a function of the electric field on the electrodes at ends of the insulator [10]. Once initiated, the arc then propagates across the gap with a finite velocity. This velocity is a function of the electric field at the end of the arc, which is a function of the applied voltage. As voltage (field) increases, the velocity approaches a limiting value [11]. The velocity of an arc along a surface is greater than for an arc in the air, because the material provides free electrons when hit with the ultraviolet light from the plasma in the arc.

The scaling concept originates from the idea that these velocities are a function of the electric field. Scaling to keep the electric field the same as a function of time will result in similar phenomena in terms of the transition between air and surface flashover. The electric field as a function of time is directly proportional to V(t)/d. The voltage on the leading edge of a pulse waveform can be approximated by (dV/dt)•t, where (dV/dt) is a fixed value. Thus, to keep V(t)/d constant, the scaling concept requires that (dV/dt)/d be constant.

The maximum value of (dV/dt) for our pulsar is approximately 1/7 of the one at Hydro Quebec that was used for the full-scale testing. In that case, the flashover path changed from being in the air

to being along the insulator surface when dV/dt $\geq$ 7 MV/µs. Our conjecture was that the same phenomena would be observed using our pulser but with objects scaled by a factor of 1/7th. Thus, the phenomena would be the same, i.e., the transition from air to surface flashover would occur at a dV/dt of 1/7th that for full scale, or about 1 MV/µs.

Prior to the testing, we did a literature search and consulted with a San Diego expert in high voltage [12] to try to validate our scaling conjecture. The primary references available on fast rise time impulse breakdown is work done in the 1960s by the Atomic Weapons Research Establishment (AWRE) in Aldemaston, England, by Charlie Martin [13]. A rough empirical equation has been developed that describes the breakdown across gaps greater than 10 cm long with very divergent fields:

$$E_{\pm} \cdot (d \cdot t)^{1/6} = K_{\pm} P^n$$

where E is the pulse peak electric field (V/d kV/cm), $\pm$ indicates different values for each polarity,

d is the length of the gap,

t is the pulse duration,

K is a constant that depends upon polarity,

P is the gas pressure of the gas between the gaps, and

n is a constant that depends upon the gas.

For air, $K_{\pm} = 22$, and n = 0.6.

The pulse duration is defined as the effective pulse width and is equal to the time for which the voltage is higher than 63% of peak of the pulse.

The above equation indicates similarity for cases where the electric field and product of gap length times pulse duration remain constant and can be used to validate our scaling conjecture as follows. The pulse duration can be thought of as the inverse of the rise time, i.e., longer pulses imply slower rise time. Thus, keeping the factor d•t constant requires that rise time and gap length be scaled by the same factor. This implies that the peak field for breakdown will be the same in both cases.

The phenomenon of surface breakdown along a dielectric insulator is quite complicated, depending upon the material and the condition of the surface (dirt, oil, etc.) as well as the value of the electric field in the region of the triple points (dielectric, metal, air interfaces). Consequently, no simple equations exist that can be used to validate the surface effect scaling. Nevertheless, as discussed above, the concept of an E-field-dependent velocity in the air and a different velocity along the surface would result in the same scaling factor for surface and air breakdown as long as the entire insulator were scaled, including the triple points. As will be seen below, the experiments qualitatively confirmed this conjecture. Testing models with more than one scale factor would provide quantitative confirmation.

The limited literature search [14–19] indicated that surface flashover in vacuum seems to be triggered by charge injection into the dielectric at the triple points at the ends of the insulator. Surface composition and condition also affect flashover. Consequently, different surface materials and shapes (rain sheds) may well change surface flashover characteristics. Residual charge on the insulator surface or in the dielectric are found to reduce the surface flashover voltage. This leads to the

conjecture that there may well be a residual charge distribution on the insulator dielectric due to the RF voltage, which may reduce the surface flashover voltage. This effect needs to be investigated as well. One concern is that surface flashover for long gaps in air is not well understood, and there is no complete theory that can be applied as a basis for the corona ring design at this time. Thus, the design approach must be empirical. Scale modeling is a good way to sort through configurations but the final design must be tested at full scale. If possible, the effect of RF should be included in the testing.

CUTLER INSULATOR SCALE MODEL TESTS – SEPTEMBER 2005

CALIBRATION

The first part of the September tests involved calibrating the voltage and current dividers. The voltage calibration used the standard technique we have developed at the EBHVTF using a capacitive voltage divider. Both the voltage and current dividers supplied with the IG were found to have division ratios equal to the stated values (300:1 for the voltage divider and 100:1 for the current divider). A string of attenuators was used to bring the output voltages from these dividers down so that they could be displayed on the scope (~50 dB for voltage and ~35 dB for the current). The attenuator strings were calibrated as part of this process.

Note that throughout these tests we never used a charging voltage more than 80 kV/stage (80% of the maximum rated value). Hipotronics (test equipment manufacturer) recommends this practice. Operation at higher charging voltages is possible but significantly reduces the lifetime of the capacitors. With the calibrated dividers and using the shorting bars for the front resistors, the maximum observed peak voltages were 1.2 MV, with a time to the peak of 0.6 μs and corresponding peak currents of 20 kAmps. This voltage is double the maximum charging voltage for the capacitors of 600 kV. Hipotronics confirmed this was acceptable operation.

SCALE MODEL INSULATORS

Cutler

Model insulators were constructed using a scale factor of 1/7 that of the Austin Insulators Inc. safety core insulators in place at Cutler. During the first test period, we did preliminary tests with a scale model of the Cutler insulator made from a hollow PVC pipe (1 inch diameter), with copper end fittings, aluminum rings, and attaching hardware. With high dV/dt pulses, this model flashed over inside the PVC pipe, blowing off the end-caps.

