failure electrical

11 King Philip Trail
Norfolk, Massachusetts
02056

t: 508.520.7006
f: 508.520.7009
www.failureelectrical.com

Date: 15 October 2018
To: Cathy Kennedy
Deputy Solicitor
Grenfell Tower Inquiry
From: J. Duncan Glover
Re: Damage Assessment: Fourteen Exhibits
Case: Grenfell Tower Fire

## 1. INTRODUCTION

Laboratory examinations were performed on fourteen Exhibits. The purposes of the examinations are to assess arc damage, if any, and in some cases to examine wire stranding.

### 1.1 Exhibits Examined

January 2018 Examinations

Laboratory examinations were first performed on the following five Exhibits:

(1) MJS/1: section of electrical conductor
taken from MJD/32 (wiring & miscellaneous);
(2) MJS/2: conductor removed from BPS/3 (fridge freezer wiring);
(3) MJS/6: extractor fan motor;
(4) SLW/110: section of wire
from BPS/4 (compressor unit for fridge freezer), and
(5) SLW/111: Section of stranded conductor, wire diameter 1.05 – 1.10 mm,
strand diameter 0.18 – 0.19 mm,
from BPS3 (conductors from fridge freezer base)

On 25 January 2018, Computed Tomography (CT) scans were performed at X-Tek Systems Ltd (Nikon Metrology UK Ltd), Icknield Industrial Estate, Tring. On 26 January 2018, optical microscopy, Scanning Electron Microscopy (SEM), and Energy Dispersive

X-Ray Spectroscopy (EDS) were performed at the National Physical Laboratory, Hampton Road, Teddington, London. I did not attend these laboratory examinations, as I had not yet been retained by the Grenfell Public Inquiry.

September 2018 Examinations

Further Laboratory examinations were performed on the following ten Exhibits:

(1) MJS/1: section of electrical conductor from MJD/32 (wiring & miscellaneous) Note: this is a repeat of the 25 & 26 January 2018 examinations of MJS/1;
(2) JDG/1: small section of wire taken from MJD/38 (medium sized freezer)
(3) JDG/2: wire section from BPS/3 (conductors from fridge freezer base)
(4) JDG/3: coil from MJD/52 (miscellaneous wiring)
(5) JDG/4: wire strand from MJS/6 (extractor fan motor)
(6) JDG/5: PTC component from BPS/4 (compressor unit for fridge freezer)
(7) JDG/6: wires from compressor relay compartment, BPS/4 (compressor unit for fridge freezer)
(8) JDG/7: wire strand from MCL-20 (debris from window area)
(9) RAM/211: piece of compressor mounting plate, split from BPS/4 (compressor unit for fridge freezer)
(10) SLW/118: section of three-core stranded flex, diameter 0.99 – 1.08 mm, strand diameter 0.20 – 0.21 mm, from MCL-06 (remains of mains supply flex associated with fridge freezer).

On 24 September 2018, optical microscopy, SEM and EDS were performed on Exhibits MJS/1, JDG/1, JDG/2, JDG/3, JDG/4, JDG/7, and RAM/211 at the National Physical Laboratory. On 25 September 2018, CT scans were performed on Exhibits MJS/1, JDG/1, JDG/5, JDG/6, and SLW/118 at X-Tek Systems Ltd (Nikon Metrology UK Ltd). I did attend these laboratory examinations.

I examined all fourteen Exhibits during my inspections at Bureau Veritas. I also examined photographs, X-Rays and other images derived from CT scans, and SEM analysis including EDS files for the Exhibits. Based on these examinations, I prepared this memo assessing arc damage to the fourteen Exhibits. As stated in the Conclusions of this memo, two of the Exhibits, MJS/1 and JDG/1, have confirmed arc damage. None of the other Exhibits has confirmed arc damage. Details are provided herein.

This memo is organized as follows. Section 2 provides a brief review of guidelines for interpreting damages to copper conductors, based on NFPA 921: *Guide for Fire and Explosion Investigations*, 2017 edition. Section 3 gives a damage assessment for each of the fourteen exhibits. A summary and conclusions are given in Sections 4 and 5. Appendices A1 – A14 contain figures including photographs, microscopic photographs, CT scans, SEM images and EDS spectra for the Exhibits. References are given in Appendix B.

# TABLE OF CONTENTS

## 2. INTERPRETING DAMAGES TO COPPER CONDUCTORS

This section provides a brief review of guidelines for interpreting damages to copper conductors, based on the 2017 edition of NFPA 921: *Guide for Fire and Explosion Investigations* [Ref.1]. Sections of NFPA 921 Chapter 9, entitled *Electricity and Fire,* are either excerpted or paraphrased herein. Specific sections of NFPA 921-2017 that are excerpted or paraphrased are referenced in square brackets []. Specifically, the following types of damage to copper conductors are discussed in this section: (1) arc damage of energized copper conductors; (2) melting caused by fire; and (3) alloying.

### 2.1 Arc Damage of Energized Copper Conductors

Abnormal electrical activity will usually produce characteristic damage that may be recognized after a fire. Evidence of this electrical activity may be useful in locating the area of fire origin. The damage may occur on conductors, contacts, terminals, conduits, or other components. However, many kinds of damage can occur from nonelectrical events. This section will give guidelines for deciding whether observed damage was caused by electrical energy and whether it was the cause of the fire or a result of the fire. These guidelines are not absolute, and many times the physical evidence will be ambiguous and will not allow a definite conclusion [NFPA 921 Section 9.10.1].

Short circuits and high-current ground faults, such as when an energized copper conductor touches the neutral conductor or a metal surface that is electrically grounded, can produce violent events. Because there may be very little resistance in the short circuit, the fault current may be many hundreds of amperes or greater. The energy dissipated at the point of contact may be sufficient to melt the metals involved, thereby creating a gap and a visible arc and throwing sparks. Protective devices (e.g. circuit breakers or fuses) in most cases will operate ("trip") in a fraction of a second and prevent repetition of the event [NFPA 921 Section 9.9.5.1].

An electrical arc is a high-temperature luminous electrical discharge across an air gap or through a medium such as charred insulation. Temperatures within the arc are in the range of several thousand degrees C, depending on the arc current, voltage drop and metal involved. In 240-volt ac systems, arcs do not form spontaneously under normal circumstances. In most cases, the arc is so brief and localized that solid fuels such as wood structural members cannot be ignited. Fuels with high surface-area-to-mass ratio, such as cotton batting, tissue paper, and combustible gases and vapors, may be ignited when in contact with the arc [NFPA 921 Section 9.9.4.1].

A parting arc is a brief electrical discharge that occurs as an energized electrical path is opened while current is flowing, such as by turning off a switch or pulling a plug. At 240 volts ac, a parting arc is not sustained and will quickly be quenched. Ordinary parting arcs in electrical systems are usually so brief and of low enough energy that only combustible gases, vapors, and dusts can be ignited [NFPA 921 Section 9.9.4.4].

Another kind of parting arc occurs when there is a bolted (metal to metal contact) short circuit between an energized conductor and neutral wire or a bolted ground fault between an energized conductor and a metal surface that is electrically grounded. The surge of current melts the metals at the point of contact and causes a brief parting arc as a gap develops between the metal pieces. The arc quenches immediately but can throw particles of molten metal (sparks) around [NFPA 921 Section 9.9.4.4.2].

Arcing between two copper conductors separated by solid electrical insulation can occur if the insulation becomes carbonized. Two primary means by which carbonization occurs is by flow of electrical current or by thermal means not involving electricity. If carbonization is due to flow of electrical current, the phenomenon is commonly called arc tracking. Non-electrical means of creating carbonization usually involve some type of heating, which can be due to heat-producing devices or due to fire itself [NFPA 921 Section 9.9.4.5].

Arc tracking may occur on surfaces of non-conductive materials if they become contaminated with salts, conductive dusts, or liquids. It is thought that small leakage currents through such contamination cause degradation of the base material leading to arc tracking and subsequent charring or ignition of combustible materials around the arc. Arc tracking can be a problem in 240-volt ac systems [NFPA 921 Section 9.9.4.5.1].

Electrical arcing produces very high temperatures and localized heating in the path of the arc, which typically melts copper conductors at locations where the arc makes contact with them. Because the arc itself is normally small in area and short in duration, the arc damage is localized, with a sharp line of demarcation between the melted and unmelted portions of the copper conductor. Due to the high temperature and rapid cooling of electrical arcing on conductors, polished cross sections of arc beads on stranded and solid copper conductors may show high internal porosity. Arcing may produce molten particles that are sprayed from the arc location and that may collect on nearby areas of the conductor or on adjacent surfaces. Magnification and some minor cleaning using a dry brush or an ultrasonic bath may be necessary to detect fine features including the demarcation between the melted and unmelted regions of a conductor. The following traits are commonly exhibited for arc damaged conductors [NFPA 921 Section 9.11.1.1]:

(1) Sharp demarcation between damaged and undamaged area of the energized copper conductor
(2) Round, smooth shape of artifact
(3) Localized point of contact
(4) Identifiable corresponding area of damage on the opposing (neutral) conductor or opposing grounded metal surface
(5) Locally enlarged grain size
(6) Resolidification waves
(7) Copper drawing lines visible outside the damaged area
(8) Small beads and divots over a limited area

(9) High internal porosity when viewed in cross-section

Figures 1 through 7 excerpted from NFPA 921-2017 show the results of arc damage to copper conductors as follows: (a) notches in the sides of the conductors (Figures 1 and 2); or (b) rounded or irregular shaped beading on the end of a severed conductor (Figures 3 - 7) [NFPA 921 Section 9.11.1.2].

