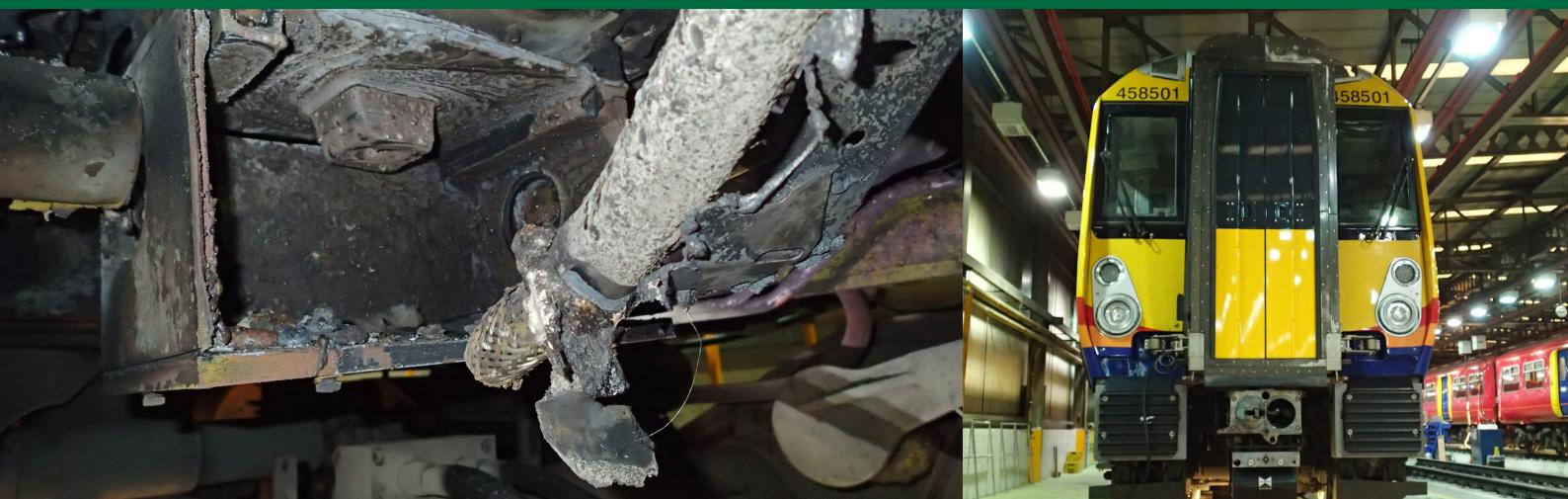




Rail Accident Investigation Branch

Rail Accident Report



**Electrical arcing and fire under a train near
Windsor & Eton Riverside
30 January 2015**

Report 18/2015
October 2015

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.

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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.

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Electrical arcing and fire under a train near Windsor & Eton Riverside, 30 January 2015

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Summary

On the evening of 30 January 2015, the 19:53 hrs South West Trains service from Windsor & Eton Riverside to London Waterloo left its origin station on time. After the train had travelled about 400 metres, there was a small explosion under the sixth carriage, followed by about 22 seconds of severe electrical arcing.

The train, which was formed of two class 458/5 electric multiple units (ten carriages), was travelling at about 14 mph (23 km/h) at the time. The brakes applied because of damage to air pipes, and the train stopped very rapidly. Some smoke entered the carriages through ventilators. There were two passengers in the sixth carriage, and they moved quickly into another part of the train. The driver contacted the signaller by radio to ask for the electric power to be switched off. While he was doing this, the floor of the sixth carriage was penetrated by fire, and smoke rapidly filled the vehicle. A few minutes after this, the lights in the rear five carriages went out.

There were 19 passengers on the train. Some of them operated the emergency door release in the rear carriage, got down onto the track, and walked back to Windsor station. Railway staff later evacuated the remaining passengers to the track, and helped them walk back to the station. The fire brigade were called, and confirmed by 20:50 hrs that the fire was out. None of the passengers were hurt, but the guard of the train was taken to hospital and treated for smoke inhalation.

The fire occurred because a joint between three power cables, located under the floor of the sixth carriage, had not been secured correctly when the carriage was reassembled after being rebuilt and refurbished in 2014. Electrical arcing had developed at the loose joint, and this damaged the ends of the cables and eventually led to the arcing which badly damaged the structure of the train. This in turn caused a fire that penetrated the floor.

The RAIB has made four recommendations. One, addressed to Wabtec Rail Ltd, covers the review and improvement of quality assurance arrangements at the factory where the refurbishment work was done. The second, addressed to Network Rail, relates to the need for changes to the rules relating to the conditions under which passengers are evacuated from trains after incidents. The third and fourth, addressed to South West Trains, concern the way in which the emergency lighting on the trains is configured to operate in the event of a loss of external power, and the need to review the risks associated with power cables and the joints between them. The investigation also identified four learning points for the railway industry, relating to the design of electrical junction boxes, the need for train crew to be fully aware of how on-train equipment works, the organisation of train conversion projects, and the importance of ensuring that records relating to train design are accurate and kept up-to-date.

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 On the evening of Friday 30 January 2015, train 2U64¹, the 19:53 hrs South West Trains service from Windsor & Eton Riverside to London Waterloo, had travelled about 400 metres after starting its journey, when severe electrical *arching* began under the sixth carriage of the ten-carriage *electric multiple-unit* (EMU) train. This lasted for about 22 seconds.
- 4 The train, which was travelling at about 14 mph (23 km/h) at the time, stopped immediately. Some smoke entered the carriages through ventilators. There were two passengers in the sixth carriage, and they moved quickly into another part of the train. The guard of the train moved from the tenth to the sixth carriage to investigate, and the driver also moved to the middle of the train. They could see that there was still smoke coming from below the sixth carriage, so the driver returned to the front of the train from where he contacted the signaller by radio to ask for the electric power supply to be switched off. While he was doing this, fire broke through the floor of the sixth carriage, and smoke rapidly filled the vehicle. A few minutes after this, the lights in the rear five carriages went out.

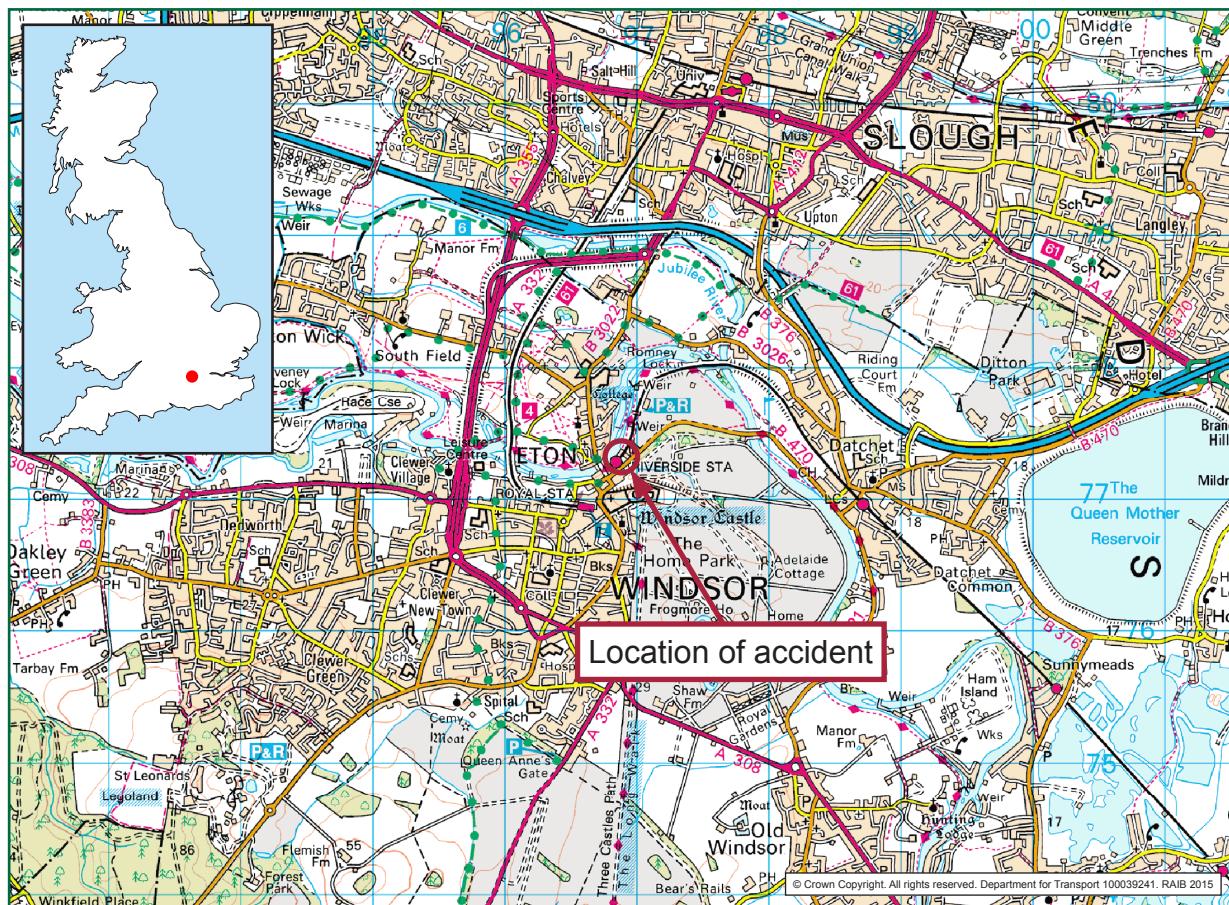


Figure 1: Extract from Ordnance Survey map showing location of accident

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

- 5 There were nineteen passengers on the train. Some of them used the emergency handles to open the train doors, and then got down onto the track and walked back to Windsor station. The guard, assisted by the crew of another train that was in the station, evacuated the rest of the passengers to the track, and helped them to the station. The fire brigade were called, and confirmed by 20:50 hrs that the fire was out. None of the passengers were hurt, but the guard was taken to hospital and treated for smoke inhalation.
- 6 The fire was a result of severe arcing in a junction box fixed under the carriage floor, where power cables from the *collector shoes* on either side on the train are connected to the main power cable (*bus line*) which runs along the train. The fire had burnt through the floor of the carriage, and the arcing had also destroyed parts of the structural members of the carriage body.

Context

Location

- 7 Windsor & Eton Riverside (hereafter referred to as Windsor) station is the terminus of a double track branch line, and is 25.5 miles (41 km) from London Waterloo. The line is electrified at a nominal 750 volts direct current (DC) on the *third rail* system, and carries a service of passenger trains which run every 30 minutes in each direction throughout the day.
- 8 There are two platforms at Windsor station (figure 2).

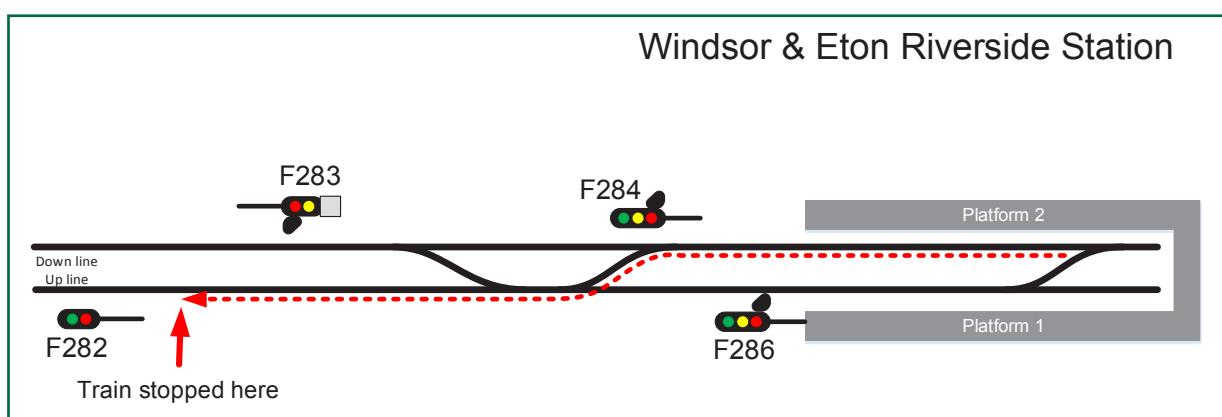


Figure 2: Track and signalling layout, showing route of train

Organisations involved

- 9 The train was operated by Stagecoach South Western Trains Ltd (which trades as South West Trains (SWT)), who employed the driver and guard.
- 10 The railway infrastructure, including the signalling and electrical control, is owned and operated by Network Rail. At the time of the accident, Network Rail and SWT operated in alliance as The South Western Railway, which staffed the Wessex Integrated Control Centre (WICC) at Waterloo.