For that reason, we constructed the remaining scale model insulators using similar copper end fittings and aluminum rings and attaching hardware but replacing the hollow PVC pipe with a solid polycarbonate rod. The polycarbonate plastic rod makes an excellent insulator. This material is similar to the material used for the see-through body of the full-scale insulator tested at Hydro Quebec (Figure 2). The specifications for the plastic in this insulator are given in Appendix A: Polycarbonate Plastic Specification. The scale model of the Cutler insulator suspended in place for testing is shown in Figure 10.

Figure 10. 1/7th Scale model of the Cutler safety core insulator.

Reduced Air Gap Configurations

The proposed concept for protecting the safety core insulator from lightning involves reducing the air gap distance and moving the air (flashover) path farther away from the insulator. The concept is to decrease the ratio of the air gap path to the surface flashover path. At the same time, it is desirable to move the air gap path farther away from the insulator surface. We tested five configurations to investigate this concept. Four of the test configurations are shown in Figure 11. Some of these configurations have reduced RF withstand capability over the original configuration because the air gap has been shortened. The amount of reduction in RF withstand voltage is approximately equal to the percentage the air gap is reduced.

Configuration 1, on the left in Figure 11, is a drawing of the scale model Cutler insulator pictured in Figure 10. Configuration 2, in the center of the figure, is similar, but the small ring at the grounded end has been replaced with a larger ring, making it symmetric. This configuration has only slightly less air gap than configuration 1.

Configurations 3 and 4 are shown on the right in Figure 11. They are also symmetrical and use rings of the same size as the high-voltage end of the Cutler insulator but they have been moved closer together so that a portion of the insulator body is covered. This shortens the flashover path in air and significantly reduces the field on the triple points at the end of the insulator body. Configuration 3 reduces the air gap between the rings to 2/3 of that of configuration 2.

Configuration 4 is similar to configuration 3 except that the rings are moved closer together so that the air gap is reduced to 1/2 that of configuration 2. A test sample of configuration 4 is shown in Figure 12.

A fifth configuration was tested (not shown in Figure 11) using the high-voltage end ring of configuration 4 and the low-voltage end ring the same as that on original Cutler insulators. The air gap distance for this configuration is reduced by approximately 1/4 that of configuration 2. This configuration is shown in Figure 13.
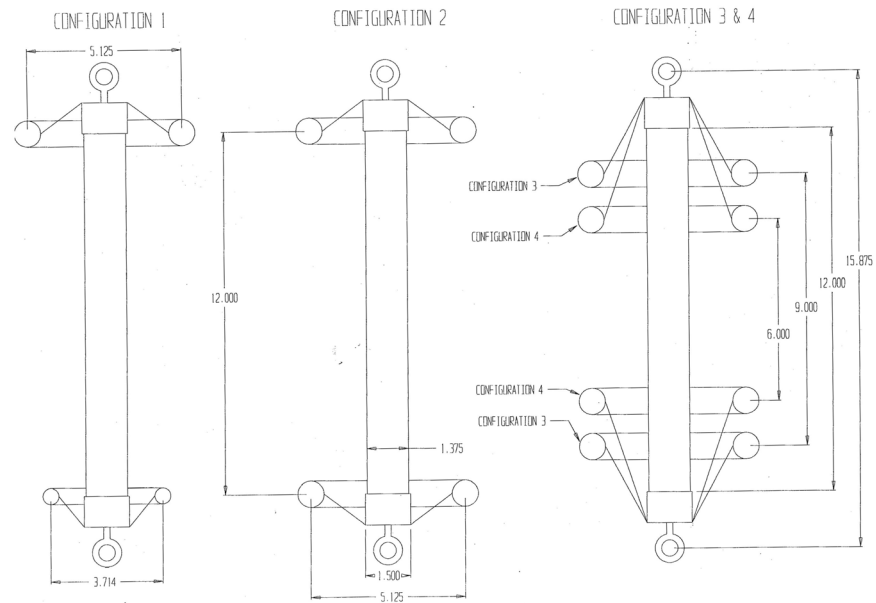
Figure 11. Scale model insulator configurations tested.

Figure 12. Configuration 4 test sample in place.

Figure 13. Configuration 5 showing the effect of surface flashover.

TEST SETUP

During the first test period, we had some trouble with induced voltages from the large current flashovers getting into our equipment. In particular, we damaged a special Lecroix storage oscilloscope and had to revert to a Hewlett-Packard® digital storage scope. Also, the noise from the larger current flashovers was very loud. For the second test, we set up a portable screen room about 50 feet away from the test object and grounded all our equipment carefully. Earplugs were provided to all the observers. The portable screen room is shown in Figure 14. The Hipotronics control console and the digital scope can be seen on the right-hand end of the table. The video recording equipment can be seen at the left-hand end of the table.

Figure 14. Portable screen room used for testing.

FLASHOVER LOCATION

The test plan called for using a digital video camera for recording each flashover. The video was to be recorded on a DVD that allowed playback immediately after each shot. We had used this technique previously to locate flashover paths in the VLF/LF Aguada helix house and at Hydro Quebec. In those cases, the videos were recorded using an analog video camera. Unfortunately, the digital video camera we used in the tests described here did not give an accurate image of the flashover location, and we abandoned that effort early in the test.

We tried to locate the arc using direct visual observation, including putting mirrors at the side and behind the test object (Figure 10), but this was only partially successful. Part of the reason this did not work well is that the transparent polycarbonate rod lets light through from all angles and the surface reflects light as well, so the intense light from an arc always seemed to come from the surface of the polycarbonate rod. We had several observers looking from different angles, and we even tried moving an observer to partially shielded positions closer to the test sample. There were times when visual observations could confirm that the flashover was in the air away from the rod but, in general, visual observation was not a reliable way to determine if the flashover path was along the surface or in the air.

