11165 Session 2022

B1 INSULATED CABLES
PS 1 - Learning from experiences

Developments towards a Risk Based Maintenance program to reduce fires at LV cable terminations and plastic enclosures

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SUMMARY

Electricity customers connected to underground LV reticulation in New Zealand are typically connected to the network via a fuse inside an LV enclosure on the boundary of the road and the property. Every year, a small percentage (estimated at < 0.1%) of this asset type may catch fire following an internal component failure, a so called "pillar fire". The root cause of these failures is yet to be confirmed, although several potential causes have been identified. Furthermore, several risk mitigation techniques have been identified.

This paper describes the efforts and progress to date to support the development of a risk-based maintenance strategy to reduce the instance of "pillar fires". This paper is part of a larger effort to develop a risk-based maintenance strategy; a framework to optimise and justify maintenance tasks balancing cost, risk, and performance. An understanding of the failure mode(s) leading to fires is required to select the optimal combination of inspection and maintenance actions.

The understanding of the main failure modes was gained through improved inspections, failure investigations, lab testing and literature research, and is reported in this paper.

First, case studies of defect and failure investigations are provided as real-world examples. Laboratory testing of plastics was performed which confirms the flammability and burn rate of various materials used to construct the enclosures. The laboratory tests confirm material performance information provided by manufacturers.

A discussion of investigations into failure modes of internal components such as the LV cable, fuse carriers, fuses, etc. that may lead to a fire, follows. A functional failure analysis produced a list of potential triggers, causes, deterioration processes and root causes. The relationships identified by the functional failure analysis and their effects on the components with potential consequences are explored.

Potential test, inspection, and maintenance tasks are described, with developments of some tasks in progress. Potentially useful condition monitoring technologies such as fault detection on LV cable circuits and IoT sensors are touched on.

Finally, current and future work to further develop asset management processes is summarised with interim conclusions that follow from the analysis of the investigation and inspection performed to date.

KEYWORDS

Risk Based Maintenance, Cable, Fuse, Low Voltage, Pillar, Plastic, Root Cause Analysis, Failure Modes, Inspection

1 Introduction to the problem

Electricity customers connected to underground LV reticulation in New Zealand are typically connected to the underground LV network via a fuse inside a pillar (a LV ground mounted enclosure) on the boundary of the road and the property - see the single line diagram in Figure 5.

Every year in the order of 200 fires at pillars occur in New Zealand, as estimated by the authors. Even though this is a tiny percentage of the entire fleet, currently estimated at less than 0.1%, if this asset type catches fire after an internal component fails, a so-called "pillar fire", see Figure 1. Such a fire can be a significant hazard to people, property, and reputation due to the high number of assets in this fleet [1]. Therefore, it is considered to be important to improve the control of these hazards through a Risk Based Maintenance strategy [2].

Uncontrolled fires and other events at plastic pillars initiated thorough reviews of the risk associated with this type of asset and the technical knowledge available. The reviews included identification of methods to identify defects and confirm failure modes. The goal of the investigation was first to understand what caused the failure and secondly how failures can turn into a fire at the pillar. The root cause of these failures is yet to be confirmed, although several potential causes have been identified.

Electricity pillars are made from plastic, and also from a variety of other materials, such as plastic, steel, aluminium, concrete, fibreglass reinforced resin and a combination of these materials. Figure 4 shows examples of plastic enclosures, the focus of this paper. Figure 3 shows some of the types of internal components mounted inside these enclosures.

Figure 1 – A plastic pillar on fire, the subject of the case study below: before the fire (left), while on fire (middle) and zoomed in (right)

Figure 2 – the remains of two other plastic pillars after a fire

Figure 3 – examples of internal LV pillar components: mainly fuses, relays and links

Figure 4 – examples of plastic pillars commonly installed on the LV underground network in New Zealand

