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CRADA Final Report
for
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Application of High-Speed Infrared Imaging to Study Transient Joule Heating in Station Class Zinc Oxide Surge Arresters

R. B. Dinwiddie
Hsin Wang
Oak Ridge National Laboratory
Metals & Ceramics Division

Bengt Johnnerfelt
PTHV Surge Arrestor

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Oak Ridge National Laboratory
Oak Ridge, Tennessee 37831
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Abstract

Zinc Oxide based surge arresters are widely used to safeguard and improve reliability of the electrical power delivering and transmission systems. The primary application of surge arresters is to protect valuable components such as transformers from lightning strikes and switching transients in the transmission lines. Metal-oxide-varistor blocks (MOV, e.g. ZnO) are used in surge arrester assemblies. ORNL has developed an advanced infrared imaging technique to monitor the joule heating during transient heating of small varistors. In a recent short-term R&D effort, researchers from ABB and ORNL have expanded the use of IR imaging to larger station-class arrester blocks. An on-site visit to the ABB facility demonstrated that the use of IR imaging is not only feasible but also has the potential to improve arrester quality and reliability.

The ASEA Brown Bower (ABB) Power and Technology & Development Company located at Greensburg PA having benefited from collaborative R&D cooperation with ORNL. ABB has decided a follow-on CRADA project is very important. While the previous efforts to study surge arresters included broader studies of IR imaging and computer modeling, ABB has recognized the potential of IR imaging, decided to focus on this particular area. ABB plans to use this technique to systematically study the possible defects in the arrester fabrication process. ORNL will improve the real-time monitoring capability and provide analysis of the infrared images. More importantly, the IR images will help us understand transient heating in a ceramic material from the scientific standpoint. With the improved IR imaging ABB and ORNL will employ the IR system to visualize manufacturing defects that could not be detected otherwise. The proposed on-site tests at ABB Power Technology & Development processing facility will identify the defects and also allow quick adjustments to be made since the resulting products can be inspected immediately. ABB matched the DOE $50K funding with $50K funds-in to ORNL. ABB also provided about $75K in-kind effort for on-site testing, and R&D to improve the fabrication process.

Statement of Objectives

The CRADA project between ORNL and ABB Switchgear was aimed at understanding joule heating of station class surge arresters during electrical breakdown. The infrared imaging technology developed at ORNL was used to obtain temperature maps of the arrester during and after the impulse.

The ORNL objectives are:

1) To improve and develop specific procedures and algorithm for the high-speed infrared imaging system of surge arresters;
2) To use the first-hand knowledge to improve understanding of surge arresters and maintain ORNL's leading role in varistor research; and
3) To meet DOE's goals of improving the safety and reliability of the power transmission and distribution systems.

The ABB objectives are:

1) To use the advanced IR imaging technique to identify manufacturing defects in surge arresters;
2) To adjust and improve fabrication processes to identify and eliminate the source of the defects; and
3) To improve the fabrication and inspection of surge arrester and provide higher quality products to the market.

Benefits to the Funding DOE Office's Mission

This project is a good example of applying new IR imaging technology to the power transmission market. It is closely related to DOE's mission in energy transmission and safety of the electrical grid. Surge arresters protect vital equipment and components in the power transmission system during unexpected power interruptions. With increasing concern in the nations energy supply and delivery systems, improved reliability is the most important task. Moreover, this study provides information on arresters that has never been available before. ORNL researchers, as well as the electronic ceramic research community, will benefit from the improved understanding of electronic breakdown in grain- boundary devices.

Technical Discussion of Work Performed by All Parties

This CRADA was based on work performed under a Fiscal year (FY) 2000 Laboratory Technology Reservoir ((LTR) sponsored small CRADA, which was a feasibility test for the application of IR imaging. The LTR project was a success. After completing lab tests at ORNL for subscale arresters, the more challenging task was learning the proper way to shield the IR camera in a high RF environment at the ABB testing facility. The IR camera survived very high-energy tests (4 ms pulse with V=21kV, I = 850 A and Energy = 46 kJ). This not only proved the feasibility of the technique, but more importantly revealed information about various defects in the arresters. The ability to show the defects as an IR image had never been done for the production scale arresters. The result was on technique that has two major uses: 1) to identify defects in the arresters and relate the defects to the fabrication process, and 2) to use the IR imaging as a real-time assembly line inspection tool.

In this follow-on CRADA project, the effort was focused on IR imaging

Experimental Approach

<u>Facilities and equipment:</u> This project was performed at ORNL's Metal and Ceramics Division and facilities of the ABB Power Technology & Development Company at Greensburg PA.

The key equipment for this study was a Raytheon, Radiance HS high-speed, high-resolution infrared camera. Built initially for US military applications, this camera utilizes the focal plane array (FPA) imaging technology and advanced digital image acquisition system. The camera operates in a snapshot mode with it 256 x 256 pixel array exposing to 3-5 μm thermal radiation simultaneously. The camera takes images at 144 Hz at full frame. When zooming down to 64 x 64 pixel format, it can take images at 6 kHz. The other most important feature is the temperature resolution of 0.015°C. It remains the most sensitive IR camera available. In the previous feasibility study, we discovered a shielding weakness of the camera in the high-power testing environment. The IR camera survived the most severe arrester testing after ORNL improved the RF protection. This system is portable. and was used successfully at ABB test facility.

ORNL has developed arrester test capability for subscale blocks. For example, the pulse generator located in the

M&C Division was used to test arresters from ABB as part of the previous CRADA. ORNL also has extensive image analysis software that will be made available for this project.

Full size arrester blocks will be tested at ABB's High Power testing facility. ABB's arrester production facility will provide all the specimens needed in the project.

Original Work Plan:

Task 1: ABB will produce a series of arrester blocks with artificial defects. Blocks from normal production will be selected for testing. Blocks with adjustments of specific processing parameters will be made following a formal design of experiments approach

Task 2: ORNL will use its existing and new IR cameras to refine imaging and analysis capabilities, namely to improve the camera synchronization with high power testing.

Task 3: IR imaging tests will be conducted at ORNL on subscale blocks. Full size blocks will be imaged at the ABB testing facility.

Task 4: ORNL will conduct image analysis and provide ABB with temperature maps of arresters produced using current production processes. ABB will vary the fabrication parameters to produce additional blocks for more testing based on a design of experiments approach.

Task 5: ORNL and ABB will explore the possibility of integrating IR imaging technology into ABB's production line as an inspection tool and feedback sensor.

Work Performed by both Parties and Discussion

All the planned tasks were completed at ORNL and ABB. Three trips were made to ABB testing facilities. Each trip typically collected more than 2 GB of IR images. The images were taken back to ORNL for further analysis. Technical data and field trip reports were made available to both parties. Selected results from work performed during the project are described below:

Artificial Defects:

In large station-class arresters, the infrared technique has not been previously explored. In this study, we prepared two types of artificial defects in the arrester block: the first, a surface dimple, 0.25 mm – 0.5 mm deep and 2.5 mm in diameter, was machined before putting on the electrode.