By serendipity, we discovered there was a slight modification of the surface of the plastic when flashover occurred along the surface. This was not a carbon track but a slight distortion of the surface, probably caused by surface melting that could be seen upon close examination of the polycarbonate plastic. The surface distortion was apparent when the polycarbonate rod was viewed up close with the back lighting in the test cell, and it can be seen by close examination of Figure 13. The test procedure was modified after this was discovered.

The modified test procedure started each test sequence with a new clean sample of polycarbonate rod. The test sequence started at the lowest charging voltage and slowly increased to the maximum.

The insulator rod was carefully examined following each pulse that resulted in a flashover. The appearance of the surface distortion revealed the level at which the flashover path transitioned from being in the air to being along the surface.

Future tests will use a high-speed video camera and possibly a temperature-sensitive paint on the surface of the insulator. The paint will give a clear indication of surface flashover, but once flashed, the sample will be ruined due to the tracking of the paint. The insulating capability of the polycarbonate rods by themselves seemed to remain unchanged even though they had been flashed over on the surface (see next section).

TEST RESULTS

Voltages and Currents

The test results were similar with the previous test in that no flashover occurred at low peak voltages. As the charging voltage was increased, flashover would start to occur across the air gap between the rings. For some configurations, flashover would transition from ring-to-ring in the air to being along the surface of the polycarbonate rod as the charging voltage (and hence dV/dt) was increased.

We recorded the peak voltages and currents for each flashover. At low charging voltages, there would be no flashover. As the charging voltage was increased, the flashover would occur well after the peak voltage occurred. These flashovers always occurred from ring-to-ring in the air. As the charging voltage increased, the time between pulse start and flashover decreased. Eventually, the time to flashover became short enough so that flashover occurred on the leading edge of the pulse. When this occurred, the peak voltage was determined by the time that flashover occurred. Generally, as the charging voltage was increased, the time to flashover decreased and the maximum value of the voltage increased.

However, a very interesting phenomenon occurred for those configurations exhibiting surface flashover. At charging voltages above the point where surface flashover started, the time to the flashover and the peak voltage observed decreased with increasing voltage. This was a surprise. At the time, we thought it might have to do with the fact that the polycarbonate rod had been tracked, changing the flashover characteristics of the insulator.

To check this hypothesis, a test was done by increasing the charging voltage in steps up to the maximum and then reducing the charging voltage in the same steps back down to the starting level. As the charging voltage was increased, the flashover path transitioned to the surface. The charging voltage was increased more and, at higher voltages, several flashovers occurred on the surface. After reaching the maximum, the charging voltages were reduced using the same steps, starting at the highest level. The peak voltages and currents for the decreasing set of voltages were the same as those for the increasing voltage sequence. Visually, it appeared that the transition back to ring-to-ring flashover was at the same voltage as when the insulator surface had not been affected. This indicates that the reduction in peak flashover voltage at higher charging voltages was not due to modification of the insulator surface.

A possible explanation for this is that the time to complete surface flashover is less than that for the air flashover, and it appears that the delay time decreases significantly as dV/dt increases. This could be due to a rapid increase in the surface flashover velocity with E, or the reduced time to reach the surface flashover initiation voltage, or the result of more energy being available to complete the surface flashover. Another possibility is that this is an artifice resulting from the circuit ringing.

Flashover Path

The primary objective of these tests was to investigate different ring configurations to see if there were some that might be able to protect the body of the insulator from lightning strikes having large values of dV/dt. Our pulsar was capable of dV/dt ~ 2.0 MV/μs and the scale factor was 7, corresponding to a full-scale dV/dt ~ 14 MV/μs, which equates to about 40% more than available at Hydro Quebec. Within that limitation, we found that configurations 3 and 4 always flashed over in the air. It is likely that these configurations would flash over along the surface at some increased level of dV/dt. All other configurations did flash over along the surface at some point as the voltage (dV/dt) increased. These results are indicated in Table 1.

Table 1. Test results – surface flashover

#	Description	Surface Flashover
1	Cutler 1/7 scale model	Yes
2	Cutler with large rings at both ends	Yes
3	Large rings – spacing reduced by 1/3	No
4	Large rings – spacing reduced by 1/2	No
5	Large ring HV end, original Cutler ring at ground end	Yes (partial)

CONFIGURATION 5 RESULTS

Configuration 5 is shown in Figure 13 and Figure 15. This configuration performed similar to the configurations 1 and 2 in that as the charging voltage (dV/dt) increased, the flashover path transitioned from being in the air to going along the surface. However, in this instance the surface path was only along a portion of the insulator, a partial surface flashover.

The flashover path for this insulator started on the large ring and went from there through the air to the surface of the polycarbonate rod and then down the rod to the grounded end, terminating at the triple point formed by the edge of the copper end-cap. The lower portion of the surface flashover path can be seen on the insulator surface in Figure 13. Figure 15 shows the model insulator with the flashover path highlighted by a ribbon.

Figure 15. Configuration 5 insulator model with highlighted flashover path.

Note that on the high-voltage end the arc starts on the ring and then goes to the insulator surface, terminating on the triple point at the low-voltage end of the insulator. This same type of behavior was observed in the full-scale testing at Hydro Quebec. During that test, at dV/dt levels where the flashover path was transitioning from being in the air to going completely along the surface, some flashovers seemed to start from the big ring and then dive down to the surface of the insulator body. An example of this is shown in Figure 16.

Figure 16. Cutler insulator at Hydro Quebec showing partial surface flashover.

