EXAMINATION OF TWO IN-SERVICE-AGED PVC CABLES FROM A NUCLEAR POWER PLANT

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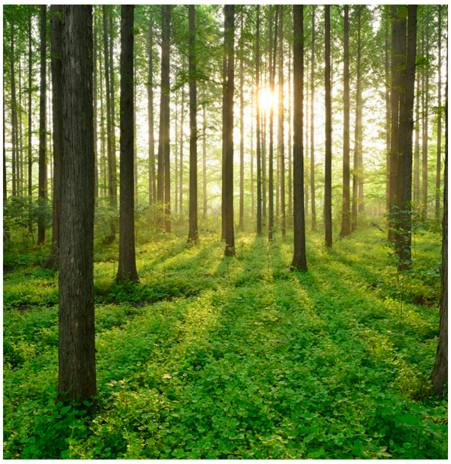

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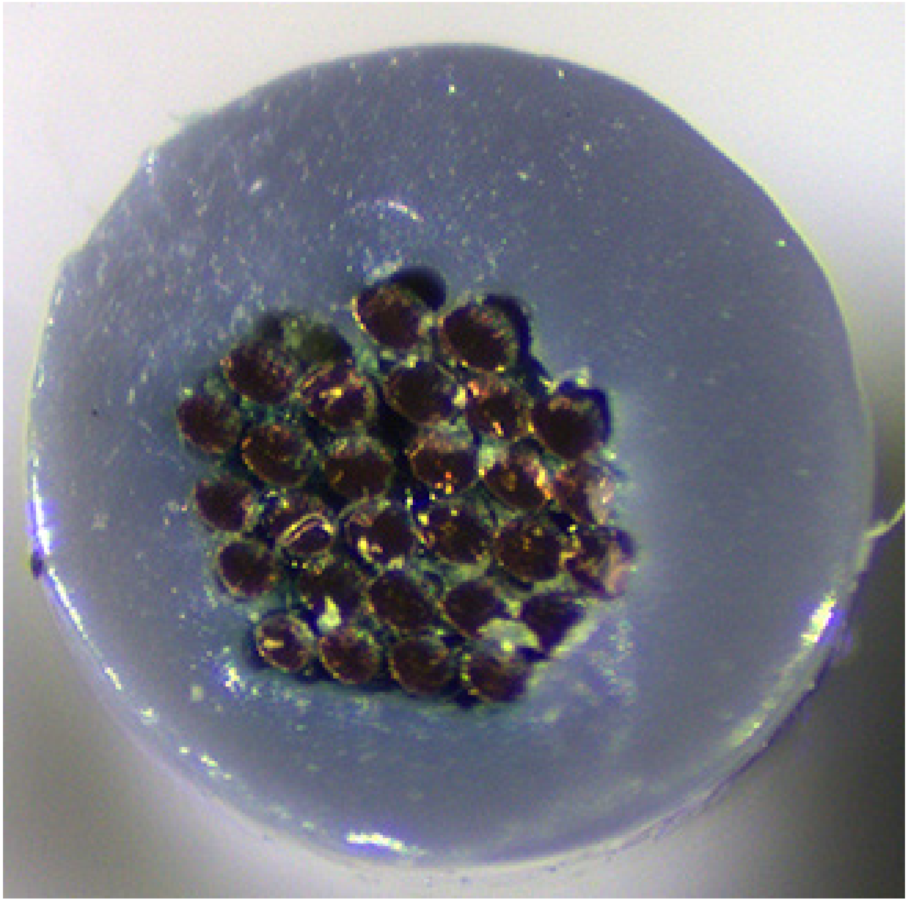

Energiforsk

Examination of two In-Service-Aged PVC Cables from a Nuclear Power Plant

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Foreword

This report forms the results of a project performed within the Energiforsk Polymers in Nuclear Applications Program.

The Polymers Program aims to increase the knowledge of aspects affecting safety, maintenance and development of components containing polymers in the Nordic nuclear power plants. A part of this is to investigate possibilities to facilitate and simplify the work that is performed in the nuclear business.

The longevity and reliability of PVC cables are crucial for the safe operation of nuclear power plants. Ensuring these cables can withstand prolonged use without degradation is vital to prevent potential reactor trips and maintain safety standards.

This study investigates two PVC instrumentation wires used for over 40 years in a nuclear power plant. The aim was to determine if these cables could continue to be used safely for an additional 20 years.

The results showed that while the cables differed in composition, both had the potential for extended use. The main degradation mechanism identified was the loss of the DEHP plasticizer, but the cables remained flexible and safe for further use.

The study was carried out by Karin Jacobson, PDS consulting. The study was performed within the Energiforsk Polymers Program, which is financed by Vattenfall, Uniper, Fortum, TVO, Skellefteå Kraft and Karlstads Energi.

These are the results and conclusions of a project, which is part of a research Program run by Energiforsk. The author/authors are responsible for the content.

Summary

As part of a project on long-term use of polymeric materials in nuclear power plants, two PVC instrumentation wires used in service for over 40 years have been examined. The aim was to assess their potential to be used for another 20 years.

It was found that the PVC in the two cable types contained the same plasticiser type (DEHP), but that they differed in type and amount of organic fillers. Cable specimens from a previous ageing program were available and analysed in more detail. It is confirmed that loss of plasticizer is the determining factor for the service life of the cable insulators. It was found that the two cables differed in the rate of plasticiser loss during the ageing program. The elongation at break of both cable material were, however, found to still be more than 50% absolute value based on current property even after an additional post-ageing thermal exposure at 75 °C that was designed to correspond to approximately 20 years in-plant ageing. The instrumentation wires can thus probably be use for another 20 years without the risk of embrittlement that could lead to an unwanted electrical fault. It is, however, advised that additional samples are taken out after 10 years to verify that the in-service ageing is still following the ageing processes predicted from the accelerated test program.

Keywords

PVC, Cable insulation, Plasticizer, Diethyl-hexyl-phthalate (DEHP), In-Service Ageing, Continued Use, Nuclear Power

Kabelisolering, Mjukgörare, Åldring, Kärnkraft, Fortsatt användning

Sammanfattning

Som en del i ett projekt om långtidsegenskaper hos polymera material i kärnkraftsindustrin har två instrumenteringskablar av PVC undersökts. Kablarna har använts i över 40 år i ett kärnkraftverk. Syftet var att undersöka om kablarna har potential att användas i ytterligare minst 20 år.