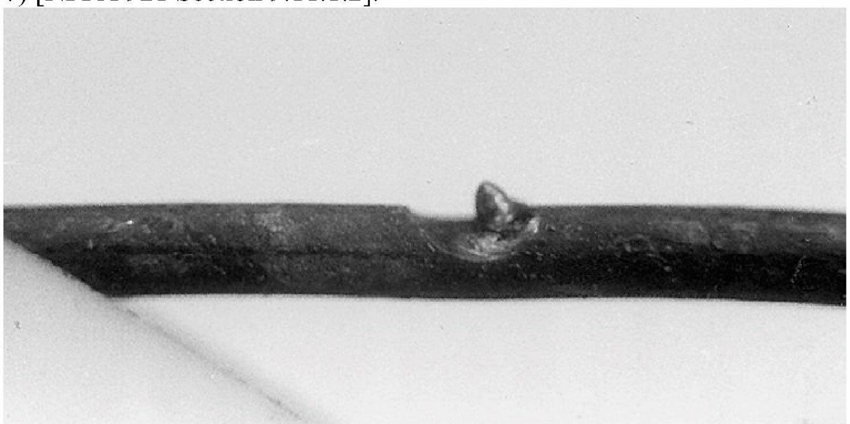

**Figure 1**. A solid copper conductor notched by a short circuit [NFPA 921 Figure 9.10.2]

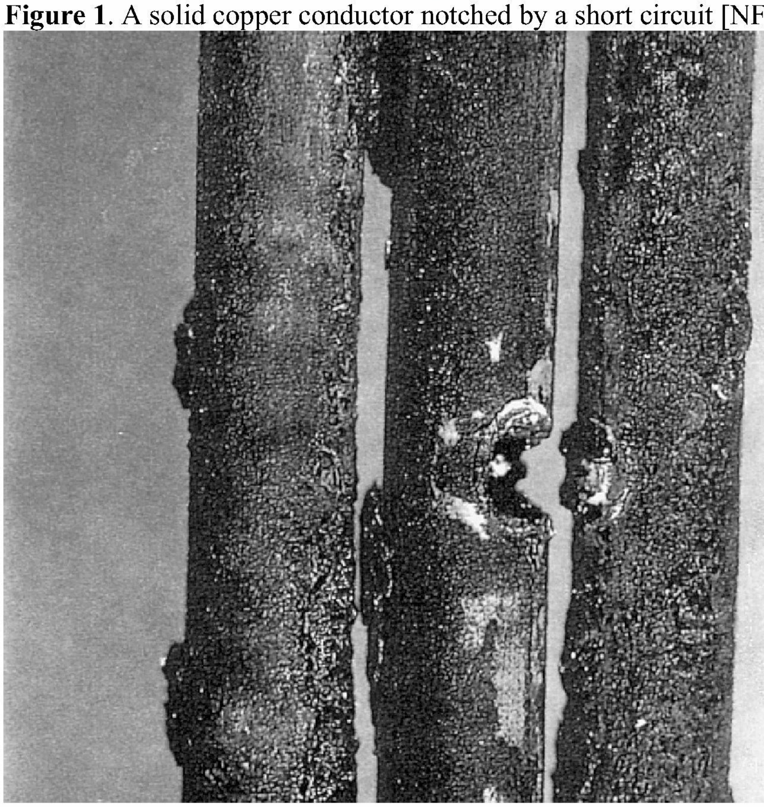

**Figure 2.** Spot arc damage to 14 AWG (American Wire Gauge) conductor caused by arcing through a charred insulator during a laboratory test [NFPA 921Figure 9.10.3.2(b)].

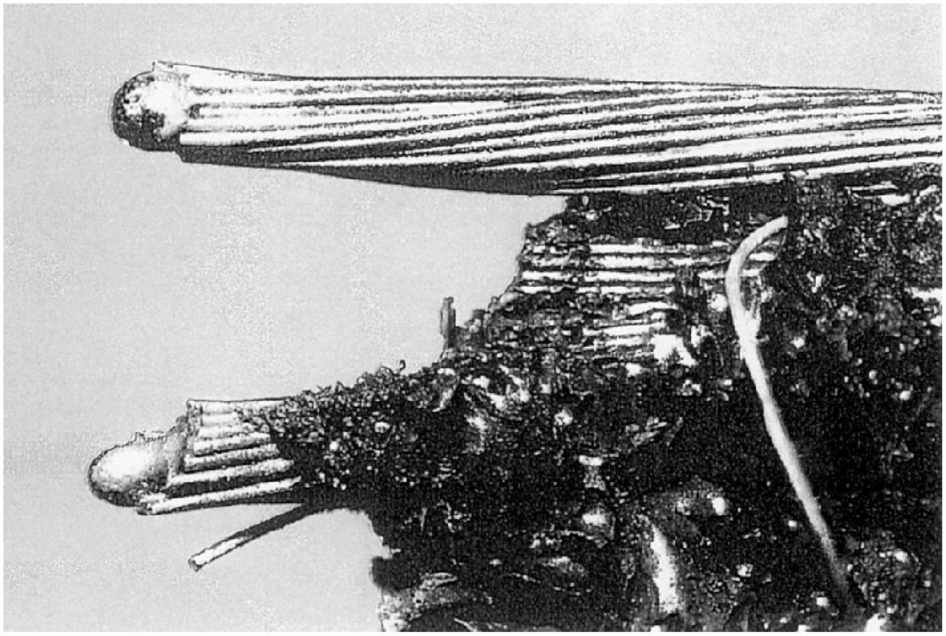

**Figure 3**. Copper conductors severed by arcing through charred insulation [NFPA 921 Figure 9.10.3.1(a)]

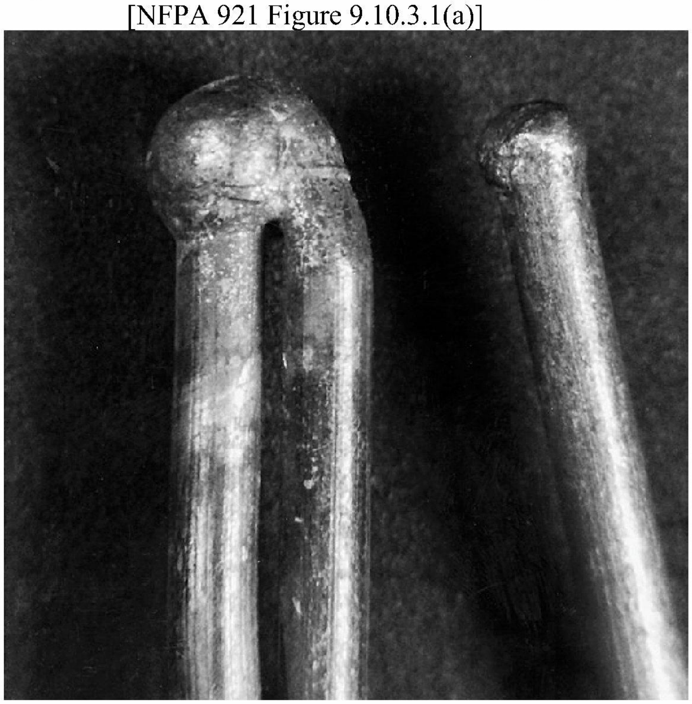

**Figure 4**. Copper conductors severed by arcing through charred insulation with a large bead welding two conductors together [NFPA 921 Figure 9.10.3.1(b)]

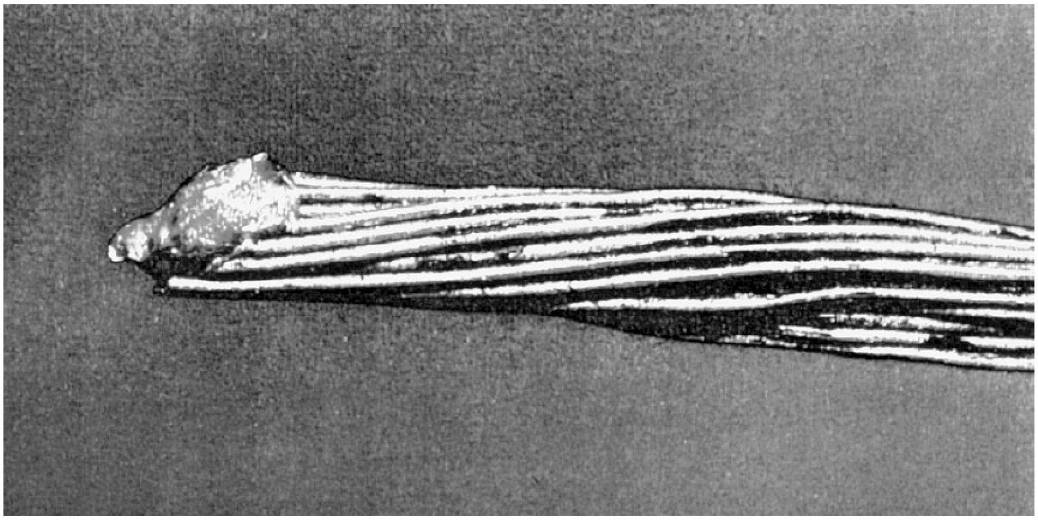

**Figure 5**. Arc damage to 18 AWG (American Wie Gauge) cord caused by arcing through charred insulation [NFPA 921 Figure 9.10.3.2(a)]