It is interesting to note in Figure 16 that the surface termination point of the arc is at the triple point on the high-voltage (large ring) end of the insulator.

DISCUSSION

The test results are consistent with there being a large difference in the propagation time of a leader in air and a leader along the surface of the insulator. It is likely that the leaders propagating along the surface of the insulator originate from a location at or near the triple point at the ends of the insulator. Figure 16 is a good illustration of this. In that figure, there are several leaders in air coming off the smaller ring. The picture is a time exposure, so these leaders stopped propagating when the voltage dropped to zero at flashover completion. The picture shows how far the leaders got before flashover occurred. The leader going along the surface propagated much faster and, in this case, one of the air leaders from the ring made the connection near the surface, completing the current path.

From the picture, it appears that the surface leader propagation velocity was a minimum of 2 to 4 times faster than the air leader velocity based on the difference in the path lengths. However, the path length difference is not entirely due to the propagation velocity because it takes more voltage to initiate corona at the triple point because they are partially shielded. The delay between corona (leader) initiation on the small ring and at the triple point will depend upon the magnitude of dV/dt and the difference in the initiation voltage at these points. The delay will decrease with increasing dV/dt.

The electric field grading for insulators is designed to keep the triple points from corona at the operating voltages. They are also designed such that flashover from excessive RF levels always occurs in the air away from the insulating material. For impulse flashover with low values of dV/dt,

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flashover occurs in the air, the same as with RF. There is a minimum delay for air flashover and, as dV/dt increases, this delay allows much higher voltages to be reached before flashover occurs. For any given insulator configuration, there is a dV/dt level that results in enough voltage prior to flashover so that the triple points do go into corona. Surface flashover propagates faster than flashover in air and, once the required voltage is reached, the flashover will complete across the surface.

Figure 17 shows several idealized waveforms that illustrate what happens when the insulator is hit with a voltage impulse. The waveforms are labeled in terms of the slope of the leading edge (dV/dt) in MV/µs.
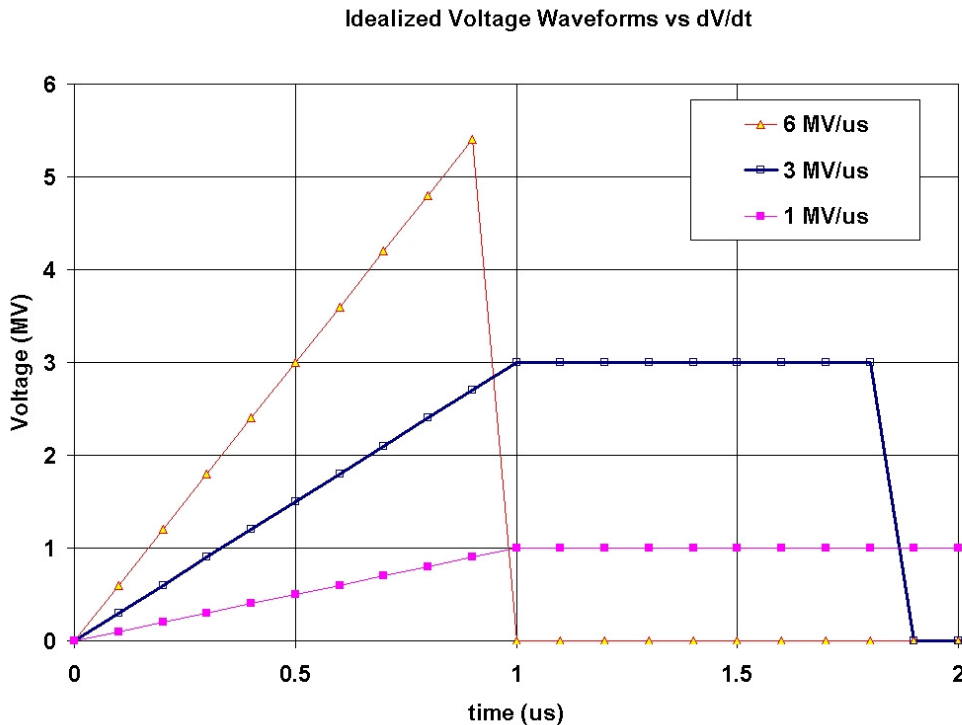
Idealized Voltage Waveforms vs dV/dt

Figure 17. Flashover phenomena for low dV/dt waveforms.

At low values of dV/dt, flashover occurs well after the peak of the waveform. The 1 MV/µs curve has a peak voltage of 1 MV. This was the threshold for flashover in the Hydro Quebec tests. At that level, flashover did not occur until almost 10 µs after the waveform started (off scale to the right in the figure). As dV/dt increases, the delay to flashover in air reduces. This can be seen in the curve for 3 MV/µs curve, which is similar but the delay is less, with flashover occurring at 1.8 µs. When 6 MV/µs is reached, flashover occurs on the leading edge of the pulse and the peak pulse voltage is reduced over what it would be if flashover had not occurred.

