Sample CONFIDENTIAL REPORT

Prepared for

Area 51

Investigation of a Failed 11kV Cable Termination from Location X

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Approved By: ....

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Executive summary

Area 51 experienced the failure of an 11kV cable termination at its secret location in November 2011. The termination was made using Company Z heatshrink components fitted to a 1000mm2 XLPE insulated cable and was greater than 10 years old. The circuit contained three single core cables per phase (nine cores total) and was solidly bonded (earth screens bonded to earth at both ends of the circuit).

The investigation included examination of the failed termination and one equivalent non-failed termination removed from the same circuit. The examinations included initial visual examination, systematic disassembly and microscopic examination of key areas of the cable insulation. Information provided by Company Z was also considered.

The investigation found that the terminations had been assembled with semi-conductive paint around the screen cut rather than the stress relieving mastic that is intended to be used. That resulted in electrical stress being concentrated near the screen cut, causing that area of the termination to break down electrically, leading to partial discharge and eventual failure. The non-failed termination showed evidence of this mode of degradation, although it had not yet failed.

It is not certain why the paint was used instead of the mastic, or at what point in the supply chain the paint was introduced. The instructions provided to the jointer were not available during the investigation, so it is not certain whether the jointer was following erroneous instructions or whether the jointer made the error of applying the incorrect material.

The report also discusses options for asset management of the remaining similar terminations, including partial discharge monitoring in the short term and termination replacement in the longer term.

Scope and Objectives

The scope of the project:

The investigation included examination of the failed termination and one equivalent non-failed termination removed from the same circuit. The examinations included initial visual examination, systematic disassembly and microscopic examination of key areas of the cable insulation. Information provided by Company Z was also considered.

The objective is to:

The investigation aimed to answer the following questions:

1. What was the fault mechanism?
2. Is the cable termination method correct for cable?
3. Are the materials selected correct?
4. Is the workmanship of the cable jointer defective?
5. Is there any deterioration of the good (control) cable termination, which will be an indication that a similar fault will develop in the other cables associated with the failed one?

6. Would a partial discharge monitoring method be able to identify impending failure of other terminations or is there an alternative non-intrusive technique?

7. Are there any other implications for other similar terminations or cable circuits?

Key Project Learning

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Contents

1. Samples Supplied

Parts of two terminations were supplied (Figure 1):

1. part of the failed termination, which had been cut below the lug and below the end of the heatshrink termination body,

2. part of a non-failed termination, which had been cut below the lug and on the plain cable section below the termination. The heatshrink termination sleeve was not present on this sample when it was delivered to EA Technology, but for the purposes of this investigation, it is assumed that the sleeve had been present when the termination was in service.

Figure 1. Samples supplied to EA Technology for examination.
Non-failed termination is upper in the picture, failed termination is lower.

Good practice in investigations of this type would normally involve removal of the complete terminations in one piece with no items removed from them prior to investigation. The investigation proceeded with a comprehensive examination of the available evidence, and in this case significant features relating to the cause of failure were found within the evidence supplied. If the sections of the terminations that have not been supplied are subsequently found to contain critical evidence, then EA Technology will not be held responsible for any inaccuracies resulting from non-presentation of that evidence.

Markings on the heat shrink sleeve of the failed termination and on the stress control tube of the non-failed termination showed that these components had been made by Company Z: it was therefore assumed that the termination kit was manufactured by Company Z.

2. Examination

2.1 Electrical testing

On each sample, a small section of the cable copper tape screen was exposed at the lower end to allow the probes of a low resistance ohm-meter to make contact with the screen. The resistance between the screen and the outer end of the earth bond lead was then measured. The measured resistances are shown in Table 1.

Table 1. Earth bond resistances

Termination	Earth bond resistance
Failed	2.89mΩ
Non-Failed	2.24mΩ

While EA Technology does not have any firm benchmark figures for acceptable resistance for bonds of this type, the resistances of the two bonds were broadly similar, indicating consistency in this aspect of the terminations.

2.2 Failed termination

2.2.1 Disassembly and visual examination

On the failed termination, arcing damage on the conductor was visible in the fault hole. The area in and around the fault hole showed no evidence of contamination or mechanical damage that pre-dated the fault damage. The fault appeared to be near the screen cut (where the extruded insulation screen of the cable is cut, effectively the end of the earth plane around the cable) and was next to the point where the earth bond lead was fitted onto the copper tape screen of the cable (Figure 2). None of the yellow mastic tape that is part of the Company Z termination design and should be fitted around the screen cut was seen in the termination: for reference, a view of a similar termination equipped with yellow mastic tape is given in Figure 3.