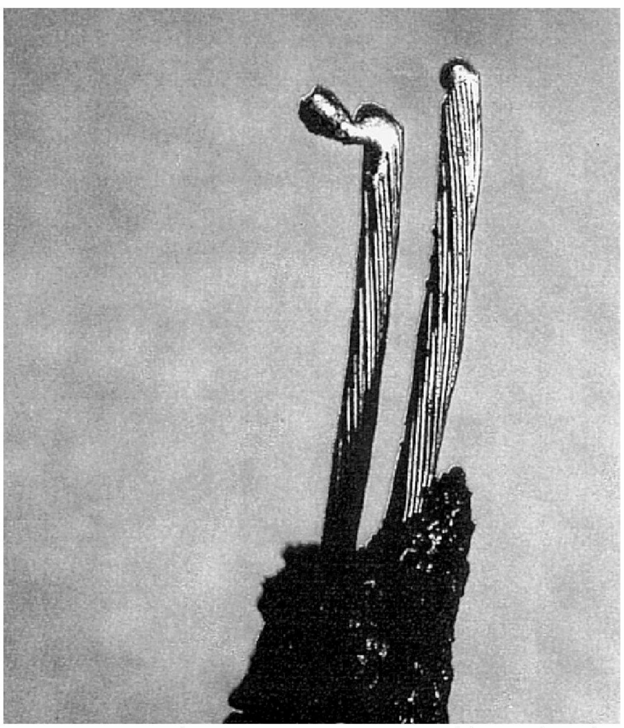

**Figure 6**. Arc damage to 18 AWG cord by arcing through charred insulation during laboratory test [NFPA 921 Figure 9.10.3.2(c)]

**Figure 7**. Stranded copper lamp cord severed by a short circuit [NFPA 921 Figure 9.10.2.2]

## 2.2 Melting of Copper Conductors Caused by Fire

Copper conductors may be damaged before or during a fire by other than electrical means and often these effects are distinguishable from arc damage [NFPA 921 Section 9.10.6].

When exposed to fire or glowing embers, copper conductors may melt (the melting temperature of pure copper is 1085ºC/1984ºF). At first, there is a blistering and distortion of the surface, as shown in Figure 8 [NFPA 921 Section 9.10.6.2].

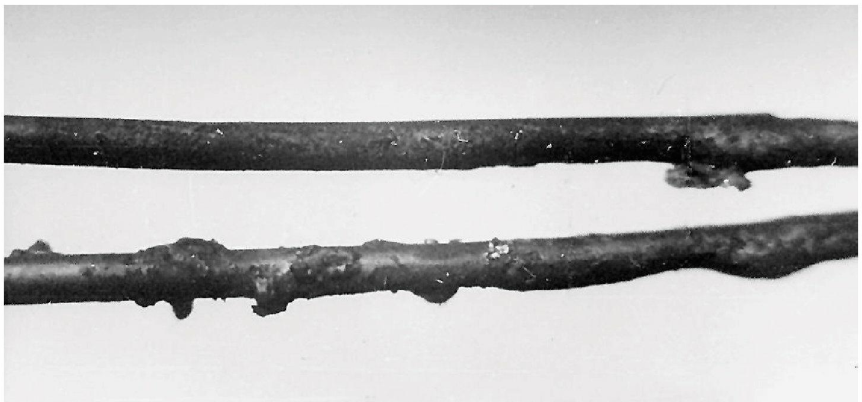

**Figure 8**. Copper conductors fire-heated to the melting temperature, showing regions of copper flow, blistering and surface distortion [NFPA 921 Figure 9.10.6.2(a)]

The next stage is some flow of copper on the surface with some hanging drops forming. Further melting may allow flow within thin areas (i.e. necking and drops), as shown in Figure 9. In that circumstance, the surface of the conductor tends to become smooth. The re-solidified copper forms globules. Globules caused by exposure to fire are irregular in shape and size. They are often tapered and may be pointed. There is no distinct demarcation between melted and unmelted surfaces [NFPA 921 Section 9.10.6.2].

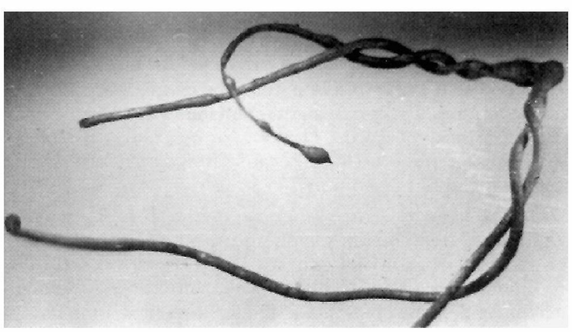

**Figure 9**. Fire-heated copper conductors showing globules [NFPA 921 Figure 9.10.6.2(b)].

Stranded copper conductors that just reach the melting temperatures become stiffened. Further heating can let copper flow among the strands so that the conductor becomes solid with an irregular surface that can show where the individual strands were, as shown in Figure 10 [NFPA 921 Section 9.10.6.2.1].

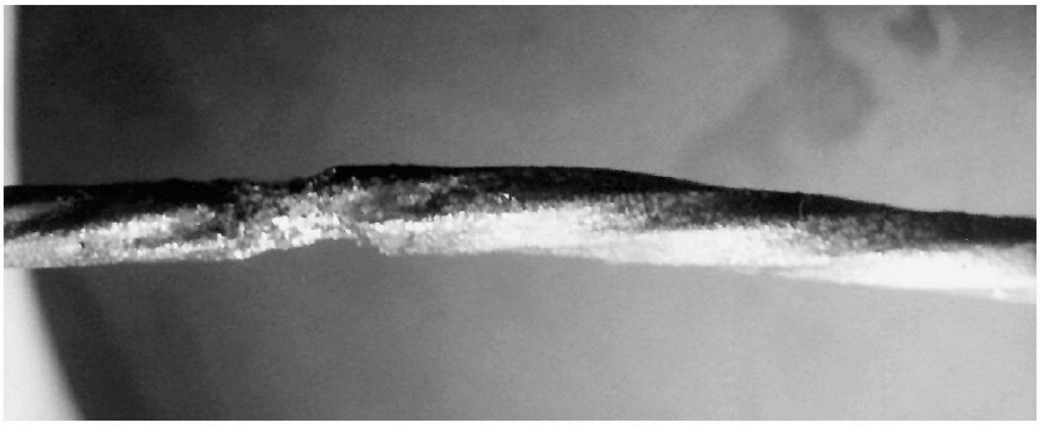

**Figure 10**. Stranded copper conductors in which melting by fire caused the strands to become fused together [NFPA 921 Figure 9.10.6.2.1(a)].

Continued heating of stranded copper conductors can cause the flowing, thinning, and globule formation typical of solid copper conductors. Large-gauge stranded copper conductors that melt in fires can have the strands fused together by flowing metal or the strands may be thinned and stay separated. In some cases, individual strands may display a bead-like globule even though the damage to the conductor was from fire melting. Figures 11 and 12 show examples [NFPA 921Section 9.10.6.2.1].