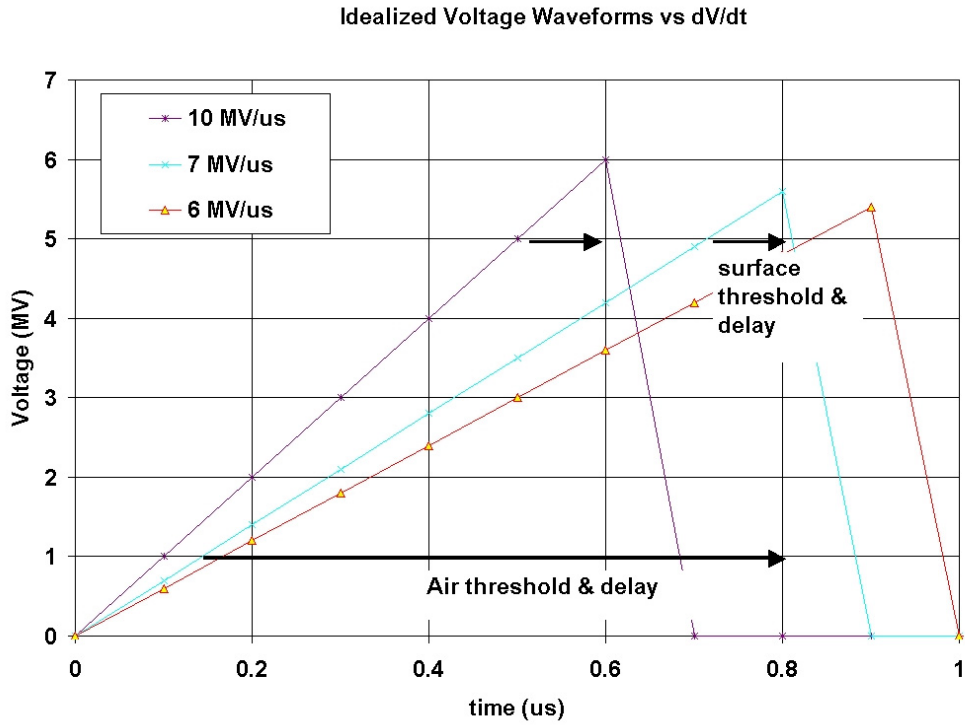Figure 18 shows similar waveforms, but with high values of dV/dt.

Figure 18. Flashover phenomena for high dV/dt waveforms.

This figure includes the 6-MV/μs curve where flashover just started to occur on the leading edge of the pulse. The next curve, 7 MV/μs, is where flashover began occurring on the surface. The picture in Figure 16 shows the flashover path observed for this level of dV/dt. At greater values of dV/dt the flashover path was entirely along the surface (Figure 2).

The observed air flashover initiation threshold is 1 MV. Assuming the surface flashover initiation threshold is 5 MV gives a much faster surface propagation time than the factor of 2 to 4 estimated from the ratio of surface and air path lengths in Figure 16. To illustrate this, arrows have been placed in Figure 18 indicating both the air flashover threshold and delay time and an estimated surface flashover threshold and delay. From the figure, it can be seen that for values of dV/dt less than 7 MV/μs the timing is such that flashover will be in the air. At a value of dV/dt of 7 MV/μs, the combination of thresholds and delays makes it such that flashover occurs at the same time for surface and air phenomena. Thus, at this value of dV/dt, flashover will occur sometimes on the surface, sometimes in the air, and sometimes a combination of surface and air. The figure shows that when dV/dt > 7 MV/μs, the shorter delay time for surface flashover results in the surface flashover path, completing well before the air path is completed.

The time delay of the leaders across the gap is a function of voltage. The delay decreases with increasing voltage until it reaches a minimum determined by maximum leader velocity. Figure 19 shows the delay for the air gap flashover from pulse initiation as a function of dV/dt. The data were generated using the computer program written by Monga [11].
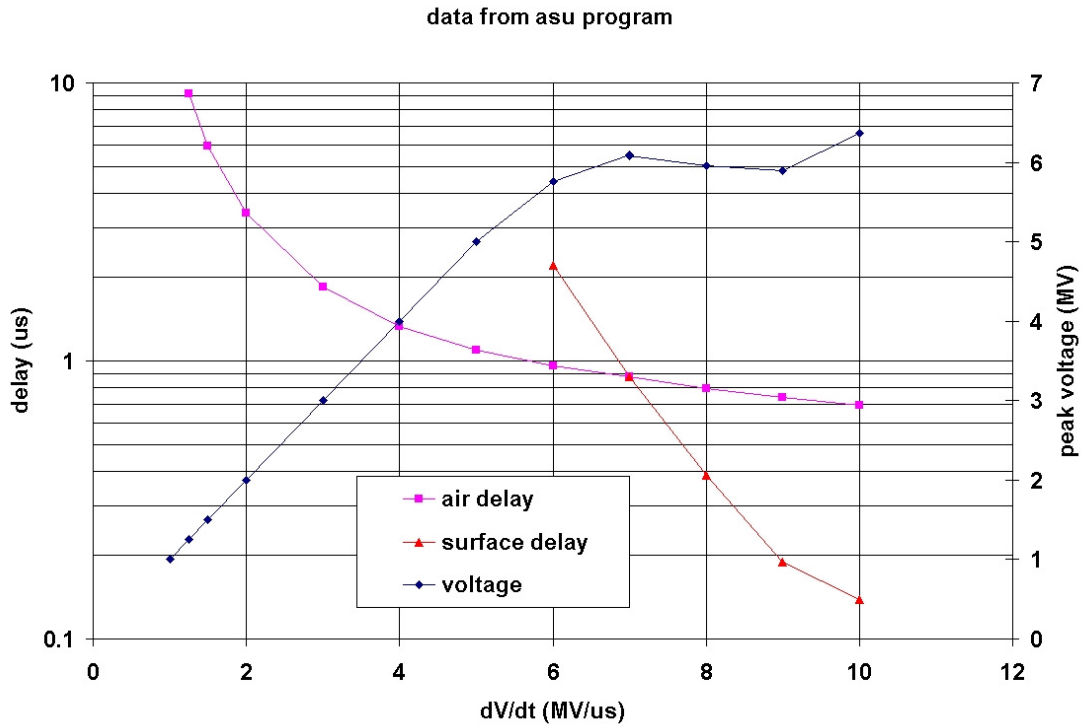
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Figure 19. Delay and peak voltage for air and surface flashover.