The small thickness variation is enough to generate high current concentration simulating surface defects in real arresters; the second used a small tube, 4 mm in diameter, of powder 10-20 vol% with lower resistivity, which was mixed with regular powder. The mixture can create enough difference in breakdown voltage and cause current concentration in the area simulating processing defects. The arrester blocks with artificial defects were subjected to standard energy-withstand tests. Although, the defects are extreme conditions that seldom occur in manufacturing process, they served as well-controlled defects. The infrared imaging showed for the first time how the current concentration occurred and the progressive damage to the arrester. In fact, a regular arrester with hot spots was tested and similar failure features were observed as the artificial defects.

Surge arresters were prepared by or at ABB Switchgear facility in Ludvika, Sweden. They were standard 6kV, 62 mm diameter and 42 mm thick, ZnO arrester blocks. The average grain size of the arrester is 10 μm. Two types of defects were put into the arresters as previously described. As shown in Figure 1(a), a small dimple, 2.5 mm in diameter and 0.2-0.5 mm deep, was machined into the specimen. An aluminum electrode was then put on the surface. The 1-2% change in thickness is enough to produce large current concentration in this highly non-linear material. As shown in Figure 1(b), a small tube containing a mixture of regular powder and 10-20 vol% low resistivity powder was imbedded in the green body. The location of the tube was marked. The block was then sintered exactly as regular production blocks

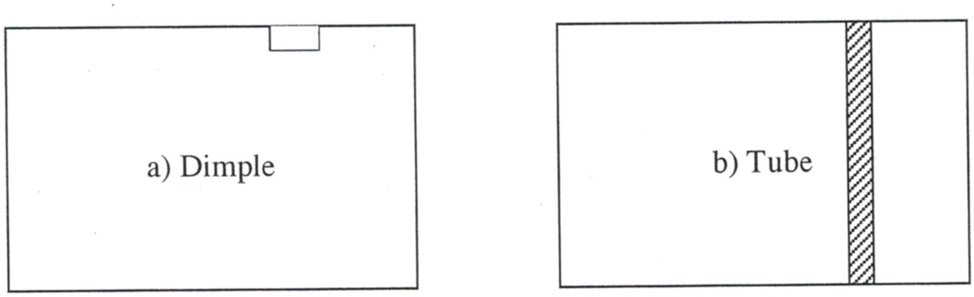


Figure 1. a) Artificial surface defect: machined dimple, b) current concentrating "tube" by mixing 10-20 vol% low resistivity powder with regular powder.

Energy-withstand tests were carried out at the ABB High Voltage Testing facility in Ludvika Sweden. Following standard testing protocol for arrester blocks, a 4-millisecond square wave impulse was injected into each arrester. Depending on the voltage rating of each block, a predetermined amount of energy was injected to the block. The typical temperature rise after a single pulse is about 25-30° C.

To calibrate the temperature, a small thermocouple was placed on the block surface after the impulse. Multiple images with a temperature marker were taken while the arrester block was cooling down. Then the IR intensity vs. Temperature calibration was used to convert to the temperature specific camera settings, distance and surface condition.

Artificial Defects: Dimples

Dimpled arrester blocks were prepared with various dimensions. A typical dimple has a diameter of 2.5 mm and is 0.25-0.5 mm deep. Three IR sets of images were taken for each defect: 1) dimple surface, 2) the dimple-free surface, and 3) the cross-section after cutting the arrester in half. In each test, the same amount of energy was injected into the block. In the cross-section tests, since only half of the sample was tested, the total surface temperature rise was similar to the other two tests. Figures 2(a), (b) and (c) are IR images of a dimpled block with line temperature profiles. In Figure 2(a), the dimple was facing the camera and located at the 12 o'clock position. The IR image showed a sharp temperature peak of more than 32° C at the dimple site indicating current concentration. It was shown for the first time that the hot dimple area was surrounded by a cold ring near the background temperature. This is due to the unique nonlinear I-V behavior of the ZnO arrester. The dimple made a small surrounding area inactive (or less active) due to lower resistance paths. The area away from the dimple was not affected but had a much lower current going through it. The average temperature rise on the arrester surface was about 1° C.

When the arrester was turned around with the camera observing the dimple-free surface, the IR image, as shown in Figure 2(b) exhibited a much broader peak with a temperature rise only about 1.6° C. The cold ring observed from the other side disappeared. The overall temperature rise was about 0.9 C. This proved that the current concentration caused by localized defects (such as a dimple) could diffuse as more current paths become available away from the defects. In fact, the effect of the dimple was hardly noticeable from the opposite side when the dimple depth was smaller than 0.2mm. However, the dimple site can exhibit a very localized high temperature.

Figure 2(c) confirms the current concentration and diffusion in an arrester block by imaging the cross- section area when the arrester was cut in half. Since the cut was about 0.1-0.2 mm from the dimple, the observed temperature was different from the top view. The hot area, cold ring and current concentration and diffusion can all be observed clearly.

Artificial Defects: Tubes

Unlike dimples, which simulate surface defects, tubes in the arrester were made to simulate 3-dimensional defects that extend through the entire thickness of the arrester. Figure 3(a) shows the temperature map and line profile of a tube, 4 mm in diameter and with 10 vol% low resistivity powder. The line-temperature profile through the tube showed a sharp temperature peak with half-peak width about 4 mm. There was an 8-9 ° C temperature increase in the rest of the block. We also observed a colder area surrounding the tube. However, this area was much larger than the dimple, Figure 2(a).

When the arrester block was turned around and injected with similar energy, we observed almost identical temperature map and temperature distribution, as shown in Figure 3(b). The peak temperature increase was about 15 ° C, with a similar temperature dip in the surrounding area.

The block was then cut and observed from the cross-section view. Figure 3© shows that the temperature rose sharply at the tube position. The overall temperature was higher because only half of the block was used to take the same energy. A closer look at the tube also showed the tube is not uniform. Since the mixing and dispersion of the powders were not uniform.

Figure 4 shows the failure of one of the blocks with an artificial defect. The high current concentration caused local melting and cracking of the sample. The result was a high temperature flash that overloaded the camera. The following images show the damage done by the pulse.

