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INITIATION SITE ANALYSIS OF VENTED WATER TREES GROWING FROM THE CONDUCTOR SCREEN OF SERVICE AND LABORATORY AGED XLPE CABLE INSULATION

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ABSTRACT

The main purpose of this paper is to present results from examinations of initiation sites of vented water trees growing from the conductor screen of laboratory and service aged XLPE insulation systems. This has been discussed in terms of cable operation conditions during service, cable design and semi-conductive material properties.

The results show that stress-induced electrochemical degradation (SIED) causing growth of vented trees from the conductor screen, occur in service aged medium voltage XLPE cables. A prerequisite for the formation of such structures is liquid water in the conductor (causing corrosion of the Al conductor). During normal service operation this was found to be less probable. Corrosion of the Al conductor can also occur during laboratory standardized long-term wet ageing tests (e.g. CENELEC HD605) by condensation of water at the conductor diffused through the insulation. The data from the lab-scale model systems using the accelerated SIED test, indicate that optimization of the material characteristics by e.g. type and content of carbon black as well as peroxide content can have a significant impact on SIED formation.

Keywords
Water treeing, XLPE insulation, stress induced electrochemical degradation (SIED), conductor screen.

INTRODUCTION

Water tree degradation occurs in all known polymeric materials and the water trees grow by the combined action of an electrical field, ions and water [1]. It is generally observed that the old Nordic cable designs from the seventies are particular vulnerable to degradation, with the majority of the vented trees growing from the insulation screen consisting of graphite painting and semi-conductive tapes. However, in a study of XLPE cables produced from about 1975 to 1985, i.e. with extruded semi-conductive insulation screens, vented trees growing from the conductor screen are more frequently observed [2].

A mechanism that can initiate vented water trees from the conductor screen is the so-called stress-induced electrochemical degradation (SIED) [3]. This is essentially a mechanism causing porous structures in the conductor screen. The porous structures can then act as pathways for impurities from the metallic conductor to the XLPE insulation surface.

It has been proposed that the porous channels are generated by an electrochemical reaction between the aluminium conductor and the semiconductive layer under the influence of mechanical stress. When an electrolyte is present in the conductor area of an insulation system a galvanic cell is formed between the conductor as the anode and the carbon black of the semiconductive layer as the cathode [3].

The main cause for the formation of these zones is proposed to be the formation of hydrogen gas during corrosion by water of the Al conductor [4]. Although it is well known that also other initiation sites are involved (e.g. protrusions and water soluble impurities), it is the SIED mechanism that will mainly be paid attention to in this paper.

This paper presents results from examinations of initiation sites in service and laboratory aged XLPE cable systems. This includes SEM and light microscopy examinations and measurements of electrical conductivity and carbon black content of the conductor screen. In case of the service aged cables, the water causing the water trees had either diffused through the insulation to the conductor screen from outside (wet environment) or diffused from the interstices between the conductor strands (water in the conductor). The laboratory ageing was performed with liquid water subjected to the conductor strands for the cable model system (equivalent to water in the conductor) and to the insulation screen of the medium voltage cables.

EXPERIMENTAL

Test Samples and Ageing Conditions

Service and Laboratory Aged MV XLPE Cables

Table 1: Description of the examined medium voltage XLPE cables.

No.	Rated Voltage [kV] Uo)	Aged in: Service (S) Laboratory (L)	Ageing time (years)	AC breakdown voltage (Uo)
1	12 (6)	S	13	5-7
2	24 (12)	S	22	4
3	12 (6)	L	2[1]	13-24

[1] Cable ageing according to the CENELEC procedure [5]

A description of the examined MV cables with stranded Al conductors is presented in Table 1. All of the cables had stranded Al-conductors. Cable 1 was equipped with a strippable outer insulation screen and had been in service for 13 years without any service failures. This cable had previously been characterized, and had an AC breakdown voltage of about 5 - $7U_o$ [2]. Cable 2 had the same design as Cable No.1, but had an insulation thickness of 5.5 mm. This cable had suffered from service failure. The AC breakdown voltage of this cable was about $4U_o$. No radial or longitudinal water blocking system was used for these cables. Both these cables had steam cured XLPE insulation. The last cable was aged for two years in the laboratory according to the CENELEC procedure and had a fully bonded insulation screen and water blocking powder in the Al conductor [5]. This cable represents one of several typical cable core designs presently used in the Nordic countries The AC breakdown voltage of this cable was about 13-24 U_o