Undersökningen visade att de två kabeltyperna innehöll samma sorts mjukgörare men hade olika typ och mängd av fyllmedel. Prover från ett tidigare utfört åldringsprogram var tillgängliga och analyserades i mer detalj. Det är tydligt att mjukgörarförlust kommer att vara det som avgör livslängden hos kabelisoleringen. Det visade sig att de två kabletyperna skiljde sig åt vad gäller hastigheten på förlusten av mjukgörare under åldringsprogrammet. Töjningen hos båda kabelmaterialen visade dock att den var mer än 50% absolut töjning även efter den längsta efteråldringstiden som var designad att motsvara mer än 20 år i drift. Instrumentkablarna kan därmed troligen användas i ytterligare 20 år utan att de riskerar att bli så spröda att det kan leda till ett oönskat elektriskt fel. Det är dock rekommenderat att nya kablelprover tas ut efter 10 års verklig åldring för att se om de följer det förväntade åldringsförloppet från den accelererade provningen.

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1 Introduction

As part of a project on long term operation of polymeric materials in nuclear power plants, samples have been retrieved and examined to determine their present status and possible continued use. The present report concerns two sets of instrumentation wires with a long service record provided by a nuclear power plant.

The main problem when examining polymeric samples after prolonged use is that most often there is a lack of data on the original performance and initial properties of the material. In some cases, there is good documentation about which polymeric material has been used, or at least a tradename, but this information rarely contains any detailed information about the formulation/composition. In some cases, not much more might be known than the mechanical properties. Since polymeric materials are not standardised, their composition can change with time even if the same tradename is used. Another very common problem is the lack of information about the exact dynamic service conditions during the application period. Any insight into what the failure mechanism will actually be, may also be absent.

To be able to answer the question about the status of the component and predict its further use, a questionnaire has been developed to be answered by the NPP operators as best as possible.

The questions are:

- What do you want to know about the sample? Is it remaining service life, or a suitable replacement material or something else?
- What has the material been used for? What is the function(s) of the part/sample?
- How was the sample installed (photos and/or drawings are very helpful)?
- How long was it in service?
- How long has it been out of service?
- What are the service conditions (temperature, atmosphere (air, nitrogen, oxygen), irradiation, pressure, UV-light, oil, grease etc)?
- What type of material is it, supplier, name, code? Any information helps here.
- What happens if the function fails, how critical is it, what are the consequences?
- Do you have any input as to what could be a suitable lifetime criterion for the part? (e.g. low sealing force, cracks allowing unwanted leakage, increased hardness with loss of ability to follow movements etc)

From these questions the following information has been gathered about the instrumentation wires:

The conductors are placed inside relay cabinets which have an inside temperature of 30^{0}C. The atmosphere is normal air. There is no radiation, and the pressure is normal. There is no light when the door is closed during operation. The only information found about the origin of the cables is that they are made of PVC and marked with "BJURHAGEN".

It has been observed that there is plasticiser coming out of the wires and since they are not supposed to be renewed during the NPP lifetime and since the plant is scheduled for at least another 15 years of service, the main concern now is if these cables will perform satisfactorily. The same type of wires is used in several cabinets. When the door of a cabinet is opened, the conductors are moving as well, so there is some concern that the cable insulation could break if it becomes too hard and brittle with time. Failure of the conductors may cause an unwanted electrical fault.

The photos in Figure 1 and Figure 2 were provided by the nuclear power plant to demonstrate the observation of the plasticizer oozing out of the cables during service.

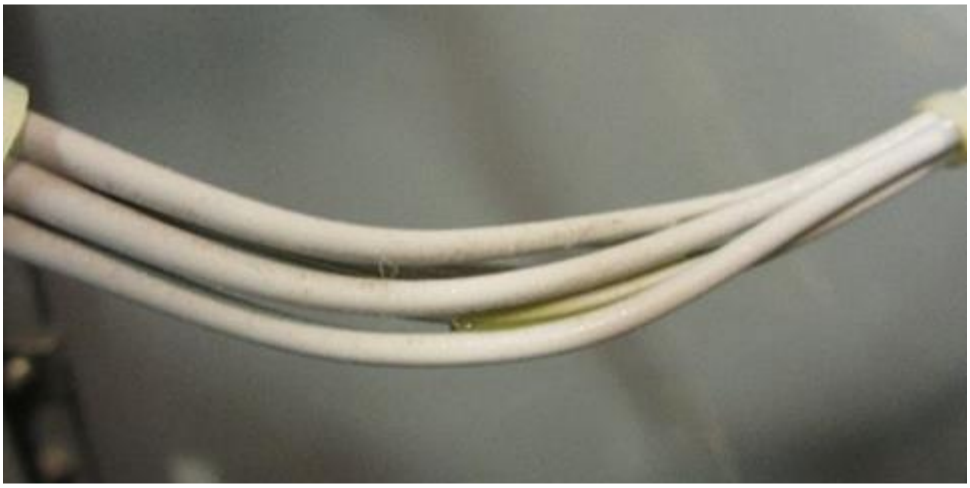

Figure 1. Photo provided by the nuclear power plant which captures the observation of the plasticizer exuding from the cables during service.

Figure 2. Photo provided by the nuclear power plant which captures the observation of the plasticizer coming out of the cables during service

The conductors have been in service since 1979-1980 and were withdrawn from operation during the 2022 revisions in the plant. The operating time was thus 42-43 years. The samples had been out of service for 1.5 years before the present investigation was initiated.

There are two types of conductors: 0.5 mm^2 and 0.75 mm^2.

Previous ageing program

A previous ageing program had already been performed by the NPP on the two cable types. It involved thermal ageing under air at 75°C for a duration up to 2040 hours, which corresponds to 20 years in 30 °C, assuming the activation energy of plasticizer loss to be 0.9 eV (87 kJ/mol). Samples had also been pulled from the testing at shorter ageing times, 510, 1030 and 1534 hours. Material had also been kept in the oven for up to 2159 hours at 75°C (corresponding to 21.5 years at 30°C).

Some observations that had been made during the exposure were that on the surface of the 0.5 mm^2 conductor there was a significant amount of plasticizer present prior to further thermal ageing tests. During checks after 1030 hours, a green substance was seen at the end points. The green substance was assumed to be the plasticizer, but it was not chemically analyzed.

Before thermal ageing tests on the 0.75 mm^2 conductor cable, the surface was noticeably sticky/greasy. No major change to this appearance was observed during the test.