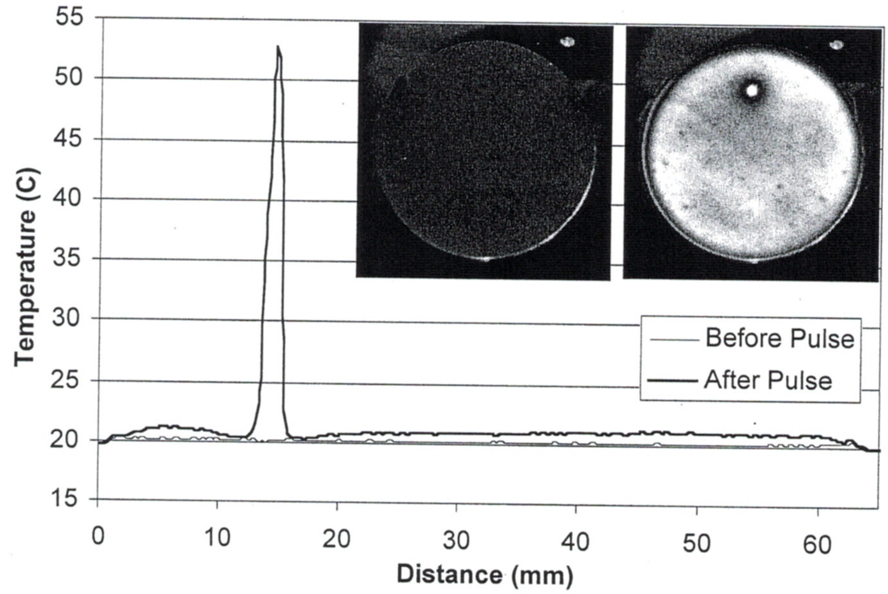


Figure 2(a) Temperature distribution on the surface with a small dimple.

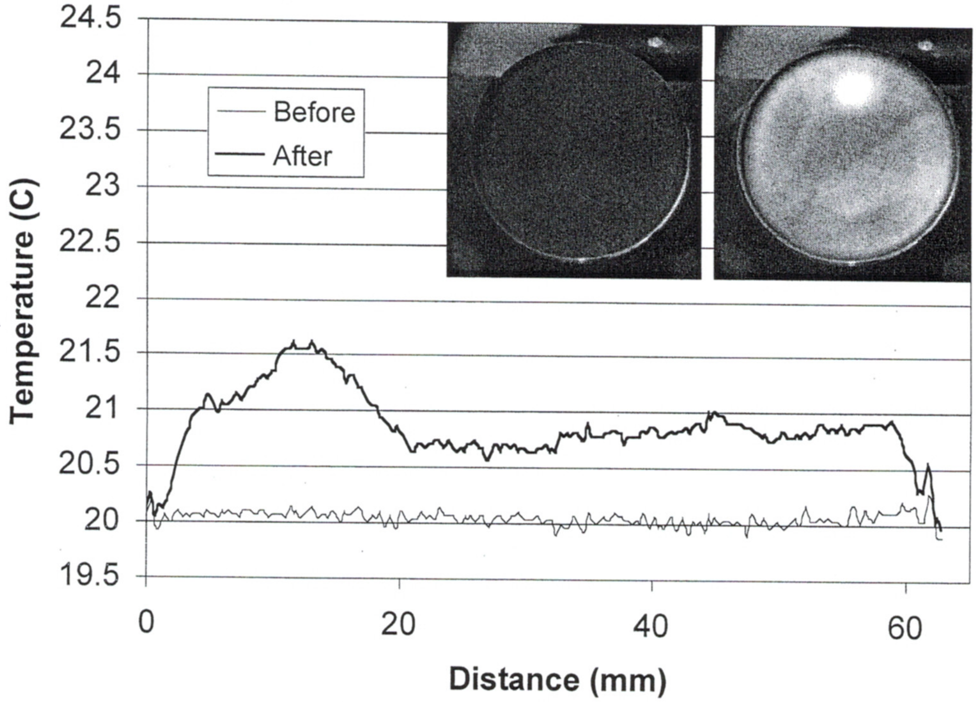


Figure 2(b) Temperature distribution on the surface opposite to the dimple.

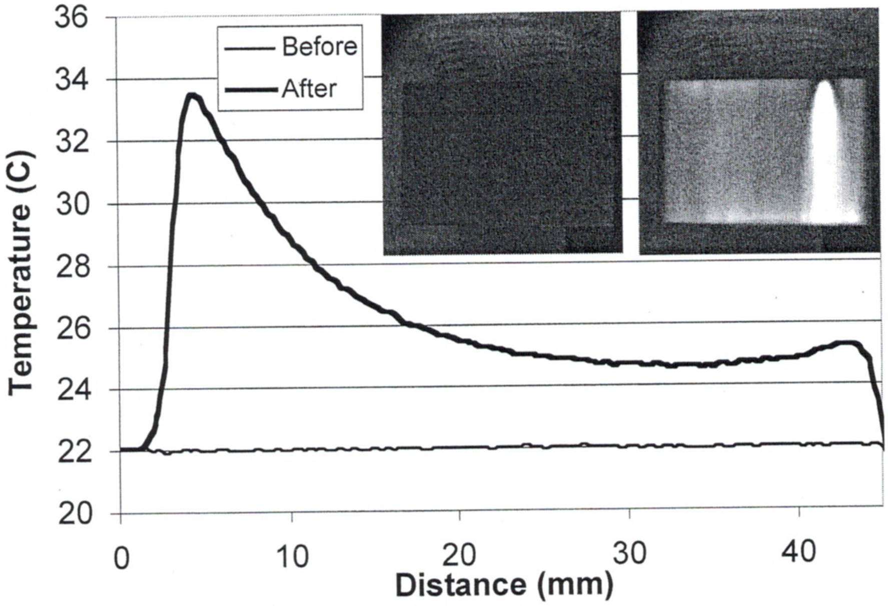


Figure 2(c) Cross-sectional view of temperature distribution caused by a dimple.

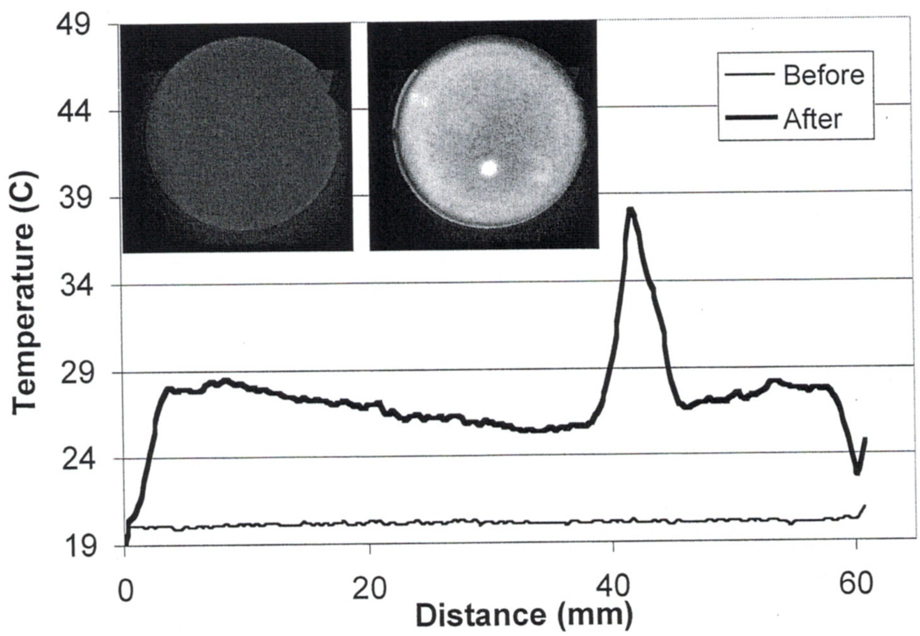


Figure 3(a) Bottom surface temperature distribution of a 4 mm diameter tube defect with 10vol% low resistivity powder.