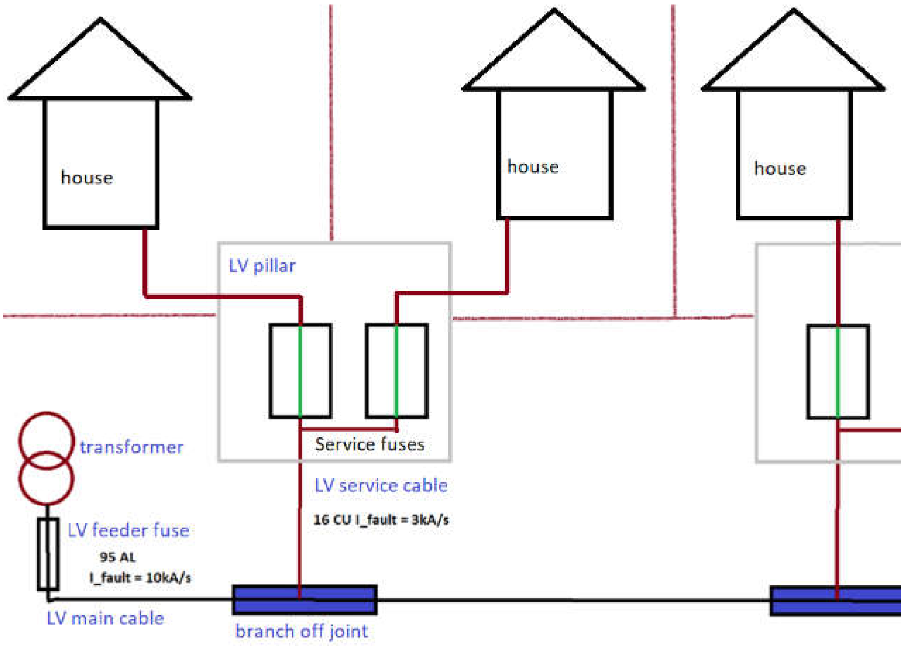

Figure 5 – typical NZ residential LV network configuration including function of plastic pillars used in the LV network: transformer, circuit fuse, main LV cable, branch off joint and short cable to pillar on the property boundary, which encloses the main service fuses for two or three dwellings

2 *Failure Mode, Effects and Consequence Analysis (FMECA)*

A practical failure mode, effects and consequence analysis is a core function to optimise inspections and maintenance on assets [3]. The function of a service pillar is to provide a cost effective, safe and reliable isolation point between the network and the customer's electrical installation. A failure impacts the asset's ability to perform its intended primary and secondary functions, namely to supply power and to protect members of the public by preventing access to the electrical components.

Failures of the pillar as a whole, or of one or more components inside, encompass a wide range of possibilities. Various triggers, causes and contributing factors include vehicle impact, moisture, undersized components and many more.

Consequences of a failure include electric shock due to unauthorized access to internal live components, a customer outage due to a break in the electrical circuit or a fault current tripping an upstream fuse, damage to property due to a fire of the pillar housing or an uncontrolled arc flash.

Effects of a failure are the impact of the failure on the asset and system itself: i.e. how the failure of an internal component for instance may lead to various effects, such as a fire at the pillar is a second follow on question we hope to answer in section 8. The intensity and time that these effects last largely determines the probability that the consequences described above are realized.

The authors believe there is strong evidence that faults in pillars typically occur at the fuse carriage of cartridge fuses. These components housed in pillars may ignite or may cause the plastic of the pillar to ignite due to a failure and lead to a fire at the pillar. Other potential causes and contributing factors were also considered, such as loose connections due to vibration, overheating of internal components, and high continuous current from PhotoVoltaics (PV).

In the following sections we hope to provide sufficient evidence that one of the main failure modes is corrosion of the cable terminal of the fuse holder. This hazard is not limited to pillars; a fire at a distribution transformer has recently also been caused by a fuse. Figure 6 shows how corrosion may lead to a "pillar fire".

Failure investigations are an opportunity to (better) understand how "pillar fires" might start, and what the underlying failure modes are. Assuming that component failures inside a pillar lead to a fire, the main questions to answer in a "pillar fire" investigation are:

- What causes the plastic to heat up to a point of ingnition?
- What triggers the ignition and what sustains the fire?
- How flammable are pillar lids and internal components?

Understanding the failure modes and failure causes are the foundation to outline effective maintenance actions to prevent failures and thus the associated fires.