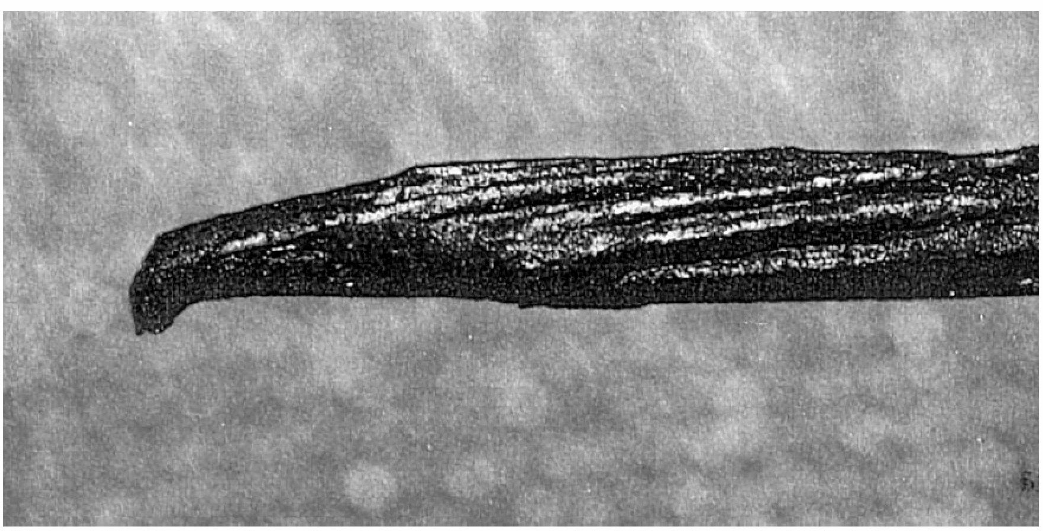

**Figure 11**. Fire melting of stranded copper wire [NFPA 921Figure 9.10.6.2.1(b)]

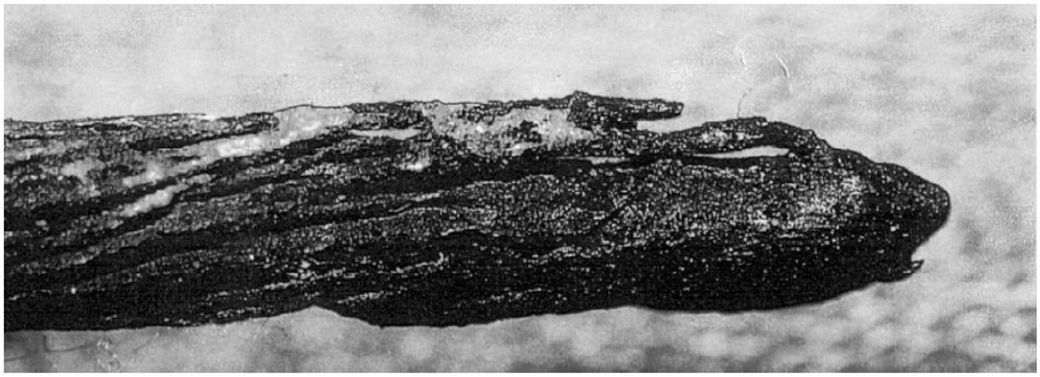

**Figure 12**. Another example of fire melting of a stranded copper wire. [NFPA 921Figure 9.10.6.2.1(c)]

In contrast to damage caused by an arc, when copper conductors are melted by fire, the damage is spread over a larger area without a distinct line of demarcation between the melted and unmelted regions. Conductors melted by fire may exhibit irregular or rounded globules, or smooth or rough tapered ends. The following are commonly exhibited for fire-melted conductors [NFPA 921 Section 9.11.2]:

(1) Visible effects of gravity on the artifact
(2) Extended area of damage without a sharp line of demarcation from undamaged copper
(3) Gradual necking of the conductor – assuming this is not due to a mechanical break
(4) Low internal porosity viewed in cross-section.

## 2.3 Alloying Damage

Metals such as aluminum and zinc can form alloys when melted in the presence of other metals. If melted aluminum drips onto a bare copper conductor during a fire and cools, the aluminum will be just lightly stuck to the copper. If that spot is further heated by fire, the aluminum can penetrate the oxide interface and form an alloy with the copper that melts at a lower temperature than does either pure metal. After the fire, an aluminum alloy spot may appear as a rough gray area on the surface, or it may be a shiny silvery area. The copper-aluminum alloy is brittle, and the conductor may readily break if it is bent at the spot of alloying. If the melted alloy drips off the conductor during the fire, there will be a pit that is lined with alloy. The presence of alloys can be confirmed by chemical analysis [NFPA 921 Section 9.10.6.3].

Copper conductors, terminated in connections, or terminals containing solder may have areas of alloying, globules, rounded ends, or pitting after a fire. These effects are caused by the interaction between the copper and solder [NFPA 921 Section 9.10.6.3.3].

Alloying (also denoted "Eutectic Melting") involves damage that occurs when a metal of different composition contacts the subject metal (in this case, copper). The original melting may or may not be electrically related, but the damage to the subject metal (copper) caused by deposition of the second metal does not involve an electrical current and is not a form of electrical damage. Alloying is very easily identifiable by use of a scanning electron microscope (SEM) and Energy Dispersive X-Ray Spectroscopy (EDS) techniques which permit elemental analysis, but it can often be identified in the field. The damaged area (of copper) will be directly below an object (e.g. aluminum, zinc, tin, lead) that melted and dripped, and the damaged area may show a distinctly different metallic color. The investigator is cautioned to fully examine the eutectically melted area and the cause for the two metals to have come in contact. Alloying is not removed by ultrasonic cleaning [NFPA 921 Section 9.11.3].

Table I lists the melting temperature of a few metals. During a fire aluminum, tin or zinc may act as a melting-point depressant of copper, since each of these metals has a melting temperature much lower than that of copper. That is, when melted aluminum, tin, zinc, or a combination of these metals drips onto copper, a copper alloy may be formed that melts at a lower temperature.

**Table I. Melting Temperature of Metals**

| **Metal** | **Symbol** | **Melting Temperature** | |
|---|---|---|---|
| | | **° C** | **° F** |
| Aluminum | Al | 660 | 1220 |
| Copper | Cu | 1085 | 1984 |
| Tin | Sn | 232 | 449 |
| Zinc | Zn | 420 | 787 |

Figure 13 shows an aluminum-copper phase diagram. The amount of copper that is present in an aluminum-copper alloy is plotted on the x-axis. The minimum temperature to which an aluminum-copper alloy must be heated to put the alloy in a liquid solution is shown on the y-axis. For example, 100% copper by weight forms a liquid solution (i.e. melts) at 1085ºC (the melting temperature of copper), which is shown on the far right of the phase diagram. Also, 0% copper by weight (i.e. 100% aluminum) forms a liquid solution at 660ºC (the melting temperature of aluminum), which is shown on the far left of the phase diagram. Figure 13 also shows that aluminum-copper alloys with percent copper by weight between 10 and 60%, will melt below the melting temperature of aluminum.

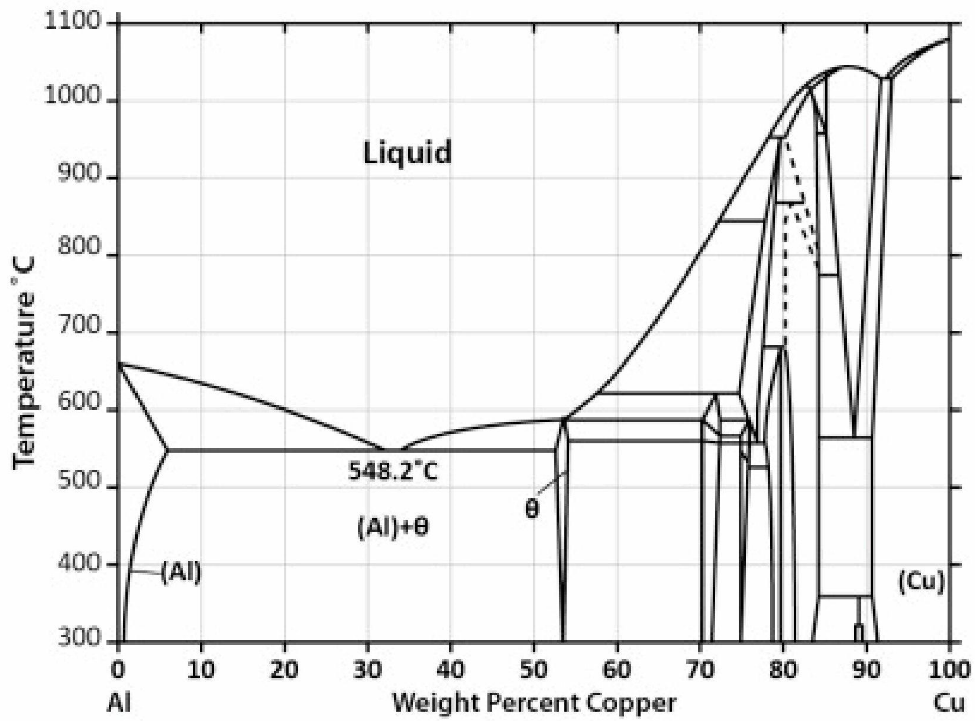


**Figure 13.** Aluminum-Copper Phase Diagram [https://www.imetllc.com/training-article/phase-diagram]

Figure 14 shows a copper-zinc (Cu-Zn) phase diagram. The Cu-Zn phase diagram shows that the melting point of a copper-zinc alloy (i.e. brass) with 40% Cu/60% Zn is about 835ºC/1535ºF, which is significantly lower than the melting point of Cu.

