Rail Accident Investigation Branch

Rail Accident Report

Explosion inside an underframe equipment case at Guildford
7 July 2017

Report 05/2018
March 2018

This investigation was carried out in accordance with:

- the Railway Safety Directive 2004/49/EC;
- the Railways and Transport Safety Act 2003; and
- the Railways (Accident Investigation and Reporting) Regulations 2005.

Any enquiries about this publication should be sent to:

RAIB
The Wharf
Stores Road
Derby UK
DE21 4BA

Email: enquiries@raib.gov.uk
Telephone: 01332 253300
Fax: 01332 253301
Website: www.gov.uk/raib

This report is published by the Rail Accident Investigation Branch, Department for Transport.

Preface

The purpose of a Rail Accident Investigation Branch (RAIB) investigation is to improve railway safety by preventing future railway accidents or by mitigating their consequences. It is not the purpose of such an investigation to establish blame or liability. Accordingly, it is inappropriate that RAIB reports should be used to assign fault or blame, or determine liability, since neither the investigation nor the reporting process has been undertaken for that purpose.

The RAIB's findings are based on its own evaluation of the evidence that was available at the time of the investigation and are intended to explain what happened, and why, in a fair and unbiased manner.

Where the RAIB has described a factor as being linked to cause and the term is unqualified, this means that the RAIB has satisfied itself that the evidence supports both the presence of the factor and its direct relevance to the causation of the accident. However, where the RAIB is less confident about the existence of a factor, or its role in the causation of the accident, the RAIB will qualify its findings by use of the words 'probable' or 'possible', as appropriate. Where there is more than one potential explanation the RAIB may describe one factor as being 'more' or 'less' likely than the other.

In some cases factors are described as 'underlying'. Such factors are also relevant to the causation of the accident but are associated with the underlying management arrangements or organisational issues (such as working culture). Where necessary, the words 'probable' or 'possible' can also be used to qualify 'underlying factor'.

Use of the word 'probable' means that, although it is considered highly likely that the factor applied, some small element of uncertainty remains. Use of the word 'possible' means that, although there is some evidence that supports this factor, there remains a more significant degree of uncertainty.

An 'observation' is a safety issue discovered as part of the investigation that is not considered to be causal or underlying to the event being investigated, but does deserve scrutiny because of a perceived potential for safety learning.

The above terms are intended to assist readers' interpretation of the report, and to provide suitable explanations where uncertainty remains. The report should therefore be interpreted as the view of the RAIB, expressed with the sole purpose of improving railway safety.

The RAIB's investigation (including its scope, methods, conclusions and recommendations) is independent of any inquest or fatal accident inquiry, and all other investigations, including those carried out by the safety authority, police or railway industry.

This page is intentionally left blank

Explosion inside an underframe equipment case at Guildford, 7 July 2017

Contents

This page is intentionally left blank

Summary

At approximately 14:37 hrs on 7 July 2017, an explosion occurred in an underframe equipment case on train 2G44, the 14:37 hrs Guildford to London Waterloo service, as it was about to depart from platform 2 at Guildford station. The explosion resulted in debris being ejected onto other platforms and a car park near the station. There were no injuries to passengers or staff. There was damage to the train, and to station furniture.

The explosion was caused by an accumulation of flammable gases within the traction equipment case under one of the coaches of the train. The gases had been generated following a failure within a large electrical capacitor located within the equipment case. The capacitor failure was caused by a manufacturing defect.

The traction equipment on this train had been recently retrofitted, replacing older equipment with a modern version. The failed capacitor was part of this replacement equipment. The design and installation of this new equipment was managed by a project team which had not adequately considered the risk of explosion caused by a capacitor with a manufacturing defect. Consequently, the train did not have any engineering safeguards to prevent such an explosion.

As a result of the investigation, the RAIB has made one recommendation to UK train operating companies and the suppliers of their rolling stock. The recommendation relates to reviewing the design of electric traction systems in their fleets to check that there are adequate safeguards in place to prevent similar potentially harmful explosions and address any shortcomings identified.

The RAIB has also identified six learning points. These cover project risk management, the need for thorough investigations following technical failures, ensuring that accurate and complete records of serious failures are maintained, and ensuring that procurement specifications for future rolling stock takes into account the findings of this investigation.

Introduction

Key definitions

1 Metric units are used in this report, except when it is normal railway practice to give speeds and locations in imperial units. Where appropriate the equivalent metric value is also given.

2 The report contains abbreviations and technical terms (shown in *italics* the first time they appear in the report). These are explained in appendices A and B. Sources of evidence used in the investigation are listed in appendix C.

The accident

Summary of the accident

3 At approximately 14:37 hrs on 7 July 2017, an explosion occurred in an underframe equipment case on train 2G44[1], the 14:37 hrs Guildford to London Waterloo service. The train comprised two four-car Class 455 units, and was departing from platform 2 at Guildford station (figures 1 and 2). The explosion resulted in debris being ejected onto other platforms and a car park near the station.

4 There were no injuries to passengers or staff. There was damage to the train, and to station furniture.

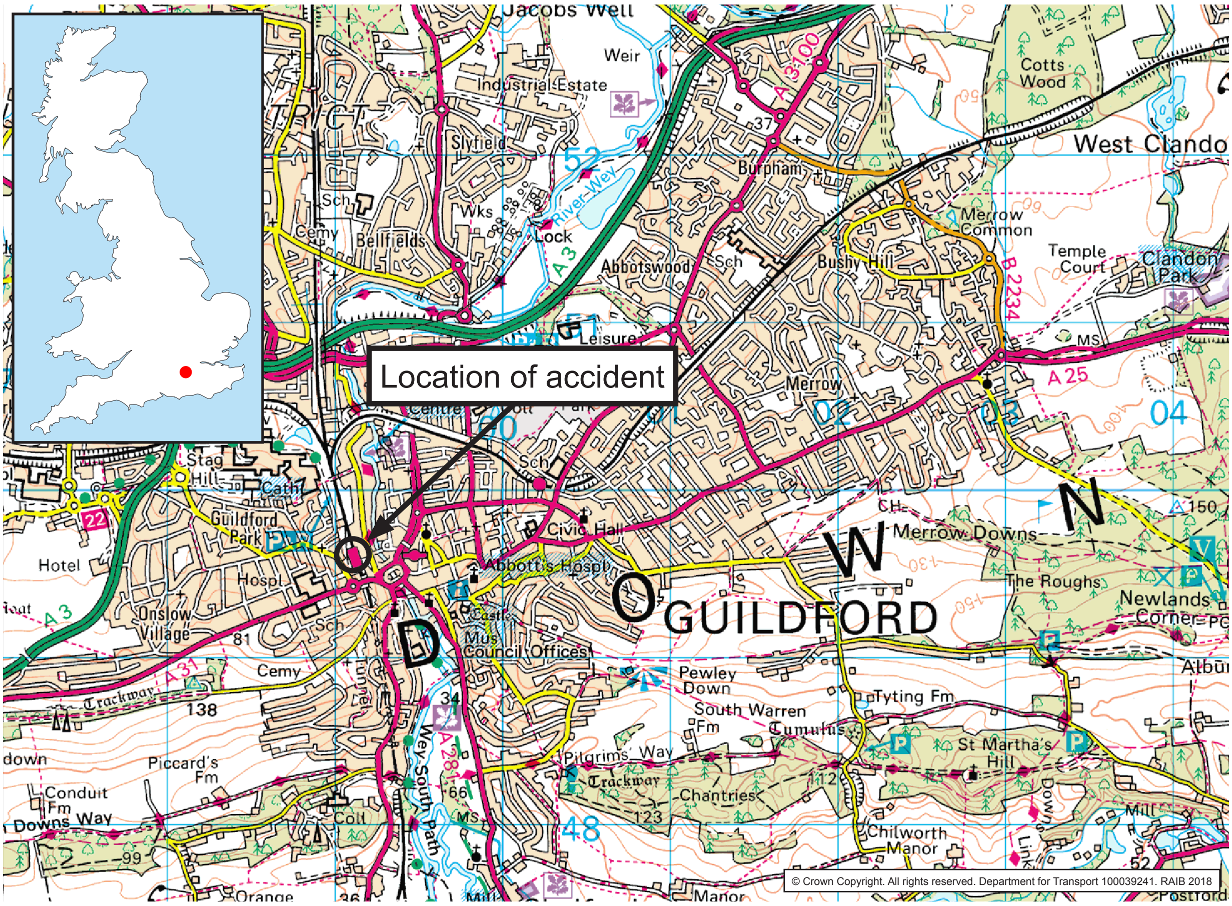

Figure 1: Extract from Ordnance Survey map showing location of the accident

[1] An alphanumeric code, known as the 'train reporting number', is allocated to every train operating on Network Rail's infrastructure.

Figure 2: Guildford station in the context of the railway route network

Context

Location

5 Guildford station in Surrey (figure 1) is on the main railway line between London Waterloo and Portsmouth (figure 2) and is located at 30 miles and 27 chains from a datum point at London Waterloo[2]. The station is a junction where several lines meet, and many suburban services terminate there. There are seven platforms in regular use.

6 The railway through Guildford is electrified using the *third rail* power supply system at a nominal voltage of 750V DC.

Organisations involved

7 South West Trains[3] (SWT) operated train service 2G44 and employed the staff on the train and at Guildford station. South West Trains was also responsible for all routine maintenance of the train involved.

8 Network Rail owns and manages the railway infrastructure at Guildford, including the traction power supply system. There is no evidence that the condition or maintenance of the infrastructure had any bearing on the accident.

9 Porterbrook Leasing owns the train involved in the accident and had a lease agreement with South West Trains.

[2] Distance measured via Woking.