Figure 2. View of the fault hole in the failed termination

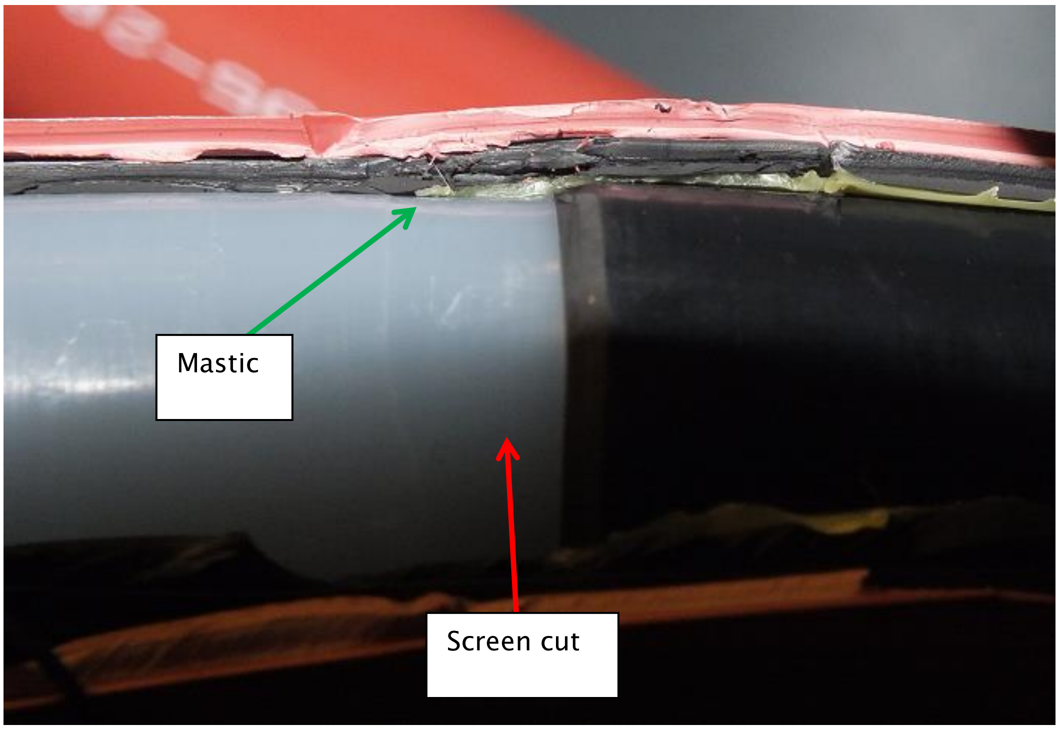

Figure 3. Yellow stress relieving mastic around a screen cut in a cut away view of a correctly assembled termination

As far as could be ascertained from the available evidence, the heatshrink tube appeared to have been shrunk down evenly to avoid unwanted air pockets. The heatshrink tube was then cut along its length and removed. The inside of the tube was examined, but no significant features were found.

The stress control tube showed a crease aligned with the fault damage: this may have been a result of the fault rather than an assembly defect (Figure 4). The remainder of the tube appeared to have been shrunk into place evenly with no other defects on the stress control tube noted.

Figure 4. Failed termination: stress control tube creased next to fault damage

The stress control tube was cut along its length and removed. Inspection of the inside of the tube showed no further features of interest.

With the screen cut now exposed, it was seen that there was no yellow stress relieving mastic around the screen cut, but instead there was a ring of paint instead (Figure 5). An area of paint that had not suffered fault damage was tested with a multimeter in resistance mode. The electrodes were pressed into the paint with a 5mm gap between them and a resistance of 4.4kΩ was measured: a similar measurement on the cable extruded semiconducting screen gave a resistance of 3.5kΩ. These measurements indicated that the paint was probably semi-conductive. Such paint would not relieve stress, but would instead concentrate electrical stress at the upper end of the paint. The fault hole was coincident with this painted layer.