The threshold for air breakdown was a peak pulse voltage of 1 MV, corresponding to dV/dt of 1 MV/μs. The delay curve in the figure shows a corresponding time delay of 9 μs. As the voltage increases, the delay decreases, asymptotically approaching a value of 0.6 μs. The figure also contains a speculative curve for surface flashover assuming a threshold of 5 MV and an assumed delay curve. When dV/dt is less than 7 MV/μs, the delay of the air flashover is less than that for surface flashover and flashover occurs in the air. The voltages for air flashover are those from the program. However, when dV/dt is greater than 7 MV/μs, surface delay is less and flashover occurs on the surface. For this region, the peak voltage shown was estimated using the postulated threshold and delay curve shown. Under these assumptions, the peak voltage actually decreases in a range of dV/dt just above where surface flashover starts. This reduction in peak voltage was observed in the Dixon scale model tests.

The above explanation of the dV/dt surface flashover threshold phenomena leads to one potential method for increasing the surface flashover threshold by adding shielding around the triple points to increase the surface flashover initiation voltage. An example is shown in Figure 20, where the threshold for surface flashover has been increased to 10 MV. In this case, using the previously postulated delay, surface flashover will not occur until dV/dt reaches 20 MV/μs.

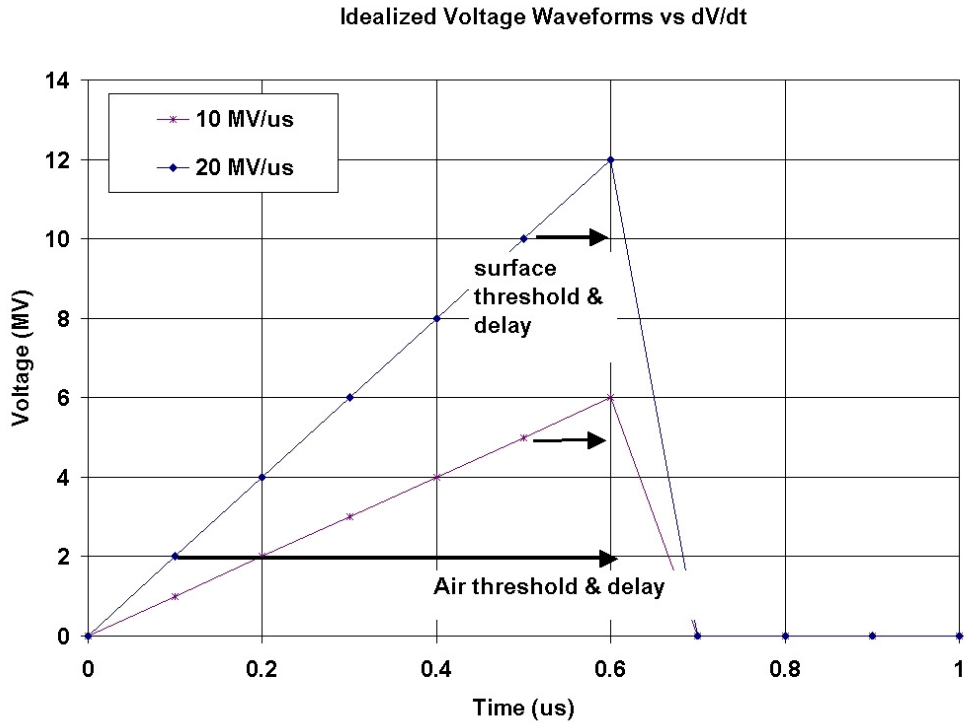**Idealized Voltage Waveforms vs dV/dt**

Figure 20. Flashover phenomena with increased surface flashover threshold.

Note that very high dV/dt rates lead to very large voltages across the insulator. For example, in Figure 20 the peak voltage experienced would be 12 MV. This voltage does not last long but there may be failure mechanisms that can result from this voltage. For example, dielectric punch-through happens fast, and this could result when the voltage is high enough even though it was there for a very short period. Computer analysis of the cutler safety core insulator interior was done to examine the possibility that breakdown could occur on the pin inside the high-voltage end-cap if enough oil leaked out to expose a portion of the pin to air [20].

The critical breakdown gradient for a 1.5-inch-diameter pin in air is 22.6 kV/cm [10]. The calculations indicated that the gradient on the pin inside the insulator cap, with enough oil removed to partially expose the pin to air, was 6.3 E-4 kV/cm/Kv. This requires 29.3 MV across the insulator to reach the critical level for breakdown on an internal pin exposed to air. The breakdown voltage would be considerably greater if the pin is surrounded by oil. It is unlikely that this voltage level was reached, even with the 100-kAmp lightning strike. It is also unlikely that the oil level was low enough to expose the internal pin to air [21].

An alternative method to increase the dV/dt threshold for surface flashover and to reduce the maximum voltage appearing across the insulator is to reduce the threshold and delay for air flashover by reducing the spacing between the corona rings. This reduces both the flashover voltage and the delay time because the gap is smaller. As mentioned before, one drawback to this approach is that the RF withstand voltage for the insulator will be reduced. The combination mode flashover shown in Figure 16 makes it clear that it is also necessary to make the air flashover path some distance away from the surface so the surface and air paths do not interconnect.

CONCLUSIONS

The results of the tests indicate that scale modeling can be used to determine some of the impulse flashover characteristics of full-scale insulators, including the path of flashover. The scale factor is chosen such that the product of dV/dt / insulator length = constant.

The test results validated that for the existing Cutler insulator configuration, the flashover path follows the surface of the insulator when dV/dt is greater than 7 MV/μs.