[3] The franchise for train services in the south-western area of London and the surrounding areas was re-let during 2017. On 20 August 2017, the operator became South Western Railway.

10 Vossloh-Kiepe (UK) Ltd retrofitted the traction equipment on the Class 455 units under contract to Porterbrook Leasing. It became Kiepe Electric UK Ltd from January 2017 following a change of parent company.

11 Vossloh-Kiepe (Deutschland) GmbH designed and manufactured the replacement traction equipment which was fitted to the train. This organisation became Kiepe Electric GmbH from January 2017.

12 Electronicon Kondensatoren GmbH supplied electrical *capacitors* to Vossloh-Kiepe (and then to Kiepe Electric) for incorporation into the Class 455 replacement traction equipment.

13 Lloyds Register Rail (LRR) was contracted by Vossloh-Kiepe (UK) Ltd to carry out the necessary safety engineering tasks related to the traction retrofit project. This included managing the hazard identification and risk assessment processes. This was necessary because Vossloh-Kiepe (UK) Ltd did not have the necessary expertise for such work within its own organisation. In July 2015, following acquisition by Ricardo, LRR was re-branded as Ricardo Rail.

14 Aegis Engineering Systems was contracted by LRR to act as Independent Safety Assessor (ISA) for the traction retrofit project.

15 All of these organisations freely co-operated with the investigation.

Train involved

16 Train 2G44 was the 14:37 hrs SWT service from Guildford to London Waterloo via Oxshott. The train was formed of two four-coach Class 455 *electric multiple units* (EMUs) coupled together. Unit 5901 was leading and unit 5870 was trailing. Both units were built by British Rail Engineering Ltd at its York works in the 1980s.

17 Each four-coach unit comprises three trailer (non-powered) coaches and one powered coach on which all of the electrical traction equipment is located, referred to as a *Motor Open Standard* (MOS) coach (figure 4). The MOS coach of unit 5901 on which the explosion occurred was number 62826. This was the third coach from the front of train 2G44.

18 Class 455 EMUs have operated for the whole of their service life on suburban services on the former British Rail Southern Region. There are 91 Class 455 EMUs operated by South West Trains. Routine maintenance is carried out predominantly at SWT's depot at Wimbledon. There is no evidence that the maintenance work carried out by SWT on unit 5901 had any bearing on the accident.

Staff involved

19 Train 2G44 was crewed by a driver and a guard, both employed by SWT. The station staff at Guildford were also employed by SWT. Other than operating the train in the normal manner, there is no evidence that any actions of these staff had any bearing on the accident.

External circumstances

20 Friday 7 July 2017 was a warm and sunny day. The temperature around the time of the accident, measured at a location less than a mile from Guildford station, was 28 degrees Celsius. It is possible that the high ambient temperatures may have had a small bearing on the accident, as discussed later at paragraph 71.

The sequence of events

Events preceding the accident

21 Unit 5901 had been modified with a new traction system (paragraph 31) as part of a fleet-wide modification programme. The unit was released into traffic from the modification programme on 10 March 2017. The modification work was undertaken by Kiepe Electric UK Ltd using premises leased at the Eastleigh railway works.

22 The unit had passed all the planned tests during the modification process with no problems reported, and had been accepted back into passenger traffic by SWT. Since returning to passenger service, there had been no reported relevant defects with the unit, nor any maintenance interventions on the new traction system.

23 Prior to operating train 2G44, the two units had operated train 2D33, the 13:09 hrs Waterloo-Guildford via Leatherhead service. This train arrived at Guildford at 14:19 hrs and terminated in platform 2.

24 Shortly before the scheduled departure time of train 2G44, the driver went to the leading cab, in coach 77814, and prepared for departure to London.

Events during the accident

25 At 14:37 hrs, the driver attempted to start the train by taking power. However, before the train had moved, the guard heard an explosion, and he immediately sent an emergency stop signal to the driver.

26 The guard then opened the train doors, and evacuated the passengers. SWT estimated that 50 to 60 passengers were on the train at the time, and that 6 or 7 of them were in MOS coach 62826. There were no reported injuries to passengers or staff on the train.

Events following the accident

27 A large piece of debris, weighing 22 kg, was found on the neighbouring platform 3 (figure 3), where damage had been caused by the debris to a station seat. Smaller pieces of debris were found adjacent to platform 8 (approximately 50 metres away) and in a Network Rail staff car park (70 metres away).

28 Following the explosion, station staff carried out checks to confirm that there were no injuries to persons on the station, and that no serious damage had been caused to the station or its buildings.

29 Train 2G44 was cancelled and considerable disruption was caused to train services in the Guildford area due to the need to isolate the third rail power supply. To minimise the disruption, train 2G44 was moved to a nearby siding for detailed examination.

30 The examination showed that a major failure had occurred in a *traction equipment case* located on the underframe of MOS coach 62826. Unit 5901 was moved back to Eastleigh works on 10 July 2017 for repairs. The damaged traction equipment case was replaced and the unit was tested. It was subsequently returned to SWT's Wimbledon depot on 13 July 2017 and was then returned to passenger service.

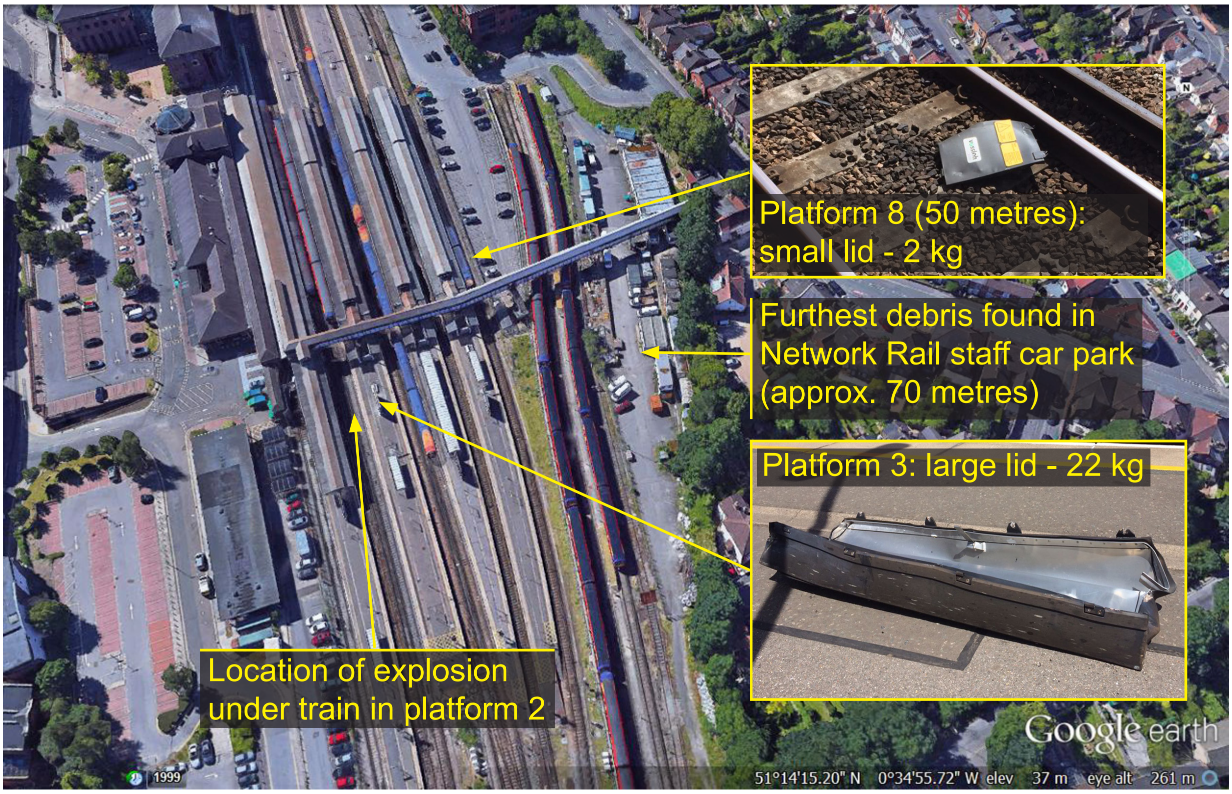

Figure 3: Locations of debris found after the explosion

Key facts and analysis

Background

The Class 455 traction retrofit project

31 The Class 455 traction retrofit project was conceived by SWT and Porterbrook Leasing during 2012. The aim of the project was to enable the introduction of additional, newer, vehicles into operation with SWT. These vehicles were needed to increase the capacity of SWT's services. However, there was a shortage of maintenance facilities for these additional vehicles. The chosen solution was to reduce the maintenance requirements for older vehicles and hence free-up capacity which could then be used to accommodate the additional vehicles.

32 When they were built, the Class 455 EMUs were fitted with direct current (DC) *traction motors* and *camshaft control*. Both of these systems require considerable amounts of skilled maintenance. Class 455 units also lacked any form of *dynamic braking* and the resulting more frequent brake pad changes were a major maintenance task.

33 In order to reduce the maintenance requirements of the Class 455 EMU, Porterbrook entered into a contract with Vossloh-Kiepe (UK) Ltd in April 2013 to carry out the following work:

- replacement of the DC traction motors with alternating current (AC) traction motors;
- replacement of the camshaft controller with an Insulated Gate Bipolar Transistor (IGBT) *inverter* and control system (see paragraph 36);
- provision of a dynamic braking system in addition to the existing air-operated friction braking system; and
- provision of a modern wheelslip/slide protection system.