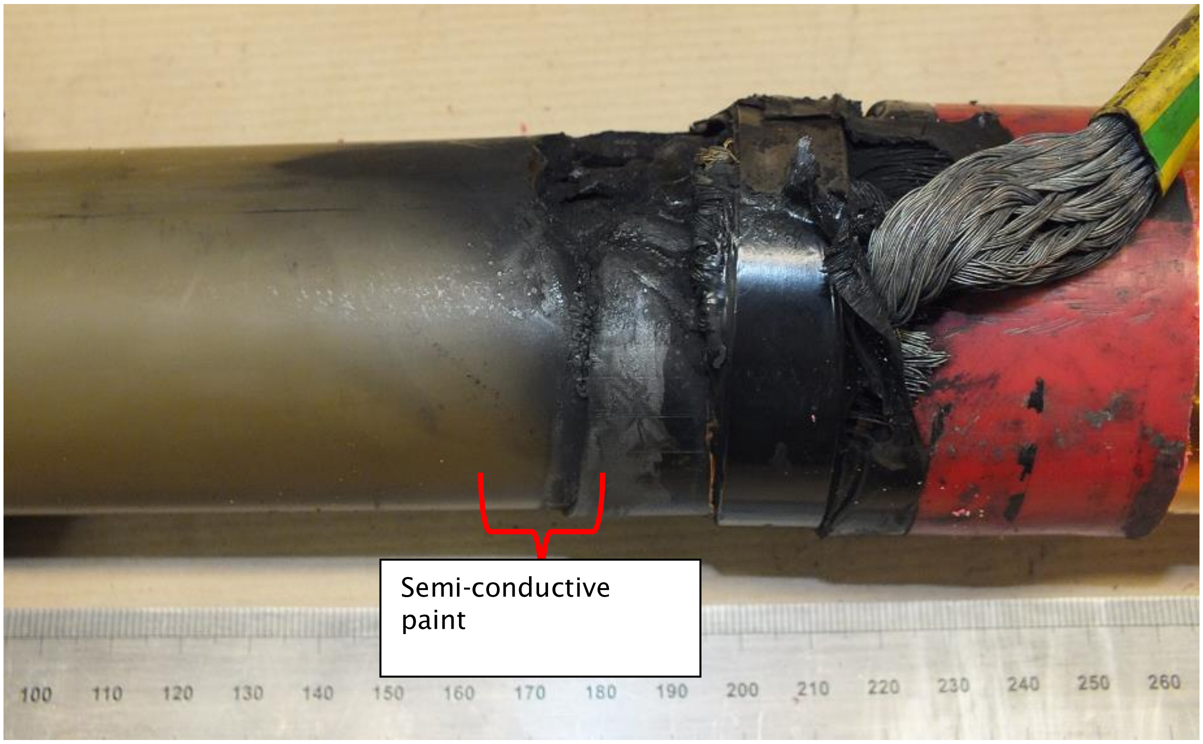

Figure 5. Semi-conductive paint applied around the screen cut

The cable oversheath was cut along its length and removed. The exposed copper tape screen on the cable appeared to be relatively undamaged and no further features were seen on the roll spring earth bond (Figure 6).

Figure 6. Exposed copper tape screen undamaged

The roll spring and earth lead were removed. Some blackening of the contact area between the copper tape and earth lead was noted, but all arcing was in a position next to the roll spring, not directly inside it (Figure 7). This indicated that the fault was not directly related to the earth lead to copper tape bond.

Figure 7. Contact area between copper tape and earth lead blackened, but not arc damaged. Arcing damage on the tape is above the roll spring position.

The copper tape screen was removed from the cable. A line of arc erosion was seen in the cable insulation (Figure 8). The alignment of that feature was marked along the full length of the sample for future reference during cross sectioning and microscopic examination of the cable.

Figure 8. Linear arcing damage in the cable

2.2.2 Cross sectioning and optical microscopy

Two cross section slices were cut through the sample and prepared for microscopic examination. One slice contained the screen cut and associated semi-conductive paint and the other slice was from the upper end of the sample where there was little discolouration of the XLPE. The slices had the conductor strands removed and the insulation surface was polished to allow microscopic examination (Figure 9).

Figure 9. Slices prepared for microscopic examination

Examination of the slice that contained the screen cut showed no evidence of widespread treeing in the insulation, although much of it was heat damaged which may have obscured such damage in the insulation.

Examination of the slice that was remote from the fault showed no electrical damage (as would be expected from a slice taken from this low stress area of the termination). No specific features were found that coincided with the line of the linear damage found below the fault damage. A faint extrusion seam was found approximately 120º around the cable from the linear damage alignment: both the faint nature and position of the seam suggested that it had played no part in the creation of the linear arcing damage.

2.3 Non-failed termination

2.3.1 Disassembly and visual examination

The heatshrink sleeve was not present on the termination as received by EA Technology, so no comment can be made on its condition. The stress control tube had been evenly shrunk into place with no defects noted (Figure 10). The stress control tube was cut along its length and removed: no features of interest were found on its inner surface.