Preparation and Ageing of XLPE Model Insulation Systems
The design of the test cell for the accelerated laboratory ageing of the XLPE model systems was the same as previously described in [6]. It essentially consists of Al wires taken from a commercial available medium voltage cable, a semiconductive and a XLPE insulation layer. These layers are crosslinked together at 200°C under pressure for five minutes. This plaque was then subjected to a large mechanical stress during ageing. The electrical stress during ageing was 5 kV/mm and the water/sample temperature was 50°C

The semi-conductive screens were modified by changing 1) the carbon black content, 2) the peroxide content and 3) the additive package.

Characterization of the Degradation

Microscopical Examinations
In case of the MV XLPE cables, 50 mm of each cable was helically sliced with a thickness of 0.5 mm. Then the slices were soaked in hot water for two hours in order to make any SIED structures (and water trees) visible. All the SIED structures were recorded:
i) the position along the cable,
ii) the corresponding Al conductor strand it was initiated from,
iii) the length and
iv) any visible water trees initiated from the structures.
Water tree analysis was then performed after methylene blue dye staining recording the length and number of trees growing from the semi-conductive screens.

In case of the XLPE model insulation system the composite plaques were cut into two halves which were stained in methylene blue solution. Finally the samples were cut into 1 mm thin slices, and the water trees and SIED analysis was performed on 20 slices.

Measurements of Volume Resistivity (VR)
Measurements of volume resistivity on the conductor screen of the cables were performed at ambient temperature according to the procedure described in IEC 60 840. Prior to measurements the metallic Al conductor was removed and the cable was cut in two halves. The reported value is the average of these two measurements. Initially, drying was performed at 40°C in vacuum for 14 days. After volume resistivity measurements on these dry samples, they were soaked in water for 14 days at RT prior to measurements of the wet samples. In case of the XLPE model system the measurements were performed at 90°C.

Measurements of Carbon Black Content
The carbon black content of the conductor screen of the cables were determined by thermo gravimetric analysis according to the procedure described in IEC 60 811.

EXPERIMENTAL RESULTS AND DISCUSSION

MV XLPE Cables

SIED and Water Tree Analysis
SIED structures were observed in Cable 2 and 3 as indicated in Figure 1. No such structures were observed in Cable 1 as indicated in Table 2. Cable 2 had likely water in the conductor during service, which was observed by significant corrosion products caused by water present in the interstices between the strands. However, local corrosion zones at the surface between the conductor screen and the Al strands were observed as indicated in Figure 2 b). All the observed SIED structures were located within such zones (see Figure 2 d).