34 The new equipment was expected to require significantly less maintenance than the original equipment. It was also envisaged that the modified trains would be more reliable. There was no attempt to increase the performance of the trains (such as increasing maximum speed, acceleration or braking rates). This would retain compatibility between modified and unmodified trains.

The new traction equipment

35 On Class 455 EMUs, all of the new traction equipment is located on the underframe of the MOS coach (figure 4) and includes:

- two traction equipment cases, identified as no. 1 and no. 2, each containing two IGBT inverters (one for each traction motor); and
- four AC traction motors, one on each of the coach's wheelsets.

36 The traction equipment coach uses the nominal 750 Volt DC supplied to the train from the third rail. This supply provides electrical current to the *DC link* within the traction equipment. The IGBT inverters provide a controllable AC frequency and voltage to the traction motors. Each of the four traction motors drives an axle of the MOS coach through a gearbox.

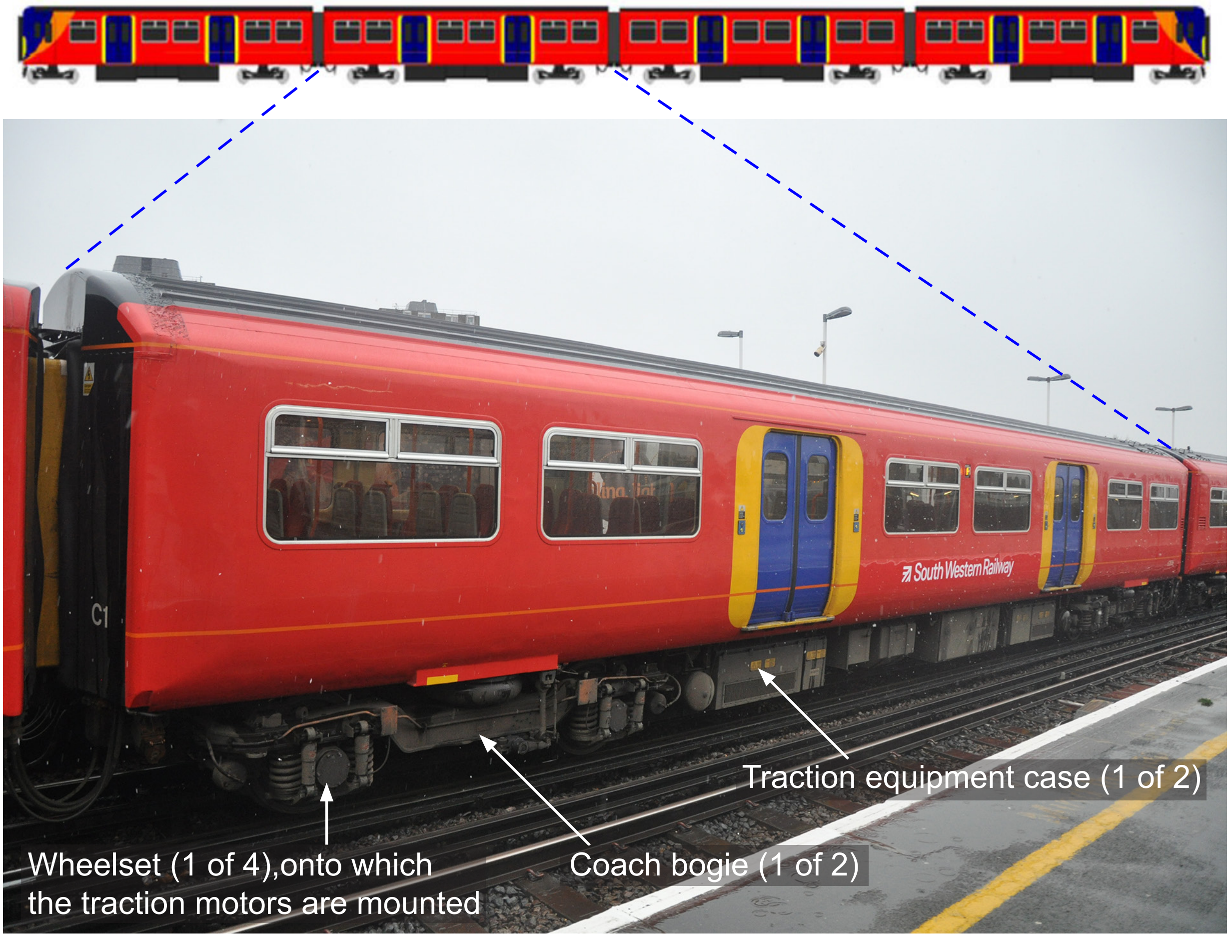

Figure 4: Class 455 unit and Motor Open Standard coach. Photograph is not of the unit involved in the accident

37 The traction equipment cases are sealed to the ingress protection 'IP55' standard[4] to protect the equipment within the case, particularly the electronics, from the harsh service environment on the underframe of railway vehicles. The IP55 standard means that the equipment within the case is protected from:

- dust particles (although limited dust ingress is permitted); and
- low pressure water jets from any direction.

38 It is necessary to provide, as far as possible, a smooth and stable electrical supply to each IGBT inverter. In order to achieve this, amongst other functions, each IGBT inverter has a large capacitor associated with it, known as the DC link capacitor (figure 5). A capacitor is a device that stores electric charge. It is this storage of charge which provides the smoothing and stabilisation of the inverter supply voltage. At its simplest, a capacitor comprises an insulator (known as the *dielectric*) between two conductors. The larger the area of the conductors and the closer they are together, the higher the capacitance. This explains the concept of the film-type capacitors used in the new traction equipment, which use multiple *windings* of a metallised film to get a large area into a small space (paragraph 49).

[4] As defined in standard BS EN 60529: 1992 'Specification for degrees of protection provided by enclosures (IP Code)'.

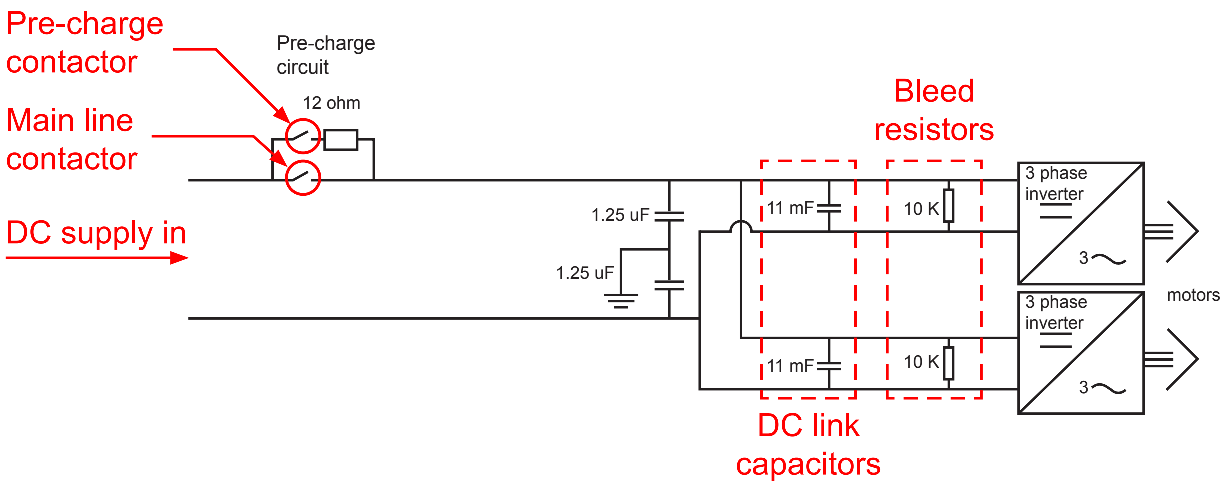

Figure 5: Simplified electrical schematic for Class 455 IGBT propulsion, showing equipment for two traction motors

39 There is one DC link capacitor per IGBT inverter, and hence four DC link capacitors per MOS coach. Each DC link capacitor measures approximately 640 mm x 250 mm x 196 mm and has a capacitance of 11 millifarads[5] (11000 μF).

40 The electrical supply to the DC link is switched by two *contactors* within the traction equipment case (figure 5). These are:

- A large main line contactor, which connects the IGBT DC link to the supply from the conductor rail. This contactor remains closed (and keeps the DC link energised) unless the train is stationary for more than ten minutes, when the contactor will automatically open.
- A smaller pre-charge contactor which closes before the main line contactor. The purpose of the pre-charge contactor is to allow a reduced current supply to the DC link to charge the DC link capacitors. This reduces electrical wear on the main line contactor.

41 When the driver of a train that has been stationary for more than ten minutes first takes power from the cab controls, the control system will initially close the pre-charge contactor. When the system detects that the DC link voltage has risen to greater than 90% of the supply voltage, the main line contactor closes. This sequence typically happens in less than a second.

42 It is necessary to provide for a controlled discharge of the DC link capacitors to ensure the safety of maintenance staff working on train electrical equipment. To provide this controlled discharge, *bleed resistors* (figure 5) are provided. The bleed resistors will discharge the DC link capacitors in approximately five minutes after the supply to them has been removed.

[5] The unit of capacitance is the *Farad* (F) and is a measure of how much charge the capacitor is storing when there is a given voltage across it. The Farad is a large unit and so capacitance is often expressed in microfarads (μF) (millionths of a Farad).

Supplier accreditation

43 Railway Industry Standard RIS-2450-RST Issue 1 December 2016[6], 'Qualification of Suppliers of Safety Critical Engineering Products and Services' provides guidance on the management of suppliers. The objective of this standard is to ensure that appropriate controls are in place to ensure that suppliers of safety critical equipment are competent. A key element of this is to ensure that such suppliers have their own corresponding systems in place to validate suppliers further down the supply chain.