Figure 10. Non-failed sample, stress control tube in good condition

The insulation appeared to have been discoloured and the screen cut was also surrounded by paint, similar to the failed termination (Figure 11). A 15mm long line of material erosion was found next to the screen cut (possibly the result of arc erosion by partial discharge) (Figure 12), and some white deposits, typical by-products of partial discharge activity, were found next to the screen cut (Figures 13 and 14).

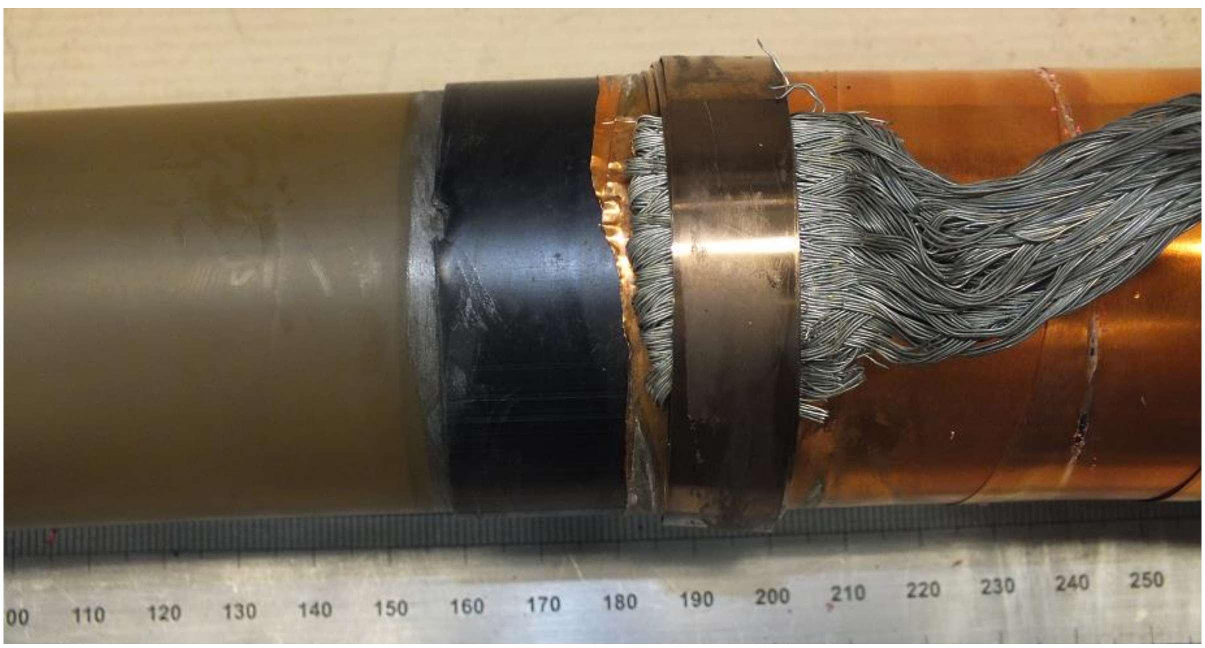

Figure 11. Non-failed termination: paint around the screen cut and discoloured insulation

