

STIM and Micro-PIXE Analysis of Water Trees in HV Cables

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Abstract

Microscopic water trees that prematurely degrade the insulation of underground electric power cables were analyzed using a scanning proton microbeam. Field-aged cable samples were collected from the Eastern Region operational area of Saudi Electricity Company (SEC). The cable samples were stripped of all layers leaving behind only the XLPE (Cross-linked Polyethylene) insulation layer. The insulation layers were microtomed into 10- μm thin sections which were then observed under an optical microscope to visually detect water trees. The insulation sections found to contain water trees were scanned by the proton microbeam. Topographic images of water trees produced using the STIM (Scanning Transmission Ion Microscopy) technique were acquired. Elemental composition and distribution maps for the water trees were measured using the PIXE (Particle Induced X-ray Emission) technique. The results obtained are discussed to evaluate the usefulness of the proton microbeam technique as a novel tool to study the water-treeing problem in HV cables from a different perspective than the usual electrical tests.

Key words: Water trees, HV Cables, Optical Microscopy, STIM, Micro-PIXE

Introduction

Polymeric insulation in power cables was first introduced over 50 years ago. Major utilities in the world opted for underground transmission and distribution systems from safety considerations, pressures from environmentalists and also for esthetic reasons. However, premature degradation of the underground cables soon became a costly problem for the utility sector. One of the major causes of this premature

degradation has been attributed to a phenomenon called water treeing. Water trees are bush-like, hydrophilic, and microscopic structures that develop in cable insulation in humid conditions under the influence of electric field and are affected by a variety of factors. These water trees carry water-soluble impurities from the surrounding materials causing degradation of the dielectric and mechanical properties of the insulation. In spite of the technological developments in producing better materials for cable manufacture including the use of cross-linked polyethylene (XLPE), it has not been possible up to now to completely overcome the problem of water tree growth in the cables. Understanding of this complex phenomenon is still limited although much research has been done over the last 25 years. A large number of studies have been reported dealing with various macroscopic aspects of water trees^{1, 2}. However, very few studies^{3, 4} have so far been attempted to study the problem from the point of view of microscopic examination of the water trees. Determination of the elemental concentrations and distribution profiles in the water trees can provide useful data in understanding the mechanism of water tree inception and growth.

Water tree structures have typical dimensions ranging from several micrometers to several hundred micrometers and may contain impurity elements in ppm concentrations. The micro-PIXE (Proton Induced X-ray Emission with a microbeam) technique⁵ provides a unique non-destructive way to determine elemental composition and distribution profiles with a high degree of elemental detection sensitivity at a micrometer spatial resolution. The present study is an attempt to evaluate the usefulness of the micro-PIXE technique in water tree analysis.

Experimental Method

Sample Preparation

Samples of six field-aged underground high voltage cables were obtained from the Saudi Electricity Company (SEC), Eastern Region Branch. The cables had a voltage rating of 35 kV, a single core copper conductor with a cross sectional area of 500 mm², and an XLPE insulator of thickness 1 cm. The cables were in service for about 17 years in Jubail Industrial City close to the Arabian Gulf.

The collected cable section was cut into small pieces. The inner conductor core and all the outside layers surrounding the XLPE insulation were removed. The bare insulation was microtomed into 10- μ m thin slices for micro-PIXE measurements. The microslices were cleaned using triple distilled, deionized water to remove any external contamination.

Optical Microscopy Measurement

The thin insulation sections were examined under an optical microscope to visually detect the presence of water trees. Water trees observed were photographed with a video camera attached to the microscope and the images were stored as in a PC. These images served to localize the water trees present in the insulation sections for nuclear measurements.

STIM Measurement

The insulation sections determined by optical microscopy to have the presence of water trees were placed before the proton microbeam and a STIM (Scanning Transmission Ion Microscopy) image of the sample surface was quickly obtained. The sample was then moved around the incident beam direction until a complete water structure was within the scanning area of the microbeam.

Micro-PIXE Measurement

Micro-PIXE measurements on the water trees located by the STIM image were carried out using a 2.1 MeV scanning proton microbeam. The microbeam spot size was about 1 μm at a beam current of about 50 pA. An elemental spectrum and simultaneously elemental distribution maps from each water tree were acquired. Elemental concentrations were calculated using the quantitative analysis software GUPIX⁶.