44 Vossloh-Kiepe (UK) Ltd provided evidence to Porterbrook and to SWT that it was compliant with RIS-2450-RST. Its immediate supplier, Vossloh-Kiepe (Deutschland) GmbH had a similar process in place to verify the competence of Electronicon to manufacture the capacitors used in the replacement traction equipment.

Identification of the immediate cause

45 **An accumulation of flammable gases exploded and ruptured the traction equipment case.**

Identification of causal factors

46 The accident occurred due to a combination of the following causal factors:

a) there was a defect in a capacitor winding which led to the production of the flammable gases (paragraph 47);

b) the flammable gases produced by the defective capacitor were unable to escape from the traction equipment case (paragraph 66);

c) there was a source of ignition in the traction equipment case (paragraph 73);

d) an earlier investigation of previous capacitor failures did not identify all of the capacitor windings at risk (paragraph 76); and

e) the engineering safeguards provided did not adequately mitigate the risks from a capacitor with a manufacturing defect (paragraph 81).

Each of these factors is considered below.

Defect in the capacitor windings

47 **There was a defect in a capacitor winding which led to the production of flammable gases.**

48 The capacitor was designed and manufactured by Electronicon, to a specification provided by Vossloh-Kiepe. The design objective was to maximise the capacitance in the available space envelope.

49 The DC link capacitors fitted to the modified Class 455 EMUs are film-type capacitors, composed of a series of windings. Each capacitor contains a total of 48 windings, comprising 32 'short' windings and 16 'long' windings.

[6] Document may be found at https://www.rssb.co.uk/rgs/standards/RIS-2450-RST%20Iss%201.pdf.

50 The windings are formed using polypropylene film (the dielectric), metallised by coating with an aluminium/zinc layer. The metal layer is approximately 50 *angstrom*[7] thick. The metallised film is tightly wound on a specialised machine to form each winding. The individual windings are connected electrically in parallel, encased in resin and housed in an aluminium case.

Failure of film-type capacitors

51 A property of film-type capacitors is their ability to 'self-heal'. Self-healing occurs on a microscopic level at minor irregularities in the polypropylene film. Such irregularities can result in a small electrical discharge between the metallised layers at weak spots in the polypropylene film. This discharge vaporises and removes the metallic coating around the weak spot, which electrically isolates the irregularity. The self-healing process is depicted in figure 6. It continues through the lifespan of a capacitor. As this occurs on a microscopic level, the resulting loss of capacitance is negligible, even after a typical 30-year life span for a film-type capacitor.

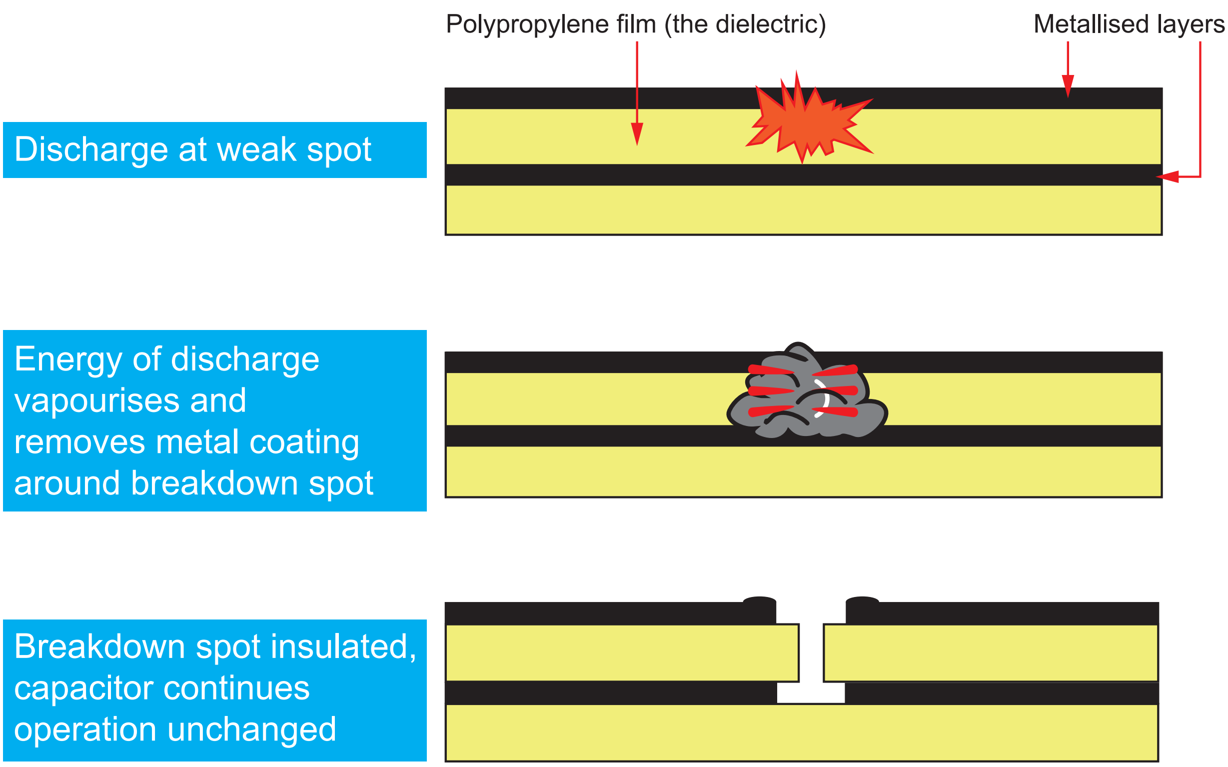

Figure 6: The process of self-healing within a film-type capacitor

52 However, in some circumstances, it is also possible for the self-healing process to fail. This can occur if the polypropylene film is damaged or distorted. Such damage can lead to direct electric discharge at the site of an irregularity. Increased conduction of leakage current between the metallised layers then occurs, and this leads to localised heating as shown in figure 7.

53 The localised heating will then further degrade the polypropylene film in the vicinity, resulting in further discharges and damage to the film. This process can create a runaway process of damage and heating to the capacitor winding. Ultimately this heating can lead to *pyrolysis* of the polypropylene film.

[7] ie 5 millionths of a millimetre (approximately equal to the diameter of 50 hydrogen atoms).

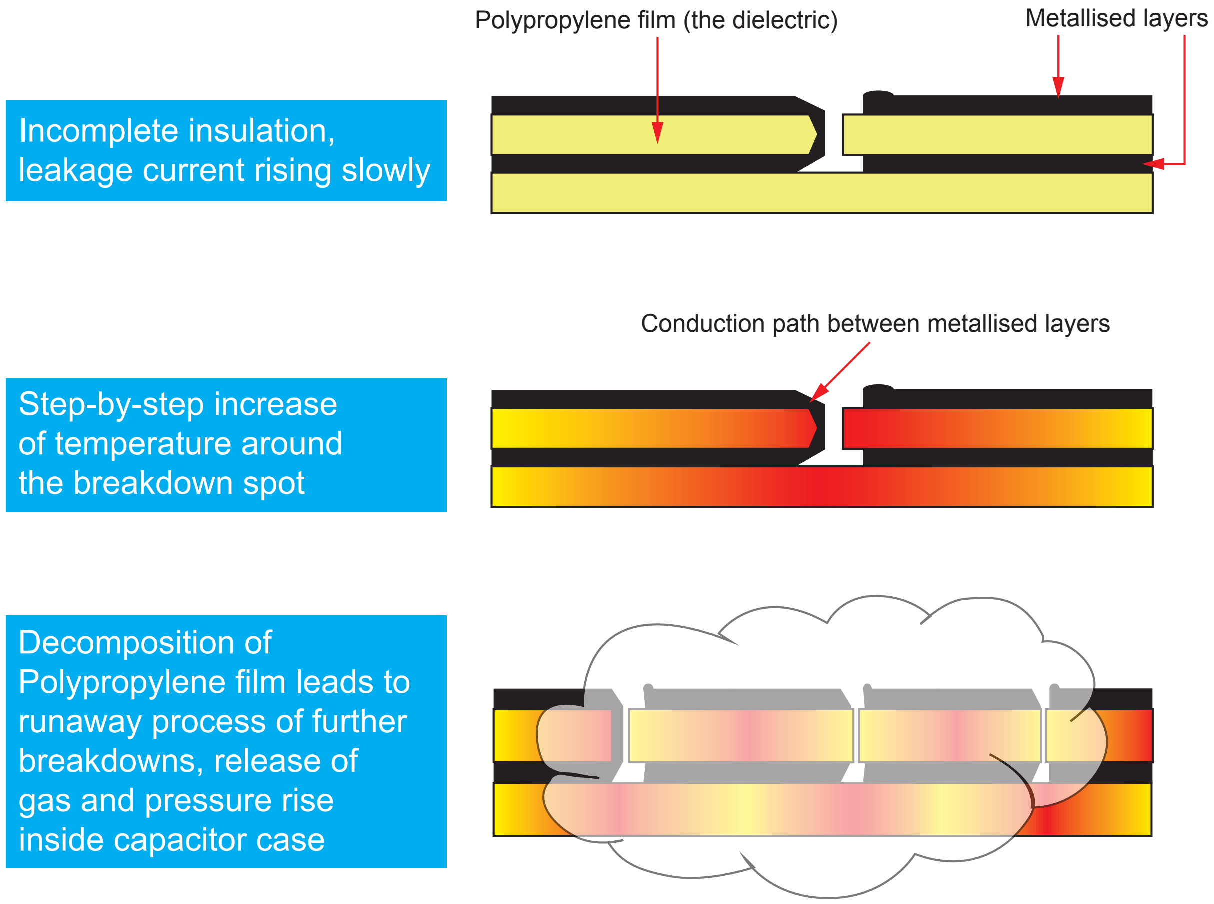

Figure 7: Drawing illustrating failure of self-healing

Pyrolysis of the polypropylene film

54 Pyrolysis of polypropylene occurred when the material was heated in the absence of oxygen, such as within the sealed capacitor case. Electronicon, the capacitor manufacturer, has indicated that this process will occur if the windings are heated above 300 degrees Celsius. The polypropylene degrades into a variety of gases, which include Butene, Decane, Pentane, and Pentene. When mixed with oxygen, all of these gases are explosive.