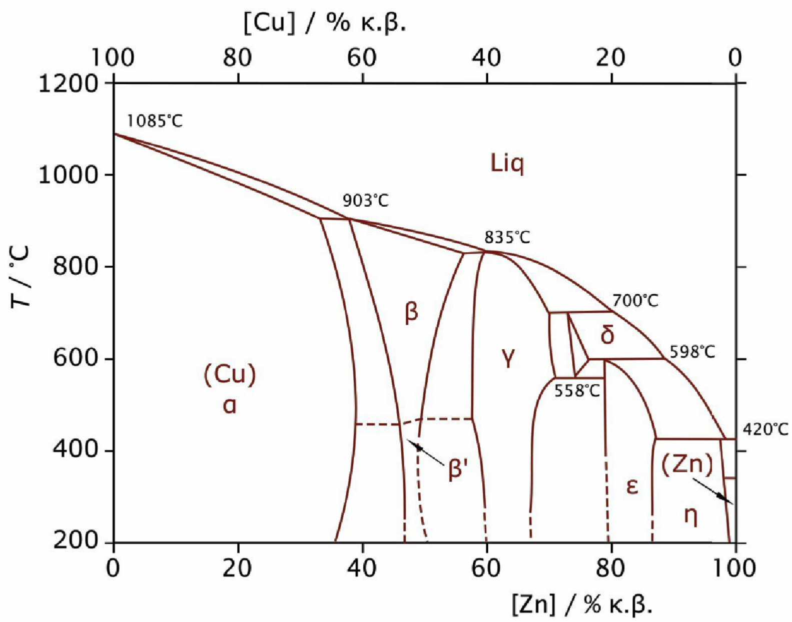


**Figure 14.** Copper-Zinc Phase Diagram [en.wikipedia.org/wiki/File:Cu-Zn-phase-diagram-greek.svg]

## 3. DAMAGE ASSESSMENT

This section gives a damage assessment for each of the fourteen exhibits. Photographs, CT scans, SEM images, X-Ray maps, and EDS spectra are given in Appendices A1-A14.

### 3.1 MJS/1: Section of Electrical Conductor Taken From MJD/32 (Wiring & Miscellaneous) from Flat 16 (also denoted Flat 6, 4th Floor) Appendix A1

Photographs: Figures A1-1 to A1-7

As shown in Figures A1-1 and A1-2 (Appendix A1), Exhibit MJS/1 consists of two stranded copper wire segments approximately 11 cm (110 mm) in length with a separate stranded copper wire segment approximately 5 cm (50 mm) in length. Approximately 15 mm from one end of the two wire segments, there is an apparent fused area approximately 3 mm in length (See Figure A1-3). As shown, wire insulations are missing, having been consumed in the fire.

Figures A1-4 to A1-7 show close-up views of the fused area. Examinations of these figures show a sharp line of demarcation between the fused area and adjacent unmelted copper strands.

As shown in Figures A1-4 and A1-5, there are missing/melted strands of each wire segment, which is consistent with electrical arcing from one wire segment (“hot” wire) to the other (neutral or grounding wire). That is, there is an area of arc damage on one wire segment and an identifiable corresponding area of arc damage on the opposing wire segment.

Both the sharp line of demarcation and missing/melted strands of both wire segments are consistent with arc melting in the fused area.

CT Scans: Figures A1-8 to A1-12

Figures A1-8 shows an overall CT Scan of the two stranded wire segments, and Figure A1-9 shows a CT close-up of the fused area. Similar to the close-up photos of Figures A1-4 to A1-7, these CT scans show: (1) a sharp line of demarcation between the fused area and adjacent unmelted strands; and (2) missing/melted strands of both wire segments in the fused area.

Figure A1-10 shows a CT cross-section at a non-fused location of the two stranded copper wire segments. As shown, each wire segment has 24 strands. Using the caliper tool on the CT scan, I measured the strand diameter to be approximately 0.18 mm. Figure A1-11 shows a second CT cross-section at a non-fused location, which was taken on 25 September 2018. As shown, each wire segment has 24 strands. Using the CT caliper tool, Nikon personnel measured the strand diameter to be approximately 0.16 mm.

Figure A1-12 shows a CT cross-section showing melted strands between the two wire segments in the fused area.

<u>SEM Images, X-Ray Maps, and EDS Spectra: Figures A1-13 to A1-26</u>

Figure A1-13 shows a SEM image of Exhibit MJS/1 for a site in the fused area of the two wire segments. EDS analysis is performed between the white lines in this figure, which includes both the exhibit and an additional "fringe" area outside the exhibit. Figure A1-14 shows X-Ray maps of copper (Cu), oxygen (O), calcium (Ca), aluminum (Al), sulphur (S) and chlorine (Cl) for this site. The aluminum, which is shown as green color in the lower left of Figure A1-13, lies <u>outside</u> the exhibit in the fringe area. The aluminum appears to be from the surface of the mounting plate below the exhibit.

Figures A1-16 and A1-19 show SEM images of Exhibit MJS/1 for two other sites. The corresponding X-Ray maps, Figure A1-17 and A1-20, also show that the aluminum lies <u>outside</u> the exhibit. As such, the aluminum is from the mounting plate, <u>not</u> the exhibit.

Figures A1-15, A1-18 and A1-21 show the EDS spectra for the three sites. Percentages by weight of the various elements (Cu, O, C, Al, Ca, S, Cl, Zn, Si, and Ti) are shown in the upper right corner of these figures. Review of these spectra shows that in all cases removal of the aluminum (Al), carbon (C) and oxygen (O), would yield greater than 90% by weight copper(Cu). No other significant quantities of melting-point depressant metals are found. As such, alloying damage to Exhibit MJS/1 is ruled out.

On 24 September 2018 SEM images, X-Ray maps, and EDS spectra were taken with Exhibit MJS/1 mounted on a carbon sheet. Two sites in the fused area were examined. Prior to the work, Exhibit MJS/1 had been ultrasonically cleaned.

Figure A1-22 shows a SEM image of MJS/1 for one of the sites examined on 24 September 2018. EDS analysis is performed between the white lines in this figure, which includes both the exhibit and a fringe area of the carbon sheet. Figure A1-23 shows X-Ray maps of (in descending order) copper (Cu), carbon (C), oxygen (O), sulphur (S), chlorine (Cl), aluminum (Al), argon (Ar) and silicon (Si) for this site. Aluminum is present only at a few spot locations. Figure A1-24 shows the EDS spectrum for this site. As shown, the aluminum does not show up in the spectrum.

Figures A1-25 and A1-26 show the SEM image and X-Ray maps of MJS/1 for the second site that was examined on 24 September 2018. The SEM image includes both the exhibit and a fringe area on the carbon sheet. Again, the X-Ray maps show that aluminum is present only at a few spot locations. Figure A1-27 shows the EDS spectrum for site 2. As shown, aluminum does not show up in the spectrum.

The SEM images, X-ray maps and EDS spectra performed with MJS/1 mounted on a carbon sheet confirm that no significant quantities of melting-point depressant metals are found in MJS/1. As such, alloying damage to Exhibit MJS/1 is ruled out.

Summary: MJS/1

Exhibit MJS/1 consists of two stranded copper wire segments approximately 11 cm in length with a separate stranded copper wire segment approximately 5 cm in length. Approximately 15 mm from one end of the two wire segments, there is an apparent fused area approximately 3 mm in length.

Damage in the fused area of Exhibit MJS/1 is arc damage. Both the sharp line of demarcation and missing/melted strands of both wire segments are consistent with arcing from one wire segment ("hot" wire) to the other wire segment (neutral or grounding wire) in the fused area. That is, there is an area of arc damage on one wire segment and an identifiable corresponding area of arc damage on the opposing wire segment. No significant quantities of melting-point depressant metals are found in MJS/1. As such, alloying damage to Exhibit MJS/1 is ruled out.

In the non-fused area, each wire segment has 24 strands with an approximate strand diameter of 0.16 to 0.18mm.

### 3.2 MJS/2: Conductor Removed from BPS3 (Fridge-Freezer Wiring) Kitchen – Flat 16 Appendix A2

Photographs: Figures A2-1 to A2-7

As shown in Figures A2-1 to A2-3 (Appendix A2), Exhibit MJS/2 consists of a stranded copper wire segment approximately 2.5 cm (25 mm) in length with possible melting at one end. As shown, wire insulations are missing (except for some charred remains), having been consumed in the fire.

The end with possible melting, Figure A2-2, shows a diffused melting region that does not have a sharp line of demarcation between melted and unmelted strands.

As shown in Photographs A2-5 to A2-7, there are broken strands at other locations along the exhibit. Some of the broken strands have rounded ends but there is no indication that an arcing event occurred from these strands to another wire. That is, corresponding damage on an opposing wire segment has not been identified.

CT Scans: Figures A2-8 to A2-10

The CT scan at the end of MJS/2 with possible melting also shows a diffused melting region without a sharp line of demarcation between melted and unmelted strands.

SEM Images, X-Ray Maps, and EDS Spectra: Figures A2-11 to A1-26

There are SEM images, X-Ray maps, and EDS Spectra for MJS/2 at the unmelted end (denoted Site 9), at six locations along the wire segment (denoted Sites 8, 7, 6, 5, 4, and 3), and at the end that is possibly melted (denoted Top End).

Figures A2-11 and A2-12 show the SEM image and X-Ray maps for the unmelted end (Site 9). As shown the aluminum (red area in the top center of Figure A2-12) lies outside the exhibit in the fringe area. The aluminum appears to be from the surface of the mounting plate below the exhibit. There are no indications of melted copper for Site 9.

Similarly, the X-ray maps (not included in Appendix A2) for all other sites show that the aluminum lies outside the exhibit in the fringe area. There is no indication of aluminum anywhere on MJS/2.