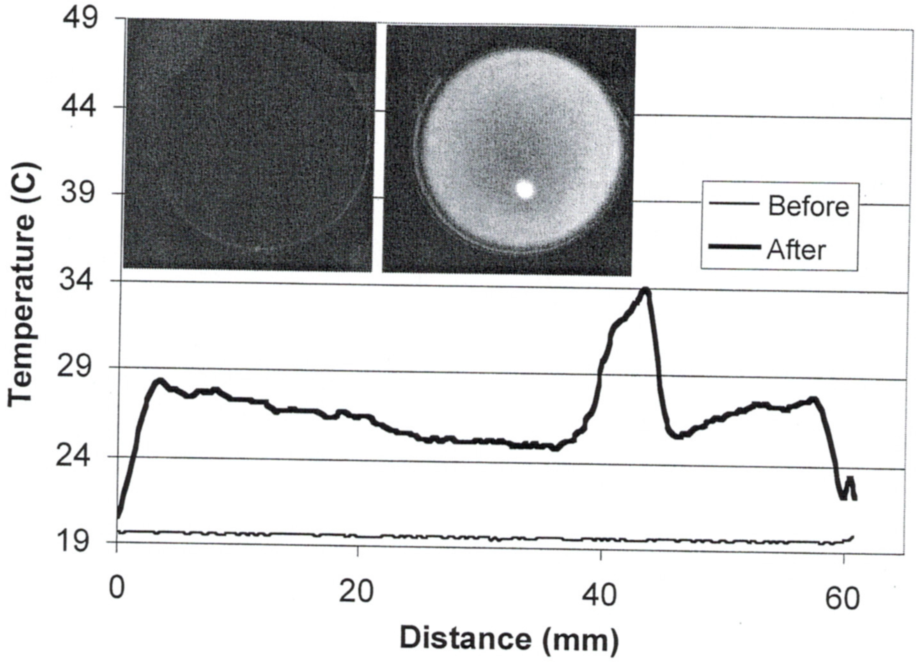


Figure 3(b) Top surface temperature distribution of a 4 mm diameter tube defect with 10vol% low resistivity powder.

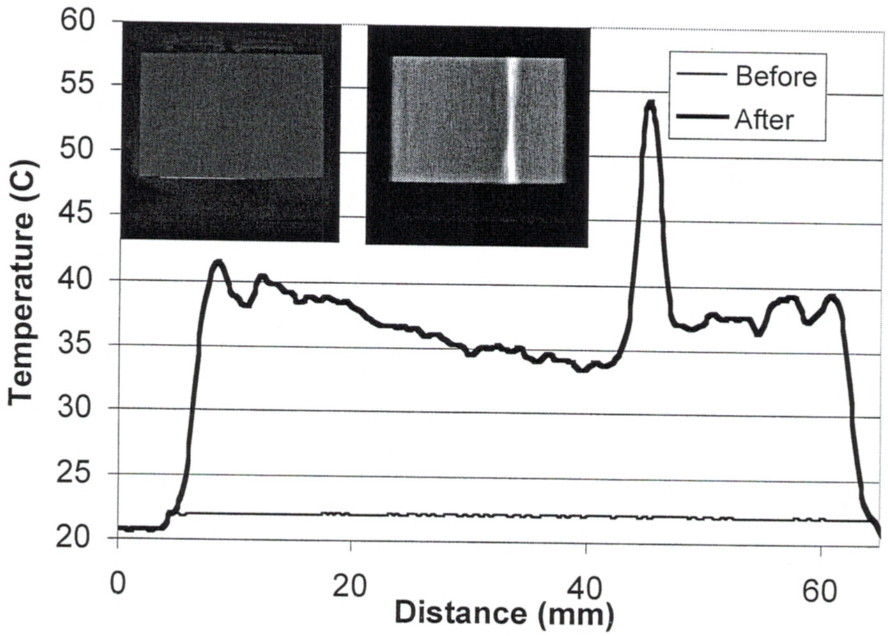


Figure 3(c) Cross-section view of a tube defect.

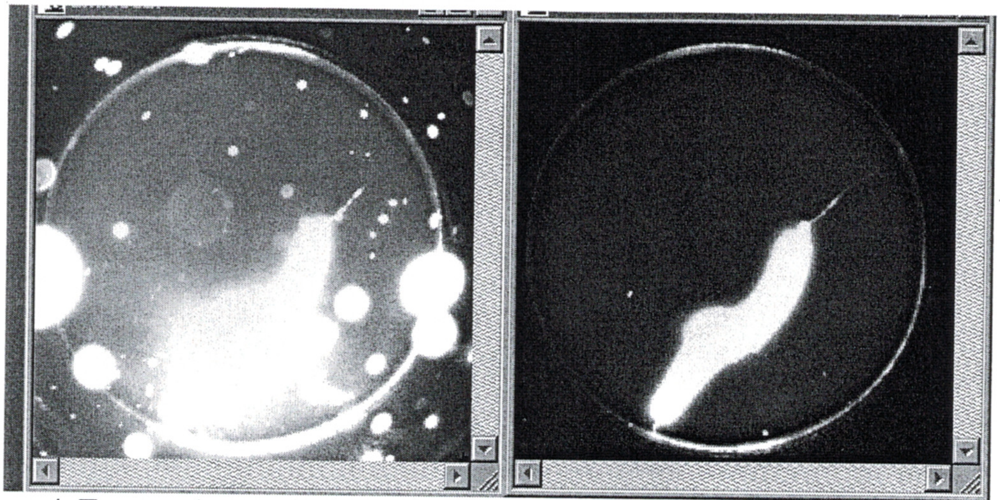
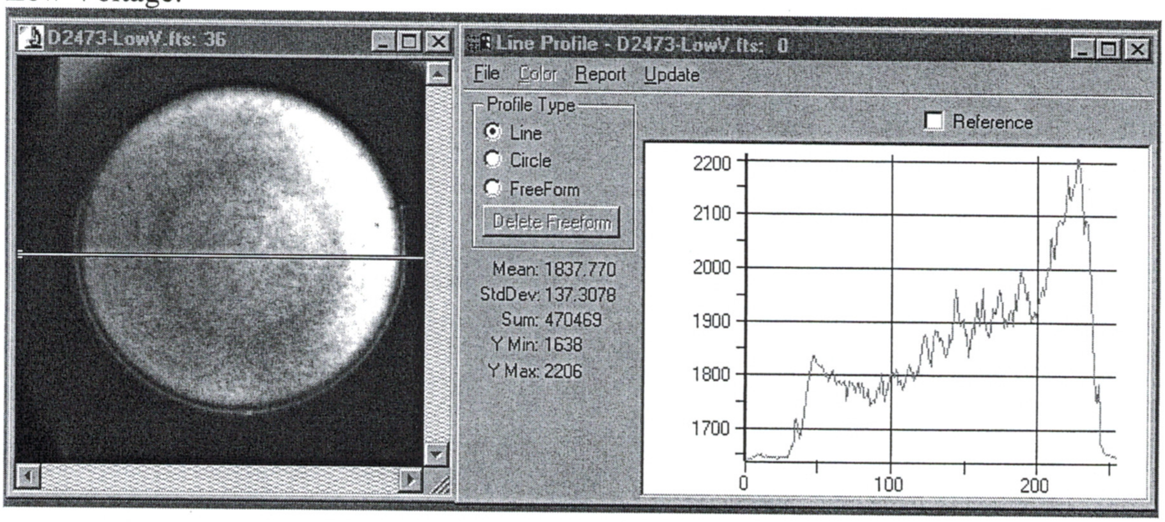