55 The composition of the gases produced is highly dependent on the temperature within the capacitor. The temperature reached at the site of the failure within the capacitor is not known, and therefore it is not possible to determine the precise composition of the gases which led to the explosion at Guildford.

Previous capacitor failures during the Class 455 traction retrofit project

56 Before the explosion at Guildford, there had been seven previous failures of the DC link capacitors in the Class 455 units, as summarised in table 1.

Failure date	Circumstances of failure
November 2015	On test at Vossloh-Kiepe in Germany.
January 2016	On test at Vossloh-Kiepe in Germany.
24 September 2016	Occurred within a capacitor fitted to unit 5726 while on test during traction retrofit modification at Eastleigh.
26 September 2016	Occurred within a capacitor fitted to unit 5726 while being returned to Eastleigh from SWT's Wimbledon depot.
1 October 2016	Occurred within a capacitor fitted to unit 5726 while in passenger traffic at Strawberry Hill (south-west London).
13 October 2016	On soak test at Eastleigh depot, UK
1 June 2017	On soak test at Eastleigh depot, UK

Table 1: Capacitor failures experienced during the Class 455 traction retrofit project prior to the accident at Guildford

57 The November 2015 failure occurred within a long winding. Investigation by Electronicon showed that this failure occurred due to a defect with the process used to solder the electrical connections within the capacitor. Changes were made to both the soldering process and the test process, and no further defects of that type occurred.

58 All of the subsequent failures in table 1 occurred due to defects within short windings. Following the four failures which occurred in September and October 2016, an investigation was carried out by Electronicon. This investigation, which reported during November 2016, found that all of the short windings which had failed were manufactured in a production cycle which commenced on 14 November 2014.

59 Electronicon's investigation concluded that the most probable cause of the failures was that an operator of a winding machine had carried out an unauthorised change to the parameters used by the machine to control the feed speed of the metallised polypropylene film, as it was being wound. This change led to damage and irregularities within the winding which in turn led to failures of the capacitor's self-healing capability (paragraph 52).

60 The capacitor involved in the accident at Guildford was dismantled and examined at Electronicon's factory in Germany, witnessed by Kiepe and RAIB. The examination (figures 8 and 9) showed that a short winding had failed in a manner which was similar to the failures covered by Electronicon's November 2016 report.

61 Although Electronicon's November 2016 investigation identified the cause of the capacitor failures, it did not fully identify all of the capacitor windings which were at risk from defective manufacture. This is discussed further at paragraph 76.

Figure 8: The damaged capacitor removed from coach 62826 prior to examination at Electronicon's facilities in Germany

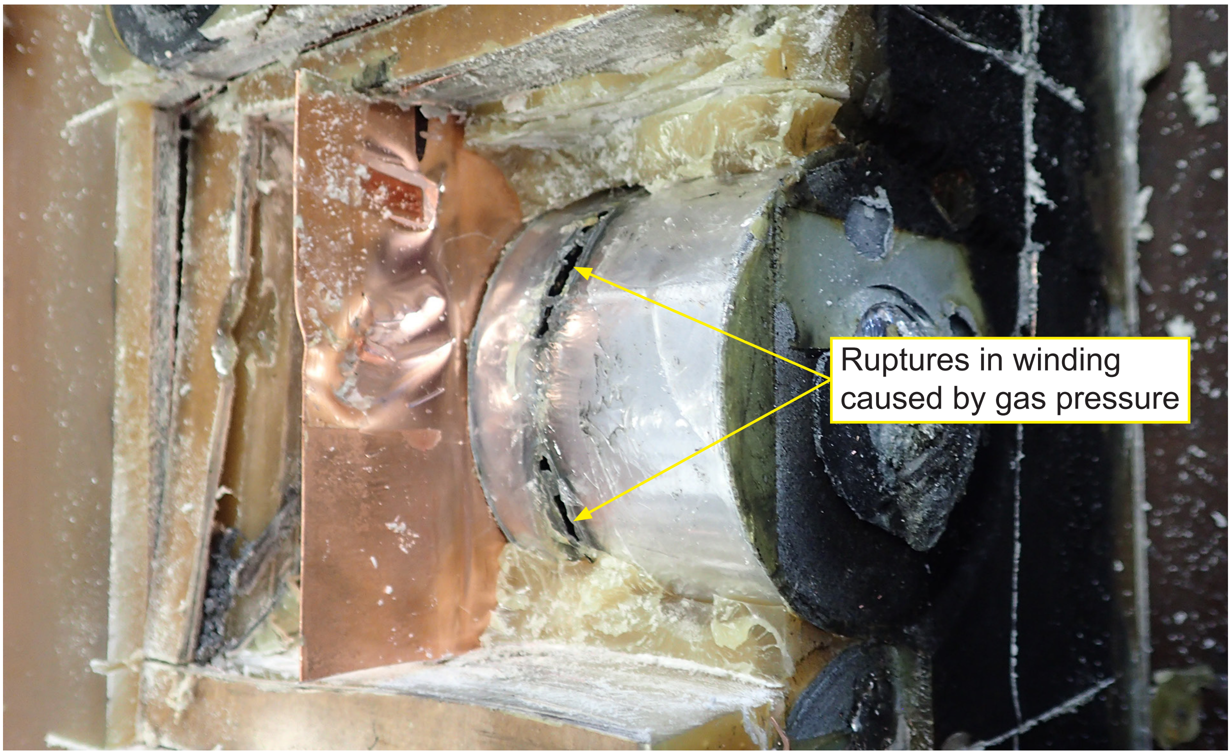

Figure 9: The failed short winding, with resin cut away to expose the ruptures at the point of gas escape indicated

The testing process used during capacitor manufacture

62 The DC link capacitors used in the traction equipment retrofitted to Class 455 were manufactured in accordance with international standard EN 61881-1, 'Railway applications – Rolling stock equipment – Capacitors for power electronics Part 1: Paper/Plastic film capacitors', edition 1, published 2010. This standard specifies a test process to be used when manufacturing such capacitors.

63 The routine test carried out by the manufacturer in accordance with the specifications of the relevant standard EN 61881-1 is intended to be used in a mass-production environment, and focusses on testing each capacitor to ensure compliance with the specified electrical requirements. Additionally, Electronicon carried out a routine test on all windings before assembly into the capacitors. Neither of these routine tests was designed to identify the winding defects which led to the failure at Guildford. This was because, to identify any such failures of self-healing, voltage has to be applied to the capacitor for a prolonged period. Such a test is not practicable within the capacitor production process.

The soak test

64 Following the investigation into the earlier capacitor failures, Electronicon advised Vossloh-Kiepe to implement a '*soak test'* from October 2016. The soak test was carried out on assembled traction equipment cases incorporating the capacitors and involved the application of an elevated voltage of 1200 V to the DC link for four hours. This test successfully identified defective capacitors on 13 October 2016 and 1 June 2017 (table 1).

65 The soak test was effective in identifying capacitor defects which would have become apparent after a short period in service, such as the three failures on unit 5726 in September and October 2016 (table 1). These occurred within a few days of the unit being released from the traction retrofit modification programme. However, the subsequent failure of the capacitor on unit 5901 at Guildford, which occurred after the unit had been operational for approximately four months, shows that this soak test could not be relied upon to identify every possible failure. The traction equipment which was fitted to unit 5901 was soak tested on 6 March 2017 without any problems becoming apparent.

The traction equipment case

66 **The flammable gases produced by the defective capacitor were unable to escape from the traction equipment case.**

67 Once the short winding had failed, and the heating process had initiated the pyrolysis of the polypropylene into gases, the internal pressure within the capacitor case would have risen to a point where the capacitor case would rupture.

68 Although it is not possible to establish with certainty the time between the failure of the winding and the subsequent rupture of the capacitor case, Electronicon has advised the RAIB that the timescale is likely to have been of the order of tens of minutes.

69 The capacitor case was manufactured from aluminium. Electronicon has advised RAIB that the internal pressure at which the case would be expected to rupture is approximately 7 bar. Once the case ruptured (figure 8), the flammable gases produced by the pyrolysis of the polypropylene film passed directly into the traction equipment case.

70 The voltage applied to the capacitor was sufficient to provide the energy required to heat and pyrolise the polypropylene film. The main line contactor remained closed for 10 minutes after the arrival of train 2D33 at Guildford (paragraph 40). The capacitor was therefore energised while the unit was stationary. Once the main line contactor had opened, the bleed resistors (paragraph 42) would have discharged the capacitors in around 5 minutes. Therefore, in the 18 minutes during which unit 5901 was at Guildford station (between its arrival as 2D33 and departure as 2G44), the DC link capacitors were fully or partially energised for a period of around 15 minutes. During that time, further pyrolysis would have taken place, leading to the continued generation of flammable gases (paragraph 54).