Results and Discussions

A STIM image of a water tree is shown in figure 1 along with the corresponding optical microscope image. An X-ray elemental spectrum from a spot on the water tree is shown in figure 2. Elemental concentrations from the spectra were obtained by measuring certified standards. Quality control was ensured by running the standards at the start of each measurement. S and Pb were present in all the insulation samples, including non-water treed regions, as major elements. Interference of S K X-rays and Pb M X-rays in the figure was resolved by the quantitative analysis software using the standard peak stripping method. Table 1 shows the elemental concentrations and the ranges for the measurements made. The errors were mostly statistical, although detector efficiency, background subtraction, peak overlaps also contributed to overall errors for low-Z elements. Traces of Si (~ 100 ppm), Ca (~50 ppm), Fe (~50 ppm) and Zn (~30 ppm) were detected. The concentrations of S range from 10,000 ppm to about 28,000 ppm and the concentrations of Pb varied from about 70,000 ppm to about 200,000 ppm. The presence of Si may be due to the silica-based catalysts used in polymerization of the base ethylene compounds of the insulation. S may have originated, in addition to other sources, from the antioxidants used in cable manufacture to inhibit oxidation of the insulation. Other elements are possible contaminants from the soil and/or other cable components. The contaminants from outside sources diffuse into the cables and get trapped by the water trees where they tend to pre-concentrate. The relatively large amounts of Pb and S point to the existence of Pb contaminated soil in the area where the cables were laid. In addition to the possible high natural levels, further contamination of the soil with Pb and S might have occurred from leaded gasoline leaking into the area from a very nearby gas station. In fact, the cable samples had a tell-tale smell of gasoline when collected. However, more detailed investigation involving soil analysis will be required to draw any firm conclusion in this regard. The distribution maps of S and Pb in the water tree are shown in figure 3. The distributions of these two elements were found to be well

correlated to each other. The correlation lends further support to the above conjecture that the two elements might have originated from a common source in the ground.

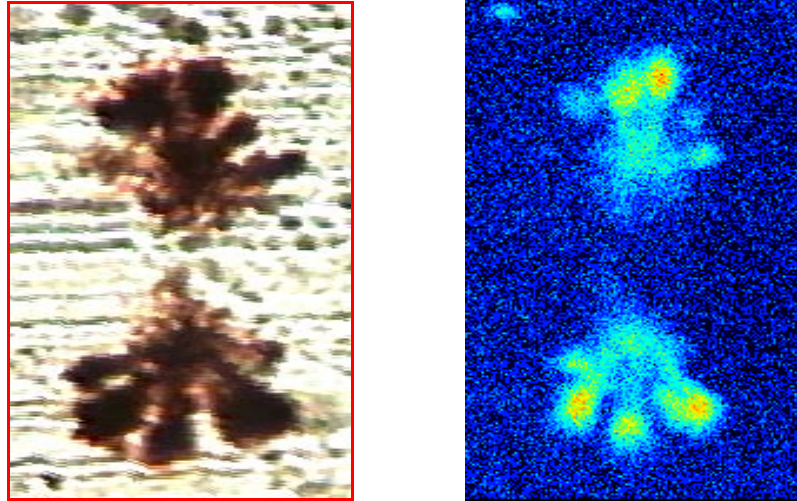


Figure 1: Optical image (left) and STIM image of a water tree in a HV cable sample.