A limited set of alternate corona ring configurations was tested and it was determined that the rings can be adjusted closer together to force impulse flashover to occur in the air between the rings and not along the body of the insulator, at least for the levels of dV/dt that we could simulate. These results indicate that the Cutler safety core insulators can be protected from lightning-induced impulse flashovers with the appropriate corona ring configurations. However, the closer spacing results in a somewhat reduced level of RF withstand.

Another approach, not tested, is to put two or more insulators in series. In this case, dV/dt across each insulator would be reduced by the voltage division ratio, a factor something less than the number of insulators in series. Most other sites have more than one insulator between the active antenna components and ground, and this is thought to be the primary reason that lightning-induced failures have not occurred at those sites.

The air flashover path should be kept well away from the surface path so that combination surface–air flashover does not occur. The optimum distance is probably a function of the surface path length, and this should be explored using the scale models.

Corona rings designed for lightning protection should be symmetrical on both ends of the insulator.

Surface flashover is initiated at the triple points at the ends of the insulator. Further shielding the triple points should increase the dV/dt threshold for surface flashover.

The surface material, shape, and condition may affect the surface flashover threshold.

Insulators energized at RF may have different surface flashover characteristics than un-energized insulators. Both of these effects should be investigated at least at the scale model level.

Finally, scale modeling is a good way to sort through corona ring configurations and search for optimum aspect ratios, but the final design must be tested at full scale. If possible, the effect of RF should be included in the testing.

RECOMMENDATIONS

The objective of the work described in this report is to understand the failure mechanism of the insulators at Cutler. It is part of an overall effort that includes determining how to fix the problem at Cutler and the implications for the other Navy VLF/LF sites. The work described in this report verifies that the general failure mechanism at Cutler involves high dV/dt impulses occurring across the insulators resulting from lightning strikes. The implications for other sites will be reported separately.

The U.S. Navy has started a procurement program to replace the insulators at Cutler with fail-safe insulators. This will be done in two phases, one for each six-panel array. The first is scheduled for the summer of 2007 and the second for the summer of 2009. The cost of this replacement is significant. Following the replacement of the insulators in the first array, there will be enough safety core insulators to double-insulate the second array. If it can be shown that the use of modified rings and/or

double-insulating would enable the safety core insulators to operate reliably at Cutler, the second procurement could be avoided, with considerable savings to the Navy.

Therefore, it is recommended that the U.S. Navy pursue design and testing of a modified corona ring assembly for the Cutler safety core insulator assembly for Cutler that will significantly increase the surface flashover threshold, thereby enabling reliable operation at with the existing insulators.

Design and testing would consist of the following:

1. Theoretical and empirical (at Dixon) investigation of the corona onset levels at the triple point.

2. Computer analysis of the existing insulators to design corona mitigation hardware for the triple point.

3. Modification of impulse generator circuitry to maintain fast raise time but reduce ringing and peak current.

4. Future scale model tests with high-speed photography available to determine the flashover path.

5. Scale model impulse tests to examine the effect of material, surface shape (rain sheds), and surface condition.

6. Scale model impulse tests at Dixon with appropriate material as determined from item 5 above for a Cutler insulator to determine optimum aspect ratios for corona rings and minimum air-gap to surface-length ratios.

7. Scale model tests at Dixon, including impulse and impulse + RF tests.

8. Scale model tests using a different scale to be conducted at a facility having a large lightning simulator like Hydro Quebec. These tests would be useful for quantifying the velocity factors and for simulating the response of the insulators to higher dV/dt impulses than are available for full-scale testing.

9. Full-scale testing of a final set of designs at a facility like Hydro Quebec with a large lightning simulator.

REFERENCES

[1] Hansen, P. M., "Mean Time Between Failure for Safety Core Insulators,"[1] SPAWAR Systems Center San Diego, San Diego, CA.

[2] Hansen, P. M., "Safety Core Insulator Fiberglass Belt Simulated Failure Test," SPAWAR Systems Center San Diego, San Diego, CA. 20 September 2004[2].

[3] Cummins, K. L. and E. P. Krider, "Analysis of Lightning Strike Data at VLF/LF Sites," Technical Report, University of Arizona, Institute of Atmospheric Physics, April 2006.

[4] Zueck, R., "Panel Insulator Failure on 21 August 2004 at Naval Computer and Telecommunications Area Master Atlantic Station (NCTAMSLANT) Detachment Cutler, Maine, Naval Facilities Engineering Command – Engineering Service Center," Site Specific Report SSR-3045-SHR, Port Hueneme, CA, June 2005.

[5] Dube, R. and M. Lafreniere, "Test Report - Acrylic Insulator," IREQ Report 53021602, Hydro Quebec Institute for Research, 6 June 2003.

[6] Watt, A. D. and P. M. Hansen, "Notes on Lightning Caused Insulator Failure," SPAWAR Systems Center San Diego, San Diego, CA, 15 February 2005[3].

[7] Hansen, P. M., "Response of VLF Antennas to a Direct Lightning Strike," Report in Progress, SPAWAR Systems Center San Diego, San Diego, CA.

[8] Dann, G., "Test Plan - Lightning Simulation on Safetycore insulator using Impulse Generator," Naval Facilities Engineering Command – Engineering Service Center, Port Hueneme, CA, March 2005

[9] Dann, G. and P. M. Hansen, "Quick-Look Report - Investigation of Lightning Effects on Insulator," Naval Facilities Engineering Command – Engineering Service Center, Port Hueneme, CA, June 2005.

[10] Hansen, P. M. and A. D. Watt, "VLF/LF High Voltage Design and Testing," Technical Report 1904, SPAWAR Systems Center San Diego, San Diego, CA, September 2003.