- 11 The train involved in the accident was owned by Porterbrook Leasing Company Ltd (Porterbrook). It had recently been refurbished and lengthened in a project carried out under a contract between SWT, Porterbrook and Alstom Transport, who had originally manufactured the train. Alstom sub-contracted the refurbishment and conversion work to Wabtec Rail Ltd, which undertook the work at its factories at Loughborough and Doncaster.
- 12 All parties freely co-operated with the investigation.

Train involved

- 13 Train 2U64 was formed of two class 458/5 EMUs, 458535 (leading on departure from Windsor) and 458501. The fire occurred under the sixth carriage of the train, vehicle 67601, the leading carriage of unit 458501.

Rail equipment/systems involved

- 14 Signalling on the Windsor branch line is controlled from Feltham signal box. The electric power supply is controlled from Raynes Park electrical control room (ECR).
- 15 Electric power to the track at Windsor station is fed from the *sub-station* at Datchet, some 2.8 km (1.75 miles) from Windsor. Because the line terminates at Windsor, this section is fed from one end only.

Staff involved

- 16 The driver of train 2U64 had nine years' experience of train driving, all spent with SWT at Wimbledon Park depot. He had not previously been involved in any incidents in which he had had to deal with fires or the need to evacuate passengers.
- 17 The guard of train 2U64 had been employed by SWT since 1999, as a guard at Wimbledon Park depot for the whole period. He had not previously been involved in any emergency situations.

External circumstances

- 18 It was a cold, dry evening, with scattered cloud, and at the time that the accident took place the temperature at Heathrow airport, 6 miles (10 km) from the scene of the accident, was 3°C. The external conditions played no significant part in the accident.

The sequence of events

Events preceding the accident

- 19 On 30 January 2015, units 458501 and 458535 had been in service coupled together all day. The crew involved in the Windsor accident came on duty at 12:30 hrs, and after working together on other units, took over the train at Waterloo station in time for the 18:28 hrs departure to Windsor. The train arrived at Windsor on time at 19:23 hrs, and the crew met on the platform. They discussed a problem on the train. One of the intermediate doors in the gangway between the two units was jammed shut, preventing anyone from walking through the train. This was a minor problem, and did not mean that the train had to be taken out of service.
- 20 The guard explained to the driver that the door had stuck on the journey from Waterloo. He said that he had reported this problem to the WICC, and that he had also reported it two days earlier when he had previously worked on these units. The WICC asked the guard to try and free the door, so he and the driver attempted without success to do this while the train was at Windsor. They discussed how they would deal with the situation in which the train was calling at a station with a short platform, and passengers wanted to get out from a part of the train that was not at a platform.
- 21 The driver and guard then went to the front and rear cabs, and prepared the train for departure.

Events during the accident

- 22 Train 2U64 left Windsor on time at 19:53 hrs. The driver applied 32% power for about 20 seconds, accelerating to 12.6 mph (20.3 km/h) to pass over the *points* outside the station (where speed is restricted to 15 mph (24 km/h)) and then shut off power and let the train coast. After passing over the points, the driver applied full power. About two seconds after power was applied (and one minute after leaving the station), when the train was travelling at 14 mph (23 km/h) there was a flash and a bang from under the sixth carriage, and severe arcing started (see paragraph 62). Nine seconds later, *circuit breakers* on the train operated, but the arcing continued. It damaged air pipes and cables on the train, causing the brakes to apply and the train to stop, fifteen seconds after the arcing began.
- 23 There were two passengers in the sixth carriage at the time the arcing began. CCTV of the interior of the train shows that both passengers ran out of the carriage, towards the rear of the train and into the seventh carriage, evidently very alarmed at what was happening. Some smoke came into the sixth carriage, probably through the ventilation system.
- 24 The arcing stopped 22 seconds after it had begun. The train was then stationary, having travelled 405 metres from leaving Windsor station.

Events following the accident

- 25 About twenty seconds after the train stopped, one of the passengers who had run from the sixth carriage returned to it and collected his belongings, and then went back to the seventh carriage.

- 26 The train driver did not know why the train had stopped. He looked around the controls and the driving cab to see what the problem was. The first thing that he noticed was that the *train management system* (TMS) screen was indicating 'Train not in service', with no other information displayed. The driver attempted to use the cab-to-cab telephone to contact the guard, but got no answer. He then contacted the signaller at Feltham, and explained what had happened. The driver told the signaller that he was going to leave the cab and go in search of the guard.
- 27 The guard was travelling in the rear cab of the train. When it stopped, he looked out of the cab window and saw sparks coming from underneath the centre of the train. He tried to make a public address announcement, and was unable to hear anything coming from the loudspeakers in the adjacent carriage. He then tried to contact the driver on the cab-to-cab telephone, and was unable to get any response.
- 28 Two minutes after the train stopped, the guard left the rear cab and began to walk through the train towards the front. He spoke briefly to the passengers as he passed, telling them that he was trying to find out what was happening. When he reached the seventh carriage he met the two passengers who had run from the sixth carriage. They told the guard what they had seen and heard, and he stated that he told them to move back to the rear of the train. The guard continued towards the front. As he passed through the sixth carriage he became aware that there was a 'little bit' of smoke in it.
- 29 The guard reached the driving cab at the front of the sixth carriage. He was unable to go any further because of the jammed door (paragraph 19). He used the cab-to-cab phone again to try and contact the driver, but was again unsuccessful. He then used his company mobile phone to contact WICC, about four minutes and 50 seconds after the train had stopped.
- 30 The guard explained to the controller at WICC what had happened. While he was talking, the driver arrived in the adjacent cab at the rear of the fifth carriage. The driver leaned out of the window and called to the guard, who leaned from the window of the cab he was in and began a conversation with the driver (while keeping WICC on the line), six and a half minutes after the train had stopped.
- 31 The guard and driver began to discuss what to do next. They could see that, although the flashing had stopped, clouds of smoke were continuing to billow from under the sixth carriage, and were entering the cab where the guard was. The guard opened the door to the saloon of the sixth carriage, and found that it was also full of smoke (CCTV shows that smoke began to emerge from the floor just over five minutes after the guard arrived in the cab, and eight minutes and twenty seconds after the train had stopped (figure 3)).
- 32 The guard and driver agreed that the driver should return to the front cab, and contact the signaller to get the power switched off, so that they could safely get down onto the track to examine the train, and if necessary evacuate the passengers. The driver therefore left the middle cab five and a half minutes after he had arrived there (eleven and a half minutes into the incident), and returned to the front of the train. The guard continued to converse with the WICC controller.



Figure 3: smoke breaks through the floor of carriage 67601

- 33 Three passengers went into the sixth carriage at about this time, and used their mobile phones to take photographs of the smoke-filled vehicle. CCTV shows that they retreated, coughing, to the seventh carriage after about one minute (figure 4).



Figure 4: Passengers taking photographs of the smoke in car 67601

- 34 When the driver arrived at the front cab, he used the radio there to contact the signaller. The driver told the signaller that there was smoke coming from under the train, and asked for the power to be switched off so that he could go onto the track and examine the train. The signaller contacted the *electrical control operator* (ECO) at Raynes Park ECR, and relayed this request. The ECO switched off the power at about 20:10 hrs, fifteen minutes after the train had stopped.
- 35 The guard, in the middle cab, was still in phone contact with WICC. He could see that passengers near the back of the train had opened at least one set of doors, and were about to get down onto the track, but with the adjacent carriage full of smoke, he believed that he was trapped where he was. At 20:09:31 hrs all the lights in the rear five-car unit went out (the emergency lighting in the front five-car unit remained on).
- 36 The guard was now shouting through the darkness to the passengers at the back of the train, telling them to get back into the train. The WICC controller advised the guard to get down onto the track and deal with the passengers. Having received confirmation that the power was off, the guard terminated the conversation with WICC (17 minutes after it had started, and almost 23 minutes after the start of events), and got down onto the track, where he joined the driver in examining the underside of the train.
- 37 Another train had arrived at Windsor station immediately before train 2U64 departed. The driver of this train (2U66), who had got into the cab at the London end of the train ready for departure, was surprised to see that the train that had just departed had stopped a few hundred metres out of the station. Some minutes later several passengers appeared out of the darkness and walked onto the platform. They told the driver and guard of train 2U66 that there was a fire on board the train they had come from (2U64).
- 38 The driver of train 2U66 contacted the signaller, and confirmed that the current had been switched off. The driver and guard of train 2U66 walked up the track to train 2U64, where they found that there were still eleven passengers on the train. With the assistance of Network Rail staff, the crew of train 2U66 evacuated the remaining passengers from train 2U64 at about 20:45 hrs.
- 39 The emergency services were called by the WICC at about 20:16 hrs, some minutes after the lights went out in the train. The British Transport Police and the Royal Berkshire Fire and Rescue service attended, arriving at the station about 20:20 hrs.
- 40 The fire service investigated the area under the sixth carriage where the smoke had appeared to originate. They used extinguishers to cool the area, and after cutting away part of the floor covering in the carriage, established that there was no longer any smouldering material present.
- 41 None of the passengers were hurt, but the fire brigade identified that the guard of train 2U64 appeared to be suffering from the effects of smoke inhalation. He was treated on site and then taken to hospital, but was released after being checked over. He subsequently experienced some breathing difficulties, but was able to continue working, and has since made a full recovery.

- 42 The recovery of the train was protracted because the damage to the sixth carriage (the leading vehicle of unit 458501) had rendered the braking system inoperative: the main air pipes had been holed, and one of the *secondary suspension* air bags had deflated. The train was returned to the platform at Windsor early on the morning of 31 January, and remained there while it was made fit to travel. It finally left Windsor at 00:20 hrs on the morning of 1 February (Sunday), and travelled at 5 mph (8 km/h) overnight to the SWT depot at Wimbledon, arriving there at 06:50 hrs.

Key facts and analysis

Background information

The class 458/5 conversion project

- 43 The units involved in the accident, 458501 and 458535, were created during 2014 from vehicles which originally entered service as part of two different types of electric multiple unit, class 458 and class 460. Both types were built by Alstom, at its Washwood Heath (Birmingham) factory, which has since closed. Class 458, which originally consisted of 30 four-car units constructed between 1998 and 2002, was leased to SWT and used on outer suburban duties, mainly between Waterloo and Reading. Class 460, consisting of 8 eight-car units, was built in 2000 and 2001 and used on Gatwick Express services between London Victoria and Gatwick Airport. Between 2010 and 2012 they were replaced on these services by other trains, and placed into store pending conversion to class 458/5.
- 44 As part of SWT's plans to operate 10-car trains on many of its services, the class 458 and class 460 fleets have been merged to create 36 five-car class 458/5 units (with four vehicles being scrapped). Twelve driving cars from class 460 were converted by Wabtec at Loughborough, and given new driving cabs and interiors, and were then sent to Wabtec's factory at Doncaster where they were formed into new five-car units with refurbished intermediate cars from class 460s. These six trains became class 458/5 units 458531 to 458536, and entered service between March and October 2014.
- 45 The conversion of the class 458 units followed on from the class 460 units, and was carried out by Wabtec at Doncaster. Each unit was rebuilt with modified driving cabs, and given an additional intermediate carriage from a class 460 unit. The interiors of the carriages were stripped and refitted, with modified seating layout and new flooring, seats and trim. There were some consequential alterations to the electrical wiring in and between the vehicles, and alterations to the traction control, traction gearing and couplers. Modifications to the bogies, including some axle changes, required them to be removed from under the vehicles.
- 46 Unit 458501 was the second of the class 458 conversions to pass through the works at Doncaster.