There was no color change observed during the ageing test, but both types of conductors became noticeably stiffer with additional thermal ageing. However, a wrap-test of the conductors did not cause a breakage in the insulation, meaning severe embrittlement had not yet occurred.

Aim and scope

From the feedback of the previous ageing program there were already indications that the cables were going to last for at least another 20 years. There were, however, still some uncertainties if this conclusion really is justifiable, due to the limited knowledge about the cable material and the limited testing that had been performed. The main aim with the present investigation was thus to carry out a more thorough analysis of the PVC material in the insulators, and thereby add confidence to the previous conclusion. The aim was also to explore if and how relatively simple material analyses could also be helpful in other predictions of long-term behavior of PVC cables in NPP applications. The scope was thus to gather as much relevant information as possible about the insulator materials using standard laboratory techniques.

2 Experimental

2.1 MATERIALS

Initially four to five strands of cable pieces, approximately 20 cm long, of the two types (0.5 and 0.75 mm^2) were sent for analysis. These had been post-exposed for 2159 hours during the ageing program described above. Later an additional one to two cable pieces of each type of cable and ageing time, approximately 15 to 20 cm long, were supplied. They had been post-aged for shorter times: 0, 510, 1030 and 1534 hours at 75°C.

Prior to the post ageing, the 0.5 mm^2 cables had a diameter of approximately 1.8 mm, and the 0.75 mm^2 was approximately 2.2 mm in diameter.

2.2 MEASUREMENTS

The measurement procedures have in general been optimised for the specific purpose of the test and are based on the expertise of the examiner, rather than necessarily following a specific standard.

2.2.1 FTIR

The FTIR (Fourier Transformation Infrared Spectroscopy) measurements were made on a Perkin Elmer, FT-IR Spectrometer Frontier with the Universal ATR sampling accessory and diamond sensor at RISE in Kista, limited to qualitative spectral analysis.

2.2.2 GC-MS

The GC-MS (Gas Chromatography Mass Spectroscopy) analyses of the samples were performed using pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS) at RISE in Stockholm. The results are obtained as a so-called pyrogram, with the intensity of the pyrolysis products (total ion current, TIC) set against the retention time. Mass spectra are recorded for GC peaks, which enables identification of the chemical structure of the released compounds from the sample. The obtained pyrolysis products were methylated simultaneously in the pyrolysis chamber by tetramethylammonium hydroxide (TMAH) to improv the separation of polar compounds on the GC-column.

2.2.3 DSC

A Mettler Toledo DSC3+ (Differential Scanning Calorimeter) at RISE in Kista was used to measure the Tg of the PVC material. The measurements were run with a fast heating (20 K/min) from 25 to 200° C in nitrogen and then a slower cooling (-10 K/min) in nitrogen from 200 to -70°C. 40 uL aluminum crucibles with pierced lid were used for the measurements. Three to four repeat measurements were made on each sample.

2.2.4 TGA

A TGA/DSC 3+ from Mettler Toledo at RISE in Kista was used for the TGA (thermal gravimetric analysis). The thermal degradation of the PVC materials in the cables was investigated using the ISO 9924-3 method B. In this method the sample is heated from 35 to 800°C in nitrogen and then cooled down to 400°C and heated again to 850°C in air. The gas flow was 100 cm^3/min and 70 uL alumina crucibles were used.

2.2.5 Tensile testing

The tensile testing was performed at RISE in Borås on a Zwick Z1 tensile tester equipped with a 1 kN load cell. The conductor was removed, and test pieces of each insulation were cut to a length of approximately 75 mm. The absolute elongation at break was measured between the grips.

Initial grip separation: 50 mm.

Rate of grip separation: 25 mm/min

Conditioning and tests were performed in standard climate: +23 ±2 °C and 50 ±5 % RH.

2.2.6 Thickness measurements

The thickness measurements were performed on ten different positions along a cable using a digital calliper.

3 Results

3.1 INVESTIGATION OF CABLES POST-AGED FOR 2159 HOURS AT 75°C

The first set of samples that was sent for analysis had all been post-aged for 2159 hours at 75°C. A photo of the 0.5 mm² cable strands can be seen in Figure 3, with a close-up of the ends of the strands in Figure 4. The cables had a green sticky deposit on the outside, especially at the ends of the cable pieces. The cables could still be bent easily without any signs of embrittlement.

Figure 3. A photo of the 0.5 mm² cable strands post-aged for 2159 hours at 75°C

Figure 4. A close-up of the photo in Figure 3 showing the end section of the 0.5 mm² cable strands post-aged for 2159 hours at 75°C

Figure 5 shows the strands from the 0.75 mm^2 cable after post-ageing for 2159 hours at 75°C. An enlargement is shown in Figure 6. These samples did not have as much green deposit as the 0.5 mm^2 cables, but were notably sticky on the outside. They felt stiffer than the 0.5 mm^2 cables, but also could still be bent without any signs of embrittlement.

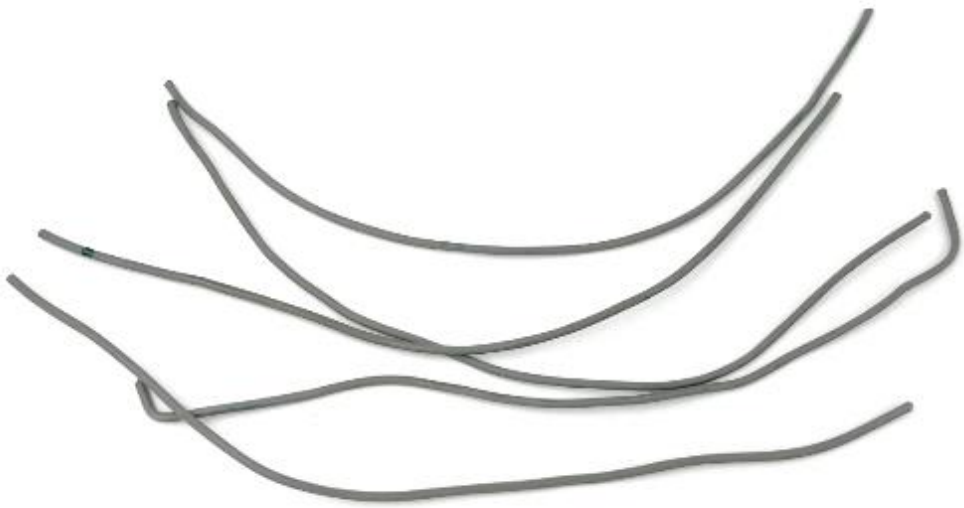

Figure 5. The strands from the 0.75 mm^2 cable after post-ageing for 2159 hours at 75°C

Figure 6.Enlarged view of one of the 0.75 mm^2 cables showing the green sticky deposit that was found to a lesser degree on these cable strands compared to the 0.5 mm^2.