For five (Sites 8, 7, 6, 5, 4) of the six locations along the exhibit, after removing the aluminum (Al) and oxygen (O) from the spectra, the remaining composition is greater than 85% copper (Cu). No other significant quantities of melting-point depressant metals are found. As such, alloying damage to Exhibit MJS/1 is ruled out at these sites. Also, the

SEM images show fire damage (blistering and surface distortion) with no indication of arc-melting for Sites 8, 7, 6, 5 & 4.

Figures A2-23 and A2-24 show the SEM image and EDS spectrum for Site 3. As shown in the EDS spectra, there are detectable amounts of melting point depressants Tin (13% Sn) and zinc (12% Zn) compared to the copper (45% Cu). It is likely that Site 3 is near the Top (possibly melted) End of exhibit MJS/2.

Figures A2-25 and A2-26 show the SEM image and EDS spectrum for the Top (possibly melted) End of MJS/2. The EDS spectrum shows less copper (27% Cu) than zinc (47% Zn). Removal of the aluminum (Al) and oxygen (O) from the EDS spectrum shows ≈ 40% Cu/60% Zn. As shown in Figure 14, the melting point of a copper-zinc alloy with 40% Cu/60% Zn is about 835ºC, which is significantly lower than the melting point of Cu. This a clear indication of alloying at the Top End of MJS/2.

Summary: MJS/2

Exhibit MJS/2 consists of a stranded copper wire segment approximately 2.5 cm (25 mm) in length with possible melting at one end. Wire insulations are missing (except for some charred remains), having been consumed in the fire.

The fusing of copper strands at one end of Exhibit MJS/2 was caused by fire attack aided by large amounts of zinc, which acted on the copper as a melting point depressant (alloying). This end of MJS/1 with possible melting shows a diffused melting region that does not have a sharp line of demarcation between melted and unmelted strands. There is no indication of arc damage at this end.

The rest of the wire segment was damaged by fire attack with no indication of arc damage. There are broken strands at locations along the exhibit, some of which have rounded ends; but there is no indication that an arcing event occurred from these strands to another wire. That is, corresponding damage on an opposing wire segment has not been identified.

**3.3 MJS/6: Extractor Fan Motor**
**from Exhibit MCL-20-076029-14062107:**
**Debris from Window Area**
**Kitchen – Flat 16**
**Appendix A3**

<u>Photographs: Figures A3-1 to A3-4</u>

Photographs A3-1 to A3-4 (Appendix A3) show Exhibit MJ/6, the remains of the extractor fan motor from Flat 16.

Figure A3-2 shows an exemplar extractor fan motor from Flat 13 alongside that from Flat 16. The exemplar motor is from a Cyfan-C extractor fan, serial No. 3089894 manufactured by Nuaire. The exemplar fan motor is a 24-volt DC brushless motor with copper motor windings. As shown, there is a printed circuit board associated with this motor.[1]

The photographs of Exhibit MJ/6 show fire damage with no indications of any arc damage or melting of copper motor windings.

<u>CT Scans: Figures A3-5 to A3-8</u>

Figures A3-5 to A3-8 show CT scans of Exhibit MJ/6. The CT scans do not show any arc damage or melting of copper motor windings. Also, there is no indication of arc damage or melted copper for the motor circuit board (Figure A3-8).

<u>SEM Images, X-Ray Maps, and EDS Spectra: Figures A3-9 to A3-13</u>

Figures A3-9 to A3-13 show SEM images, X-Ray maps (Site 22 only) and EDS Spectra for Exhibit MJ/6 at two sites: Site 22 and Site 23. The X-ray maps and EDS spectrum for Site 22 include copper (20% Cu – the motor windings) on an iron (10% Fe-the motor core) background. The SEM image for Site 22 does not show any melted copper. The SEM image and EDS spectrum for Site 23 include iron (48% Fe - the motor core), with very little copper (less than 2% Cu) at this site.

[1] Note: Both the exemplar (Flat 13) and subject (Flat 16) extractor fans have a separate control board. The control board for the subject extractor fan is a separate exhibit not included with Exhibit MJ/6.

Summary: MJS/6

Exhibit MJ/6 is the remains of the extractor fan motor from the kitchen of Flat 16. Exhibit MJ/6 exhibits fire damage only. There is no indication of arc damage or melting of copper motor windings. Also, there is no indication of arc damage or melted copper for the motor circuit board.

It is noted that the extractor fan control board, which is a separate exhibit not included with Exhibit MJ/6, is not evaluated in this memo.

### 3.4 SLW/110: Section of Wire Taken from Within BPS4 (Compressor Unit for Fridge Freezer) Kitchen – Flat 16 Appendix A4

Photographs: Figures A4-1 to A4-6

As shown in Figures A4-1 to A4-5 (Appendix A4), Exhibit SLW/110 consists of a stranded copper wire segment approximately 4 cm (40 mm) in length with remains of insulation and/or other debris. The copper strands are separated at both ends of the wire segment. The photographs show only mechanical deformation of the strands with no indication of melted copper or fused strands.

Exhibit SLW/110 was found by fire investigators to be affixed to the steel mounting plate for the compressor of Exhibit BPS4, the fridge-freezer in Flat 16 [see Figure A4-6, MET00012629.jpg and Paragraph 8.5 of the 07 November 2017 Bureau Veritas report – MET00007996_0018]. A plastic refrigerator wheel, which melted during the fire, had also been also at this location on the steel mounting plate.

CT Scans: Figures A4-7 to A4-9

Similar to the photographs, the CT scans of Exhibit SLW/110 show only mechanical deformation of the strands with no indication of melted copper or fused strands (See Figures A4-7 to A4-9).

SEM Images, X-Ray Maps, and EDS Spectra: Figures A4-10 to A4-16

There are SEM images, X-Ray maps, and EDS Spectra for SLW/110 at three sites: (1) Site 13 (one end); Site 14 (somewhere between ends); and Site 15 (the other end).

Figures A4-10 and A4-11 show the SEM image and X-Ray maps for Site 13 (one end). As shown the aluminum (red area in the top left of Figure A4-11) lies outside the exhibit in the fringe area. The aluminum appears to be from the surface of the mounting plate below the exhibit. There are no indications of melted copper for Site 13.

Similarly, the X-ray maps (not included in Appendix A4) for the other two sites show that the aluminum lies on the mounting plate below the exhibit. There is no indication of aluminum anywhere on SLW/110.

The EDS spectra for Sites 13, 14, and 15 show detectable amounts of zinc: 4% Zn in Figure A4-12, 3.5% Zn in Figure A4-14 and 8% Zn in Figure A4-16.

The composition data from EDS spectra for Sites 13, 14 and 15 were estimated and the Cu/Zn ratios were calculated with other elements removed as shown in Table II. The data shows up to 38% Zn, but the morphology of the conductors does not indicate melting of copper either electrically, by alloying, or from fire attack.

The presence of Zn on Cu wire surfaces without melting of copper is common in fire situations, since the wire is frequently near other metallic surfaces with Zn. Zinc vapors may condense on copper surfaces during a fire.

The SEM images for Sites 13, 14 and 15 show only mechanical deformation of the strands.

<u>Summary: SLW/110</u>

Exhibit SLW/110 consists of a stranded copper wire segment approximately 4 cm (40 mm) in length with remains of insulation and/or other debris. The copper strands are separated at both ends of the wire segment.

Exhibit SLW/110 was found by fire investigators to be affixed to the steel mounting plate for the compressor of Exhibit BPS4, the fridge-freezer in Flat 16.

Exhibit SLW/110 shows signs of mechanical deformation only. There is no indication of arc damage or melted copper. EDS spectra with aluminum, carbon, and oxygen removed show up to 38% zinc (Zn), but the morphology of the conductors does not indicate melting of copper either electrically, by alloying or from fire attack.

**Table II : EDS Analysis of Exhibit SLW/110**

| SLW_110 | | original report values | Al removed | Al/C/O removed | Cu/Zn only |
|---|---|---|---|---|---|
| | | % | % | % | % |
| Site 13 | C | 35 | 40.2 | 0.0 | |
| | Cu | 24 | 27.6 | 64.9 | 85.7 |
| | O | 15 | 17.2 | 0.0 | |
| | Al | 13 | 0.0 | 0.0 | |
| | **Zn** | 4 | 4.6 | 10.8 | **14.3** |
| | Ca | 3 | 3.4 | 8.1 | |
| | Mg | 1 | 1.1 | 2.7 | |
| | Si | 1 | 1.1 | 2.7 | |
| | Na | 1 | 1.1 | 2.7 | |
| | Cl | 1 | 1.1 | 2.7 | |
| | Si | 1 | 1.1 | 2.7 | |
| | Ti | 1 | 1.1 | 2.7 | |
| | | 100.0 | 100.0 | 100.0 | 100.0 |
| Site 14 | Cu | 43 | | | 92.5 |
| | C | 30 | | | |
| | O | 16 | | | |
| | Ca | 4 | | | |
| | **Zn** | 3.5 | | | **7.5** |
| | Al | 2 | | | |
| | Si | 0.5 | | | |
| | Mg | 0.5 | | | |
| | Ti | 0.5 | | | |
| | | 100.0 | | | 100.0 |
| Site 15 | C | 40 | | | |
| | O | 24 | | | |
| | Cu | 13 | | | 61.9 |
| | **Zn** | 8 | | | **38.1** |
| | Al | 5 | | | |
| | Ca | 5 | | | |
| | Na | 2 | | | |
| | Mg | 1 | | | |
| | Si | 1 | | | |
| | Ti | 1 | | | |
| | | 100.0 | | | 100.0 |

**3.5 SLW/111: Section of Stranded Conductor,**
**Wire Diameter 1.05 – 1.10 mm,**
**Strand Diameter 0.18 – 0.19 mm**
**From BPS3 (Conductors from Fridge-Freezer Base)**
**Kitchen – Flat 16**
**Appendix A5**

Photographs: Figures A5-1 to A5-3

As shown in Figures A5-1to A5-3 (Appendix A5), Exhibit SLW/111 consists of a stranded copper wire segment approximately 10 cm (100 mm) in length. Almost all wire insulation is missing, having been consumed during the fire. One end of the wire segment has a grey/silver appearance (Figure A5-2), which is most likely the result of solder remains.