The source of the arcing and the damage to the train

- 47 The RAIB examined unit 458501 at SWT's depot at Wimbledon on 2 February. The area under vehicle 67601 where the arcing took place is shown in figure 5, and the arrangement of the power cables is shown in figure 6a.



Figure 5: the area where the arcing took place, showing damage to the junction box, cables and structural members

- 48 Although, because of the nature of the event, much of the evidence had been destroyed, the origin of the arcing was almost certainly the joint where the two power cables from the collector shoes on each side of the carriage (the shoe cables) are connected to the cable which carries traction current through the unit (the bus line). The joint is mounted under the vehicle floor, close to the bogie on which the collector shoes are mounted. The construction of this joint is shown in figure 6b. It consists of a single zinc plated steel M16 hexagon head setscrew, 45 mm long, which passes through holes in the ends of the lugs which are crimped to the three cable ends, and is screwed into a through tapped hole in a boss which is welded to a plate, forming a bracket assembly. The joint also includes a plain washer and a helical spring washer. Alstom document FMI J06 ALST 0078 specifies that the setscrew should be tightened to 173 Nm.
- 49 This bracket is bolted to a pillar of insulating material. The pillar is within a junction box made of the same material, MICAM EM42. This fire-resisting material is a filled epoxide resin composite with woven and non-woven glass reinforcement. The junction box is glued together, and has a lid (which is on the bottom when the junction box is mounted on the train). The lid is bolted in place with captive screws (figure 7).

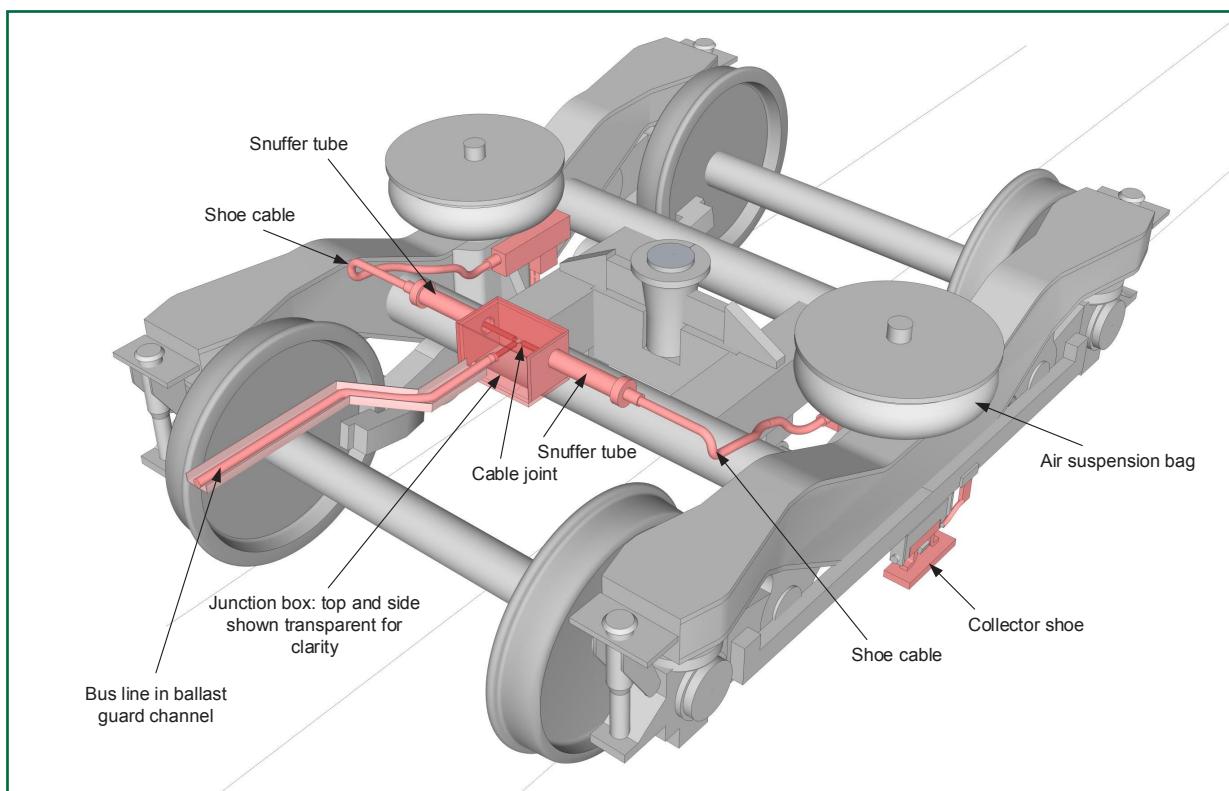


Figure 6a: Class 458/5 bogie, showing power cable arrangement

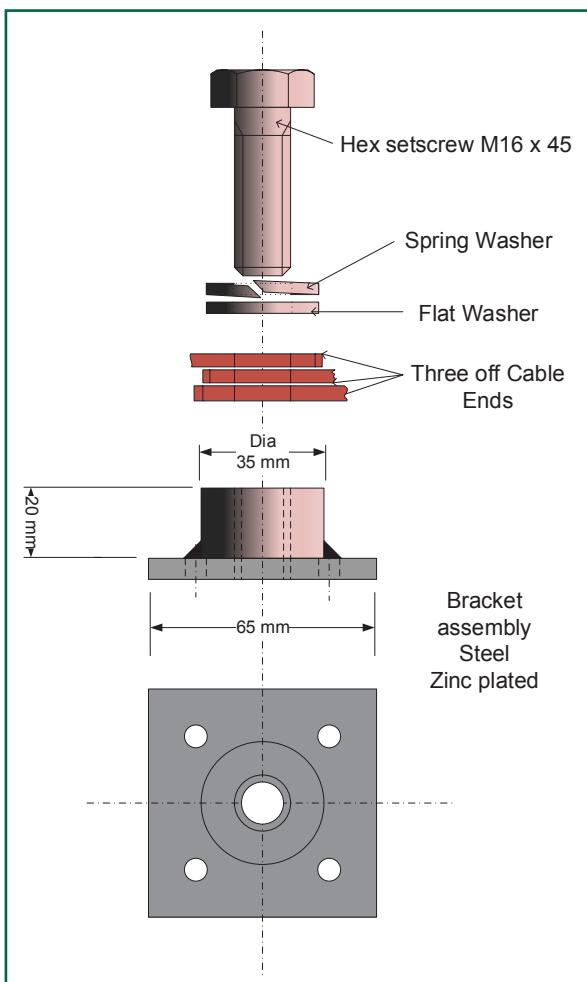


Figure 6b: details of the cable joint



Figure 7: The junction box (undamaged example: lid removed)

- 50 There are three of these junction box assemblies on each unit, corresponding to the three sets of shoe gear, one on each of the motored vehicles of the unit (see figure 11). On unit 458501, the damaged vehicle was one of the end carriages, the driving motor open standard (DMOS) known as the BJ car, at the east end of the unit (when it was in service on 30 January). The junction box is fitted under the vehicle floor adjacent to the un-motored (trailer) bogie, on which the collector shoes are mounted.
- 51 In the damaged junction box on vehicle 67601, the side through which the bus line passed had been blown out and was retrieved from the track under the train after the accident. The lid was still in place. The sides and top of the junction box had lost some thickness, but were substantially intact (figure 5 and figure 8). The bracket, washers, cable ends and securing bolt had been totally consumed by the arcing. The shoe cable on the right-hand side (in the direction of travel) had burnt back to the wall of the junction box, and the shoe cable on the left-hand side had burnt further back, some 70 mm beyond the wall of the junction box. The bus line cable was burnt back to approximately the point where the junction box wall had been.
- 52 The *snuffer tubes*, which protect the shoe cables outside the junction box, were intact, although the tube on the left-hand side had come away from the wall of the junction box. The shroud which is intended to protect the bus line cable from physical damage was burnt back about 150 mm from the junction box and displaced.

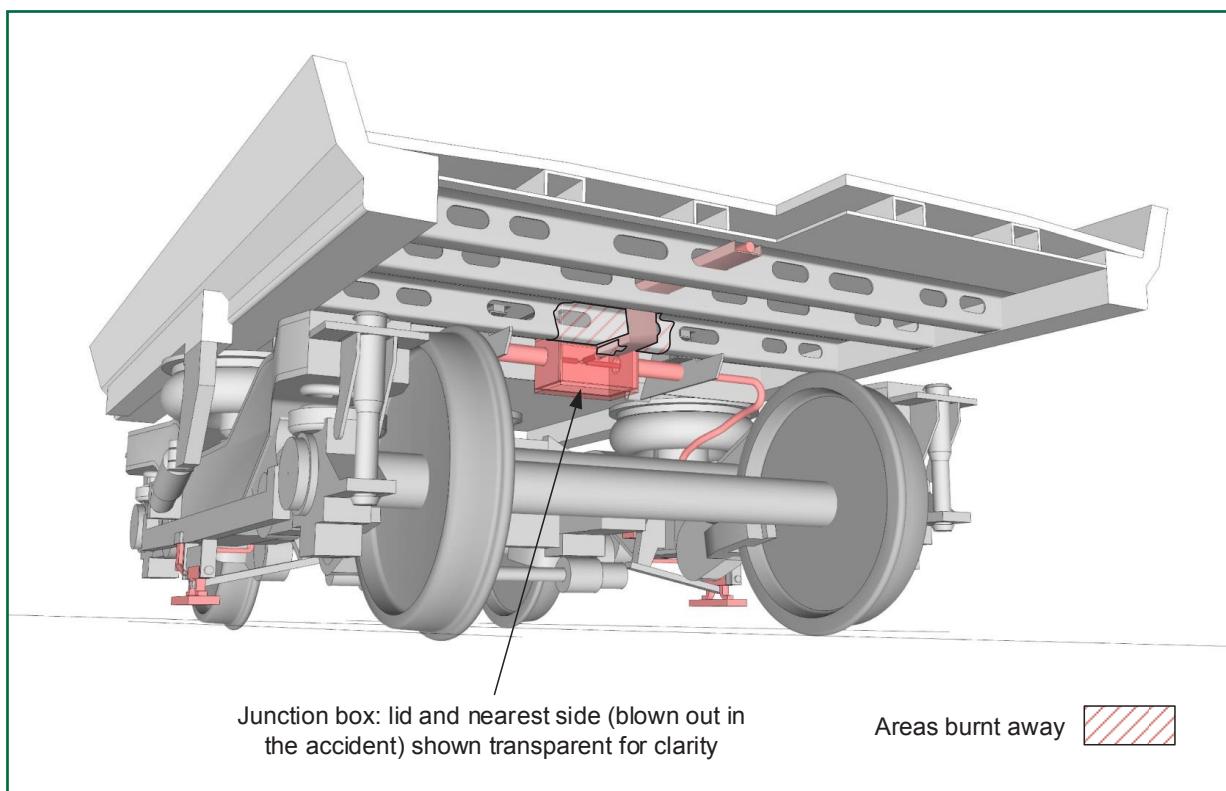


Figure 8: Damaged area under carriage 67601

- 53 The arcing burnt a hole about 300 mm by 100 mm through the outer skin of the vehicle, and destroyed longitudinal and lateral steel structural members in the vicinity of the junction box, compromising the strength of the vehicle body structure in this area. Figure 9 shows the extent of the damage, looking from above. The mineral wool and glass fibre insulation material between the outer skin and the floor was destroyed. The floor itself was affected over an area about 500 mm in diameter, with its lower skin (of aluminium) melted away, and the plywood core heavily charred and penetrated in one area.
- 54 It was not possible to be certain exactly how much of the upper surface of the floor, and floor covering, had been burnt through by the arcing or by the subsequent fire, because of the action taken by the Fire Brigade to expose any smouldering areas. However, it seems likely that a large area was heavily charred and an area at least 150 mm by 30 mm was fully penetrated (figure 9).
- 55 Air pipes (the main reservoir pipe and a brake cylinder pipe) passing through the area were burnt away, and one secondary suspension air bag was deflated.