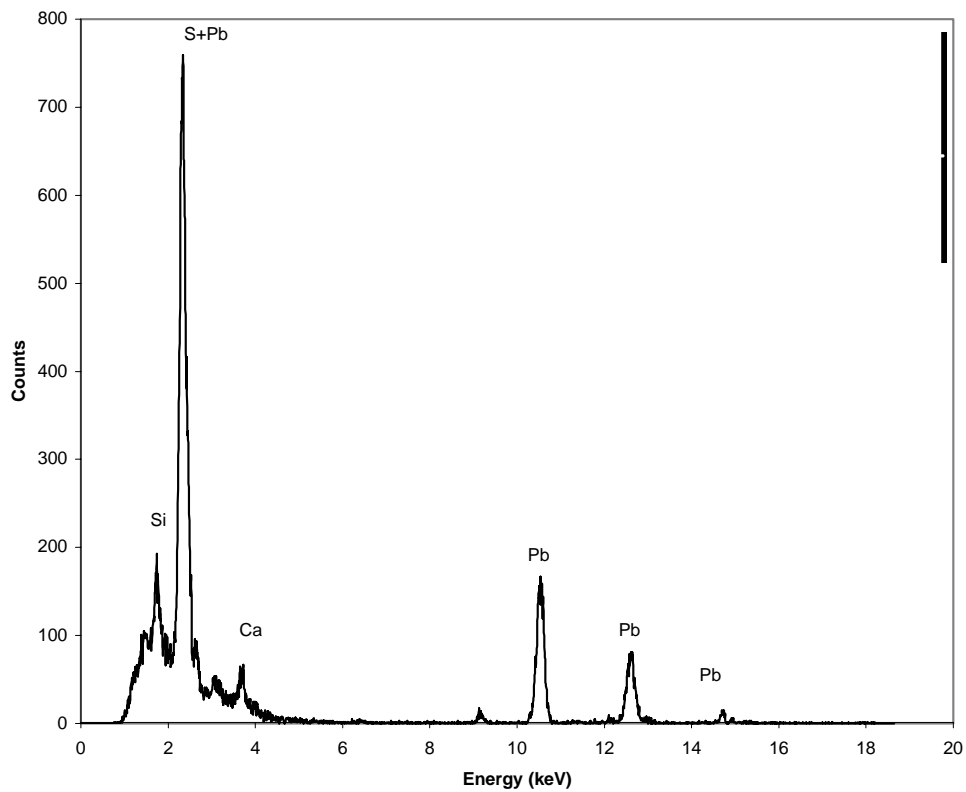


Figure 2: Micro-PIXE spectrum from a spot inside a water tree in a HV cable sample. The water tree with the spots analyzed is shown in the inset.

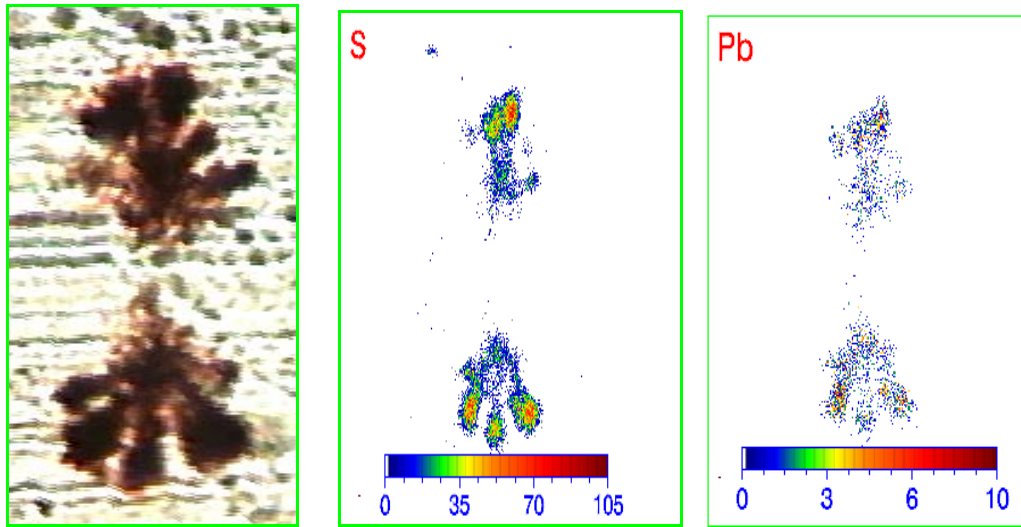


Figure 3: Optical image (left) and S and Pb distribution maps of a water tree in a HV cable sample obtained using micro-PIXE technique. The scales at the bottom of the maps indicate counts.

Table 1: Elemental concentrations from the micro-PIXE measurements (ppm \pm error%).

S. No.	Si	S	Ca	Fe	Zn	Pb
1	119 (10.3)	10254 (3.1)	49 (12.5)	36 (12.4)	27 (20.9)	70189 (1.2)
2	128 (8.6)	12389 (2.6)	80 (9.2)	47 (11.8)	41 (15.8)	84679 (0.6)
3	82 (12.6)	14236 (2.5)	47 (13.7)	52 (10.9)	36 (16.4)	90851 (0.8)
4	95 (11.5)	16247 (2.6)	23 (29.6)	35 (13.8)	22 (21.5)	100000(0.5)
5	89 (12.0)	20468 (2.1)	36 (16.5)	62 (9.7)	29 (19.7)	200000(0.3)

Conclusion

The micro-PIXE technique together with STIM technique was found to be an effective tool to determine elemental composition of water trees in high voltage cable insulation with concentrations in the order of ppm. In addition, the distribution maps of the elements detected in the water trees were obtained at a spatial resolution of the order of a micrometer. These unique data can provide a very useful basis for understanding the mechanism of growth and propagation of water trees in electric cables. This may lead to a solution of the problem of water treeing in underground power cables.

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