[11] Monga, S., "Breakdown Mechanism of Bridged Air Gaps," Report 993-76-7913, Arizona State University, December 2004.

[12] Ramrus, A., "Notes on Background Reports Pertaining to Breakdown and Surface Tracking on Air/Plastic Interfaces," Applied Pulse Technology, Inc., 12 September 2005.

[13] Martin, T. H., M. Williams, and M. Kristiansen, "J. C. Martin on Pulsed Power - Advances in Pulsed Power Technology," Plenum Press, Springer, 1996.

[14] Advienko, A. A. and M. D. Malev, "Flashover in Vacuum," *Vacuum* 27, 643 (1977).

[15] Advienko, A. A., "Surface Breakdown of Solid Dielectrics in Vacuum, I. Characteristics for Breakdown of Insulator Along the Vacuum Surface," *Sov. Phys. Tech. Phys.* 22, 982 (1977).

[16] Anderson, R. A., and J. P. Brainard, "Mechanism of Pulsed Surface Flashover Involving Electron-Stimulated Desorption," *J. Appl. Phys.* 51, 1414 (1980).

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[1] Contact P. M. Hansen for more information.

[2] Contact P. M. Hansen for more information.

[3] Contact P. M. Hansen for more information.

[17] Bugaev, S. P. et al., "Investigation of The Pulsed Breakdown Mechanism at the Surface of a Dielectric in Vacuum, I. Uniform Field," *Sov. Phys. Tech. Phys.* 12, 1358 (1968).

[18] Gray, E. W., "Vacuum Surface Flashover: A High Pressure Phenomenon," *J. Appl. Phys.* 58, 132 (1985).

[19] Sampayan, S. E., G. J. Caporaso, W. C. Nunnally, D. M. Sanders, J. A. Watson, M. L. Krogh, and H. U. Anderson, "High Gradient Multilayer Insulator Technology," Beam Research Program, Lawrence Livermore National Laboratory.

[20] Gorur, R., S. Monga, and S. Dalal, "Electric Field Calculations for VLF Cutler Panel Insulator and Test Jig," Final Report tasks 3.2 and 3.3, Arizona State University, Phoenix, AZ, November 2004.

[21] Hansen, P. M. "Trip Report - Visit to Austin Insulators, 23 July and 2–6 August, 2004," Trip Report, SPAWAR Systems Center San Diego, San Diego, CA, August 2004.[4]

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[4] Contact P. M. Hansen for more information.

APPENDIX A: POLYCARBONATE PLASTIC SPECIFICATION

POLYCARBONATE NATURAL ASTM D-3935 PC110B34720

Agency approvals or listings: FDA, USP

Base resin trade names: LEXAN

MECHANICAL PROPERITIES

Specific gravity (ASTM D 792): 1.20

Tensile strength, ultimate (ASTM D 638): 9,000 psi

Elongation at break (ASTM D 638): 130%.

Tensile modulus (ASTM D 638): 3.1 X 1O~5 psi

Rockwell hardness (ASTM D 785): Rl18

Impact strength (73*F) (ASTM D 256) (notched): 17.0 ft-Ib/inch

Flexural strength (ASTM D 790): 14,200p.s.i.

Flexural modulus (ASTM D 790): 3.4 X 1O~5 psi

Wear factor against steel 40 psi 50 fpm: 2500 X 1 O~ 10

Coefficient of friction 40 psi 50 fpm: 0.38 Dynamic

THERMAL PROPERITIES

Melting point: 310*F

Heat deflection at 66 psi (ASTM D 648): 285* F

Heat deflection at 264 psi (ASTM D 648): 270* F

Maximum serving temperature for short term: 275* F

Maximum serving temperature for long term: 240* F

Thermal conductivity (ASTM C 177): 1.35 Btu-inch/hr-ft~2-* F

Specific heat: 0.30 Btu/lb-* F

Coefficient of linear thermal expansion (ASTM D 696): 3.7 X 10~5

Applicable temperature for thermal expansion: 0-200* F

ELECTRICAL PROPERTIES

Dielectric constant at 60 Hz (ASTM D 150) (73* F, 50% RH): 3.2

Dissipation factor at 60 Hz (ASTM D 150) (73* F): 0.001

Volume resistivity (ASTM D 257): 1O~17 ohm-cm

Dielectric strength (ASTM D 149): 380v/mil

MISCELLANEOUS

Water absorption - 24 hours (ASTM D 570): 0.15%

Water absorption saturation (ASTM D 570): 0.35%

Density (ASTM D 792): 0.0434Ib/inch~3

Flammability (UL94): V-2

Weathering resistance: Limited resistance (UV Sensitive)

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6. AUTHORS

P. M. Hansen
SSC San Diego

G. Dann
Naval Facilities Engineering Service Center

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14. ABSTRACT

This report describes an investigation into safety core insulator failures at Naval Radio Transmitting Station, Cutler, Maine. The failures are believed to be the result of lightning strikes to the antenna. Impulse tests showed that flashover occurred along the surface of the insulator when the voltage rises very fast (high dV/dt), resulting in damage to the insulators. Scale model tests were conducted to determine if different corona ring configurations could keep flashover away from the insulator body. Results indicated that the insulators could be protected from lightning-induced impulse flashovers with the appropriate corona ring configurations. Replacing or modifying the corona rings on the existing insulators would be much less expensive than replacing failed insulators. The authors recommend that the U.S. Navy pursue design and testing of a modified corona ring assembly for the Cutler safety core insulator assembly that will significantly increase the surface flashover threshold, thereby enabling reliable operation with the existing insulators.

15. SUBJECT TERMS

Mission Area: Communication and Information Systems
Naval Radio Transmitting Station, Cutler, Maine
safety core insulator failures   impulse flashover tests

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