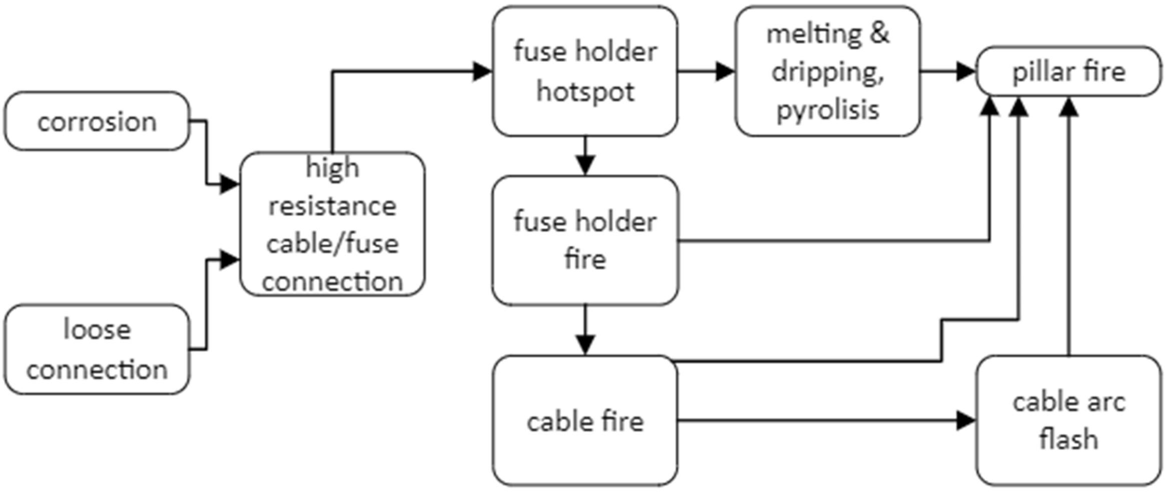

Figure 6 – Simplified process diagram: from corrosion to component failure to pillar fire

3 Case Study: fire at a plastic pillar

A fire occurred at an LV pillar which resulted in the complete destruction of the pillar, and property of the customer damaged [4]. Figure 1 above shows a pillar before, during and after a fire. Figure 2 below shows the remains of two similar style pillars, of different brands, after a fire. Additional photos and videos had become available through members of the public that provided a wealth of information to conduct the failure investigation.

The type of pillar was an older style black plastic of cube shape, several decades old. The cables rising from the mains cable were of tough plastic insulated, three core small size copper conductor (3 core copper conductor, 16, 25 or 35 mm^2). Little was left of the pillar or cables for a dissection and analysis after the event.

Review of video and photographic evidence that had become publicly available, and smart meter data, yielded various helpful observations, as detailed below.

The outcome of the failure investigation shows that the answer is complex and indicates there are many potential factors. Various potential causes, contributing factors and triggers were identified and considered, including how a component could ignite, and/or how the plastic could ignite.

Pictures and video

Pictures and a video clip were taken of a typical plastic pillar before, during and after a fire. Figure 1 shows the pillar before the event, and while it is on fire. Stills of the video are shown in Figure 7. The clip showed that a short circuit occurred while the fire was in progress, and the power stayed on for more than 2 seconds. This indicates that the short-circuit was the effect of the fire, not the cause. The consequence was further damage to third party property.

The upstream network fuse is unlikely to operate on a high resistance fault such as a brown-out of a fuse, or a high resistance connection is expected to not trip the fuse on its own. An earth loop impedance test, performed on the location shortly after the fire, showed a high fault current loop resistance, increasing the time to trip the fuses.

Figure 7 – stills from a video posted on Facebook by a 3rd party

Smart meter data

Voltage, current and power 30-minute data was obtained from the two "smart meters" of both customers, each connected to a separate service fuse each in the single pillar (as per Figure 4) — Figure 8 below shows the data from 12 Jan 2018 to 25 Feb 2018. The smart meter data showed fluctuations in the minimum voltage over time, as well as large differences between 30 minute maximum and minimum voltage. The zero voltage period on 10 Feb 2018 represents the time it took to replace the asset and reconnect power.