71 It is possible that the warm weather on 7 July 2017 (paragraph 20) may have further heated the capacitor and its windings. This is because the traction equipment case is a dark colour (and would therefore easily absorb heat), and the train was orientated north-south when stationary at Guildford. The traction equipment case in which the failure occurred faced west, towards the afternoon sun.

72 As the traction equipment case was sealed to IP55 (paragraph 37), the flammable gases could not escape. Instead, they mixed with oxygen-containing air to form an explosive mixture which was contained within the equipment case.

Ignition source

73 There was a source of ignition in the traction equipment case.

74 When the driver of train 2G44 attempted to take power to depart from Guildford, the pre-charge contactor (paragraph 40) closed. Diagnostic information from the traction equipment shows that the explosion took place at that point, before the DC link voltage had reached the point at which the main line contactor would have closed.

75 The explosion took place when the pre-charge contactor closed and produced a spark. This spark ignited the mixture of flammable gases which had escaped from the capacitor following the earlier rupture of the capacitor case.

The investigation carried out in November 2016

76 An earlier investigation of previous capacitor failures did not identify all of the capacitor windings at risk.

77 Electronicon's investigation into the failures in September and October 2016 (paragraph 58) identified that the short capacitor windings which had failed had all been manufactured in a production cycle which commenced on 14 November 2014. Electronicon has reported to the RAIB that the cause of the failures was an unauthorised change to the winding machine parameters (paragraph 59).

78 As a result of this, Electronicon advised Vossloh-Kiepe that windings manufactured on 14 November 2014 were at risk of a manufacturing defect. Arrangements were made to remove all capacitors containing such windings from the train modification programme. These actions were carried out from November 2016.

79 The production cycle which commenced on 14 November 2014 terminated at 04:50 hrs on 15 November 2014, when the winding machine was re-set to commence manufacture of a different type of winding. The Electronicon investigation did not identify that windings manufactured early on 15 November 2014 were a continuation of the batch commenced on 14 November, and hence were also at risk of manufacturing defect.

80 The winding which led to the capacitor failure at Guildford was part of the batch completed at 04:50 hrs on 15 November 2014. These windings were incorporated into a capacitor which was fitted to unit 5901 when it was modified in March 2017 (paragraph 21). Had the risk from the windings manufactured on 15 November 2014 been recognised in the November 2016 investigation by Electronicon, it is unlikely that any capacitors containing these windings would have been used on any of the class 455 units.

Engineered safeguards

81 **The engineering safeguards provided did not adequately mitigate the risks from a capacitor with a manufacturing defect.**

82 Failures of film-type capacitors which generate gases are unusual events. Data provided by Electronicon to Vossloh-Kiepe in 2013 indicated a total failure rate of 180 events per billion capacitor operating hours. Of these failures, 5%, or around 9 failures, would be expected to result in the generation and emission of gas. Electronicon has reported that these figures did not include consideration of possible manufacturing defects within capacitors. Analysis by RAIB of this failure data indicated that a gassing capacitor failure could be expected approximately once per sixty years of Class 455 fleet operation.

83 Ensuring that a capacitor is operated within the bounds of its electrical rating is a key safeguard. Exceeding the rated voltage or current can lead to capacitor failure. Some of these failures may result in gas generation. Although Vossloh-Kiepe had safeguards in place to protect against excess voltage and current, there were no safeguards to prevent an explosion resulting from a capacitor failure caused by a manufacturing defect.

84 There are three main engineered safeguards available to prevent an explosion caused by gas released from a failing capacitor:

- pressure switches which detect an increase in pressure within the capacitor enclosure, and shut down the traction equipment. Provision for pressure switches was made in the enclosure for the capacitors used on the Class 455 traction retrofit project, but this provision was not used;
- devices which detect the presence of specific hydrocarbon gases can be used to shut down the traction equipment in the event of a detected failure; or
- placing the capacitors in a ventilated part of the traction equipment enclosure to prevent the build-up of explosive gases in the event of a capacitor failure.

85 Pressure switches are a common means of detecting gas pressure increases and are the method subsequently used by Kiepe for retrofitting to the Class 455 units after this accident (paragraph 126).

86 Although Vossloh-Kiepe had considerable experience in supplying traction equipment for applications such as light rail vehicles and trolley buses, it was only in 2009 that it developed traction equipment for main line railway vehicles. In order to support this development, it was necessary to identify manufacturers of the larger capacitors required for such applications.

87 Vossloh-Kiepe therefore investigated possible suppliers, and reached agreement with Electronicon for the supply of the capacitors used on Class 455. Vossloh-Kiepe requested advice from Electronicon regarding aspects of the integration of the capacitors into the traction equipment. Responsibility for the overall system design, however, remained with Vossloh-Kiepe.

88 In January 2013, an e-mail dialogue took place between Vossloh-Kiepe's engineers and a member of the Electronicon sales team. In this dialogue, Electronicon's representative expressed the view that there had been "negative experiences" when using pressure switches, that they are only used in "exceptional cases", and that the pressure switch "would not have added additional safety". Nevertheless, Electronicon offered to produce a mock-up capacitor on which a pressure switch could be tested. However, Vossloh-Kiepe did not pursue this offer.

89 Electronicon has confirmed to the RAIB that the capacitors it supplies conform to EN 61881-1 (paragraph 62) and are classified as unprotected capacitors[8]. The unprotected status of the capacitors is also stated by the application documentation for the capacitors, and by identification labels on the capacitors (figure 10).

Figure 10: Identification label applied to a capacitor, showing manufacture against EN 61881-1 and confirming that the capacitor has no internal protection

[8] Capacitors may be protected by either internal protection devices such as internal overpressure disconnectors or by external protection devices such as pressure switches.

90 EN 61881-1, section 9.14 states: 'For power electronics capacitors, the user has to ensure by qualified installation that no danger appears due to a failing capacitor. The requirement applies in particular to unprotected capacitors.'

91 ZVEI is the German Electrical and Electronic Manufacturers' Association. Both Kiepe and Electronicon are members of this association. In 2010, ZVEI published guidance[9] on power capacitors. Section 7 of this guidance stated: 'The capacitor manufacturer cannot predict all possible stresses which a power capacitor can be subjected to and which must be taken into account in the design. This means that the user bears crucial co-responsibility here. For this reason alone, safety and quality should be the top priorities when a capacitor is selected. This is why we urgently recommend the use of capacitors with appropriate internal[10] protective devices.'

92 Guidance by EN 61881-1 and the ZVEI requires that the capacitor installation is protected, and that both the capacitor manufacturer and the capacitor user should collaborate to ensure that such protection is provided. However, the early advice provided by Electronicon in 2013 meant that a view had been formed by Vossloh-Kiepe that:

- a gassing capacitor was unlikely (paragraph 82);
- pressure switches were unreliable (paragraph 87); and
- protection from excess voltage and current was adequate to comply with the requirements of EN 61881-1 and the ZVEI guidance.

This view was also reflected in the output from the hazard identification meeting (paragraph 109). For these reasons, the DC link capacitors used on the Class 455 traction retrofit project did not have pressure switches fitted.

Identification of underlying factor

93 **The traction retrofit project did not adequately manage the risk of explosion caused by a capacitor with a manufacturing defect.**

94 Complex projects, such as the Class 455 traction retrofit project, depend on the effective inter-working of many individuals across several organisations. Usually, no single individual or organisation has complete expertise in all the components and systems which contribute to such a project.

95 It was, therefore, vital that the project approvals and risk management activities effectively drew on the knowledge and expertise which was available at the time to ensure that correct decisions and judgements were made, particularly those which affected safety. The principal means of identifying safety hazards, and deciding what mitigation should be applied, was the project's hazard identification and risk assessment process. This was a key part of the overall procurement strategy for the project and the approvals process.

[9] Guidance may be found at https://www.zvei.org/en/press-media/publications/general-safety-recommendations-for-power-capacitors/.

[10] See paragraph 89 regarding internal and external protection devices.

Porterbrook's procurement strategy

96 Porterbrook's strategy for the Class 455 traction retrofit project was to procure both the engineering and the approvals elements of the project as one contract. This is a commonly used procurement strategy, aimed at reducing project risk.

97 The contract between Porterbrook Leasing and Vossloh-Kiepe (UK) Ltd included the following main elements:

- design and manufacture of replacement traction and associated equipment for the Class 455 EMUs;
- installation of the replacement equipment onto the trains; and
- provision of the necessary approvals and safety engineering.

The project approvals and safety engineering process

98 The purpose of the class 455 traction retrofit project approvals process was to demonstrate that the safety risk from the project was as low as reasonably practicable (ALARP). The approvals process was managed in accordance with SWT's Safety Management System (SMS) and in accordance with the Railways and Other Guided Transport Systems (Safety) Regulations 2006 (ROGS). In accordance with SWT's SMS, it required that an Independent Safety Assessor (ISA) be appointed. This approach was agreed between SWT and the Office of Rail & Road (ORR).

99 The role of the ISA is to conduct an independent review and scrutiny of the approvals and safety engineering activities to ensure that such work is rigorous, complete and sufficient.

100 Under the approvals process, SWT had the final 'approval' decision. SWT's Engineering Change policy was to ensure that the changes made to the Class 455 EMUs by the traction retrofit project, were managed in such a way that any risks were demonstrably reduced to an 'as low as reasonably practicable' level. SWT's decisions regarding the acceptability of risks were informed by the work of Lloyds Register Rail and by Aegis Engineering Systems acting as the ISA.

101 SWT considered the applicability of the Railways (Interoperability) Regulations 2011 to the project[11]. However, it was agreed by SWT and ORR that the technical changes being made to the Class 455 EMU were not of sufficient magnitude to justify the application of these regulations.