The cross sections of the two cables after 2159 hours of post-ageing are shown in Figure 7 for the 0.5 mm^2 cable and in Figure 8 for the 0.75 mm^2 cable, respectively. There is a significant amount of green liquid visible on the cross section of the 0.5 mm^2 cable, but not on the 0.75 mm^2 sample.

Figure 7. The cross section of the 0.5 mm² cable which had been post-aged for 2159 hours.

Figure 8. The cross section of the 0.75 mm² cable which had been post-aged for 2159 hours.

Cutting a new fresh cross section in the 0.5 mm² cable did at first not show any of the green liquid as seen in Figure 9. Eventually this new cross section also became green, and it seemed as if the liquid migrated along the conductor.

Figure 9. Cutting a new fresh cross section in the 0.5 mm² cable post-aged for 2159 hours.

The green liquid was analyzed using FTIR, Figure 10. It was found to, at least in part consist of the plasticizer DEHP (di(2-ethylhexyl) phthalate) as seen by the similarity to the reference curve of pure DEPH also seen in Figure 10, with important key reference bands at 1725, 1600, 1580, 1275 and 740 being noticeable. This is a very common plasticizer for PVC. DEPH is colorless so the green color must originate from something else. Possibly copper ions from the conductor.

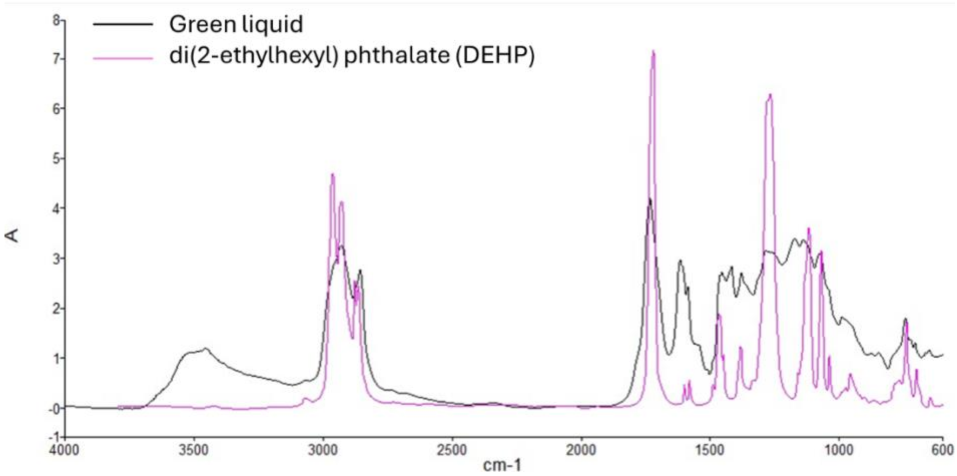

Figure 10. FTIR spectra of the green liquid (black curve) and DEHP (pink curve)

In addition to the FTIR analysis both cables were analysed with pyrolysis-gas chromatography/mass spectrometry (Py-GC/MS). The resulting pyrograms can be seen in Figure 11 for the 0.5 mm² cable, and in Figure 12 for the 0.75 mm² cable, respectively. Both cables show the typical peak of DEHP in addition to various other peaks of compounds exuded from the polymer. The fatty acid found could originated from a lubricant used during the processing of the wire and/or cable.

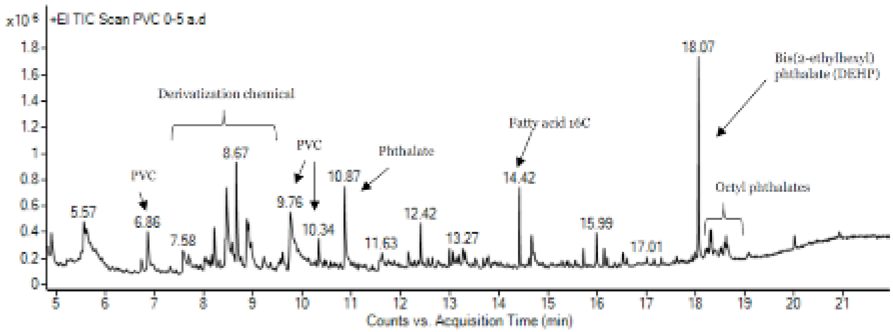

Figure 11. Pyrogram of the 0.50 mm² cable

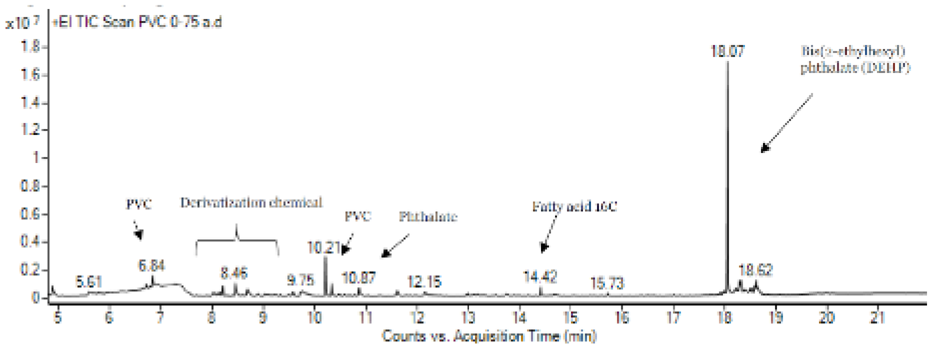

Figure 12. Pyrogram of the 0.75 mm² cable

3.2 INVESTIGATION OF NON-POST-AGED CABLE SAMPLES

Later in the investigation, a few strands of non-post-aged cables were also received. These samples had thus only been exposed in service, i.e. had been used for a bit more than 40 years inside relay cabinets having an inside temperature of 30⁰C. The atmosphere was normal air and there was no irradiation.