The voltage dips are visible weeks before the outage at both consumers (ICPs). Days before the outage, severe voltage reduction is visible on one of the ICPs, called ICP A. The outage is clearly visible in the data (red arrow). The voltage dips on ICP A are much more severe than on ICP B in the days before the outage.

Two time segments of particular interest are highlighted in Figure 8 by a green oval (5 days from 18 Jan 10:30 to 23 Jan 22:30) and a purple oval (data spanning 8 days before the failure from 2 Feb 11:30 to 9 Feb 21:30). Almost 10 drops in minimum voltage are observed a few weeks before the event (green oval), while there was no significant drop in the maximum voltage. That suggests that the minimum voltage might depend on the instantaneous current, or on moisture in the pedestal. A severe breakdown of the minimum voltage, and the maximum voltage, was visible days before the outage (purple oval and red arrow), although the drop in the maximum voltage was less pronounced. Note the minimum voltage dips below 200V and difference between max and min voltage of more than 50V.

Failure investigation Outcome

This failure investigation shows that voltage and current disturbance waveforms preceded the fault many weeks and days before the failure. These disturbances can even be detected in the data collected by the 30-minute intervals measured by the "smart meters" installed in the NZ power network.

Disturbances in voltage may be useful as a diagnostic indicator, if access is granted and the data is available in a timely manner. Fault monitoring equipment that detects "temporary short-circuit transients in a real grid as a method to identify damaged cables" as explored by [5] or Power Quality Meters as employed by [6] could provide diagnostics to detect these defects on LV underground circuits.

Secondly, analysis of the video and photos taken of the fault event indicates that a sustained arc event can be triggered by a fire occurring at a pillar. The fire in turn could be the result of a fault of a component inside a pillar.