CT Scans: Figures A5-4 to A5-7

Figures A5-4 to A5-6 show three CT scans of Exhibit SLW/111, including the grey/silver end with solder remains. There are no indications of arc damage or melted copper.

Figure A5-7 shows a cross section at one location along Exhibit SLW/111 with 24 strands. Since there are broken strands along the exhibit, some other locations have fewer than 24 strands. Using the CT caliper tool, I measured a strand diameter of approximately 0.18 mm.

SEM Images, X-Ray Maps, and EDS Spectra: Figures A5-8 to A5-14

There are SEM images, X-Ray maps, and EDS Spectra for SLW/111 at three sites: (1) Site 10 (the grey/silver end); Site 11 (near the grey/silver end); and (3) a site along the wire segment labeled “Length 004”.

Figures A5-8 and A5-9 show the SEM image and X-Ray maps for Site 10 (the grey/silver end). As shown the aluminum (red area in the top left of Figure A5-9) lies outside the exhibit in the fringe area. The aluminum appears to be from the surface of the mounting plate below the exhibit.

Similarly, the X-ray maps (not included in Appendix A5) for the other two sites show that the aluminum lies on the mounting plate below the exhibit. There is no indication of aluminum anywhere on SLW/111.

Figure A5-10 shows the EDS spectrum for Site 10, the grey/silver end. The spectrum includes tin (Sn) content. There is no lead (Pb) but this is likely due to the use of a Pb-free solder.[2] The spectrum also shows a small peak at 3 Kev which is the silver (Ag) Kα peak (this peak is not labeled in the figure). The silver (Ag) is likely from an Ag-bearing, non-Pb solder, which has a few percent Ag.

Figure A5-11 shows the SEM image for Site 11. There is possibly one strand end in this SEM image that shows a rounded end but there are no other indications of melted strands that would indicate a real thermal event. As shown in Figure A5-12, the EDS spectrum for site 11, like that of Site 10, includes small peak at 3 Kev, which is the silver (Ag) Kα peak.

Figure A5-13 shows the SEM image for the site labeled "Length 004". There are no indications of melted strands for this site. Figure A5-14 shows the EDS spectrum for this site. As shown for this site, there is no tin (Sn) content, and there is no peak at 3 Kev that would indicate silver (Ag) content.

<u>Summary: SLW/111</u>

Exhibit SLW/111 consists of a stranded copper wire segment approximately 10 cm (100 mm) in length. Almost all wire insulation is missing, having been consumed during the fire.

Exhibit SLW/111 shows solder remains at the grey/silver end of the wire segment. There is no indication of arc damage or melted copper for this wire segment.

CT scans show a strand count of 24 and an approximate strand diameter of 0.18 mm for this wire segment.

[2] On 1 July 2006, the European Union (EU) Waste Electrical and Electronic (WEESE) Directive and the Restriction of Hazardous Substances (RoHS) Directive came into effect, restricting the inclusion of lead (Pb) in most consumer electronics sold in the EU. Pb-free solders in commercial use may contain tin, copper, silver, bismuth, indium, zinc, antimony, and traces of other metals. Tin-Silver-Copper (Sn-Ag-Cu) solders are commonly used.

### 3.6 JDG/1: Small Section of Wire From MJD/38 (Medium Sized Freezer) Kitchen – Flat 16 Appendix A6

Photographs: Figures A6-1 to A6-5

As shown in Figures A6-1to A6-3 (Appendix A6), Exhibit JDG/1consists of copper wire segments approximately 4 cm (40 mm) in length with copper beads at one end. The remains of burnt insulation are affixed to the wire segments (Figures A6-1 and A6-2). In Figure A6-2 the copper beads have become separated from the wire segments.

Figures A6-3 and A6-4 show Exhibit JDG/1 after it had been ultrasonically cleaned. There appears to be at least five copper beads fused together in Figure A6-4. Figure A6-5 shows a microscopic photograph of the copper beads, taken at NPL. As also shown in Figure A6-4, the remains of one or two copper wire strands are affixed to the beads.

The number and volume of the copper beads indicate that a thermal event caused their melting. Also, the proximity of the copper wire segments to the beads as well as strands affixed to the beads indicate electrical arcing from one wire segment ("hot" wire) to another (neutral or grounding wire). That is, the beads and wire segments indicate arc damage on one wire segment and identifiable corresponding arc damage on an opposing wire segment.

CT Scans: Figures A6-6 & A6-7

Figures A6-6 and A6-7 show CT scans of wire segments from Exhibit JDG/1, which were taken at X-Tek (Nikon) - Tring on 25 September 2018. As shown, the strand count for each wire segment is 24. The approximate strand diameter, as measured by Nikon personnel, is approximately 0.16mm.

SEM Images, X-Ray Maps, and EDS Spectra: Figures A6-8 to A6-16

SEM images, X-Ray maps, and EDS spectra were taken for the copper beads of JDG/1 at NPL on 24 September 2018. As shown in Figures A6-8, A6-11, and A6-14, the SEM images were taken at three sites on the beads. In each case, the beads were mounted on a carbon sheet.

Figure A6-9 shows the X-Ray maps for Copper (Cu), Oxygen (O), Carbon (C), Calcium (Ca), Chlorine (Cl), Aluminum (Al), Titanium (Ti), Sulphur (S), and Silicon (Si) at site 1. As shown in the spectrum of Figure A6-10, site 1 on the beads consists of approximately 93% copper.

Similarly, for site 2 (Figure A6-13) and site 3 (Figure A6-16), the beads consist of more than 90% copper. No significant quantities of melting-point depressant metals are found at any of the three sites. As such, alloying damage to the copper beads for Exhibit JDG/1 is ruled out at these sites.

Summary: Exhibit JDG/1

Exhibit JDG/1consists of copper wire segments approximately 4 cm (40 mm) in length with copper beads at one end.

The copper beads of Exhibit JDG/1 are arc damage. The number and volume of the beads indicate that a thermal event caused their melting. Also, the proximity of the copper wire segments to the beads as well as strands affixed to the beads indicate electrical arcing from one wire segment ("hot" wire) to another (neutral or grounding wire). That is, the beads and wire segments indicate arc damage on one wire segment and identifiable corresponding arc damage on an opposing wire segment. Alloying damage is ruled out at three sites on the copper beads. The strand count for each wire segment is 24, and the approximate strand diameter, as measured by Nikon personnel, is 0.16mm.

**3.7 JDG/2: Wire Section**
**From BPS/3 (Conductors from Fridge Freezer Base)**
**Kitchen – Flat 16**
**Appendix A7**

Photographs: Figures A7-1 to A7-3

Figure A7-1 shows a photo of Exhibit JDG/2, a small copper wire segment taken from BPS/3 (Conductors from Fridge Freezer Base). This photo was taken after JDG/2 had been ultrasonically cleaned. As shown, all wire insulations are missing, having been consumed during the fire.

Microscopic images of a damaged end of JDG/2 are shown in Figure A7-2 for one side and in Figure A7-3 for the opposite side. There is no evidence of arc beads. Also, there is no indication that an arcing event occurred from this wire section to another wire. That is, corresponding damage on an opposing wire segment or opposing grounded metal surface has not been identified.

No CT Scans

CT scans of Exhibit JDG/2 were not taken.

SEM Image, X-Ray Maps and EDS Spectra: Figures A7-4 to A7-12

SEM and EDS analyses were performed at three sites for Exhibit JDG/2.

Figure A7-4 shows an SEM image Exhibit JDG/2 for site 1. EDS analysis was performed within the white border line in this figure. The exhibit was mounted on a carbon sheet.

Figure A7-5 shows the X-Ray maps of JDG/2 taken within the white border line for site 1. The X-Ray maps show (in order of descending amounts) tin (Sn), copper (Cu), oxygen (O), zinc (Zn), sodium (Na), carbon (C), silicon (Si), chlorine (Cl), aluminum (Al), and Sulphur (S).

Figure A7-6 shows the EDS spectrum of Exhibit JDG/2 for Site 1. As shown, there is almost as much tin (34% Sn) as copper (36%Cu). There is also carbon (10%C), oxygen (8%O), zinc (7%Zn), and sodium (3%Na) with trace amounts of aluminum, chlorine, silicon, sulphur and titanium. Damage to Exhibit JDG/2 at site 1 was caused by fire attack aided by large amounts of tin, which acted on the copper as a melting point depressant (alloying).