TGA (thermal gravimetric analysis) was used to check on the composition of the two cable types through separation of organic and inorganic material. The TGA curve of the non-post-aged 0.5 mm² cable can be seen in Figure 13. PVC pyrolyzes in two stages, first the dehydrohalogenation which can be seen as the initial drop in weight starting at 265°C and then higher temperature (starting around 400°C) decomposition of the remaining hydrocarbon polymer backbone. It is unfortunately not possible to separate the degradation of the plasticizer from the degradation of the polymer. In this case no change was seen in the decomposition above 600 °C indicating that there is no $CaCO_3$ (with well-known decomposition at 750°C) in the sample. The final inert filler content is 12 wt%.

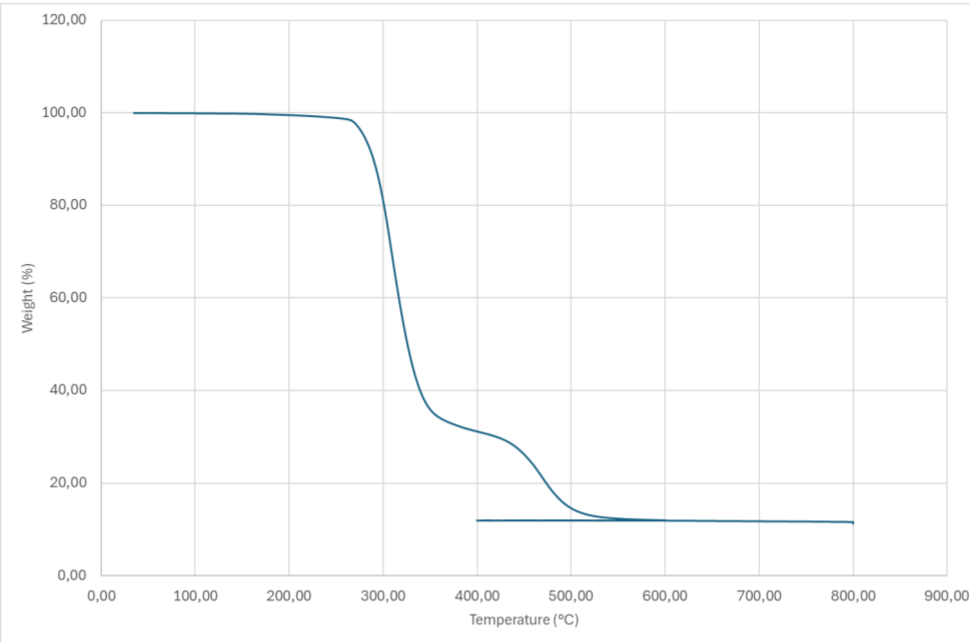

Figure 13. TGA of the non-post-aged 0.50 mm² cable

The TGA curve of the non-post-aged 0.75 mm² cable can be seen in Figure 14. It can be seen that the material in this insulator is different compared to the 0.5 mm². In this case there is an additional 5 wt% drop between 600 and 800°C, indicating that the material contains $CaCO_3$ (the carbonate is decomposed). The residual inert filler content is much higher than in the 0.50 mm² insulator material, around 30 wt% of which 13 wt% is the $CaCO_3$ and the rest is from unknown inorganic fillers.

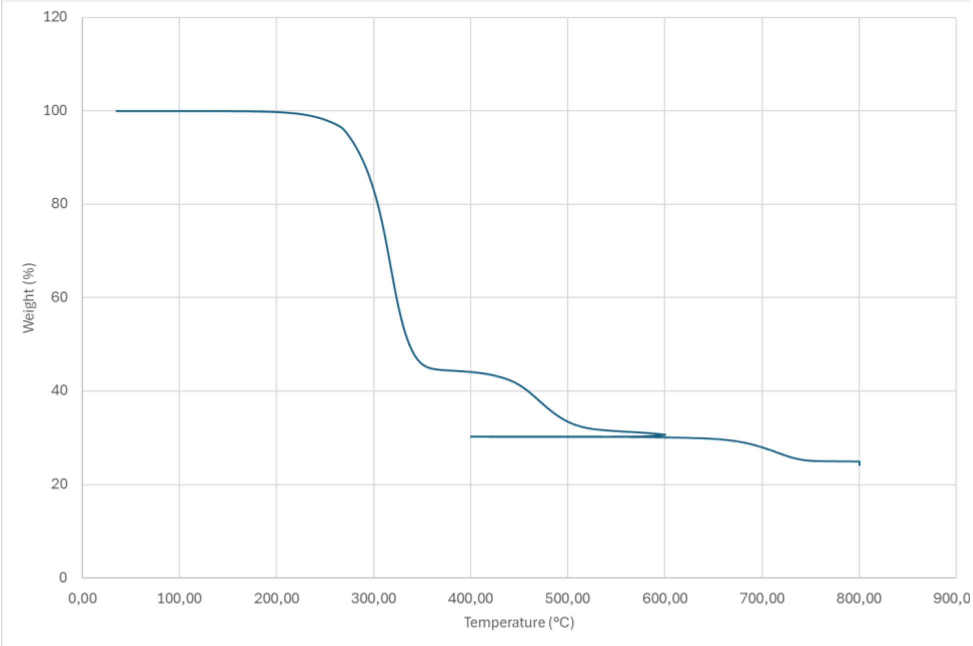

Figure 14. TGA of the non-post-aged 0.75 mm² cable

FTIR analysis of the two insulator materials, see Figure 15, confirms the observations from the TGA that the 0.75 mm² insulator contains $CaCO_3$, but the 0.5 mm² version does not. Apart from this obvious difference the two samples are quite similar in their chemical structure, which also confirms the observation from the GC-MS that both contain DEPH plasticiser.

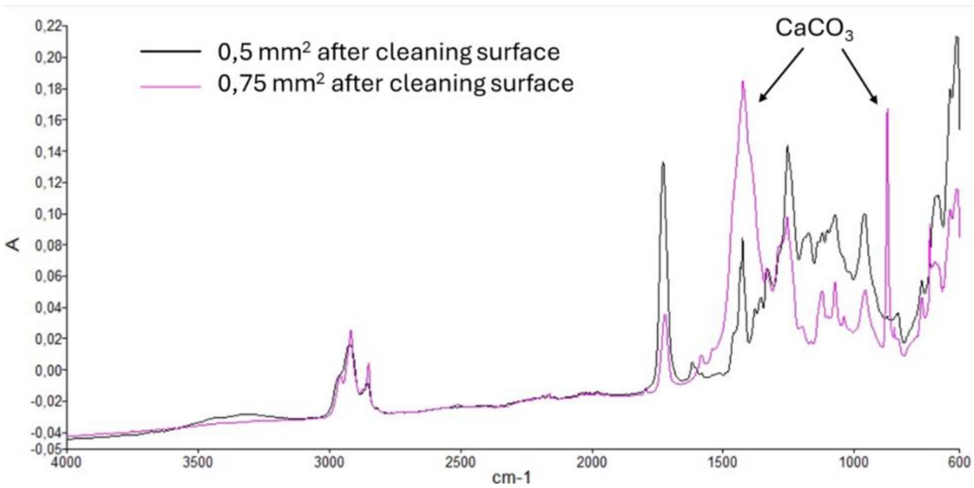

Figure 15. FTIR of the 0.50 mm² cable (black curve) and the 0.75 mm² cable (pink curve).