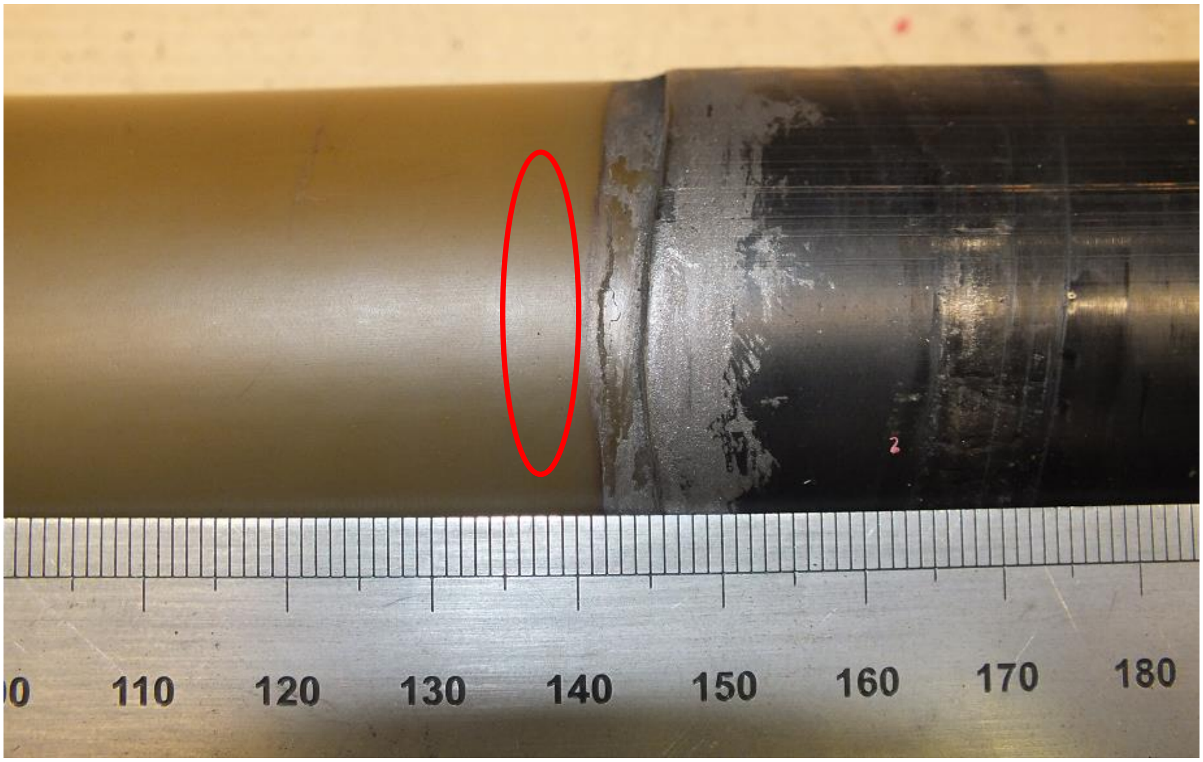

Figure 12. Line of material erosion possibly caused by partial discharge damage

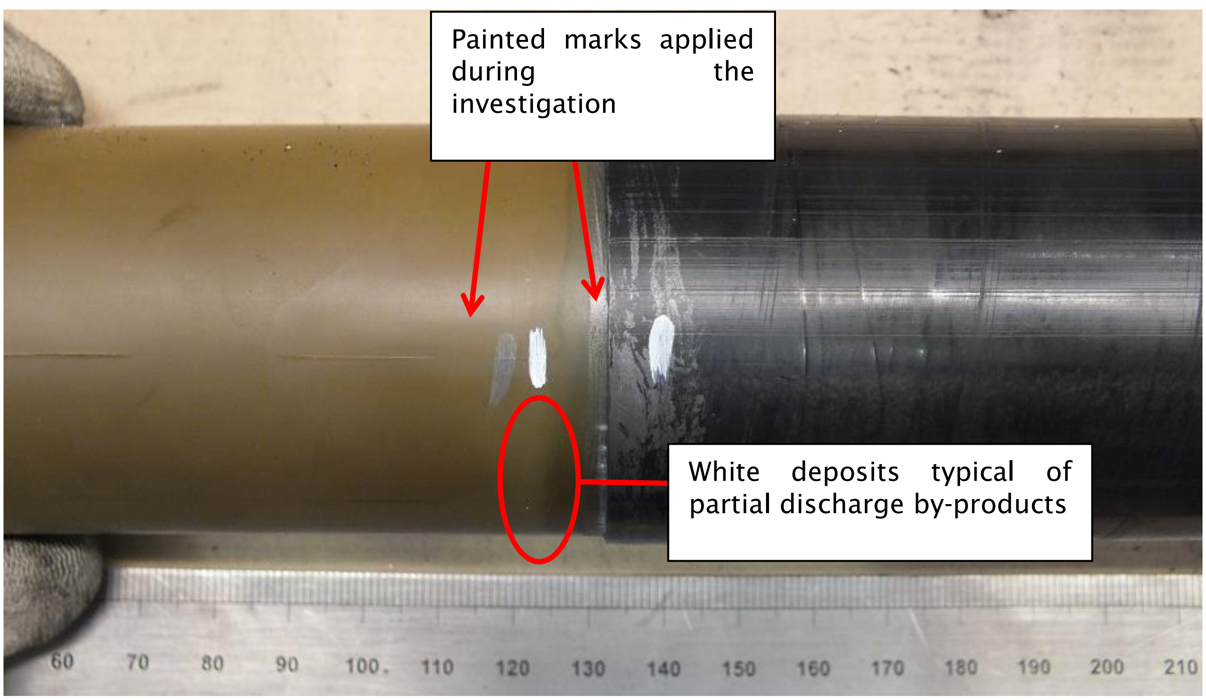

Figure 13. White deposits next to the screen cut

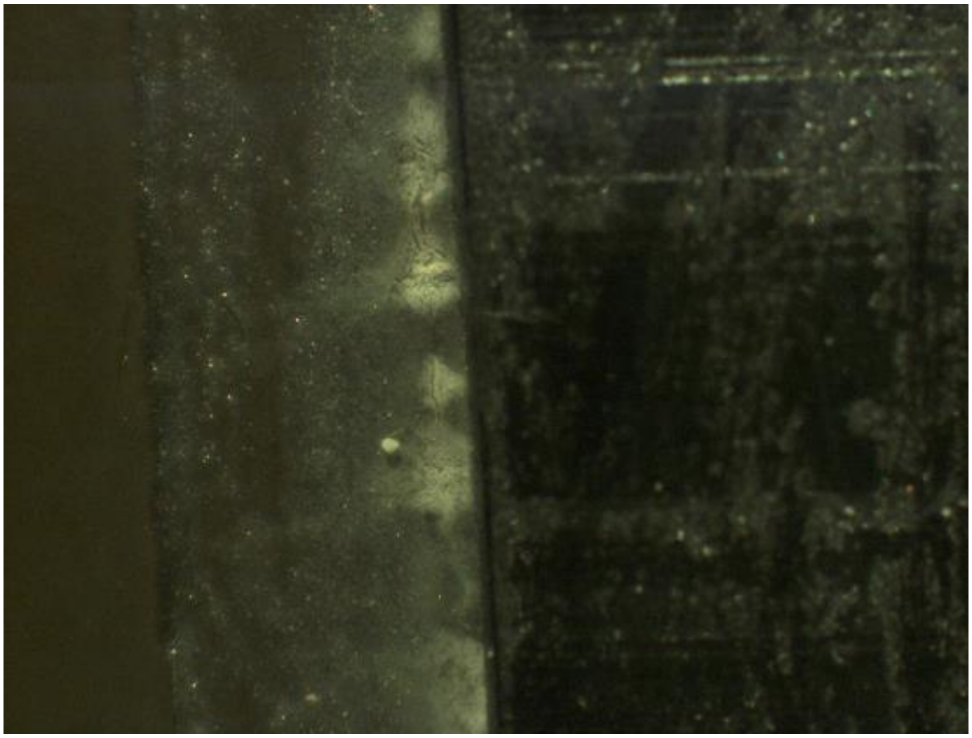

Figure 14. Microscopic view of the white deposits

There was no evidence of any degradation at the earth bond lead, roll spring or copper tape screen and those components were removed.

2.4 Cross sectioning and optical microscopy

A slice was taken through the cable including the screen cut position. The conductor