102 SWT also considered the applicability of the *Common Safety Method for Risk evaluation and Assessment* (CSM-RA) to the project[12]. SWT agreed with ORR that application of the CSM-RA was not mandated for this project; however, the methods prescribed in the CSM-RA were used (paragraph 110).

---

[11] The objective of these regulations is to achieve technical harmonisation between European railways. Such harmonisation is achieved by the implementation of technical changes when opportunity presents during major projects.

[12] Application of the CSM-RA is mandated on certain projects, such as those within the scope of the Rail Interoperability Regulations (2011). However, application of the CSM-RA may be regarded as best practice on projects.

Previous related events

103 The UK railway industry has a process in place for the reporting of high-risk safety defects on trains. This process is defined by standard RIS-8250 Issue 1 December 2016[13] which defines the requirements for recording, analysing and reporting safety-related defects on rail vehicles, their components, systems, subsystems and related documentation. Such reports are known as National Incident Reports (NIRs). The standard also defines requirements for actions to be taken following receipt of an NIR by a duty holder such as a train operator.

104 NIRs are raised by duty holders and other railway industry organisations. They have several purposes which include:

a) alerting users of similar equipment to the potential risks;

b) acting as a 'corporate memory' tool by providing a repository for records of high-risk defects on rail vehicles, and previous failures; and

c) informing future hazard identification processes.

105 A review of NIRs was carried by the project team to identify previous incidents, which could identify possible future problems. However, in many cases, the NIRs lacked sufficient depth of detail to allow a complete understanding to be formed of the cause of the failure and possible future risks.

106 The RAIB identified six previous failures of capacitors from records held on the NIR system:

a) On 6 October 1997, a failure occurred on a Class 313 EMU. NIR503 was issued. The capacitor involved appears to have been of the electrolytic[14] type.

b) On 11 August 2003, a film-type capacitor exploded on a Class 221 diesel train. NIR1635 was issued. Overheating of a terminal was an issue. Pressure switches were to be fitted to mitigate the risk.

c) On 29 May 2005, an event very similar to that of 11 August 2003 occurred, again on a Class 221 train. NIR2000 was issued.

d) On 8 June 2005, a capacitor failed on a Class 321 EMU, blowing off the covers on an underframe equipment case. NIR2005 was issued. It is not known what type of capacitor was involved.

e) On 3 September 2009, an electrolytic capacitor failed on a Class 373 'Eurostar' train. NIR2518 was issued.

f) On 23 December 2016, a film-type capacitor exploded on a Class 334 EMU at Yoker depot (Glasgow). The explosion was attributed to the combustion of gases generated by a defective capacitor. The train operator issued NIR3314 to report this incident. The cause of that capacitor failure was different to that which occurred at Guildford.

In addition to these incidents reported through the NIR system, the RAIB identified a failure which occurred on 7 July 2001 on a London Underground Northern line train. A film-type capacitor failed, and the resulting explosion blew covers off underframe equipment cases.

[13] This document, which replaces the earlier standard GE/RT8250 Issue 2 June 2007, may be found at: https://www.rssb.co.uk/rgs/standards/ris-8250-rst%20iss%201.pdf.

[14] Electrolytic capacitors use a different means of construction to a wound-film type capacitor.

107 Evidence provided to the RAIB indicates that the hazard identification meeting (paragraph 109) reviewed the previous NIR reports. The meeting participants were also aware of the Northern line failure.

Hazard identification and risk assessment process

108 The hazard identification and risk assessment processes used for the Class 455 traction retrofit project were managed by Lloyds Register Rail (LRR) with the active participation of representatives from all the organisations who were stakeholders in the project. The process was overseen by Aegis Engineering Systems acting in its role of ISA.

109 The initial hazard identification meeting was convened by LRR on 18 April 2013, and included representatives from:

- LRR;
- Vossloh-Kiepe;
- Porterbrook Leasing;
- SWT;
- Network Rail; and
- Aegis Engineering Systems.

110 LRR managed the hazard identification and risk assessment using the processes defined by the CSM-RA (paragraph 102), because this was considered to represent best practice in this area. ORR publishes guidance[15] to assist with the application of the CSM-RA. Paragraph 3.18 of this guidance states that 'The purpose of the hazard identification is to identify all reasonably foreseeable hazards which are then analysed further….'. The guidance also references a UK railway guidance note, GE/GN8642. The version of this document which was current when the hazard identification meeting was held[16] included guidance (section 4.1.8) that hazard identification processes '…require a detailed knowledge of the failure modes of components and sub-systems, including human actions and likely errors'.

111 The hazard identification process used a variety of techniques (such as checklists, guide words and brainstorming) to identify likely hazards. Identified hazards were then assessed by considering both the severity of consequence (table 2) and the frequency of the hazard occurring (table 3). The overall risk was assessed by means of a matrix (table 4) which combined the severity and frequency of the hazard occurring. A high/medium/low banding was used to determine acceptability of risk. These bands were defined as:

- high or unacceptable risk;
- medium, meaning further work required to confirm that the risk has been reduced to ALARP (paragraph 100). Such work could include verification that proposed risk mitigations have been effective; and
- low or tolerable risk.

---

[15] The most current version can be found at: http://orr.gov.uk/__data/assets/pdf_file/0006/3867/common_safety_method_guidance.pdf.

[16] Issue 1, September 2012, which can be found at https://www.rssb.co.uk/rgs/standards/gegn8642%20iss%201.pdf.

Severity		Definition
1	Minor	Single minor injury / minor Occupational Health and Safety problem.
2	Marginal	Single major injury / multiple minor injuries / serious Occupational Health and Safety problem.
3	Critical	Single fatality / multiple major injuries.
4	Catastrophic	Multiple fatalities.

Table 2: Definitions of consequence severity

Frequency		Definition
A	Frequent	100 times per year
B	Probable	10 times per year
C	Occasional	Every year
D	Remote	Every 10 years
E	Critical	Every 100 years
F	Incredible	Every 1000 years

Table 3: Definitions of frequency

Frequency		Severity			
		4 Catastrophic	3 Critical	2 Marginal	1 Minor
A	Frequent	High	High	High	Medium
B	Probable	High	High	Medium	Medium
C	Occasional	High	Medium	Medium	Low
D	Remote	Medium	Medium	Low	Low
E	Critical	Medium	Medium	Low	Low
F	Incredible	Medium	Low	Low	Low

Table 4: Risk assessment matrix

112 If the overall risk from an identified hazard was assessed as high or medium, the meeting considered possible mitigations to that hazard to reduce either the severity or the frequency of the hazard, or both. A revised risk level was then assessed and used to determine if the mitigations were adequate to reduce the risk to an acceptable level.

113 The output from the hazard identification meeting was a hazard log. This document was maintained as a dynamic document and updated as circumstances, information or experience changed, to ensure that any assumptions or judgements made in the hazard identification meeting could be reviewed as and when new failures occurred. However, the information provided for this hazard log was incomplete (paragraph 119).

Identification and mitigation of the explosion hazard

114 The hazard identification meeting worked from a standard list of possible hazards for this type of project. The only relevant hazard was defined as 'Equipment explodes or inadequate protection' and was described as 'Equipment explodes causing fire/damage to other equipment/persons/trains due to excess voltage/currents'. The mitigations recorded for this hazard were 'Equipment cases designed to contain/mitigate explosions. Film capacitors used. Equipment must have adequate protection systems for over-voltage/over-current. Compliance with NR/GN/ELP27010, EN50388[17]'.

115 The severity of this hazard without any mitigations in place was assessed as 'Catastrophic' and the frequency was assessed as 'Remote – every ten years'. With the above mitigations, the severity was judged to remain as 'Catastrophic' but the frequency was reduced to 'Incredible – once in every thousand years'. In both cases, the overall risk (table 4) was assessed as 'medium', which meant that active management to ensure the mitigations were enacted was required. The RAIB notes that the meeting was aware of the history of capacitor failures (paragraph 105). Had the frequency been taken as once every ten years, the risk would still have been categorised as 'medium' according to the risk assessment matrix used (table 4).

116 A key issue with the hazard identification process was that the hazard description limited the potential causes of the explosion hazard to 'excess voltage/current'. However, the explosion at Guildford was not caused by either of these; it was caused by a manufacturing defect within a capacitor. This potential cause of failure was overlooked in the risk assessment process because the hazard identification meeting did not clearly differentiate between the explosion hazard and the cause of the hazard (eg excess voltage/current, manufacturing defect). Guidance on hazard identification and classification provided to the industry by the RSSB[18] in guidance note GE/GN8642, Issue 2, June 2014, states (clause G.3.1.6) 'As hazards are conditions, they could have a number of different causes. For example the hazard 'train fails to stop at an intended location' could be caused by, amongst other things, brake failure, poor adhesion conditions or driver error. A robust and efficient approach to hazard definition is one where a clear distinction is made between hazards and causes.'

117 By limiting the possible causes to excess voltage or excess current, the hazard identification meeting did not consider other possible causes of capacitor failure, such as a defective capacitor, and missed the opportunity to identify the hazard which subsequently led to the accident at Guildford.

118 As a consequence, the focus of Vossloh-Kiepe's design effort in the area of capacitor safety was limited to ensuring that the capacitors were operated within their specified electrical design parameters. The possibility of such a failure being as a result of a manufacturing defect was not considered or mitigated against.

---

[17] These standards relate to the provision of railway electrification supplies. They are not relevant to the accident at Guildford, and are not discussed further.

[18] A not-for-profit company owned and funded by major stakeholders in the railway industry, and which provides support and facilitation for a wide range of cross-industry initiatives. The company is registered as 'Rail Safety and Standards Board' but trades as 'RSSB'.