3.3 INVESTIGATION OF THE FULL POST-AGED SAMPLE SERIES

In addition to the non-post aged cable samples and the samples that had been aged for 2159 hours at 75°C, there were also some samples provided from the intermediate ageing times. It was clear from the handling of these samples that there was a difference in stiffness with ageing time. Unfortunately, there was not enough material to perform tensile testing on the full series to quantify any correlation with max. tensile elongation. Attempts were made to measure the hardness and the indenter modulus, but the thickness of the material was too small to give reliable results.

TGA was used to investigate also the post-aged samples and even if the TGA could not be used to separate the PVC from the plasticiser, it could be seen that the relative amount of inorganic filler increased after post-ageing. In the 0.75 mm^2 cable the absolute filler contents increased with 5 wt% and in the 0.50 mm^2 with 2.3 wt%. This validates that there has been a loss of plasticiser during the post-ageing and that more loss occurred from the 0.75 mm^2 cable.

The average thickness could, however, be determined and was found to be affected by the post-ageing thermal exposure, as can be seen in Figure 16 for the 0.5 mm^2 cables and for the 0.75 mm^2 cables in Figure 17. There was some spread in the data, which are based on 10 separate measurement per ageing time, but the trend with decreasing thickness with ageing time is still clear for both insulator types.

Recalculating the change in thickness to the change in volume, excluding the conductor in the middle, there is a larger decrease in volume for the 0.75 mm^2 insulator, around 12v%, compared to the 0.5 mm^2 insulator that decreased with around 7v%.

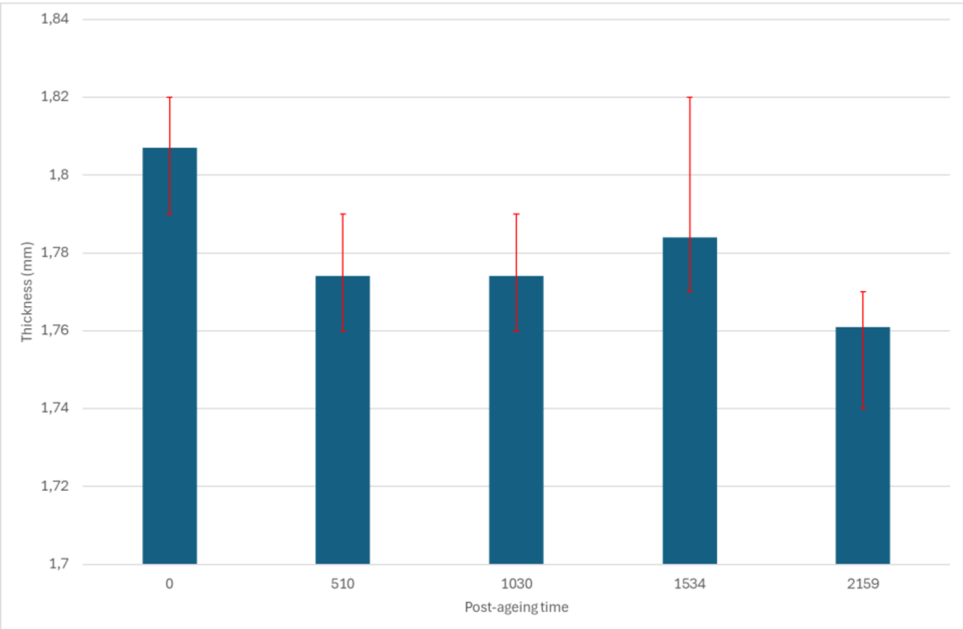

Figure 16. The average thickness of the 0.5 mm^2 cable for the different post-ageing times. The measurements are based on 10 separate measurements.

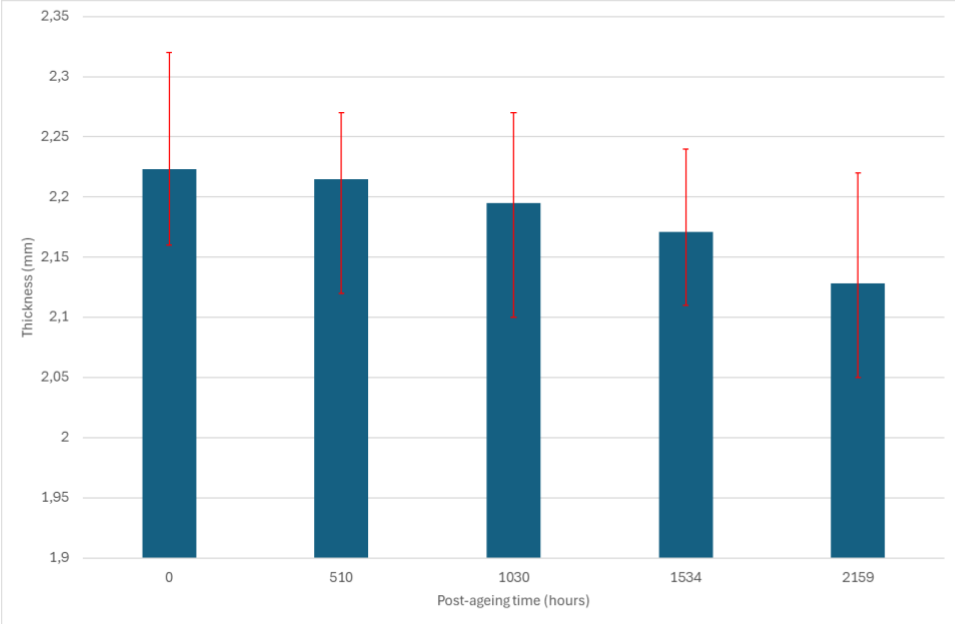

Figure 17. The average thickness of the 0.75 mm² cable for the different post-ageing times. The measurements are based on 10 separate measurements.