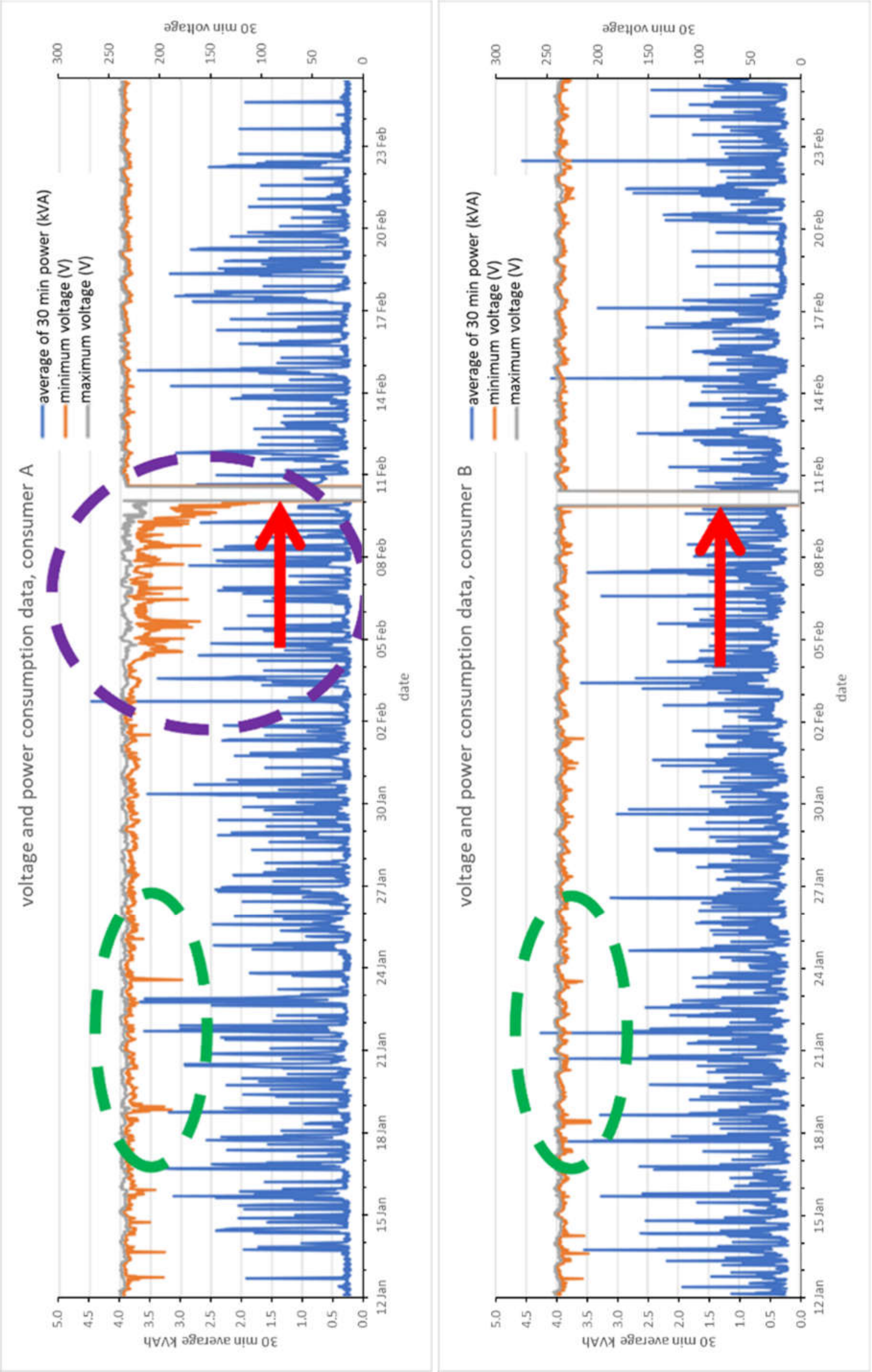

Figure 8 – voltage and consumption data for customer A and B. Note the loss of voltage during outage occurring on 10 Feb

4 Observed failures and degradation of fuses and holders

Failures of fuse holders seem to be a common occurrence and a main cause of power quality issues impacting single customer connections. The figures below show some examples of fuses and fuse holders that were damaged. Common observations of the damage are in line with overheating as described below. Most, if not all, of these fuses and fuse holders were replaced without a fire occurring at the asset.

The evidence indicates that the fuse holders currently used in pillars are indoor fuse holders and hence typically not designed to be resistant to the environment found in outdoor applications, such as inside a pillar. Continual measurements of internal conditions of 3 pillars show that the internals are consistently moist [1]. Internal T and RH data measured and recorded by IoT devices in three pillars show that the humidity in the pillars causes condensation at night (above 90%), which the authors believe leads to corrosion of the fuse holder terminals. The corrosion in turn leads to a high resistance connection, which results in a hot connection.

The heat from the hot connection can damage the materials of the nearby components. Figure 10 and Figure 9 shows heat damage of the components in a pillar (fuses, fuse holders, cable insulation), note the discolouration, charring, melting, cracking and splitting.

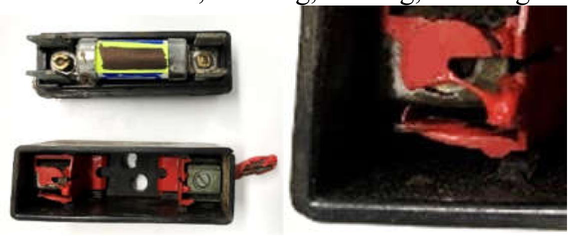

Figure 9 - Example of melted cable insulation and melted red plastic inserts

Figure 10 - Example of a failed fuse and fuse holder

5 Examples of corrosion on fuse holders

Signs of overheating due to a hot connection include melted deformed plastic (see examples in Figure 10, Figure 9, Figure 14, Figure 12), signs of incomplete combustion such as blackening, soot and brittle material of cable insulation as well as the fuse holder (see Figure 13, Figure 11, Figure 14, Figure 12), and signs of high temperature corrosion (as described below).

Heat damage to cable insulation in LV pillars is likely to have been caused by a hot connection. Electrical arcing or an open flame may also be a cause in instances where a failure has occurred. Figure 9, Figure 13 and Figure 11, among others, show some examples of melted and charred electrical cable inside a pillar.

Figure 13 shows an example of charred cable insulation and high temperature corrosion of the conductor, visible as scaling (the formation of thick layers of corrosion products on the metal surface). High temperature corrosion (HTC) is a particular deterioration process associated with high temperatures, recognisable by the corrosion products that differ from those associated with normal corrosion. See [7] for more information on corrosion and HTC.