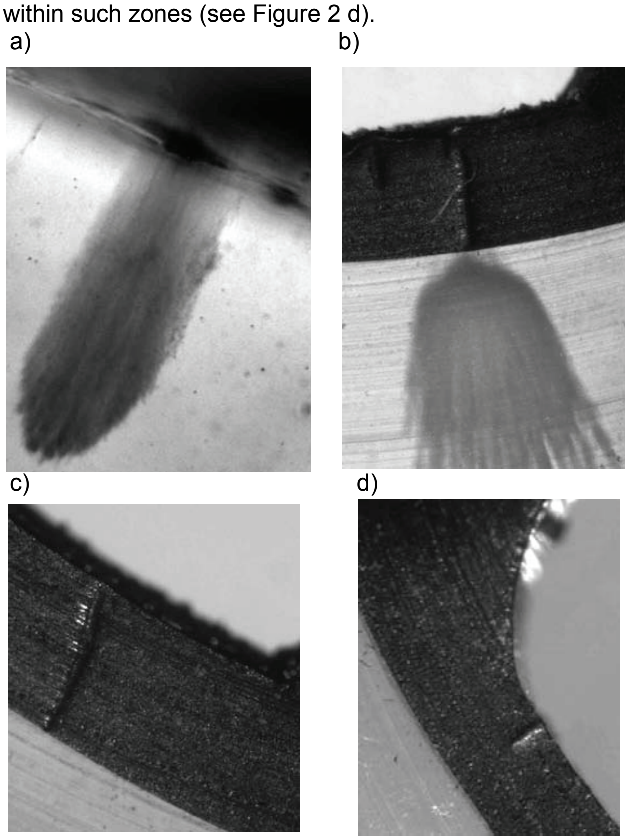


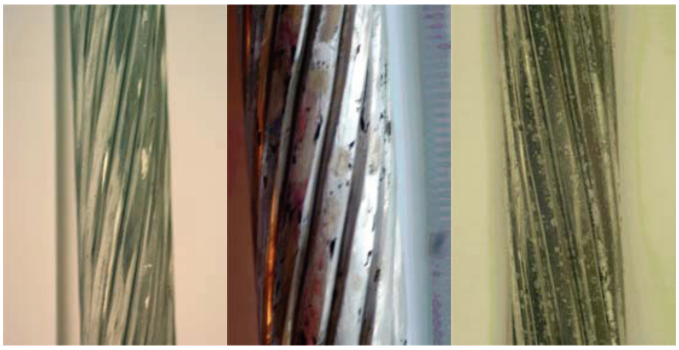
Figure 1: a) A small water tree (250 μm long) from a contamination at the interface between the XLPE insulation and the conductor screen in Cable 1. SIED structures in Cable 2 b) causing water treeing, and c) penetrating the conductor screen without causing water treeing. d) A small SIED structure detected in Cable 3.

In these zones large concentrations of K, but also other inorganic elements such as Si was detected at the surface of the conductor of Cable 2. These elements were also detected within the SIED structures.

Table 2: Results from the SIED and water tree Analysis of the MV cables

Cable No.	No. of SIED structures	No. of initiating / non-initiating bridging SIED structures	Longest observed wt [µm]	No. of wt from the conductor screen	Percentage vented trees initiated by SIED (%)
1	0	0 / 0	250	43	0
2	223	79 / 17	1900	82	96
3	4	0 / 0	0	0	-

a) b) c)



d)

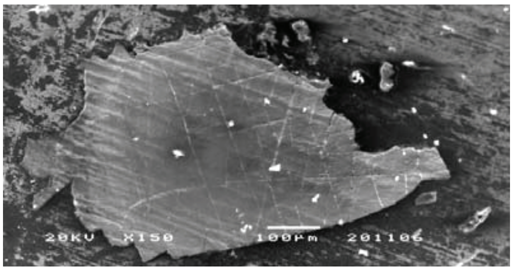


Figure 2: Photograph of the Al conductors after ageing: a) Cable 1, b) Cable 2 and c) Cable 3. d) SEM picture of a corrosion zone (light) with high concentrations of K for Cable 2.

Corrosion was also detected for Cable 3. This could be due to condensation of water in the conductor due to the pre-conditioning procedure that is used in the CENELEC test, causing liquid water to be in contact with the Al conductor (supersaturation of water) [4]. Any effect of the swelling powder on the corrosion process was not examined. However, 100% RH is not a pre-requisite for corrosion, as this also can occur at lower RH's as long as there are condensation nuclei at the Al surface causing condensation of water [7].

Inorganic elements such as K and Cl were found at the surface of the conductor strands (connected to the conductor screen). No corrosion was detected for Cable 1.

Figure 4 shows the location of SIED structures and the corresponding length along one of the Al strands in contact with the conductor screen for Cable 2. It was also found that not all the SIED structures penetrating the conductor screens initiated vented water trees as indicated in Table 2.

It was observed that the SIED structures were localized into groups. This observation was consistent with the observation of the local corrosion zones at the surface of the Al conductors, and that the SIED structures were found to initiate and grow from such zones.

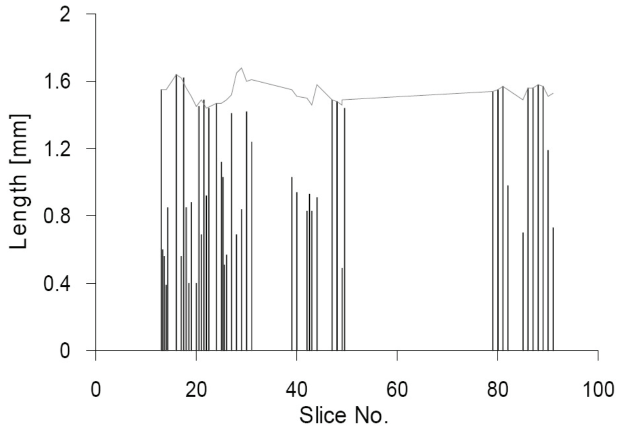


Figure 4: Example of distribution of length and position of SIED structures in Cable 2 along one of the Al strands (each slice corresponds to 0.50 mm). The solid line (horizontal) indicates the corresponding thickness of the conductor screen.