The glass transition temperature, Tg (°C), of the cables was measured using DSC. For ease of measurement, the onset of the glass transition was evaluated as shown in Figure 18. Three to four repeat measurements were made for each sample.

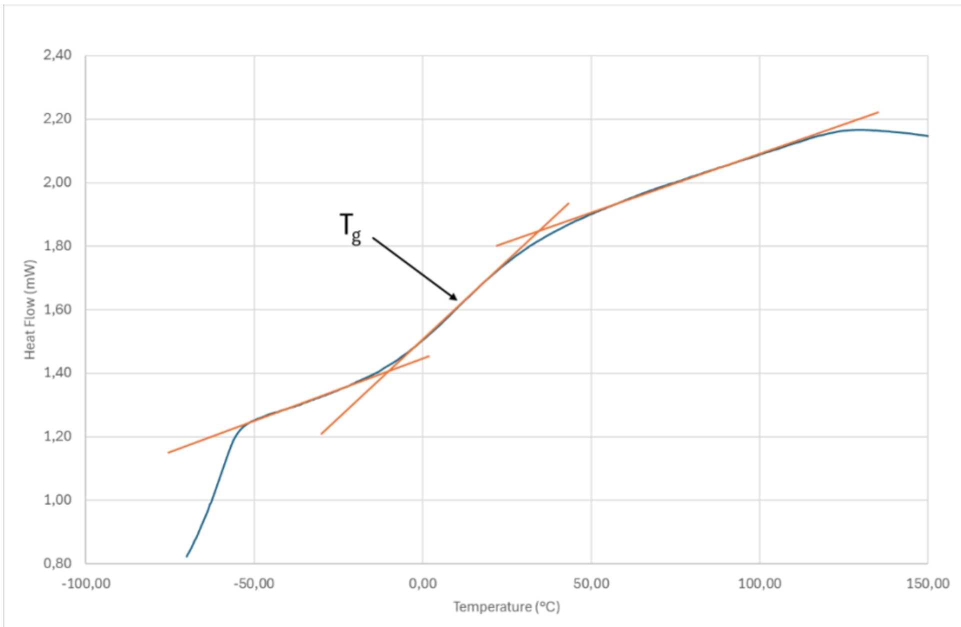

Figure 18. Determination of the glass transition temperature from DSC data. The graph shows the Tg of the 0.50 mm² insulator post-aged for 1534 h. The Tg was in this case 13°C.

Figure 19 shows the Tg as a function of post-ageing time for the 0.5 mm² and the 0.75 mm² insulators. As can be seen in the figure, the Tg increases linearly with ageing time for both materials, except for the very low starting value for the 0.75 mm^2 insulator. It is known that the Tg of PVC changes with the amount of plasticizer (wt%) in the material. According to Rijavec at al [1] the relationship between the concentration of DEHP plasticizer (C_{plast}) and Tg is:

$$Tg = -2.4C_{plast} + 76.8$$

Using the relationship above, the concentration of DEHP in the 0.5 mm^2 insulator material decreases during post-ageing from 30 to 26 wt% and for the 0.75 mm^2 from 39 to 24 wt%.

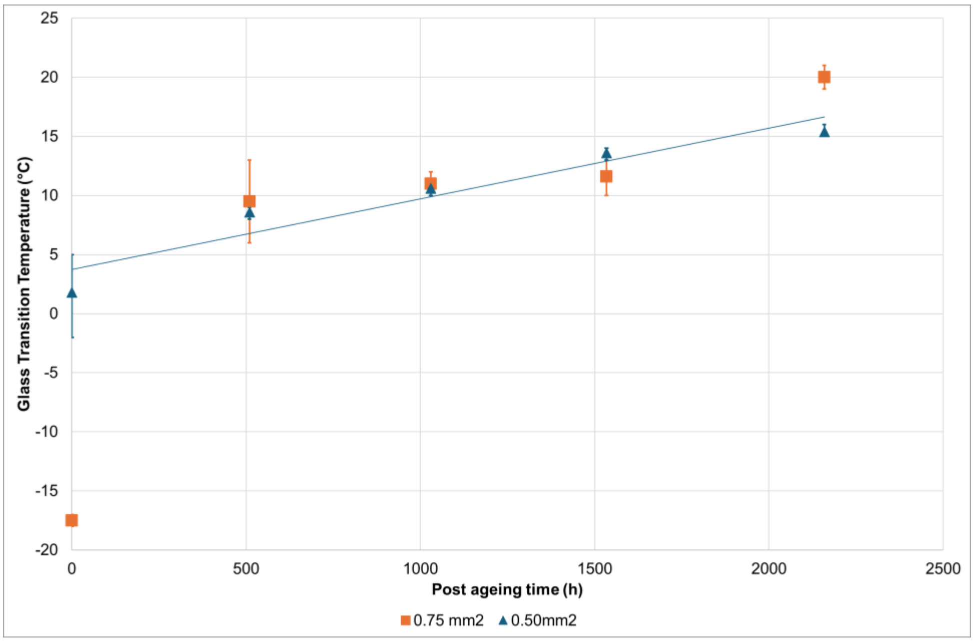

Figure 19. Tg as a function of post-ageing time for the 0.5 and 0.75 mm^2 insulators.

As mentioned above, there was not enough material to perform tensile testing on the full series, but there was enough of the material that had been post-aged for 2159 hours. The result can be seen in Table 1. As can be seen the 0.75 mm^2 material has lower elongation at break, i.e. flexibility, that the 0.5, which is also clear when handling the samples. The elongation at break (149 and203%) is however greater than 50% absolute (generally accepted arbitrary threshold for brittle concerns) for both materials even after the post-ageing, indicating that it is not yet brittle.

Table 1. Elongation of break of the 0.50 and 0.75 mm^2 cables after 2159 hours of post-ageing.

	0,5 mm^2 Elongation at break after ageing (%)	0,75 mm^2 Elongation at break after ageing (%)
1	202	98
2	208	150
3	233	81
4	183	193
5	203	149
Median value	**203**	**149**

4 Discussion

TGA shows that the two types of instrumentation wires have slightly different compositions of the insulator material. They are both PVC plasticized with DEHP and possibly also contains some fatty acid, but the filler content is noticeably different. The 0.75 mm^2 material contains approximately 13 wt% calcium carbonate and an additional 17 wt% of some inorganic filler. The 0.5 mm^2 insulator material, on the other hand, has no calcium carbonate and only 12 wt% inorganic filler.