Floor construction

- 56 During the class 458 conversion project (paragraph 45), the floor and floor covering in the vehicles were replaced. The original floor was an aluminium honeycomb structure, faced with aluminium sheet. The replacement floor was made of plywood, also faced with aluminium sheet. The cut edges of the plywood were sealed with an intumescent² compound. The new floor covering is similar to the material it replaced, and is a polymer-based material which is marketed as being compliant with the relevant standards for fire resistance.

² Intumescence substances swell when they are exposed to heat, increasing in volume and forming a coating which obstructs the spread of fire. They are intended to provide passive fire protection for structures.

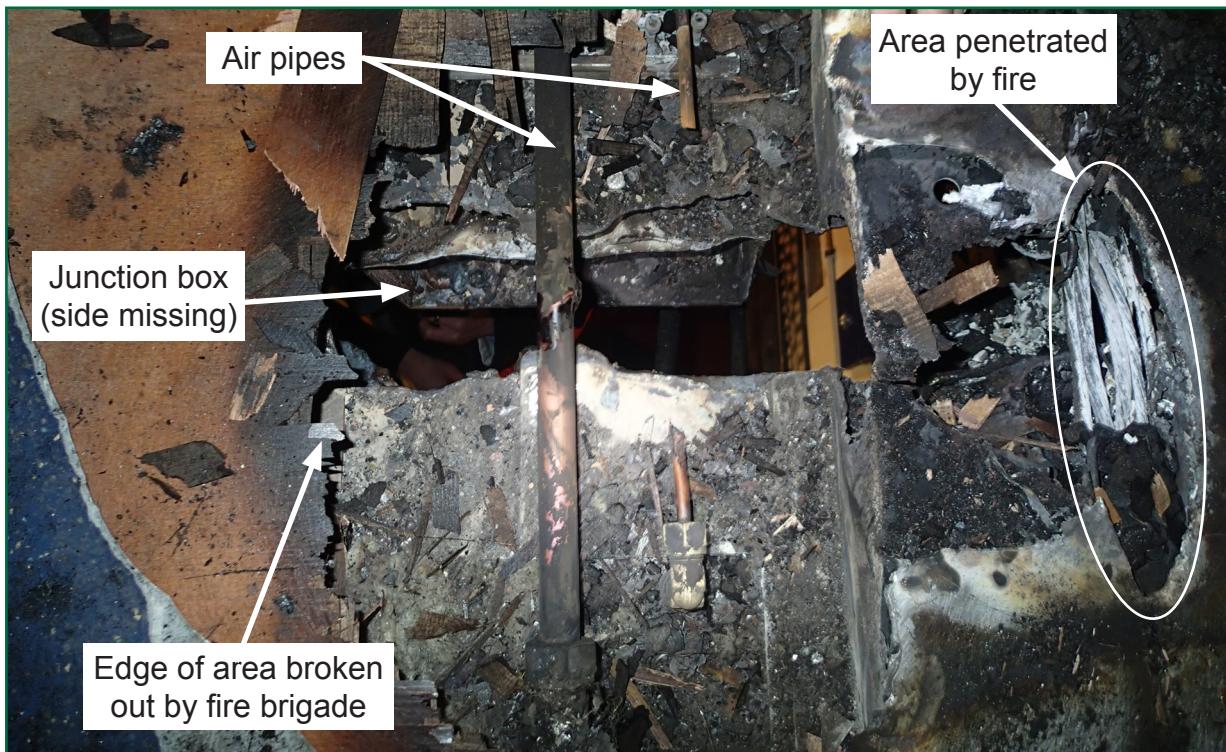


Figure 9: Damaged area of floor, viewed from above

Identification of the immediate cause

- 57 Loosening of the bolted joint between the shoe cables and the bus line led to arcing, which generated heat which burned through the floor of the vehicle.
- 58 The RAIB's examination of the train after the accident, CCTV and witness evidence and the data from the TMS showed that there had been severe arcing, which damaged the structure of the train, and the heat which damaged the structure also burned through the floor.
- 59 Evidence showed that the damage to the floor was limited to an area of very high temperature in a relatively small area under the floor of the train.

Identification of causal factors

- 60 The accident occurred due to a combination of the following causal factors:
 - a. The cable joint was loose, and came apart while the train was in service (paragraph 61).
 - b. The electrical protection arrangements on the train and the infrastructure did not prevent the arcing (paragraph 89).
 - c. The floor of the train was unable to withstand the temperatures generated during the arcing (paragraph 101).
 - d. The design of the junction box did not allow for the consequences of internal pressure build-up (paragraph 110).

Each of these factors is now considered in turn.

The cable joint

- 61 **The cable joint was loose, and came apart while the train was in service.**
- 62 The arcing that eventually damaged the structure of the train began when electric current passed through air between components that should have been securely held together: the ends of the shoe cables and the bus line. For these to have become separated, the bolted joint linking them must have been either loose or totally detached. It is possible that the cable ends had already been damaged by limited local arcing during the period that the train had been in service since the completion of refurbishment and conversion.
- 63 The initiating event for the violent arcing almost certainly occurred when the driver of the train applied power as the rear of the train was passing over the crossover from platform two to the up line. Because of the presence of the crossover, there is a gap of about 23 metres in the conductor rail for trains taking this route. The collector shoes on the rear two cars of the train are 20 metres apart. Therefore, for a short period, the only collector shoe on unit 458501 in contact with a conductor rail was the left-hand shoe on the leading vehicle, car 67601 (figure 10).
- 64 This meant that, for about half a second, a current of about 1900 amps (supplying all the traction motors on the unit) was probably passing through the loose joint. This initiated a powerful arc within the junction box, which burnt away the cable ends, creating heat and gas which raised the pressure inside the box, leading to an explosion and subsequent visible arcing (paragraph 22).

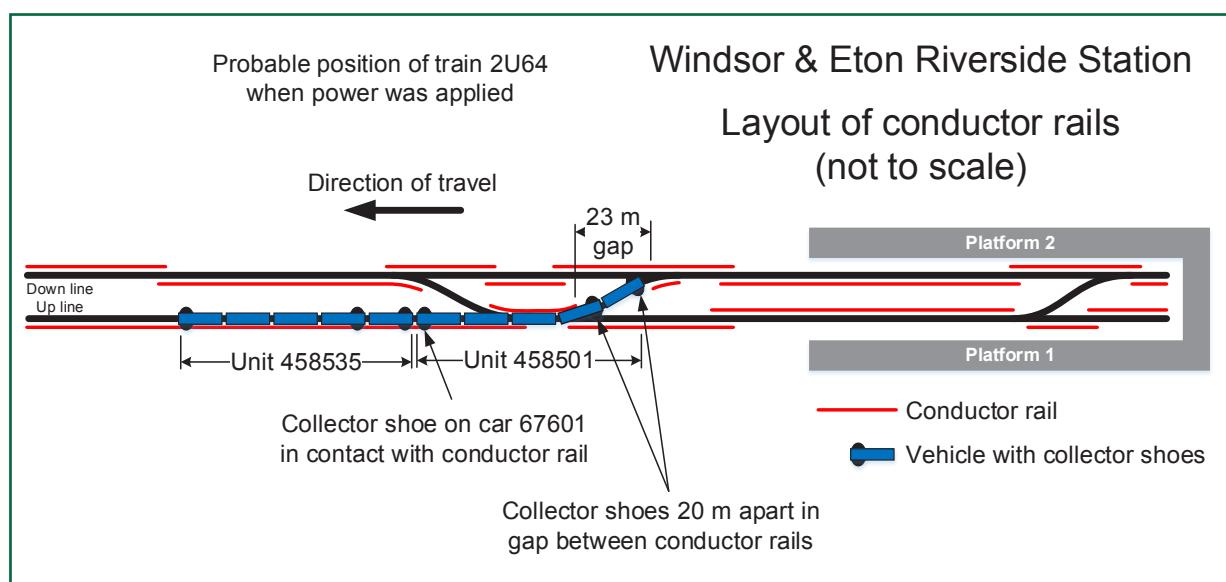


Figure 10: Layout of conductor rails and position of train at start of arcing

- 65 This causal factor arose because of a combination of the following factors:
- The joint was almost certainly not tightened when the bogie was refitted to the vehicle during the conversion project (paragraph 66).
 - The quality control procedures operated by Wabtec in the works at Doncaster did not provide any assurance that the joint had been tightened (paragraph 76).

Each of these factors is now considered in turn.

Tightness of the cable joint

- 66 The 30-strong fleet of class 458 trains had been in service for about fifteen years before the conversion project began. During this period, there is no record of any problem with the 90 shoe cable joints, or the junction boxes containing them (although evidence of minor arc damage was found in at least one cable joint during the refurbishment work at Doncaster, the RAIB does not believe this was relevant to the events under investigation).
- 67 Examination of the cable joints was not included in any of the periodic maintenance schedules for the trains. The joints were disturbed only when a bogie had to be removed from a vehicle for overhaul or repair. During the service life of the trains this was done at SWT's Wimbledon depot on many occasions. SWT states that no joint was ever found to be loose when being dismantled, and that on reassembly, its fitters torqued the joint to the figure of 173 Nm (specified by Alstom in the vehicle maintenance instructions).
- 68 Based on this experience, RAIB believes that it is very unlikely that the joint on vehicle 67601 would have worked loose in service if it had been correctly tightened. Evidence from Wabtec indicated that, at the time that unit 458501 was going through the works at Doncaster, staff in the vehicle assembly shop were re-using the existing fasteners (as specified in Alstom's instructions for the work), and tightening these joints to 90 Nm (rather than 173 Nm) because of confusion about which work instruction applied to this task (see paragraphs 132 to 136). The RAIB believes that, in the short period of time (three months) for which the train was in service after conversion, and in view of the benign conditions inside the junction box and the low levels of vibration associated with an electric train, the joint is highly unlikely to have worked loose from a torque of 90 Nm.
- 69 However, because the components of this joint had been totally destroyed in the accident on 30 January, and there was no other evidence relating to its condition, the RAIB commissioned a study of the design of the joint by a recognised consultant, to establish the adequacy of the design and the likelihood that it could come loose. Alstom also carried out a similar study, using its own staff, which concluded that, even if the joint had been tightened to only 90 Nm and the original fasteners had been re-used, it would not have worked loose.
- 70 The consultant concluded that it was likely that the failure of the cable joint was a result of the M16 screw failing to provide sufficient clamping force, because of an inadequate initial tightening and/or the use of a previously tightened screw.
- 71 Because of the design of the joint, with multiple layers of cable end lugs and washers compressed by the screw, a significant amount of clamp force will be lost over time as a result of a relaxation process called embedding³. The consultant believed that if the fastener was tightened to 90 Nm, rather than the specified 173 Nm, it could be anticipated that the loss over time would be such that the clamp force would fall below the level required for adequate electrical conductivity. However, there is presently no published evidence on the time over which the full embedding loss might be realised, or indeed whether the full magnitude of the potential embedding loss would be realised in the life of the train.