strands were removed and the insulation surface was polished to allow microscopic examination (Figure 15).

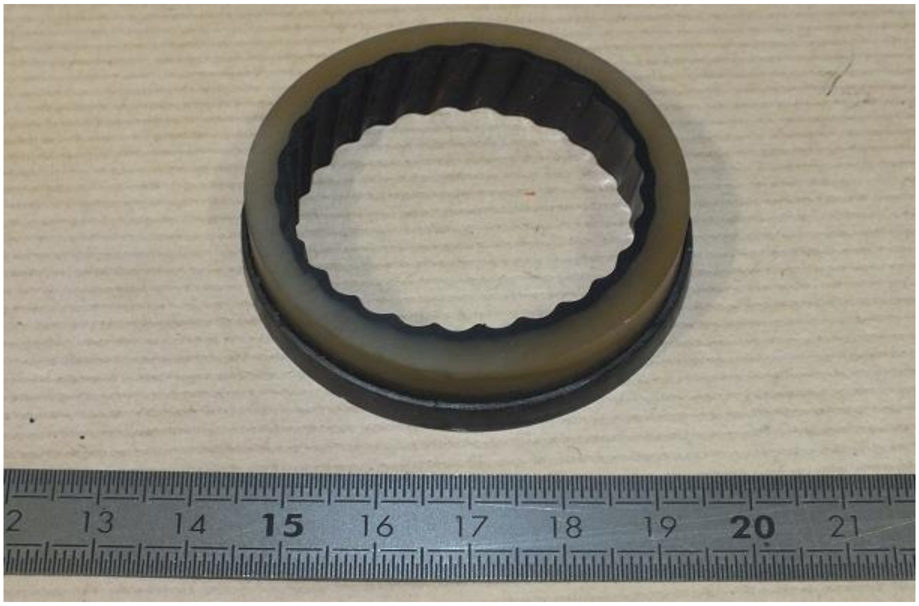

Figure 15. Cable slice prepared for microscopic examination

Examination of the slice showed no evidence of any trees or other electrical damage in the insulation material. However, a very prominent extrusion seam was noted (Figure 16). The seam was more pronounced than would be found in high quality modern cable, but the absence of any electrical damage at the seam showed that the seam had not caused any electrical damage.