Fracture patterns were detected at the surface of the conductor screen (in contact with the Al conductor) close to the SIED structures. Figure 5 shows an example of an initiation site on the surface of the conductor screen that had been in contact with an Al strand. It was observed that the SIED structures were likely connected to such initiation sites. The surface was characterized by a cracking zone and other cracks branching to each side (with less density).

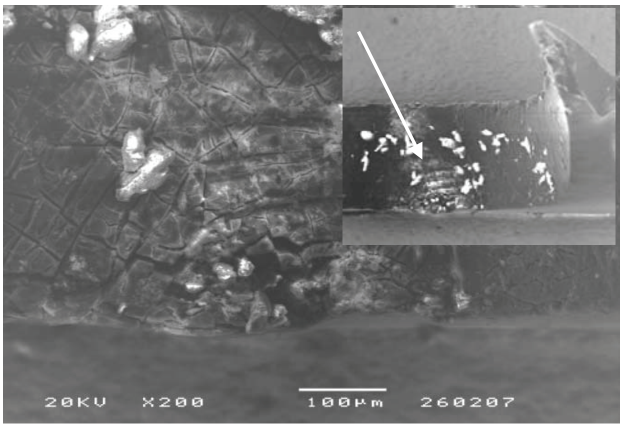


Figure 5: SEM picture of initiation site for SIED structure (see arrow indicating the enlarged area). The white particles are corrosion products from the metallic Al conductor.

Vented water trees were found to initiate from the conductor screen. As shown in Table 2, vented water trees growing from the conductor screen were detected in Cable 1. These trees were rather short and the longest tree observed was about 250 µm. The density of the trees was also low. None of these trees were initiated from SIED structures. In case of Cable 2, long trees were observed bridging about 1900 µm of the insulation wall.

All these trees were growing from the conductor screen and initiated from SIED structures. No vented water trees growing from the conductor screen were detected in Cable 3. It is possible that the density of the trees was rather low and that longer cable lengths had to be examined in order to detect the trees. This is in agreement with the corresponding high AC breakdown voltages detected for this cable. Bow-tie trees were observed in all cables, but these were relatively short.

Measurements of Volume Resistivity and Carbon Black Content

Table 3 shows results from measurements of volume resistivity and carbon black content of the conductor screens of the MV XLPE cables.

Table 3: Results from measurements of volume resistivity and carbon black content

Cable No.	Volume resistivity [Ωm]		Carbon black [%]
	Dry	Wet	
1	0.39	0.36	36.1
2	0.44	0.40	36.3
3	2.10	0.58	29.2

It is observed that Cable 1 and 2 had about the same carbon black content and also volume resistivities. Cable 3 had lower contents of carbon black and also higher resistivities. The dependence on humidity of the resistivity was also largest for this cable.

XLPE Model Insulation system

Figure 6 shows an example of water treeing and SIED structures in the XLPE model insulation system, where also ion tracks, i.e. SIED-like structures growing from defects inside the semiconductive layer, can be observed [6].

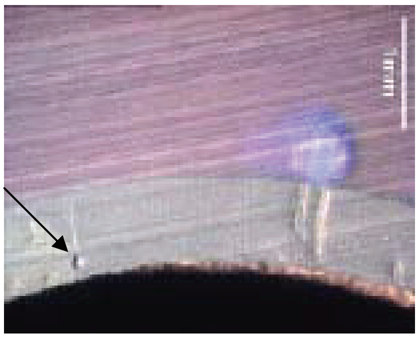


Figure 6: Example of water treeing and SIED structures in the XLPE model cables. Also ion tracks are included (see arrow) [6]

Figure 7 shows that the SIED phenomenon is enhanced with increasing conductivity of the semiconductive screen supporting the hypothesis of the galvanic cell.