³ Embedding is the term used for the plastic flattening of the surface roughness at interfaces within the joint. It can be a critical factor in joints with multiple interfaces, as in this case. Besides embedding, relaxation in the joint can occur as a result of creep and similar effects.

- 72 The consultant took the view that the figure of 173 Nm specified by Alstom was lower than the 225 Nm which (based on previously published research work) would be appropriate for a new steel (zinc plated) fastener. The re-use of zinc plated fasteners is not recommended in this application because the increase in friction when a non-lubricated plated screw is re-used results in less clamp force being provided for a given tightening torque. However, the consultant also felt that there is no evidence that any change in the figure of 173 Nm is necessary, provided that new fasteners are used. Alstom has now issued an instruction to SWT and Porterbrook to use new fasteners each time the joint is reassembled (paragraph 166).
- 73 Following the accident, SWT checked the tightness of the shoe cable joint on all the class 458/5 units that had been converted at that time. The results of this check are in Appendix D. The check did not record the actual torque to which each joint had been tightened, but found that, of the 33 junction boxes checked, 18 had not been fully torqued to the 173 Nm figure quoted by Alstom. Of these, one joint was 'finger tight' only.
- 74 The unit involved in the accident, 458501, was examined by the RAIB and SWT. The joints in the two surviving junction boxes were found to be torqued to about 90 Nm and about 30 Nm respectively.
- 75 It is unlikely that, if the joint had been tightened to any of the values that were specified to be used in the factory at Doncaster (see paragraph 68), it could have become loose in the period that the train had been in service since conversion. The results of the fleet check, and previous experience with the class 458 units, suggest that it is highly likely that a small number of joints (two or three, including the ones on the unit involved in the accident) were not tightened when the bogies were refitted at Doncaster during the class 458/5 conversion project.

Work records

- 76 During the class 458 conversion project, the bogies are removed from all vehicles for various modifications and overhaul work. Refitting the bogies to the vehicles is done in the assembly shop at Doncaster.
- 77 Wabtec prepared a 'Vehicle Business Documentation Pack' (VBDP) for the conversion project. This pack was associated with, and referred to the Alstom Field Modification Instructions (FMI) for the task. It included space for the person carrying out each element of each task to sign to confirm that they had completed that element.
- 78 The work on the bogies where the shogear is located was covered by the Alstom FMI J06-ALST-0078 (FMI 0078) 'DMOS Bogie Axle Changes For Increased Load Class 458/5 Cars'. At the time that unit 458001 (which became unit 458501) went through the shops, issue 4 of FMI 0078 applied.
- 79 The Wabtec VBDP which included FMI 0078 provided a single sheet to record the work associated with that FMI. It was issued to the vehicle assembly shop, and only the work done in that shop was recorded on the relevant sheet.
- 80 The refitting of the trailer bogies was done by mechanical fitters, who filled in the space on the VBDP relating to job numbers 11.1 and 11.2, which covered Appendix E of FMI 0078 'Trailer Bogie Refit'. This work included the connection and setting up of the secondary suspension and anti-roll bars, but not the electrical connections to the collector shoes.

- 81 The electrical work was done by electrical fitters, and there was no space on the VBDP to record that the junction boxes had been reassembled, or who had done the work. The electrical fitters therefore made no written entries on the VBDP, and it was not possible to establish subsequently who had worked on a particular vehicle.

Assembling the junction box

- 82 To assemble the junction box required the electrical fitter to feed the two shoe cables through the snuffer tubes into the connection box. The third (bus line) cable was not disturbed during the project, and so was already in the box. The fitter should then have remade the joint using the M16 bolt and washers that were already there (having been put back loosely when the bogies were removed in preparation for the modification work), torque tightened the bolt to 173 Nm, and applied a (yellow) witness mark across the bolt head, washers and bracket.
- 83 To tighten the bolt to this torque required the use of a calibrated torque wrench, one of which was normally stored on the wall in the assembly shop.
- 84 The RAIB has not been able to establish why the cable joint that was destroyed in the accident, and the one that was found to be ‘finger tight’ on the subsequent fleet check, were not tightened. It has not been possible to identify the person who worked on those vehicles (paragraph 81). The investigation has considered working practices in the factory and possible human factors which may have influenced what happened, but there is no firm evidence relating to these two cable joints.
- 85 The RAIB’s examination of the other junction boxes on unit 458501 found that there was no witness mark on the cable joint in one of them, although the bolt had been tightened to about 30 Nm.
- 86 The final stages of the assembly process were to tighten the *cable gland nuts* on the ends of the snuffer tubes, and refit the cover to the connection box using the existing captive screws. No tightening torque was specified for these screws, nor was a witness mark required. However, all the other junction boxes seen by the RAIB had witness marks on the cover screws.
- 87 At the time that unit 458501 was being reassembled, the quality assurance system that Wabtec was operating did not require any verification of the assembly of the shoe cable junction box. Wabtec believed that the signatures on the VBDP document provided adequate traceability for this work, and the cable joint had not been modified in any way in the works, or highlighted as requiring any special attention.
- 88 The Wabtec factory at Doncaster has current quality assurance certification from the British Standards Institution (BSI) for its quality management system under ISO 9001:2008 (certificate FM 00456), and is registered with the Railway Industry Supplier Approval Scheme (RISAS) for a range of products and services, including bogie and vehicle overhaul. However, Wabtec had recognised before the accident on 30 January 2015 that there were opportunities to adopt practices and procedures from other industry sectors to improve its business process with the aim of delivering consistent quality, and had begun taking action to implement this.

Electrical protection

- 89 **The electrical protection arrangements on the train and the infrastructure did not prevent the severe arcing.**
- 90 The arcing which followed the explosion in the junction box caused large electrical currents to flow in the area under the train, for at least 22 seconds. The various protection systems fitted to the train and the infrastructure power supply did not act to prevent this. The result was that a large amount of smoke entered the train, and considerable damage was caused.
- 91 The traction power at Windsor is fed from the national grid via a sub-station at Datchet, where it is transformed to a nominal 750 volts DC. The sub-station is provided with two parallel DC circuit breakers, one for each line, with a direct acting overcurrent setting of 7000 amps. This setting is intended to protect the power supply infrastructure from hard *earth faults* (resulting in high short circuit currents), and is not designed to respond to arcing faults on trains which do not usually lead to such high fault currents.
- 92 In this case the current drawn by the arcing rose to about 3600 amps nine seconds after it started (this was the current at which the on-train protection operated: see paragraph 95). It is not easy to estimate what maximum value was reached by the arc current, but it was almost certain to have been less than the overcurrent setting of the sub-station circuit breakers (allowing for the distance between the sub-station and the site of the accident). The circuit breakers are set to trip at 7000 amps to provide sufficient electrical capacity for the number of trains that may be in the area, and drawing power, at the same time. The need to be able to provide such heavy currents is a characteristic of the DC third rail system, which makes it difficult for the infrastructure protection to detect faults (such as the one at Windsor) which occur on trains.
- 93 On the class 458/5 train, there are three high speed circuit breakers (HSCB), one associated with each set of collector shoes, and referred to by Alstom as 'circuit breaker – shogear high speed' (CB-SHS) (figure 11). These are mounted on the underside of the vehicle, and there is no protection for faults which may occur in the cable between the collector shoes and the CB-SHS. The maximum rated service current for a class 458/5 unit is 1930 amps.
- 94 The CB-SHS will trip or be commanded to trip under a number of different conditions:
- overcurrent detected in bus line cable (will trip the local CB-SHS only);
 - 'HSCB Open' pushbutton pressed in driving cab (will trip all three CB-SHS in the unit);
 - operation of a *Bus Line Earth Leakage Relay*, which monitors the bus line cable for insulation failure (will trip all three CB-SHS in a unit);
 - 'HSCB Open' pushbutton pressed in control box on vehicle underframe (will trip the local CB-SHS only);
 - limit switch operated on shore supply socket (will trip all three CB-SHS in a unit); or
 - 'HSCB Emergency' pushbutton pressed in driving cab (will trip all six CB-SHS on a train if pressed in an active cab).