Figure 16. Non-failed sample: prominent extrusion seam in the XLPE

3. Discussion

3.1 Cause of failure

The terminations had been assembled using a semi-conductive paint rather than stress relieving mastic around the screen cut. This would have concentrated electrical stress at the end of the paint, making that area susceptible to electrical breakdown of the surrounding materials. On the non-failed termination, some material erosion consistent with electrical erosion was noted, and white powders typical of such partial discharge activity were also noted. The XLPE was also discoloured, which may have been caused by heating from the partial discharge activity.

The failure occurred at the paint that had been applied around the screen termination, which would in theory be the point of highest electrical stress of the termination as assembled.

It was noted that the failure occurred next to the earth current bond. There is no indication from the available evidence that the bond was a contributor to the cause of failure, but the proximity of the fault to the bond has been considered. In a solidly bonded circuit formed of single core cables, a circulating current is induced in the screens by the electromagnetic field that is set up when load current flows through the cable conductors. That circulating current will flow through the copper tape screen and earth bonds: as with any current flow, when that circulating current flows through a resistance, heat will be generated. In this case, the relatively high resistance of the copper tape screen will limit the magnitude of the circulating current to a relatively low level, so there would be no excessive heating effects generated by circulating current flowing through the resistance of the screen to lead bond. However, that bond may be slightly warmer than the rest of the termination and may therefore be more susceptible to partial discharge damage if there is some other defect that causes high electrical stress in that area. This theory is not backed up by any material evidence of experimental data, but it could explain why the failure occurred so close to the bond.

The available evidence suggests that the following sequence of events took place:

1. The terminations were assembled using semi-conductive paint around the screen cut, rather than stress relieving mastic.
2. The presence of the semi-conductive paint caused a high concentration of electrical stress in the termination.
3. The high stress led to electrical breakdown of the termination materials, leading to partial discharge in the affected areas.
4. The discharge led to overheating and further erosion of the termination materials, until the remaining solid insulation was no longer sufficient to withstand the electrical stress that was present; at that point catastrophic failure occurred.

The cause of failure is therefore identified as the use of a semi-conductive paint rather than stress relieving mastic around the screen cut.

3.2 Assessment of termination method

Generically, use of heatshrink terminations using the correct components to assemble a termination as designed by the manufacturer is acceptable for this type of cable.

However, in this case, a semi-conductive paint was applied to the screen cut instead of a stress relieving mastic. This aspect of the termination method was the cause of failure. Information supplied to EA Technology by Company Z (information supplied prior to this investigation taking place) has indicated that this type of termination has always included stress relieving mastic, so it is unlikely that the designed termination was inappropriate.

3.3 Selection of materials

The use of a semi-conductive paint rather than stress relieving mastic was a clear issue of the incorrect material being selected for use in the termination. However, it is not known why that material was selected, or at what stage in the supply chain it was introduced. Information supplied by Company Z prior to the failure occurring indicates that the design did not include this inappropriate material. However, it is uncertain whether the inappropriate material selection was made during factory assembly of the kits, assembly of the kits by a distributor, or by the jointer.

It should be noted that use of conductive or semi-conductive paint at a screen cut is a necessary part of some cable joints and terminations designed for higher voltages: in those cases, the instructions given by the accessory manufacturer will specify the use of conductive paint. By looking at the instructions provided, it will be easy to identify the accessories in which conductive paint should be used and those in which it should not be used.

3.4 Workmanship of the jointer

It is not certain whether or not the decision to use a semi-conductive paint rather than mastic was a decision made by the jointer, or whether it was an error in the instructions supplied to the jointer. If it was the former, this would be a gross error in the quality of workmanship, as the jointer should always follow the instructions provided and a good jointer would know that conductive paint should not be used instead of stress relieving mastic.

However, if the jointer was following instructions that specified the use of conductive paint, it would be the instructions that were at fault, not the jointer's workmanship. The instructions used by the jointer were not available to EA Technology, and bearing in mind the age of the terminations, it may not be possible to trace those instructions. In the absence of the jointing instructions, it has not been possible to make a definitive statement about the quality of workmanship.

It should be noted that the other aspects of the samples provided gave no reason to question the jointer's workmanship.

3.5 Evidence of impending failure in the non-failed sample

The non-failed sample showed discolouration symptomatic of excessive heating and white powders symptomatic of partial discharge, indicating that it was deteriorating due to the presence of semi-conductive paint at the screen cut. This is clear evidence that other cables that have been terminated with semi-conductive paint rather than mastic are at risk of failure, and that partial discharge occurs during the failure mechanism.