In an aqueous environment aluminium is oxidized resulting in Al 3+ and electrons. Aluminium hydroxide is formed and hydrogen gas is liberated. A fraction of the electrons released are attracted by the electrophilic carbon black present in the semiconductive layer. This flow of electrons then represents the galvanic cell current. The electron consuming reaction taking place at the cathode has been suggested to be either a reduction or an oxidation of water present in the semiconductive material.

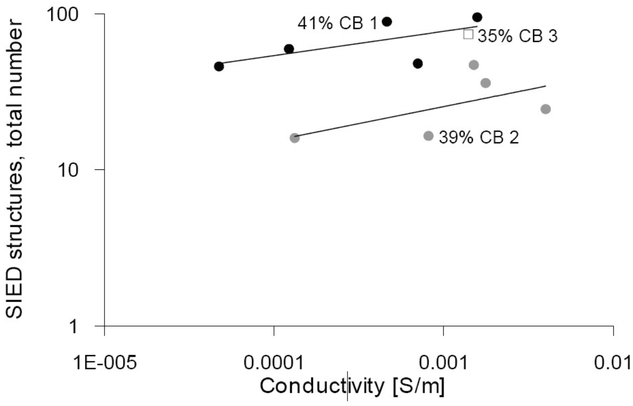


Figure 7: Number of SIED structures measured in an accelerated SIED-test. The conductivity (measured at 90°C) has been varied by the carbon black content in otherwise essentially identical compounds. Three different CB types are compared.

However, the importance of the ageing condition on the SIED formation is indicated in Table 3, where about the same carbon black content and electrical conductivity (resistivity) was determined for Cable 1 and 2. Both cables had also a wet design and were operated in wet conditions during service, but only Cable 2 had water in the conductor. A severe SIED degradation was determined for Cable 2, but no structures were determined for Cable 1.

Comparing the carbon black CB1 with CB2 in Figure 7 shows that compounds based on CB1 have developed a considerably larger number of SIED structures in the lab-scale test. The differences between these two carbon blacks are basically their reinforcing character in polyethylene matrices. CB2 involves stronger polymer-filler interactions and is believed to thus create stronger resistance to “mechanical degradation” phenomena. CB3 has a reinforcing character similar to CB1. However, it is considerably more conductive than CB1 so that it reaches the same conductivity at lower loading levels. As the response to the SIED-test is essentially the same for both compounds based on CB1 and CB3 at the same conductivity, it can be concluded that trends in Figure 6 are less likely due to variations in carbon black content, but rather due to the compounds’ conductivity and the reinforcing character of the CB, which in turn is in agreement with the proposed theory.

Yet another correlation between mechanical characteristics of the semiconductive layer and the response to the accelerated SIED test is shown in Figure 8. This plot suggests that a tighter cross-linking network improves SIED resistance. The hot set elongation of the semiconductive layer has been varied by changing the peroxide content (fully reacted in all samples) in otherwise identical compounds. Nevertheless, it can be assumed that not only the peroxide content, but also other factors affecting the cross-linking degree are relevant here. This is because from a theoretical point of view the mechanical strength of the compound on a micro-level is likely the key to the resistance to "mechanical degradation" rather than the peroxide content as such.

The above presented results point at semicon formulation design as well as cable design, since conductivity and cross-linking degree can be affected at both stages. Furthermore, these results can be explained by the theoretical description of the SIED phenomenon.

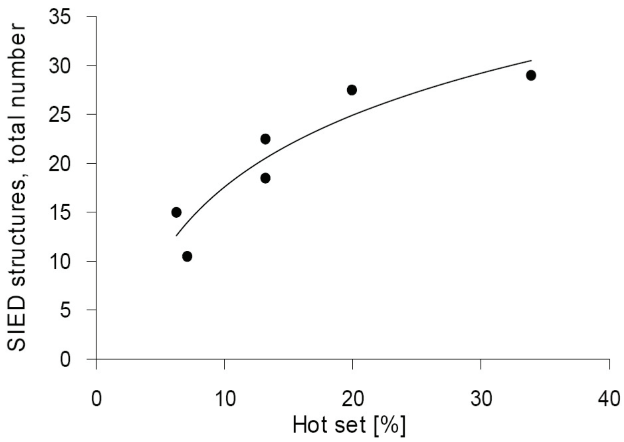


Figure 8: Number of SIED structures measured in an accelerated SIED-test. The hot set of the semiconductive layer has been varied by the peroxide content in otherwise essentially identical compounds.