Figure 11 – example of aluminium cable conductor of which the insulation has charred off (left), the heat damaged fuse holder base and insert (right) note the grub screw and part of the connection plate still connected to the conductor.

Figure 12 – example of heat damage to a black fuse carriage and the indentation on the green pillar mounting plate

Figure 13 – example of charred cable insulation and high temperature corrosion

Figure 14 – example of heat damage on the fuse holder and cable as charring, and the disappearance of cable insulation above the fuse holder. damage to the plastic body as whitening of the plastic above the fuse holder, charring of the plastic above the fuse holder, and an indentation of the cable in the top of plastic back plate

6 *Thermal image of a hot connection on a fuse holder*

Internal inspections were developed to capture defects in a pro-active, systematic manner. These inspections included a thermal scan of the pillar components. Figure 15 shows and example where a hotspot of 48.5ºC is evident at one end of the fuse holder. This has resulted in a temperature rise of 23.2ºC, when compared to the mounting plate which has a temperature of 25.3ºC. Internal inspections performed of 50 pillars in total at 5 different “pillar fire” locations yielded only 2 pillars with slight indications of possible defects.

Figure 15 – Hotspot at the Bottom of a Fuse Holder: bottom end of the fuse holder at 48.5ºC, mounting plate at 25.3ºC, incoming cables at 22.3ºC

7 *Fire behaviour: learnings from lab testing and videos of burning pillars*

Laboratory testing of pillar materials for fire response and performance, in accordance with [8] showed that the material type used for these plastic pillars can be ignited by an internal fault and may burn in the field while not assisted by a separate heat source (see [9] and [10]). This is in line with literature discussing fire behaviour of polyethylene, such as those listed in [11] and [12]. Furthermore, the laboratory tests show that the response of the materials to exposure to fire is quite consistent, regardless of the brands and makes of the plastic pillar or its age.

The two sets of photos in Figure 16 and Figure 17 videos of two different plastic pillars on fire. The power to both pillars had been turned off by the time these videos were recorded. This indicates that the fire of the plastic was self-sustaining, as described literature and laboratory tests. The flames are yellow with a blue centre, matching the behaviour of laboratory tests on combustion of PE materials.

Figure 16 – four stills from a video of a burning plastic pillar

Figure 17 – three stills from a video of a second burning plastic pillar, 28 April 2017, courtesy of Kim Hall, volunteer fire fighter

8 Hazard identification and root cause analysis

Hazards posed by electrical assets in the public space include consequences such as death or injury by electric shock, property destroyed or damaged (including buildings and houses, equipment or garden plants), asset damage, power outage to customers. Although these hazards are not unique to plastic pillars, the ubiquity and accessibility to the public of such assets compounds the probability of undesirable consequences to the network, property and people.

The main technical cause of failures of the fuse carriage is a hotspot at the wire connections, either by corrosion and/or loose connections. Most of the photos of defective components in pillars showed corrosion of fuse holders at the connections. Since these fuse holders are mounted in an environment with regular condensation and without proactive maintenance, these fuse holders could be considered to be unsuitable for their intended use. Therefor an incorrect fuse specification is a root cause of fuse failures leading to fires occurring at pillars.

Additional failure causes that were identified are firstly "floating fuses"; fuses that are not screwed onto a solid backplate, causing a short circuit to another phase or to an earthed conductor. This is considered to be a workmanship issue. And secondly, thermal overload of small fuses (a.k.a. fuse burn outs) causing these fuses to overheat due to their low heat capacity. This is also an incorrect specification issue.

9 Interim Conclusions

A systematic approach encompassing failure investigations, defect investigations, IoT sensors & internal inspections has contributed to understanding the root causes, failure modes and environmental factors. One of the main failure modes that lead to fires is believed to be hot, corroded connections at the cable/fuse holder connection due to condensation. The main root cause of "pillar fires" (a fire occurring at a pillar after a fault of the component inside the pillar) in NZ is currently believed to be incorrect fuse/fuse holder specifications

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