According to the Tg measurements the 0.75 mm^2 insulator contains more plasticiser than the 0.5 mm^2 insulator at the start of the post ageing (additional thermal ageing at 75°C). It also seems to lose more plasticizer during the post-ageing, from 39 to 24 wt% compared to the 0.5 mm^2 material that goes from 30 to 26 wt%. It is not understood why the 0.75 mm^2 insulator lost so much during the first 510 hours of the post ageing and then levelled out to the same loss rate as in the 0.50 mm^2 insulator. In order to rule-out that the first data point was not erroneous, the Tg was initially measured on duplicates and then repeated again and all measurements showed the same very low initial Tg. The non post-aged was also significantly less stiff when handling, compared to the rest of the samples in the aging series.

The difference in volume during the post -ageing did not show this large initial drop but still indicated that the 0.75 mm^2 decrease more in volume, with around 12 v% compared to the 0.5 mm^2 that lost around 7 v%. TGA data of non-post-aged material vs after post-ageing also confirms that the 0.75 mm^2 cable lost more plasticiser than the 0.50 mm^2 cable. The larger change for the 0.75 mm^2 material is unexpected since there was much more of the green liquid, which was found to be mainly DEPH plasticiser, seen after the post-ageing on the 0.5 mm^2 material. DEPH in itself is, however, colourless and hence it appears that only the 0.50 mm^2 cable displays some additional behaviour resulting in its green colour, possibly due to a reaction with copper ions in the conductor.

It was only possible to perform tensile testing on the materials that had been post-aged the longest, i.e. for 2159 hours at 75°C. Assuming that plasticizer loss is the major degradation mechanism over time, and this is quite likely given the mild exposure conditions, then with 0.9 eV (~ 87kJ/mol) as Ea this would correspond to an additional 21.5 years in service. Since the material even after this post-ageing time did not act brittle in any way, and that the elongation at break is more than 50%, then it can be assumed that it is still safe to use the cables for many more years. It is advisable that, if possible, new samples are removed in 10 years after these cables sections were taken out, i.e. in 2032, to check if the materials are performing as predicted by their accelerated ageing behaviour. The higher stiffness of the 0.75 mm^2 cable can be related to the higher filler content rather than the higher loss of plasticizer, but this would also be of interest to follow up on in the future.

Unfortunately, the cables are too thin for indenter measurements, as this could have offered another method to follow the natural ageing of the cables in a non-intrusive way. It would also have been interesting to see the magnitude of any difference between the two different types of insulation materials and how much they have been affected by the post-ageing. The indenter is specified for application to the smallest dimension of 3.26 mm in diameter. The thickness measurements are also non-intrusive and could possibly be used instead to follow the degradation. The spread in the data is, however, quite large and it might not be possible to see clear trends in shorter ageing times although ongoing deviations from a defined end-state (bare minimum diameter with significant loss of plasticiser) should be measurable.

As one of the aims and scope, the present investigation also hoped to understand if more thorough materials knowledge can be used to better predict the long-term performance of PVC insulation materials in general. The choice of material characterisation techniques was made to give fundamental information about the chemical, physical, thermal and mechanical properties of the material. The aim was to use only the most basic analytical techniques for polymeric materials that are also relatively inexpensive and readily accessible. It was found that the two PVC cable insulators had noticeably different composition in fillers, and also quite different plasticiser loss rates, which is seen as the dominant service life limiting ageing behaviour. However, with only two different compositions, it is not possible to conclude that the higher filler content in the 0.75 mm^2 insulator material made it degrade faster than the 0.50 mm^2 insulator. Additional studies would have to be conducted. However, having a correlation between filler type and/or contents with loss of plasticiser, would be valuable toward determining which PVC cables are likely to lose plasticiser and may become stiffer faster.

5 Conclusions

The questionnaire that was developed within the LTO-project was proven useful to collect relevant information in order for material experts to help the plant operators as much as possible.

The insulation materials of the two cable types were not identical. The amount and at least to some extent the type of filler was different. The type of plasticiser was the same and was identified as DEHP (di(2-ethylhexyl) phthalate), a very common plasticizer for PVC insulation materials.

It seems quite clear from this study that plasticizer loss will be the ageing mechanism that will limit the service life of the wires, ultimately via embrittlement. The Tg, TGA and thickness measurements indicated that the 0.75 mm^2 material lost more plasticizer during the post-ageing accelerated thermal exposure at 75°C. This was unexpected as the 0.5 mm^2 samples had significant green liquid deposits on the surface of the cable strands after the post-ageing. It is possible that the green color originates from copper ions and that the conductor in the 0.5 mm^2 cable was releasing more copper ions into the plasticizer than the 0.75 mm^2 cable and by this making the plasticizer much more apparent.

The tensile testing showed that after an accelerated post-ageing time proportional to 21.5 years in service, the materials did not act brittle in any way and the elongation at break was still more than 50% in absolute terms (sufficient flexibility remains). It is thus suggested that it is still safe to use the cables for many more years. It is, however, advisable that new samples are removed after approximately 10 years after the analyzed cables were recovered i.e. in 2032, to check if the materials are still behaving as predicted from the current accelerated ageing tests.

This study confirmed that both insulator types seem to have the potential to be used for another 20 years without performance-limiting embrittlement. The improved understanding of the material composition greatly contributed to increasing our confidence in the result from the accelerated testing, and will most probably also come in very helpful in future work on the aging of other PVC cables in NPP application environments. More studies are needed before any general conclusions can be made about the composition of the PVC and its ageing behavior, but the used set of experimental techniques showed how to gather and interpret the results for improved understanding of PVC ageing in cable insulators.

6 References

1. Tjaŝa Rijavec et al, Heritage PVC Objects: Understanding the Diffusion-Evaporation of Plasticizers, Polymer Degradation and Stability, 235 (2025) 111270

EXAMINATION OF TWO IN-SERVICE-AGED PVC CABLES FROM A NUCLEAR POWER PLANT

Two PVC instrumentation wires recovered from in-service for over 40 years have been examined. A thorough examination of the cable materials and an accelerated ageing study showed that the cables differed in their composition, but that both had the potential to perform satisfactorily for another 20 years in service. The main ageing mechanism leading slowly to a stiffer material is loss of the DEPH plasticiser.

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