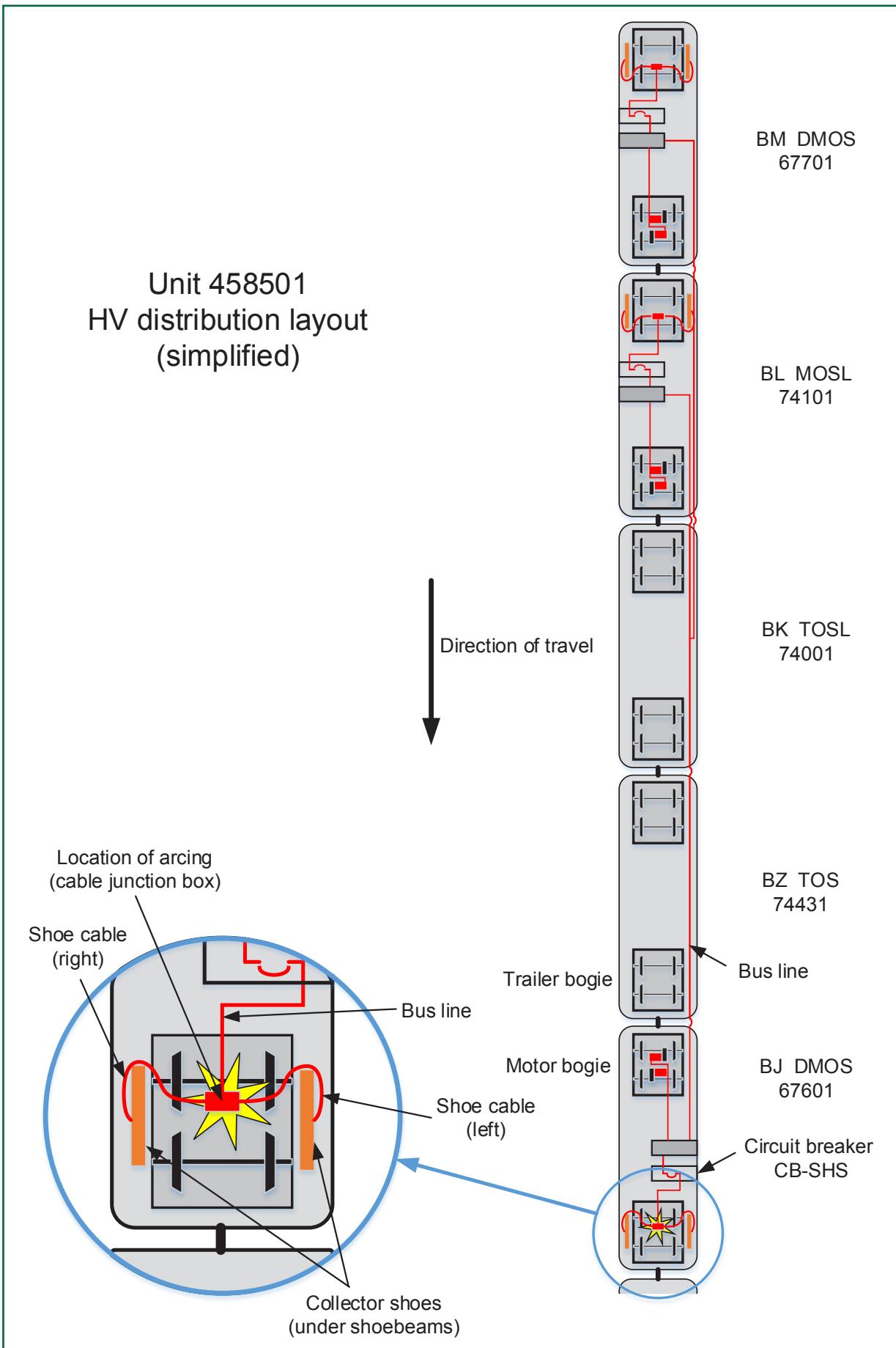


Figure 11: diagram of high-voltage distribution layout on class 458/5

- 95 In the TMS of unit 458501, all three CB-SHS are recorded as having operated at the same time (to within one second) when the train was travelling at about 14 mph (23 km/h). There is no record in the TMS of any of the push buttons having been operated. The Bus Line Earth Leakage Relay circuit does not monitor the cable on the shoe gear side of the CB-SHS and could not have detected the arcing, and the CB-SHS is rated to trip on overcurrent (instantaneous trip setting of 3600 Amps). This leads to the conclusion that the CB-SHS tripped on overcurrent when it detected high current flowing from the traction supply to the vehicle body.
- 96 This occurred some nine seconds after the start of visible arcing. The RAIB believes that this was the point at which the nature of the arcing changed. In the initial, invisible stages of the event, the arc on the train was across the loose joint in the junction box, and no sign of any unusual current flow would have been apparent to the protection equipment, either on the train or in the sub-station.
- 97 When the pressure inside the junction box caused it to burst open, the arcing became visible (and is recorded on the on-train CCTV). Arcing to earth via the vehicle bodyshell began to develop. At about this time, the TMS detected a problem with the traction equipment. Nine seconds later, the visible arcing was at its peak level, and all three CB-SHS opened. This indicates that the arc current between the traction supply and earth via the vehicle body had built up to the point where it exceeded the trip setting of the CB-SHS.
- 98 The tripping of the three CB-SHS meant that the arc was no longer fed through the bus line from the collector shoes on the ninth and last carriages of the train (the bus line only runs within each unit). However, the left-hand collector shoe of the sixth carriage was still carrying current to the arc, and because the CB-SHS on that vehicle was not between the collector shoe and the arc, it did not protect the train's structure from the further damage that occurred over the next 13 seconds, until the visible arcing ceased.
- 99 It is likely that the arcing eventually stopped when so much material had been burnt away from the underframe of the carriage that the arc could no longer jump the gap, and the gases that had contributed to the formation of the arc were also dispersing or had been consumed. The RAIB estimates that the total energy dissipated as heat during the period of the arcing was of the order of 32 megajoules⁴. By the time the arcing stopped, so much energy had entered the underframe and been converted into heat, that substantial steel structural members had been burnt away and fire was consuming part of the floor.
- 100 It is the view of the train manufacturer, Alstom, that it is not practicable to provide electrical fault protection for the length of cable that links the collector shoes to the bus line, mainly for reasons of space. On previous generations of train, shoe fuses were provided, but these were actually located on the vehicle underframes and did not protect the shoe cables. Other modern designs of third rail EMU are fitted with circuit breakers rather than shoe fuses, but in every case there is a length of unprotected cable between the shoe gear and a junction fixed to the vehicle body.

⁴ This is equivalent to the energy released in an explosion of 8 kilogrammes of TNT.

Fire resistance of the train floor

101 The floor of the train was unable to withstand the temperatures generated by the arcing.

102 As described in paragraph 56, the floor of the trains was replaced as part of the conversion project.

103 The fire performance of the floor and floor covering was reviewed on behalf of Alstom by an engineering consultant as part of the class 458 conversion project. The contract for the works stated that non-replaceable parts of the units should use material compliant with BS 6853:1999⁵ vehicle category 1b. This category covers vehicles which may work underground, and spend '*substantial operating periods in a multi-track tunnel, or a tunnel with side exits to a walkway and escape shafts*'. The class 458/5 trains spend almost no time underground (there are very few tunnels on the routes where they operate), so the application of this standard to these trains was therefore very conservative. However, all the materials described in paragraph 56 were considered by the reviewer to be compliant with this standard.

104 The requirement for control of fire spread and its products in respect of floors is in section 7.1.1 of the standard, and is that when tested in accordance with BS 476-20 and 22⁶, the total floor construction should achieve 20 minute integrity and insulation, and the average temperature of the surface should not exceed 250°C.

105 The test methods are described in BS 476 part 20:1987. They are quite complex, but the essential point relevant to this investigation is that testing should be carried out in a furnace, and during the 20 minute duration of the test, the mean furnace temperature should rise from 20°C to 781°C.

106 The melting point of steel, which formed the main structural elements of the vehicle body, is around 1400°C, and the melting point of aluminium (which formed the facing of the floor) is about 660°C. In an electric arc, very high temperatures can be generated, up to 19000°C at the arc terminals⁷.

107 The damage to the vehicle (figure 5 and figure 9) indicates that very high temperatures were developed during the arcing, which the floor was unable to withstand. The steel longitudinal channel section members immediately under the floor were burned away. During and immediately after the arcing, the temperature of the metal in contact with the floor adjacent to the areas that were burned away would have been around 1200°C (white hot, the condition of steel heated to a point just short of melting), well in excess of the temperature the floor is specified to withstand.

⁵ BS 6853:1999 'Code of practice for fire precautions in the design of passenger carrying trains'.

⁶ BS 476: 1987 'Fire tests on building materials and structures', Part 20 'Method for the determination of the fire resistance of elements of construction (general principles)' and Part 22 'Methods for determination of the fire resistance of non-loadbearing elements of construction'.

⁷ KM Kowalski-Trakofler, EA Barrett, CW Urban, GT Homce. "Arc Flash Awareness: Information and Discussion Topics for Electrical Workers". DHHS (NIOSH) Publication No. 2007-116D.

Arc barriers

- 108 The role of BS 6853 in relation to the fire performance of the train floor has already been described (paragraphs 103 and 104). The class 458 trains were designed in the late 1990s. At that time the relevant standard for fire precautions in the construction of passenger trains was BS 6853:1987⁸. This required (section 10.6) that '*special fire barriers should be fitted between the vehicle and possible sources of sustained arcing, e.g. electrically unprotected power cables.*' About the time the trains were put into service, this standard was replaced by BS 6853:1999, in which the requirements for protection against electrical fires were more explicit:

5.8 Electrical protection

Creepage and clearance distances should be set with due regard for the propensity of the materials to track and with regard for the voltage used and whether it is a.c. or d.c., so as to minimize the occurrence of electrical faults. Suitable electrical protection should be provided to ensure that the energy release rate on occurrence of a fault and the duration of the fault is minimized. This guidance applies to electrical power both as an ignition source and as a power output hazard when in the form of a power arc.

5.9 Protection against power arcs

Suitable arc resisting barriers should be used to protect the passenger compartments with particular consideration given to areas where faults are electrically unprotected other than by substation circuit breakers.

- 109 Alstom recognised that some aspects of the design of the class 458 trains would not be compliant with the revised standard, so it carried out a risk assessment in respect of these areas, which included the power electrical systems. To contain arcs in the area immediately under the vehicle floor (and specifically the joint between the shoe cables and the bus line), the junction box and snuffer tubes were manufactured from a fire-resisting material (MICAM EM42 (paragraph 49)) which had been developed for use in electrical applications.

Junction box design

110 The design of the junction box did not allow for the consequences of internal pressure build-up.

- 111 The junction box was made from sheets of MICAM EM42 glued together, with a cover of the same material, secured by steel setscrews (paragraph 49). In the accident on 30 January, pressure built up inside the junction box as the arc between the shoe and bus line cables generated heat and gas. When this pressure exceeded the strength of the box, it failed along the glued joints and one side was blown off. The fact that the side blew off, rather than the cover, meant that the subsequent arcing went horizontally towards the underframe structure, rather than downwards away from the vehicle body.
- 112 If the box had been ventilated, or otherwise provided with a means of relieving the pressure that built up inside, the box might have remained intact and contained the localised arcing, as intended by Alstom.

⁸ BS 6853: 1987 'Code of practice for fire precautions in the design and construction of railway passenger rolling stock'.

113 The RAIB has not been able to discover any evidence relating to the design philosophy for this box, or any consideration of possible failure modes at the design stage. However, Alstom's design drawings indicate that the box was intended to be sealed. Since it did not enclose any moving parts, it is possible that the potential consequences of arcing and pressure build-up inside the box were not considered by its designer. However, as the choice of material for the box, and statements made by Alstom in the 'Overview of fire safety matters' submitted in support of the original design indicate, its purpose was to act as an arc barrier between the terminal assembly (inside the box) and the earthed vehicle structure (outside the box). Alstom has stated that the designer would have assumed that the cable terminal would be correctly assembled and tightened during manufacture, and would not work loose subsequently. However, with hindsight, it could have been appropriate to have considered at the design stage how the box would behave in the event of an arc starting inside it.

Factors affecting the severity of consequences

Emergency lighting and public address systems

114 The public address system in the train was not audible, and the lighting in the damaged unit ceased to operate fifteen minutes after the start of the incident, leading to passengers leaving the train unescorted and getting on to a potentially live railway.

Emergency lighting

- 115 About 15 minutes after the start of the incident, while the guard of the train was speaking on the phone to the WICC, the internal and external lighting on the rear unit (458501) shut down. This left the unit, and the 17 passengers on board that part of the train, in darkness.
- 116 It is likely that the failure of the lighting, combined with the absence of any announcements (since witness evidence indicates that it is likely that the public address system in the rear unit was not working during the event (see paragraph 123)) encouraged the passengers to use the emergency door release handles to open one set of doors in the rear coach, from where they got down onto the track and walked the short distance to Windsor station. It is not clear from the evidence whether the passengers opened the doors before or after the train lights went out.
- 117 The traction current was switched off at about the same time as the train lights went out (or possibly up to two minutes later). The investigation has established, from examination of the damaged train and evidence from the train management system, that these two events were not linked. However, it is possible that the passengers may have believed that the lights had gone out because the current had been switched off, and that it was therefore safe to walk along the track.

- 118 The requirements for emergency lighting in trains are set out in Railway Group Standard GM/RT2130 Issue 4 ‘Vehicle Fire, Safety and Evacuation’. Relevant requirements, in section 4.1 of this standard, are that the emergency lighting will *‘operate in the event of the loss of general or standby lighting... [It] shall be independent of the main vehicle battery to avoid loss of emergency lighting as a result of loss of the main vehicle power supply... The power supply for the emergency lighting shall be suitably located within the vehicle to minimise the risk of its continued operation being prejudiced as the result of an accident... [It should] achieve the minimum specified levels at full lighting output for a period of 90 minutes when the vehicle main power supply is removed.’*

Reasons for loss of lighting

- 119 Evidence from the TMS and the on-train data recorder indicates that, at the time the train stopped, the two units became electrically uncoupled from each other.
- 120 The electrical connection between the two units is made through coupler heads which are held together by compressed air. When the arcing damaged the air pipes under car 67601, air pressure to the coupler head was lost. It is likely that the jerk as the train came to a sudden stop (following the emergency brake application also caused by the loss of air) made the coupler heads move apart far enough to break the electrical connection.
- 121 The consequence of this loss of connection is that the TMS of the rear unit (458501) would no longer be receiving instructions from the leading cab of the train, and would treat the situation as if there was no cab in service in the unit (a cab is ‘in service’ if a train driver’s key is inserted in the master switch on the control desk in the cab). The rear unit TMS would also register that the unit was no longer being supplied with traction current, because the circuit breakers had tripped in response to the arcing, and had not been reset. In this situation, the ‘automatic train trip’ function operates. This shuts down the on-train systems fifteen minutes after the TMS detects that there is no cab in service and the third rail supply has been lost (or 90 minutes after traction power is lost with a cab in service). This function, which was not originally fitted to the class 458s, was added at the request of the operator early in the trains’ service life. Documentary evidence indicates that the function was intended to conserve battery life. However, SWT has not been able to establish whether it has been effective or valuable in this respect, and in recent years the function has not been included in training SWT has given to drivers and guards.
- 122 The lights remained on in the leading unit (458535), because one of the cabs in that unit was still in service (the driver’s key was still in place in the leading cab).