Figure 4. Too much energy, the sample failed at the dimple site. A crack went through the dimple.

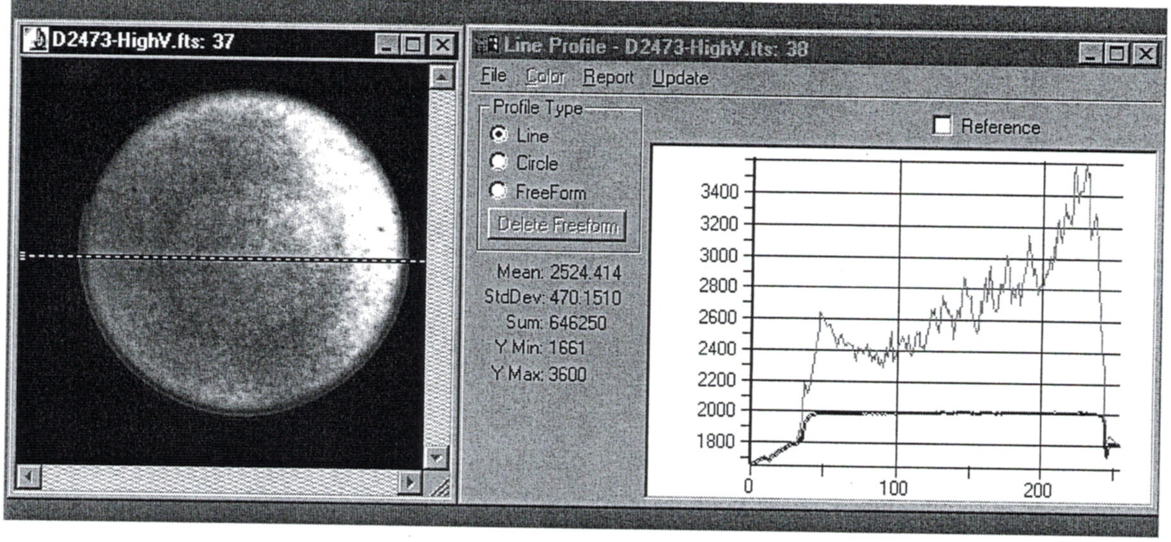
Non-uniform temperature distributions in arrester blocks~~(contents in this section contain CRADA protected information)~~

The following images showed non-uniformity observed in the ABB arrester blocks. The conditions were different for each block. The temperatures shown are not calibrated since we were mainly interested in the distribution. These are selected examples from a total of 7 GB of IR images.

Low Voltage:

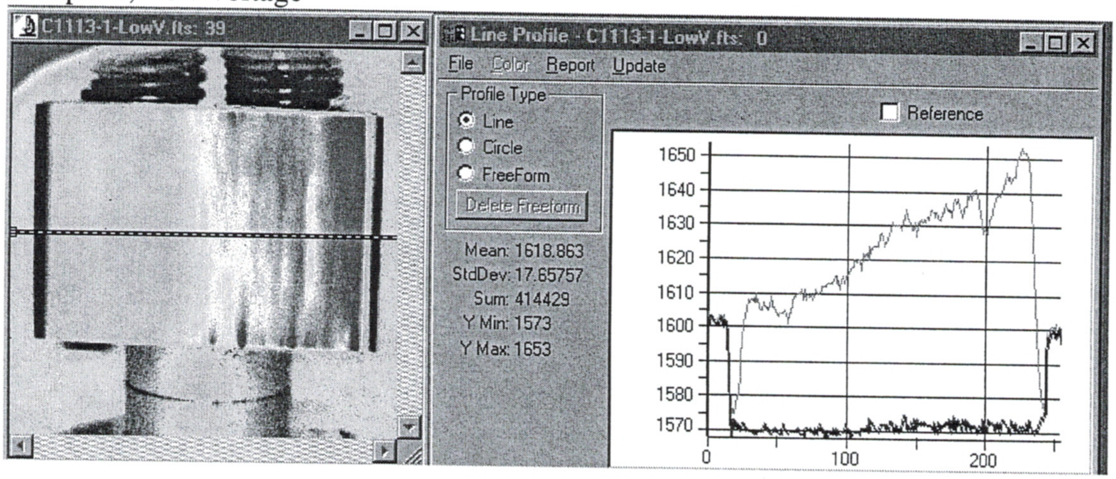


High Voltage

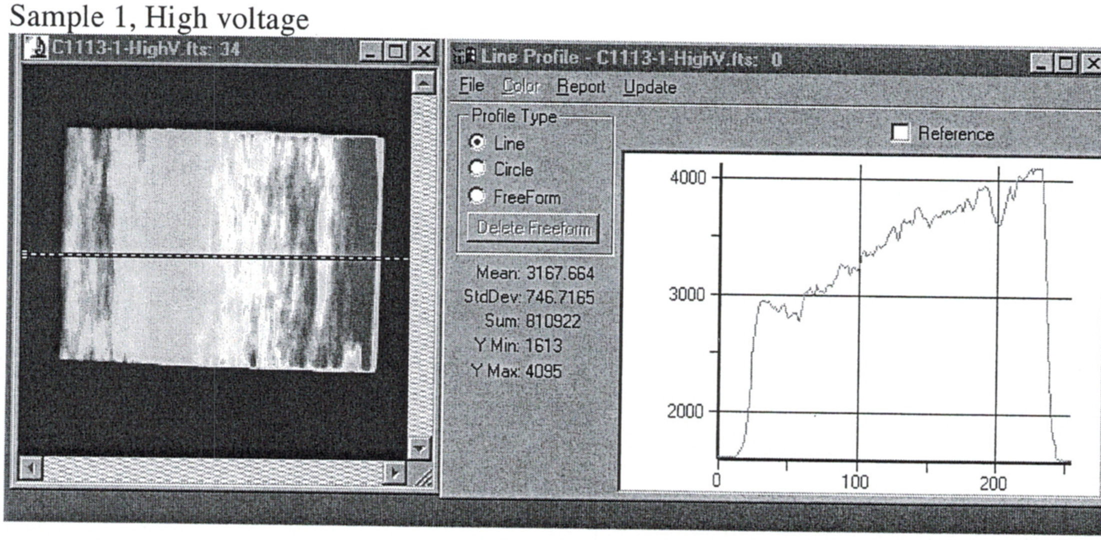


Side and Top Views of Arrester Samples

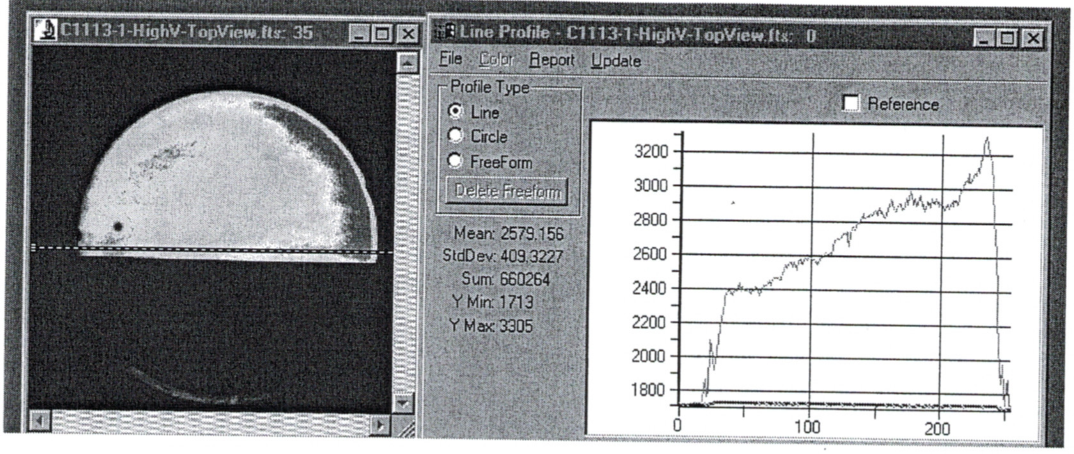
Sample 1, Low voltage



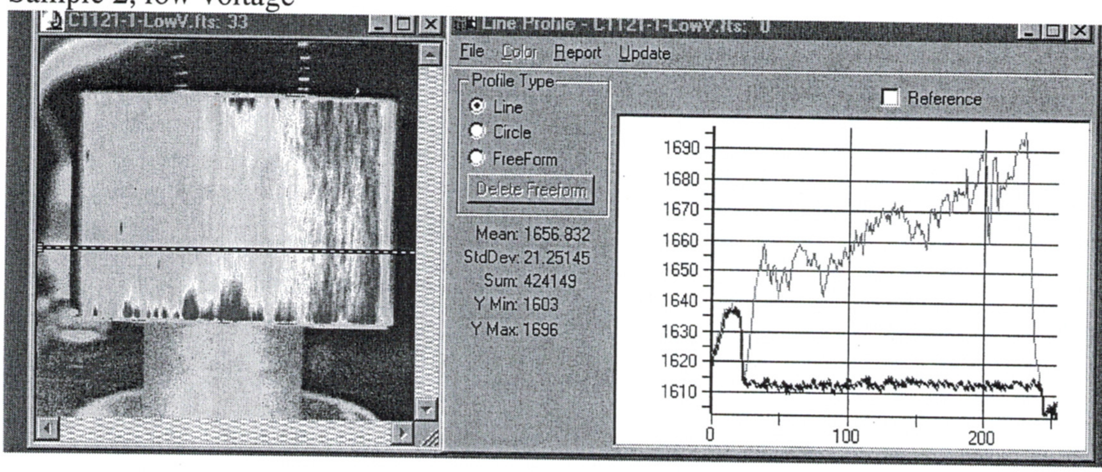
Sample 1, High voltage



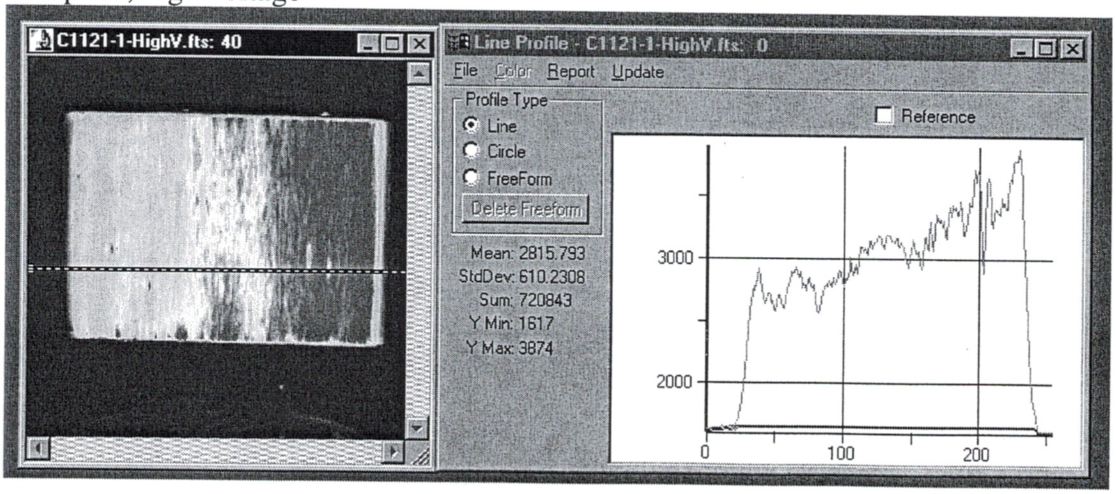
Sample 1, high voltage, top-view



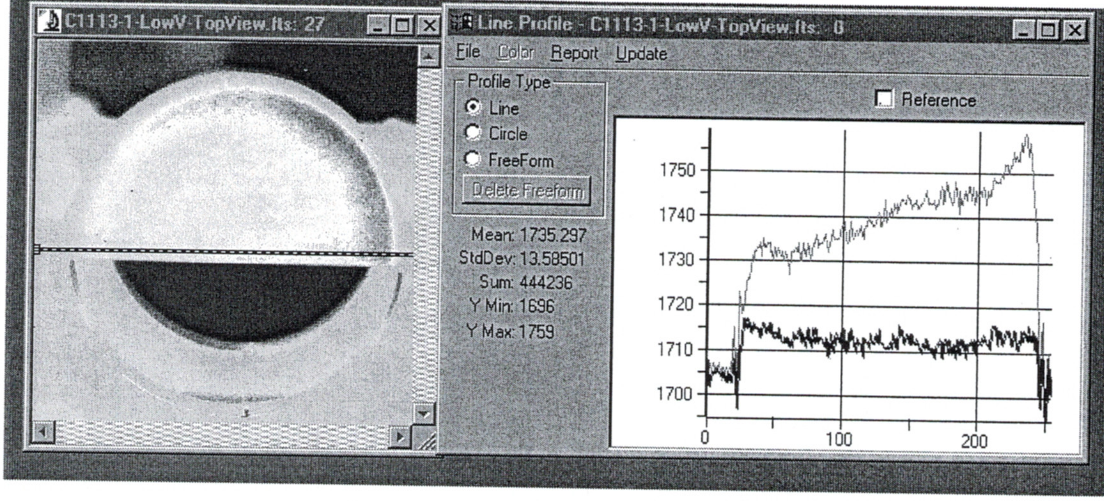
Sample 2, low voltage



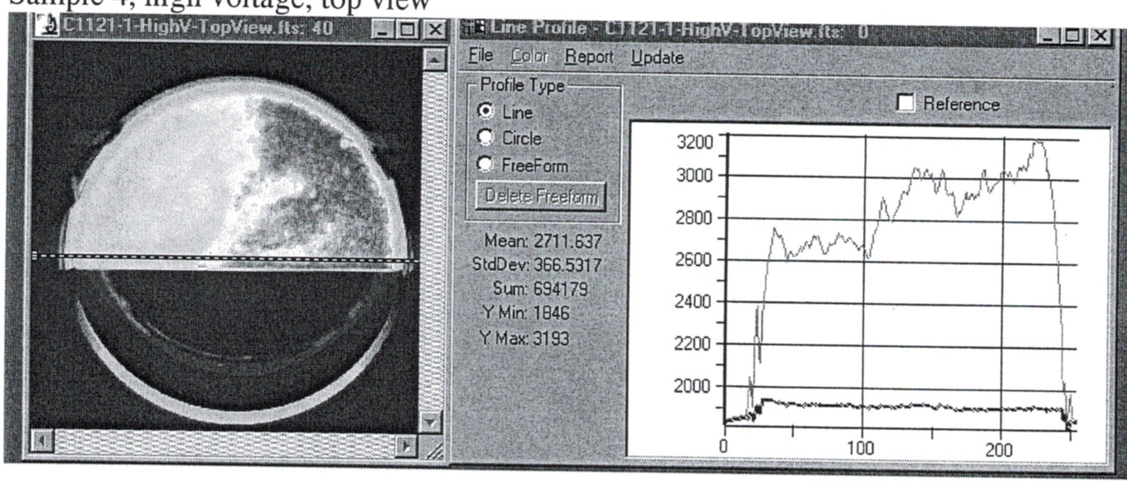
Sample 2, high voltage



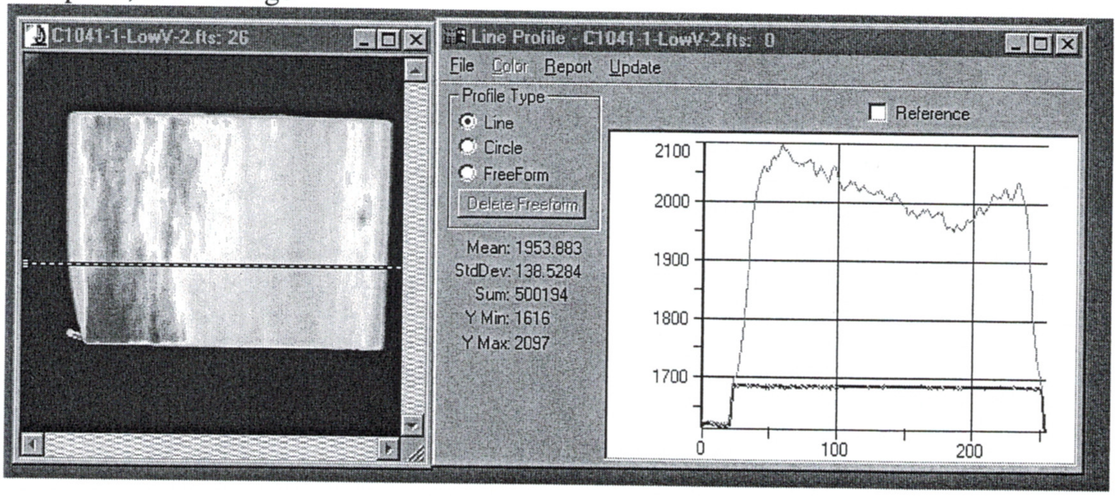
Sample 3, low voltage, top view



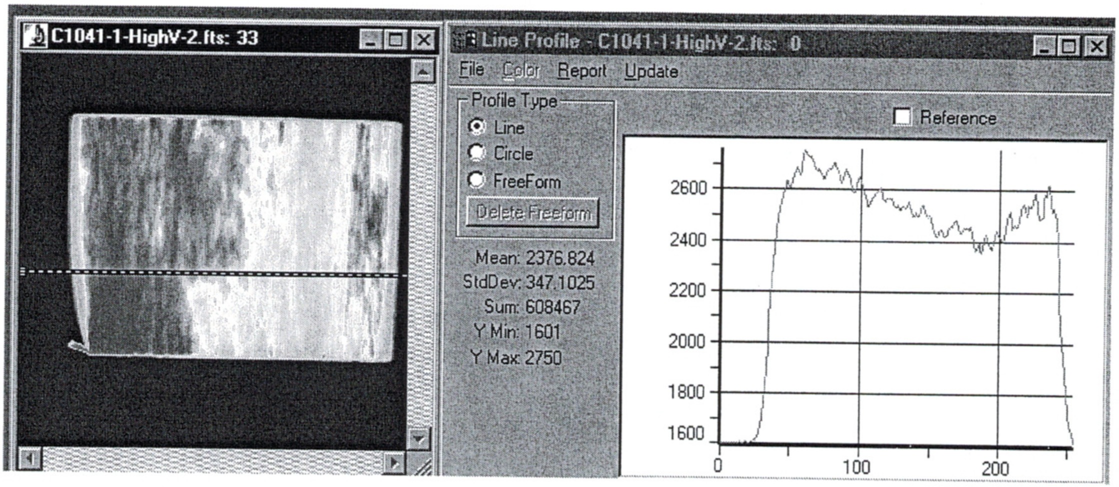
Sample 4, high voltage, top view



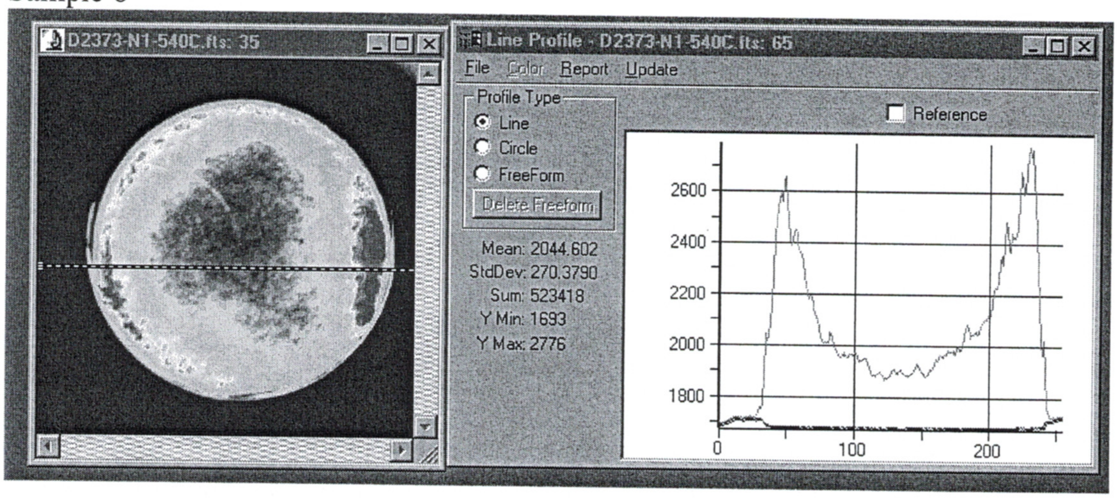
Sample 5, low voltage



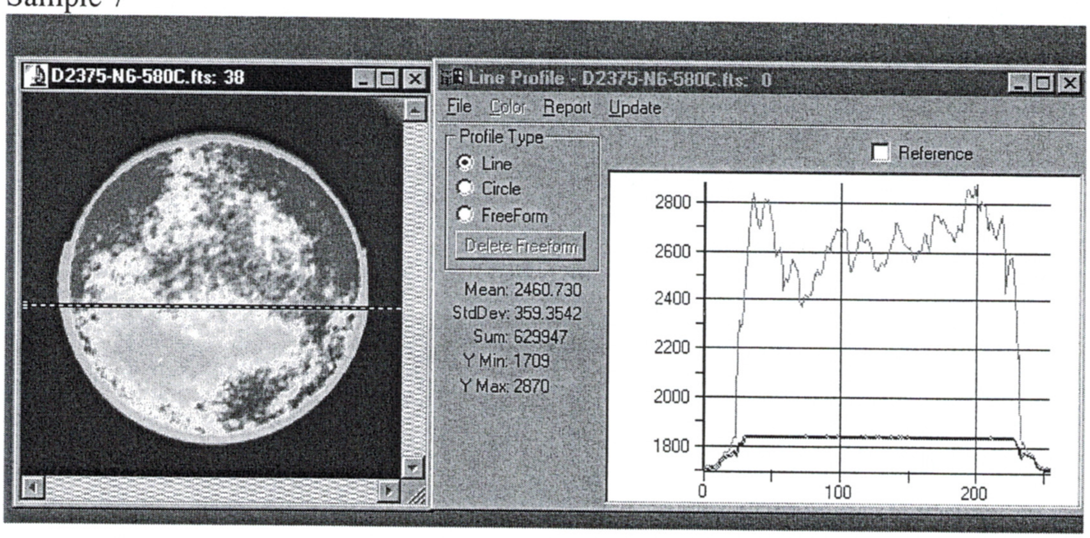
Sample 5, high voltage



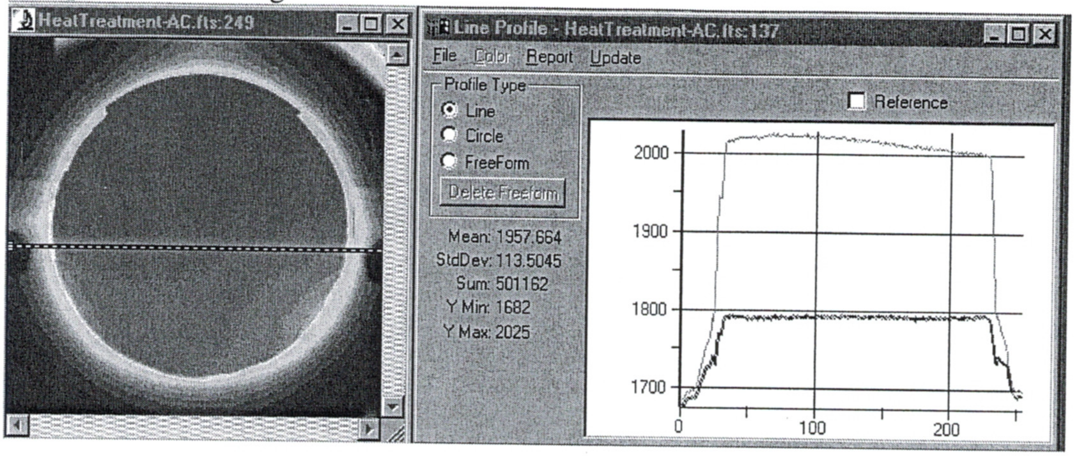
Sample 6



Sample 7



Sample 8 AC heating



Subject Inventions