However, in formulation design the significant (perhaps strongest) impact of additivation is less understood. Figure 8 shows the additive concentration dependence of generated SIED structures.

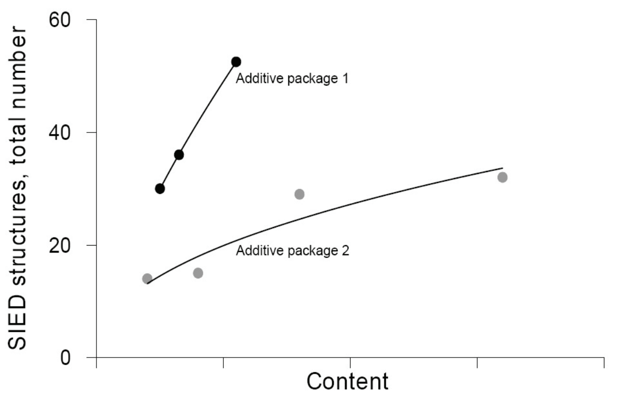


Figure 8: Number of SIED structures measured in an accelerated SIED-test. The additive content of the semiconductive layer has been varied by the peroxide content in otherwise essentially identical compounds. Two different additive packages are compared.

Furthermore comparison of two different additive packages is showing clear differences in the formation of SIED structures. However, the effect of the additive type can be even stronger. Other model compounds resulted in well above 100 SIED structures. Although the additivation is of obvious importance it is today not quite clear in what way it affects SIED.

Future Work

Further examinations of the morphology of the SIED structures in service and laboratory standardised aged cables with different cable core designs and materials will be performed.

CONCLUSIONS

The results show that stress-induced electrochemical degradation (SIED) structures causing growth of vented trees from the conductor screen, occur in service aged medium voltage XLPE cables. However, the results so far show that a prerequisite for the formation of such structures is liquid water in the conductor causing corrosion of the Al conductor.

Service aged cables without liquid water in the conductor (i.e. no corrosion) show no indication of SIED structures, although having a wet design and being operated in a humid environment. Short vented trees were yet found growing from the conductor screen. This might imply other initiation mechanisms for such conditions. However, ion tracks growing from impurities within the conductor screen can yet be formed. Formation of liquid water causing corrosion and SIED structures can also occur during laboratory standardized long-term wet ageing tests (e.g. CENELEC HD605) by condensation of water diffused through the insulation system to the conductor. This is also true for cables with swelling powder in the conductor.

The data from the lab-scale model systems using the accelerated SIED test, indicate that optimization of the material characteristics by e.g. type and content of carbon black as well as peroxide content can have a significant impact on SIED formation. Consequently, proper formulation design is essential, especially when the abovementioned service or test conditions causing corrosion occur.

REFERENCES

[1] M.T.Shaw et. al: "Water Treeing in Solid Dielectrics", IEEE Transaction of Electrical Insulation, EI , pp. 419-452, Vol. EI-19, No. 5, October 1984.

[2] S.Hvidsten and J.T. Benjaminsen: "Diagnostic testing of MV XLPE cables with low density of water trees", ISEI 2002, pp 108 – 111, Boston, MA, USA.

[3] K. Steinfeld and W. Kalkner: "SIED of the Inner Semicon Layer of XLPE Insulated Cables and Model Systems", IEEE Trans. On Diel. And El. Insulation, Vol 5, No 5, 1998, pp. 774-778

[4] M. Brüggemann, W. Kalkner, C. Broman, A. Smedberg: "Influence of Electrochemical Effects on Vented Tree Initiation in Accelerated Tests". Paper JiCable 2003.

[5] CENELEC HD 605

[6] M. Brüggemann, W. Kalkner, A. Campus and A. Smedberg: "Electrochemical Effects at the Conductor/Dielectric Interface – A Description of the Mechanism", ICSD 2004, pp. 383-386.

[7] D.Bengtsson et.al.: "The influence of CO2, AlCl3·6H20, MgCl2·6H20, NaSO4 and NaCl on the athmospheric corrosion of aluminium", Corrosion Science, Vol. 48, pp. 1848-1866, 2006.