The behaviour of other on-train systems

123 The operation of the public address system is integrated with the TMS. When the units became electrically separated (paragraph 121), the TMS of the rear unit attempted to reconfigure itself for the new situation. However, the commands that the TMS had received led the system to continue to search for a ten-car train, and it did not complete the process of configuring itself for the separation. Because of this, it is likely that the public address did not broadcast any of the guard's messages during the event. The automatic train trip function switches off all the train's auxiliary systems that run off the batteries, including the lighting, the CCTV cameras, and the public address. It would have been possible to re-set the train and restore the lighting (and probably the public address) by putting a driver's key into either cab of unit 458501. However, the train crew did not know why the lights had failed and did not realise that it was possible to turn them on again.

The management of the accident

124 The train crew did not call for assistance, and the emergency services were not mobilised until about 25 minutes after the accident.

125 When the train came to a stop, the driver and guard tried to find out what was wrong. It took them more than eight minutes (paragraph 31) to decide that the driver should contact the signaller to ask for an isolation of the traction current, with a view to examining the underside of the train. The guard believed that he had instructed all the passengers to move to the rear of the train, well away from the carriage that was full of smoke. While this was being arranged, the lights in the rear unit went out.

126 The WICC had contacted the British Transport Police (BTP) at 20:05 hrs, about ten minutes after the start of the incident, and advised them of the arcing and 'loud bang'. When it became apparent that the train was not going to be able to move, the BTP contacted Berkshire Fire & Rescue Service. A fire engine was mobilised at 20:17 hrs, and arrived at Windsor station at 20:20 hrs.

127 The situation on the train developed quite slowly. In the telephone calls that they made to the signaller and the WICC, the driver and guard did not use the word 'emergency' at any point. They believed that the incident was a low-level electrical problem, of the sort that is not uncommon on the third rail network, involving short-lived arcing that does little damage.

128 After the initial severe arcing had stopped, there was nothing visible from the inside of the train to indicate that the heat that had been generated during the arcing was continuing to burn through the floor. The guard, who was in the nearby cab, realised that the carriage was filling with smoke, but he did not know where it was coming from.

129 The driver and guard had both been trained, and their competence managed, by SWT. The train service manager at the WICC was also a SWT employee. All the staff considered that they were acting appropriately in the circumstances, but the driver and guard have accepted that, with hindsight, the situation could have been dealt with more quickly.

130 SWT has reported to RAIB that it believes that in recent years (particularly since the start of the general use of radio and mobile telephones for communications between train crew and the outside world) train crew have become reluctant to take decisions on their own initiative, and sometimes seek outside guidance even when a situation calls for rapid and effective action. SWT is taking steps to address this (see paragraph 167).

Observations

Project management

131 **The arrangements for the management of the work instructions and technical data in the class 458 conversion project were not adequate.**

Work instructions

- 132 The contract between Alstom and Wabtec for the conversion and refurbishment work to create the class 458/5 trains included the provision of modification instructions by Alstom giving details of '*the material required, the general tasks involved, broad health and safety guidelines and the standards to be achieved*'. The contract stipulated that Wabtec should convert these instructions into '*detailed shop floor work instructions taking account of their facilities, workforce skills, health and safety regulations and overall modification sequence plan*'.
- 133 The Field Modification Instructions (FMIs) that Alstom provided were very detailed. In most cases Wabtec did not rewrite the FMIs, but issued them directly to the shop floor at Doncaster as part of the VBDP (paragraph 77).
- 134 The FMIs were written around the various modifications to be performed, and were not aligned to the way the works at Doncaster was organised. For this reason, some of the record documents that Wabtec generated to go with them did not reflect the actual tasks that were needed, and so in some cases there was confusion about the details of work that needed to be recorded.
- 135 The work on the bogies of the units was covered by FMI 0002 and FMI 0078. FMI 0002 describes the work on motor bogies (changing axles, and associated minor work), and FMI 0078 covers similar work on trailer bogies, which carry the collector shoes. There are no shoe cables on motor bogies, so there is no reference to the assembly of the cable junction boxes in FMI 0002.
- 136 Evidence indicates that Wabtec, Doncaster initially issued FMI 0078 to the bogie shop and FMI 0002 to the assembly shop to cover the refitting of all bogies, and that this was the source of confusion about the correct torque to be applied to the cable junction boxes (paragraph 68).

Technical records

- 137 Witness evidence indicates that when the first class 458s arrived at Doncaster for conversion, Wabtec discovered during dismantling that there were differences between the drawings and specifications that Alstom had provided, and the trains themselves. In some cases these were minor inconsistencies between the trains and the as-built drawings, and in other cases modifications had been made to the trains during their service life, and the details of these modifications had not been transferred to the drawings held by the manufacturers.

138 Since 2006, SWT had been solely responsible for the maintenance of the class 458 fleet. In the period between 2006 and 2014, modifications made to the trains had been recorded by SWT, but had not resulted in any update to the set of drawings accessible to the fleet's owners and manufacturers. These modifications included the addition of sanding equipment and changes to seat mounting bolts.

139 The result of this was that the electrical work, in particular, did not initially proceed smoothly at Doncaster, because of the need to identify and trace wiring that was not in accordance with the drawings.

140 As well as the resulting commercial issues, the potential for confusion inherent in this situation increased the risk involved in the conversion, and may have contributed to some of the confusion around the reassembly of the junction boxes (although the design of these had not changed in any way, either during the service life of the class 458s or in the conversion programme).

Internal door

141 A jammed internal door prevented access through the train.

142 The train crew had found, when they took over units 458501 and 458535 at Waterloo earlier on 30 January (paragraph 19), that one of the internal doors had jammed in the closed position. This door closes across the gangway behind the driving cab when the cab is in use, and swings to secure the empty cab and open up access through the train when the unit is coupled to another. The door is secured by a mechanism operated by a square-ended key, which is designed to be impossible to insert or withdraw if the door is not fully locked or unlocked. Wear and/or mismatch of the key and lock mechanism can defeat this intention.

143 This almost certainly occurred in unit 458535 at Windsor, and meant that, during the events of that evening, the driver and guard were unable to get through the train, and had to lean out of adjacent cab windows to talk to each other.

144 At some point later in the evening, someone succeeded in opening the door, but there is no evidence as to who this was.

145 SWT subsequently investigated the door, and other similar doors on the two units involved. The investigation found:

Misalignment of the lock and the gated cover could be replicated dependent on angle and depth to which the T key was inserted. The condition of the key (i.e. how worn the square end had become) was also a significant factor. In this state it would not be possible for a subsequent driver or guard to insert a key and operate the lock.

146 The RAIB has discussed this problem with SWT, Alstom and Wabtec. There are a number of factors which influenced the outcome, including the design of the lock, the way the doors and the locks were installed, and the equipment issued to train crew. The RAIB has evidence that the various parties have now taken action to address these issues, and that the locks have been examined and replaced where necessary.

Evacuation of the train: rules

147 The rules relating to evacuation of passengers from trains on third rail electrified lines are difficult to apply in an emergency situation.

148 The passengers who had remained on the train after the lights in unit 458501 went out were eventually evacuated under the supervision of railway staff at about 20:45 hrs (paragraph 38), and walked along the track about 200 metres to Windsor station. The electrical supply to the third rail had been switched off by the ECO (in response to a request from the driver of train 2U64) at about 20:10 hrs (paragraph 34).

149 Rules covering the evacuation of trains following accidents or incidents appear in two places in the railway rule book. Module M1 'Dealing with a train accident or train evacuation' (issue 2, 2012) says, at section 6:

6.3 Controlled evacuation

(driver) You must tell the signaller that the train is to be evacuated and ask the signaller to provide protection on all lines that may be affected. If necessary you must also ask for the electric traction current to be switched off.

When the signaller tells you all protection has been completed, you must tell the guard.

150 In module DC 'DC electrified lines', section 6.4 says:

Detraining passengers

(all concerned) If it is necessary to evacuate passengers from a train as shown in module M1 Dealing with a train accident or train evacuation, the electricity must be switched off as shown below.

a) Emergency evacuation

In an emergency the electricity should be switched off, as shown in section 6.1 of this module, on any line where passengers may walk.

b) Controlled evacuation

Before a controlled evacuation takes place, a temporary isolation must be taken on any line where passengers may walk.

151 Section 6 of module DC describes the process for an *emergency switch-off* (ESO). Any person may request an ESO if they become aware of, among other things, a fire on a train. The person requesting the ESO must first tell the ECO that they are making an emergency call, and then explain why the electricity needs to be switched off. The ECO decides, on the information given, what action to take. They will normally switch off the current in the area where the ESO is required, and also in the abutting electrical sections, to avoid the possibility that a train might bridge the two sections and inadvertently re-energise the third rail. The ECO remains responsible for the ESO unless or until it is no longer required, or is converted to a *temporary isolation*.

152 A temporary isolation is described in section 8.2 of module DC:

(all concerned) These isolations must be granted as shown in Network Rail instructions and only to a person who has been trained in those instructions.

- 153 The instructions referred to in this module are in Network Rail's document NR/WI/ELP/3091 'DC electrified lines working instructions' (issue E2, 2006), as revised by Letter of Instruction NR/BS/LI/090 (2008). Instruction 44 covers Temporary Isolations (TI). The purpose of a TI is '*to carry out work in order to contain an incident and/or make the railway safe for normal operation. Temporary isolations shall only be taken by persons competent to do so.*'
- 154 The process for taking a TI involves appointing a Person In Charge of the TI (PICTI), who must be trained and certified in accordance with Network Rail standards, obtaining the agreement of Operations Control, switching off the section of conductor rail concerned, testing it with an approved device to confirm that it is switched off, and applying short circuiting bars to prevent re-energisation. The PICTI must arrange for all personnel to be briefed on the safe working limits of the TI before any work begins.
- 155 The railway industry's investigation into the Windsor accident identified that during and after the accident, the ESO requested by the driver of train 2U64, and initiated at around 20:10 hrs, remained in place until 23:18 hrs, when the current was recharged. No temporary isolation was requested or taken.
- 156 The passengers remaining on train 2U64 were in the dark and without heating. It was important that they were evacuated from the train as soon as possible. The railway industry investigation concluded that the arrangements involved in taking a TI offer little additional protection over an ESO, and could have resulted in a significant delay while a suitably qualified person was located and brought to the site.
- 157 The RAIB has concluded that, to keep control and encourage safe behaviour during an incident, prompt and decisive action is necessary. Experience (including this incident) shows that if railway staff do not take such action, passengers may try and leave the train without authority, putting themselves at risk. The present rules provide insufficient guidance on steps to be taken in circumstances where there is no immediate danger, but early evacuation is required in order to manage the situation effectively.

Previous occurrences of a similar character

- 158 The RAIB has investigated two previous accidents in which electrical faults led to fires under rail vehicles. These both occurred on the Tyne and Wear Metro system, at South Gosforth on 8 January 2013 ([report 18/2013](#)) and at Walkergate on 1 August 2014 ([report 09/2015](#)). Both accidents involved faults (probably arising from insulation breakdown over time) in the circuit breakers which protect the traction systems on the trains used on that network. These faults caused arcing under the coaches which persisted for some time and produced a great deal of smoke, but did not penetrate the floor. No-one was hurt in either accident, although in both cases the overhead line (which supplies power at 1500 volts DC) parted and put people on the ground at risk for a short period.

159 In both cases the period of arcing could have been greatly reduced if the electrical protection arrangements associated with the power supply system had acted to cut off the power. For various reasons, explored in the investigation reports, this did not happen. The RAIB made several recommendations following these investigations, but none of them are directly relevant to the circumstances at Windsor, where the electrical characteristics of the third rail are significantly different from the overhead line system (paragraph 92).