This suggests that all terminations that have been assembled using semi-conductive paint rather than mastic are at significant risk of failure. Based on the evidence available, it is probable that other terminations of the same type installed at the same time will probably have been assembled in the same incorrect manner. Therefore, the other terminations on the same circuit can be seen to be at high risk. Remedial actions for those terminations are discussed in Section 4.6.1.

3.6 Implications for similar circuits

3.6.1 Risk of failure at terminations

It has been established that other terminations, particularly the other terminations on the same circuit, are at risk of similar failure. The evidence suggests that partial discharge forms part of the failure mechanism, and this justifies the use of partial discharge monitoring as part of an asset management strategy. The discharge occurred within the termination, not on its surface, so the activity is more likely to be detected using Transient Earth Voltage (TEV) measurement than by using ultrasonic discharge measurement. An immediate indication of which terminations are at highest risk can be gained by undertaking a non-intrusive partial discharge survey using portable hand-held equipment. As a more thorough approach to assessing developing discharge in the near future, a TEV monitoring system could be installed on the cable boxes thought to be at risk, the levels of partial discharge could be monitored, with alarms being raised when partial discharge reaches critical levels, but before failure occurs. In this way, the cables can remain in use with a high level of mitigation against the risk of failure.

The time between discharge inception and final failure is uncertain in this case, so if PD was detected, failure could be imminent, or it could be several months away. If the time between partial discharge inception and final failure is very short, the cables would need to be isolated very soon after discharge detection in order to prevent failure. While this limitation of monitoring must have been considered, if partial discharge monitoring was implemented, it would give the best possible chance of being able to detect impending failures using non-intrusive methods.

It should be noted that monitoring will not prevent deterioration of other terminations that have been incorrectly assembled: it will only allow their condition to be monitored in order to maximise their use while minimising risk of failure. At some point in the future, the terminations at risk will need to be replaced to prevent similar failures and it would be prudent to plan a replacement programme that takes into account risk of failure and plant operational needs. Data obtained from partial discharge monitoring could be used when planning that programme to identify terminations at higher risk, allowing those terminations to be given a higher priority for replacement.

3.6.2 Prominent extrusion seam

It was observed that the non-failed sample showed a distinct extrusion seam in the cable insulation. On the failed sample, the fault damage was not aligned with the extrusion seam, so the seam was not a cause of failure. However, the very distinct nature of the extrusion seam on the non-failed sample was considered to be unusual and is an indication that the quality of cable manufacture was not as high as can be achieved in a modern good quality cable.

The analysis undertaken did not show any electrical deterioration at the seam, so on the basis of the evidence examined within this investigation there is no evidence to suggest that the seam is a risk to cable integrity in this case. Therefore, there is no evidence to suggest that any action should be taken at present in reaction to this observation. However, poor extrusion seams have been implicated in other failure investigations undertaken by EA Technology, so if future cable failures occur in this circuit, the possibility of a seam defect being the cause of failure should be considered.

4. Conclusions

C1. The cause of failure is identified as the use of a semi-conductive paint in the termination, rather than a stress relieving mastic that should have been used. That led to a concentration of high electrical stress, leading to partial discharge and catastrophic flashover.

C2. If the termination method and materials normally recommended by the manufacturer had been used, this generic type of termination would have been appropriate for this application.

C3. The incorrect materials were selected for use in the termination (semi-conductive paint rather than stress relieving mastic). It is not certain at what point in the supply chain these incorrect materials were selected.

C4. In the absence of the instructions that were provided to the jointer, it has not been possible to make a definite judgement on the quality of workmanship. If the instructions specified the use of semi-conductive paint, there would be no reason to question the jointer's workmanship. However, it the jointer chose to use the semi-conductive paint rather than mastic, the jointer's workmanship would be unacceptable.

C5. The condition of the non-failed sample showed that it was at high risk of failure by the same mechanism. Therefore, it is expected that all other terminations that have been assembled in the same way are at significant risk of failure.

C6. Use of partial discharge monitoring using TEV measurement offers the best available non-intrusive method of condition monitoring for other terminations that are thought to be at risk of failure. This offers a short-term option for keeping the cables in service while mitigating against the risk of failure.

5. Recommendations

R1. Similar terminations installed at a similar time should be considered to be at risk of similar failure.

R2. A programme of partial discharge monitoring using TEV measurement should be implemented as a short-term measure to allow the cables to continue in use until critical levels of discharge are found.

R3. A programme of termination replacement should be drawn up and implemented as a longer-term solution to preventing similar failures.

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