This CRADA project was based on an existing technology from ORNL. The basic information of the technique has been published. The application to station class arresters involved some modification of the apparatus. At the end of the project, no invention disclosure had been filed.

Commercialization Possibilities

Based on the feasibility study, this CRADA project may bring the commercialization of the IR imaging technique for arrester fabrication one step closer. IT was shown that the IR camera could be used in a high-power environment. The IR images obtained from these preliminary case studies have convinced ABB that this technique can help them improve arrester quality and reliability. ABB's willingness to continue with a follow-on CRADA project indicates the commercialization potential of this technique. With the global trend for greater safety and reliability of electric-energy delivering systems, this CRADA project with ABB may enter the market place more quickly.

Plans for Future Collaboration

Based on the results of the projects both ABB Switchgear and ORNL are very interested in continuing the collaboration. This work, the electrical grid security and reliability, which continues to be an important mission for DOE. More research opportunities are expected in FY04 and FY05. It is anticipated that the collaboration of the use of the advanced thermal imaging to better understand the arrester breakdown behavior and improve the reliability of the products will continue.

Conclusions

We have successfully completed the CRADA project with ABB Switchgear. The IR imaging technique has been proven to be the most effective method to detect various manufacturing defects in surge arresters. We have shown that this technique can reveal artificial defects as well as natural defects in production blocks. Detailed understanding of the cause of non-uniform current distribution is still lacking. We expect to collaborate in the future to better understand the relationship between microstructure and electrical properties of the ZnO surge arresters.

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