Summary of conclusions

Immediate cause

160 Loosening of the bolted joint between the shoe cables and the bus line led to arcing, which generated heat which burned through the floor of the vehicle (paragraph 57).

Causal factors

161 The causal factors were:

- a. The cable joint was loose, and came apart while the train was in service (paragraph 61). This happened because:
 - i. the joint was almost certainly not tightened when the bogie was refitted to the vehicle during the conversion project (paragraph 73, see paragraph 164, **Recommendation 1**).
 - ii. the quality control procedures operated by Wabtec in the works at Doncaster did not provide any assurance that the joint had been tightened (paragraph 76, **Recommendation 1**).
- b. The electrical protection arrangements on the train and the infrastructure did not prevent the arcing (paragraph 89).
- c. The floor of the train was unable to withstand the temperatures generated by the arcing (paragraph 101).
- d. The design of the junction box did not allow for the consequences of internal pressure build-up (paragraph 110, **Recommendation 2, Learning point 1**).

Factors affecting the severity of consequences

162 Factors that exacerbated the consequences of the event were:

- a. The lighting in the damaged unit ceased to operate fifteen minutes after the start of the incident, leading to passengers leaving the train unescorted and getting on to a potentially live railway (paragraph 114, **Learning point 2, Recommendation 3**).
- b. The train crew did not call for assistance, and the emergency services were not mobilised until about 25 minutes after the accident (paragraph 124, see paragraph 167).

Additional observations

163 Although not linked to the accident on 30 January 2015, the RAIB observes that:

- a. The arrangements for the management of the work instructions and technical data in the class 458 conversion project were not adequate (paragraph 131, **Learning points 3 and 4**).

- b. A jammed internal door prevented access through the train (paragraph 141, **Learning point 4**).
- c. The rules relating to evacuation of passengers from trains on third rail electrified lines are difficult to apply in an emergency situation (paragraph 147, **Recommendation 4**).

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

164 Immediately after the accident, SWT carried out a check of the tightness of the shoe cable joint on all the class 458/5 units that had been converted up to that time (paragraph 73 and Appendix D). The remaining class 458 units are being converted to class 458/5 at the Wabtec works in a programme which is expected to be completed in 2016, and each shoe cable joint is dismantled and reassembled as part of this process.

165 Wabtec has made changes to the quality assurance system it operates at Doncaster, to include an independent check of the tightness of the shoe cable joints on each class 458/5 unit, after they have been reassembled.

Actions reported that address factors which otherwise would have resulted in a RAIB recommendation

166 On 10 July 2015, Alstom issued a modification to the overhaul instructions for class 458/5 units, that new fasteners should be used each time the shoe cable joint is reassembled (paragraph 72). After the accident, Wabtec modified its factory processes to include the use of new fasteners when the cable joints were reassembled during the class 458/5 conversion project.

167 SWT reports that it is using the accident at Windsor as a case study in the training and competence management of drivers and guards. It has prepared a presentation based on combining the audio recording of the telephone call between the guard and the WICC with the CCTV from the train, to create a graphic record of the event. This is being used in basic training and in briefing days for all SWT train crew and relevant management teams and WICC staff. SWT also reports that it is preparing additional communications training for drivers and guards, with the intention of emphasising the use of correct communications protocols (paragraph 162b).

Learning points

168 The RAIB has identified the following key learning points⁹:

- 1 Designers of electrical junction boxes need to consider the possible failure modes of the joints that the boxes contain, and make appropriate provision for pressure relief by means of ventilation, frangible joints or other means that will both reduce the potential for explosive failure, and direct any expelled arc away from the vehicle structure. This is particularly important if the box is part of an arc protection strategy for electrically unprotected areas, as defined in paragraph 5.9 of BS 6853:1999 (paragraph 161d).
- 2 This event reinforces the need for train operating companies to provide adequate instruction, information and training to train crew so that they understand the possible ways in which on-train systems, including emergency lighting, can behave when power is cut off, and what can be done to reset systems that have been disabled unintentionally (paragraph 162a).
- 3 It is important that manufacturers, owners, operators, and entities in charge of maintenance co-operate to keep accurate drawings/records of train configuration (paragraph 163a).
- 4 Projects involving the conversion and/or refurbishment of existing trains need to be managed effectively, so that the work to be done is properly planned, documented, checked and recorded, and that involved parties work co-operatively to identify and manage hazards and risks throughout the life of a project (paragraph 163a).

⁹ '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.

Recommendations

169 The following recommendations are made¹⁰:

- 1 *The intent of this recommendation is to improve the quality, and thus the safety, of rail vehicle and component conversion and overhaul work carried out at Wabtec, Doncaster.*

Wabtec Rail Ltd should review and improve its production quality assurance arrangements to include, but not necessarily be limited to, the development of statistical confidence levels for verification of work carried out, and the provision of work instructions issued to the shop floor that are complete and suitable for the task (paragraphs 161a.i, 161a.ii, 163b).

- 2 *The intent of this recommendation is to confirm that the risk associated with the design of the cable junction box on the class 458 unit has been reduced to a level that is as low as reasonably practicable.*

South West Trains, in conjunction with Alstom and Porterbrook, should review the electrical and mechanical protection for the shoe cables, the bus line and the joint between them on the class 458/5 units, establish whether there are any reasonably practicable changes that can be made to the design of the joint to address the risk arising from failure of any associated components or assemblies, and implement any necessary modifications (paragraph 161d).

Note: This recommendation may also apply to other operators, owners and manufacturers of electric trains.

continued

¹⁰ Those identified in the recommendations have a general and ongoing obligation to comply with health and safety legislation, and need to take these recommendations 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, these recommendations are 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.

- 3 *The intent of this recommendation is to minimise the risk associated with the possible loss of emergency lighting in a train with people on board.*
South West Trains should review the need for the function that automatically shuts down the class 458/5 train after 15 minutes if traction supply is lost and no cab is in service, and 90 minutes after traction power is lost with a cab in service, and assess the risk represented by the operation of this function in circumstances where passengers or other people (such as the emergency services) may still be on the train. It should implement any actions identified by this review (paragraph 162a).
- 4 *The intent of this recommendation is to clarify the rules on the type of switch-off or isolation that is required for passenger evacuation from trains on third rail lines, to reduce delays and potential for uncontrolled egress by passengers.*
Network Rail, in consultation with those Train Operating Companies which operate passenger trains on the DC electrified networks, should assess the adequacy of the present rules relating to the evacuation of DC electric trains, and propose to RSSB any appropriate changes to module DC of the rule book to minimise the risk of uncontrolled evacuation after an incident has caused a stoppage of trains. Consideration should be given to whether there are circumstances under which it is better to permit a controlled evacuation of passengers under the protection of an emergency switch-off, rather than a temporary isolation (paragraph 163c).

Appendices

Appendix A - Glossary of abbreviations and acronyms

BTP	British Transport Police
CB-SHS	Circuit breaker – shoegear high speed
CCTV	Closed circuit television
DC	Direct current
ECO	Electrical control operator
EMU	Electric multiple unit
ESO	Emergency switch-off
FMI	Field modification instruction
HSCB	High speed circuit breaker
PICTI	Person in charge of temporary isolation
SWT	South West Trains
TI	Temporary isolation
TMS	Train management system
VBDP	Vehicle Business Documentation Pack
WICC	Wessex Integrated Control Centre

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.

Arcing	The flow of electricity through the air from one conductor to another. Arcing can produce visible flashes and flames.*
Bus line	An electrical interface which distributes electrical power to separate components of a system, typically within a train.*
Bus line earth leakage relay	Relay which monitors the bus line cable of a class 458 for insulation failure, and will operate to trip all the high speed circuit breakers in the train if an earth fault is detected.
Cable gland nut	A seal on the end of the snuffer tube (QV) which is intended to prevent entry of dirt and moisture.
Circuit breaker	An automatic switch designed to protect an electrical circuit from damage caused by overload or short circuit.*
Collector shoe	A device mounted on certain electric trains that runs along an exposed surface of a conductor rail and collects the electrical traction current.*
Earth fault	A fault condition in which electricity is incorrectly conducted to earth.*
Electric multiple unit	A train consisting of one or two or more vehicles semi-permanently coupled together, that can be marshalled with other similar trains to make a formation that has a Driving Cab at both ends, that can be driven and controlled as a single unit and whose motive power is electricity supplied externally.*
Electrical control operator	The person having control over supply to, switching of and isolation of an electrification system in a geographical area.*
Emergency switch-off	A procedure carried out by the electrical control operator when it is essential to switch off the electrical supply immediately.*
Overcurrent	A current which is higher than the continuous rating of an electrical circuit.*
Points	An assembly of switches and crossings designed to divert trains from one line to another.*
Secondary suspension	The part of a suspension system that is not connected to the axles, and may be used to control ride quality and height.
Snuffer tube	Tube made of fire-resisting material which fits over a power cable, and is intended to extinguish any fire which develops in the cable by depriving the fire of oxygen when it enters the tube.

Sub-station	A building or compound containing electrical equipment such as rectifiers, switchgear and transformers used for the provision of traction supply current to a conductor rail system, including reduction and rectification of a high voltage supply from a regional electricity company.*
Temporary isolation	A procedure carried out to isolate the electricity supply to an area of track, involving action by the electrical control operator and a competent person on site.
Third rail	An additional rail, used to convey and enable collection of electrical traction current at track level.*
Train management system	An on-train computer system which monitors and records fault and other event conditions associated with the train's electrical and electronic systems.*

Appendix C - Investigation details

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

- Information provided by witnesses;
- Information taken from the train's on-train data recorder (OTDR);
- Closed circuit television (CCTV) recordings taken from the train and Windsor station;
- Weather reports and observations at the site;
- Records and calculations provided by the train manufacturer (Alstom);
- An expert report by Bolt Science Ltd commissioned by the RAIB on the design of the shoe cable joint; and
- A review of previous RAIB investigations that had relevance to this accident.

Appendix D - Fleet check of class 458/5 cable joints

Unit No.	Coach No.	Visual Check	Torque Check	Check Date	Notes
458502	67602	OK	Fail	06/02/2015	Tightened to 178Nm
	74102	OK	Fail		Tightened to 178Nm
	67702	OK	Fail		Tightened to 178Nm
458503	67603	OK	Pass	04/02/2015	
	74103	OK	Fail		
	67703	OK	Fail		
458504	67604	OK	Fail	22/02/2015	Bolt not even finger tight
	74104	OK	Fail		
	67704	OK	Fail		
458505	67605	Not Ok	Fail	10/02/2015	2 flat washers fitted, No spring washer
	74105	Not Ok	Fail		No witness mark
	67705	OK	Pass		
458520	67720	OK	Pass	02/02/2015	
	74120	OK	Pass		
	67620	OK	Pass		
458530	67730	OK	Fail	05/02/2015	Tightened to 173Nm
	74130	OK	Fail		Tightened to 173Nm
	67630	OK	Fail		Tightened to 173Nm
458531	67913	OK	Pass	04/02/2015	
	74458	OK	Pass		
	67912	OK	Pass		
458532	67904	OK	Pass	04/01/2015	
	74457	OK	Pass		
	67905	OK	Pass		
458533	67916	OK	Fail	06/02/2015	Tightened to 178Nm
	74453	OK	Fail		Tightened to 178Nm
	67917	OK	Fail		Tightened to 178Nm
458534	67918	OK	Fail	05/02/2015	Screw torqued down to 173Nm
	74454	OK	Fail		Screw torqued down to 173Nm
	67914	OK	Fail		Screw torqued down to 173Nm
458535	67911	OK	Pass	05/02/2015	
	74455	OK	Fail		Tightened to 173Nm
	67915	OK	Pass		
458536	67906	OK	Pass	02/02/2015	
	74456	Not Ok	Fail		No spring or flat washer fitted. No torque mark, replaced and torqued.
	67902	OK	Pass		

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