The hazard log was not revisited following the initial capacitor failures

119 The first capacitor failures occurred in November 2015 and January 2016 (paragraph 56). These failures occurred within the test facility at Vossloh-Kiepe's factory in Dusseldorf. Vossloh-Kiepe did not advise its customer, nor LRR, of these failures. This was because Vossloh-Kiepe believed that they could contain the risk by testing. Electronicon was advised of the failures.

120 The output from the hazard identification process had previously assumed a failure rate of one per thousand years (paragraph 115); however, the actual failure rate, due to manufacturing defects, was two in three months.

121 Because these early failures were not advised outside Vossloh-Kiepe or Electronicon, an opportunity to re-visit the hazard log was missed. Such a re-evaluation of the hazard log could have led to an earlier recognition of a need to apply further measures to mitigate the risk of capacitor explosions.

Summary of conclusions

Immediate cause

122 An accumulation of flammable gases exploded and ruptured the traction equipment case (paragraph 45).

Causal factors

123 The causal factors were:

a) There was a defect in a capacitor winding which led to the production of flammable gases (paragraph 47).

b) The gases produced by the defective capacitor were unable to escape from the traction equipment case (paragraph 66, **Recommendation 1**).

c) There was a source of ignition in the traction equipment case (paragraph 73).

d) An earlier investigation of previous capacitor failures did not identify all of the capacitor windings at risk (paragraph 76, **Learning point 1**).

e) The engineering safeguards provided did not adequately mitigate the risks from a capacitor with a manufacturing defect (paragraph 81) **Recommendation 1**).

Underlying factor

124 The traction retrofit project did not adequately manage the risk of explosion caused by a capacitor with a manufacturing defect (paragraph 93, **Learning points 2, 3, 4, 5 and 6**).

Actions reported as already taken or in progress relevant to this report

125 Electronicon has modified the winding machine which produced the short winding which failed at Guildford. Protections were added so that it is no longer possible for an operator to carry out unauthorised changes to the machine's production parameters.

126 SWT applied containment straps to the Class 455 traction equipment cases immediately after the explosion at Guildford. Subsequently, in collaboration with Porterbrook, Kiepe and Electronicon, pressure switches have been fitted to the DC link capacitors on the Class 455 fleet. These pressure switches will detect any build-up of gas within a capacitor enclosure, and shutdown the traction system.

127 In October 2017, South Western Railway awarded Kiepe (UK) Ltd a contract for the traction retrofit of Class 442 EMUs. Kiepe has confirmed that the capacitors applied to this project will be fitted with pressure switches.

Recommendation and learning points

Recommendation

128 The following recommendation is made[19]:

1 *The intent of this recommendation is to minimise the risk of a future capacitor failure on UK rolling stock traction systems leading to an explosion and possible harm to the travelling public and staff.*

UK train operating companies in co-operation with the suppliers of their rolling stock (Rolling Stock Leasing Companies or Contracting Entities) should:

a) review the design of the electric traction systems in their current fleets and check that there are adequate safeguards in place to prevent an explosion capable of causing harm in the event of a failure of a capacitor(s); and

b) address any shortcomings identified in (a).

(paragraphs 123b and 123e).

Learning points

129 The RAIB has identified the following key learning points[20]:

1 It is important that investigation work into safety-related incidents as a result of component failure is thorough, so as to identify all of the components manufactured that could be similarly defective.

[19] Those identified in the recommendation have a general and ongoing obligation to comply with health and safety legislation, and need to take this recommendation into account in ensuring the safety of their employees and others.

Additionally, for the purposes of regulation 12(1) of the Railways (Accident Investigation and Reporting) Regulations 2005, this recommendation is addressed to the Office of Rail and Road to enable it to carry out its duties under regulation 12(2) to:

(a) ensure that recommendations are duly considered and where appropriate acted upon; and

(b) report back to RAIB details of any implementation measures, or the reasons why no implementation measures are being taken.

Copies of both the regulations and the accompanying guidance notes (paragraphs 200 to 203) can be found on RAIB's website www.gov.uk/raib.

[20] 'Learning points' are intended to disseminate safety learning that is not covered by a recommendation. They are included in a report when the RAIB wishes to reinforce the importance of compliance with existing safety arrangements (where the RAIB has not identified management issues that justify a recommendation) and the consequences of failing to do so. They also record good practice and actions already taken by industry bodies that may have a wider application.

2 Hazard identification records and hazard logs should be maintained as dynamic documents so that they remain complete and accurate as new information or failures come to light (as per Guidance Note GE/GN8642[21]).

3 Project hazard identification meetings should be convened with representatives who can competently consider all high-risk systems and/or components associated with the project (as per Guidance Note GE/GN8642).

4 It is important that a clear distinction is made between hazards and causes when carrying out hazard identification and risk assessments. This will ensure that all credible causes of a hazard are identified and addressed appropriately (as per Guidance Note GE/GN8642).

5 Duty holders should provide timely updates to NIRs so that they provide as much detail as possible on the exact causes of a failure[22] (as per Railway Industry Standard RIS-8250).

6 It is important that new rolling stock procurement programmes, or future traction retrofit projects, take into account the findings of this investigation; in particular the need for engineering safeguards to prevent a capacitor failure resulting in a potentially harmful explosion.

[21] From December 2017, GE/GN8642 Issue 2 was superceded by GE/GN8646 Issue 1; this document may be found at https://www.rssb.co.uk/rgs/standards/GEGN8646%20Iss%201.pdf.

[22] Clause 2.2.1.5 of RIS-8250 Issue 1 December 2016 states that ‘A concluding NIR shall be generated when the root cause of the defect has finally been identified’.

Appendices

Appendix A - Glossary of abbreviations and acronyms

AC	Alternating current
ALARP	As low as reasonably practicable
CSM-RA	Common safety method for risk evaluation and assessment
DC	Direct current
EMU	Electric multiple unit
IGBT	Insulated gate bi-polar transistor
ISA	Independent safety assessor
LRR	Lloyds Register Rail
MOS	Motor open standard
NIR	National Incident Report
ORR	Office of Rail and Road
ROGS	Railways and Other Guided Transport Systems (Safety) Regulations 2006
RSSB	A not-for-profit company owned and funded by major stakeholders in the railway industry, and which provides support and facilitation for a wide range of cross-industry activities. The company is registered as 'Rail Safety and Standards Board', but trades as 'RSSB'.
SMS	Safety management system
SWT	South west trains
ZVEI	Zentralverband elektrotechnik- und elektronikindustrie eV

Appendix B - Glossary of terms

All definitions marked with an asterisk, thus (*), have been taken from Ellis's British Railway Engineering Encyclopaedia © Iain Ellis. www.iainellis.com.

Angstrom	A unit of length equal to 10^{-10} m (one ten-billionth of a metre) or 0.1 nanometre.
Bleed Resistors	Resistors provided in the traction system which allow a controlled discharge of the electrical energy stored in capacitor. These resistors are necessary to ensure the safety of maintenance staff working in close proximity to this equipment.
Camshaft Control	An electro-mechanical device forming part of the traction control system for an electric train.
Capacitor	An electrical component that stores electrical energy in an electric field.
Common safety method for risk evaluation and assessment	A European Union regulation that came fully into force on 1 July 2012 and is intended to regularise risk evaluation and assessment for the main line railway industry across the EU.*
Contactor	A remotely-controlled electric switch.
DC link	The DC supply, fed from the conductor rail, provided to the inverters.
Dielectric	An electrical insulator that can be polarised by an applied electric field.
Dynamic Braking	A system of braking where the retardation effort is provided by using the traction motors to generate electricity.
Electric Multiple Unit	An electric train consisting of one or more coaches, including at least one powered vehicle, with driving cabs at each end, which can be coupled to other units and operated as a single train.
Farad	A unit of capacitance.
Inverter	Equipment which converts the DC supply voltage to a variable frequency AC voltage for the train's traction motors. The inverter is made up of a number of IGBT devices.
Motor Open Standard	One coach which forms part of a Class 455 EMU. Such a coach has standard class seating accommodation and is fitted with traction equipment.
Pyrolysis	The thermochemical decomposition of a material at elevated temperatures in the absence of oxygen.
Soak Test	A test carried out over a prolonged period, and at a voltage above normal. In this context, the objective was to cause the generation of heat within the electrical equipment in order to identify any latent defects.

Third Rail	A rail energised with the electric current required to power electric trains.
Traction Equipment Case	An enclosure mounted on the underframe of an electric train which contains traction equipment, including inverters.
Traction Motor	The electric motor used as the means of turning the powered axles on a rail vehicle using electric traction.*
Winding	A component part of a film-type capacitor. Windings are formed from a metallised film which is then machine-wound and assembled into a case to form the capacitor. In order to use, as far as possible, existing winding designs, a combination of short and long windings was used in the capacitor used on Class 455. The diameter of such windings is the same – the difference between them is the width of the film used to form the winding.

Appendix C - Investigation details

The RAIB used the following sources of evidence in this investigation:

- information provided by witnesses;
- site photographs and measurements;
- weather reports;
- meetings with the various organisations involved with the project;
- project records;
- project approvals documentation;
- train data recorder evidence;
- visit to Electronicon, Gera, Germany;
- Kiepe traction system diagnostics;
- review of published research papers; and
- a review of previous reported accidents and incidents.

This report is published by the Rail Accident Investigation Branch, Department for Transport.

Any enquiries about this publication should be sent to:

RAIB
The Wharf
Stores Road
Derby UK
DE21 4BA

Telephone: 01332 253300
Fax: 01332 253301
Email: enquiries@raib.gov.uk
Website: www.gov.uk/raib