Similar results are shown for Sites 2 and 3. As shown in the EDS spectra of Figures A7-9 and A7-12, there is almost as much tin (Sn) as copper (Cu).

Summary: Exhibit JDG/2

Exhibit JDG/2 consists of a small copper wire segment taken from BPS/3 (Conductors from Fridge Freezer Base). Damage to Exhibit JDG/2 was caused by fire attack aided by large amounts of tin, which acted on the copper as a melting point depressant (alloying).

Exhibit JDG/2 shows no evidence of arc beads. Also, there is no indication that an arcing event occurred from this wire section to another wire. That is, corresponding damage on an opposing wire segment or grounded metal surface has not been identified.

**3.8 JDG/3: Coil**
**From MJD/52 (Miscellaneous Wiring)**
**Flat 16**
**Appendix A8**

The following is excerpted from Paragraphs 13.4 and 13.4.7 of the 07 November 2017 Bureau Veritas report [MET00007996_0035]:

> *"13.4 MJD/52: Described as miscellaneous wiring. Bag contained the following:*
> *13.4.7: A small toroidal copper coil. There was piece of beading obvious on one end. It was not possible to identify what component this came from but similar toroidal coils are sometimes found in dimmer switches. It was not possible to establish a connection between it and the cause of the fire."*

<u>Photographs: Figures A8-1 to A8-5</u>

Figure A8-1 is a photo of the toroidal core referenced above, which was taken by Bureau Veritas personnel on 9 August 2017. The "*piece of beading*" as discussed in paragraph 13.4.7 above is shown in this photo.

Figure A8-2 shows the coil from MJD/52 as I observed it on 21 September 2018. At that time, there was no "*piece of beading*" affixed to the coil. Upon further examination of MJD/52, the "*piece of beading*" could not be located.

Figure A8-3 shows a separate globule that was found in MJD/52. Although the size of this globule appears larger than the "*piece of beading*" shown in Figure A8-1, it was decided to analyze this globule at NPL.

Figure A8-4 shows the globule from MJD/52, which I cut in half at NPL using a razor blade. As such, it is verified that this globule is carbonaceous material, not a copper bead.

Figure A8-5 shows Exhibit JDG/3 after ultrasonic cleaning. There is no evidence of arc damage. It is noted that the ends of the coil wires in Figure A8-4 (and Figure A8-2) have a grey/silver appearance indicating solder.

<u>No CT Scans</u>

CT scans of Exhibit JDG/3 were not taken.

SEM Image, X-Ray Maps and EDS Spectra: Figures A8-6 to A8-8

Figure A8-6 shows an SEM image at the end of one of the coil wires with a grey/silver appearance. EDS analysis was performed within the white border line in this figure. The exhibit was mounted on a carbon sheet.

Figure A8-7 shows the X-Ray images. The X-Ray maps show (in order of descending amounts) tin (Sn), copper (Cu), oxygen (O), carbon (C), iron (Fe), silicon (Si), sulphur (S), aluminum (Al), chlorine (Cl), zinc(Zn) and sodium (Na).

Figure A8-8 shows the EDS spectrum. As shown, there is more tin (Sn) than copper (Cu) for the end of the coil wire that is examined. The spectrum also shows a small peak at 3 Kev which is the silver (Ag) Kα peak (this peak is labeled Sn, not Ag, in the figure). The silver (Ag) is likely from an Ag-bearing, non-Pb solder, which has a few percent Ag.

Summary: Exhibit JDG/3

Exhibit JDG/3 is a coil from MJD/52 (Miscellaneous Wiring).

At the time of my examination, 21 & 24 September 2018, a "*piece of beading*" that is identified in the 07 November 2017 Bureau Veritas report [MET00007996_0035] for this coil was not affixed to Exhibit JDG/3 and could not be located within MJD/52.

The remains of Exhibit JDG/3 that I examined do not have any arc damage.

The ends of the coil wires for Exhibit JDG/3 have a grey/silver appearance, which is consistent with solder.

**3.9 JDG/4: Wire Strand**
**From MJS/6 (Extractor fan Motor)**
**Flat 16**
**Appendix A9**

Photographs: Figures A9-1 to A9-4

During a 21 September 2018 inspection at Bureau Veritas, Exhibit JDG/2, a wire strand, was taken from MJS/6, the extractor fan motor. As shown in Photograph A9-1, a globule was observed on this wire strand. Using calipers, the strand diameter was measured at approximately 0.19 to 0.20 mm. It was verified that this wire strand is likely from one of the wires that connects from the fan control board to the fan motor, and is not a motor winding, whose diameter was measured at approximately 0.26 mm.

Figure A9-2 shows Exhibit JDG/4 after it had been ultrasonically cleaned. A section of the wire strand with the globule became separated from the rest of the wire strand. The black color suggests that the globule is carbonaceous material. It was decided to further examine JDG/4 at NPL.

Figure A9-3 shows a microscopic photo of JDG/4 in the area of the globule, taken at NPL. The majority of the globule appears carbonaceous.

During the inspection at NPL, Dan Matthews-Key Forensics carefully shaved the globule off the wire strand, using a micro-tool. Figure A9-4 is a microscopic photo of the end of the wire strand after the globule had been shaved off. As such, it was confirmed that the globule was carbonaceous and not a copper bead. As such, Exhibit JDG/4 is not arc damaged.

No CT Scans

CT scans of Exhibit JDG/4 were not taken.

SEM Image: Figure A9-5

Figure A9-5 shows an SEM image of Exhibit JDG/4 at a location along the wire strand away from the globule. As shown, the diameter of the wire strand at one location was measured at approximately 0.15mm (153.7µm).

X-Ray maps and EDS analysis were not performed for Exhibit JDG/4.

Summary: Exhibit JDG/4

Exhibit JDG/4 is a wire strand taken from MJS/6, the extractor fan motor. A globule is affixed to this wire strand.

The strand diameter was measured at approximately 0.19-0.20mm using calipers, and approximately 0.15mm using SEM. It was verified that this wire strand is likely from one of the wires that connects from the fan control board to the fan motor, and is not a motor winding, whose diameter was measured at approximately 0.26 mm.

It was confirmed that the globule is carbonaceous and not a copper bead. Exhibit JDG/4 is not arc damaged.

**3.10 JDG/5: PTC Component**
**From BPS/4 (Compressor Unit from Fridge Freezer)**
**Kitchen - Flat 16**
**Appendix A10**

Photographs: Figures A10-1 to A10-4

Figure A10-1 shows the components of the compressor relay compartment, including a PTC assembly and Klixon relay, before their removal from the compressor for the fridge freezer from Flat 16 [Photo 111, 07 November 2017 Bureau Veritas Report, MET00007748_0061]. Figure A10-2 shows PTC components from the relay compartment including compressor relay conductors, PTC resistor, and a wire terminal block (spade connectors) that I examined on 19 June 2018. On 20 September 2018, the wire terminal block was labelled Exhibit JDG/5, so as to examine the remains of wire segments within the terminals (Figure A10-4). No arc damage is observed.

CT Scans: Figures A10-5 & A10-6

On 25 September 2018, a CT scan of Exhibit JDG/5 was performed at X-Tek Systems Ltd (Nikon Metrology UK Ltd). Figure A10-5 shows a CT scan of a wire segment in one terminal connector from JDG/5. As shown, this wire segment has 21 strands with an approximate strand diameter of 0.17mm. Based on the number of strands, this wire segment is consistent with one of the wires from the power supply cord (mains flex supply) that connects to the relay compartment for the fridge freezer from Flat 16.

Figure A10-6 shows a CT scan of a wire segment in another terminal connector from JDG/5. As shown, this wire segment has 23 strands with an approximate strand diameter of 0.21mm. Based on the number of strands, this wire segment is consistent with one of the wires from an internal five-wire cord that connects to the compressor relay compartment within the fridge freezer from Flat 16.

No SEM, X-Ray maps, or EDS Spectra

Exhibit JDG/5 was not analyzed at NPL.

Summary: Exhibit JDG/5

Exhibit JDG/5 consists of a wire terminal block from the compressor relay compartment of the fridge freezer from Flat 16. No arc damage is observed.

Using a CT scan, two wire segments from Exhibit JDG/5 are identified; (1) one wire (with 21 strands) that is consistent with one of the wires from the power supply cord (mains flex supply) for the fridge freezer from Flat 16; and (2) a second wire (with 23 strands) that is consistent with one of the wires from an internal five-wire cord to the compressor relay compartment within the fridge freezer from Flat 16. Both the power supply cord and the internal five-wire cord connect to the compressor relay compartment.

**3.11 JDG/6: Wires from Compressor Relay Compartment**
**From BPS/4 (Compressor Unit from Fridge Freezer)**
**Kitchen - Flat 16**
**Appendix A11**

Photograph: Figure A11-1

Figure A11-1 shows Exhibit JDG/6, wire segments and wire connectors from the compressor relay compartment for the fridge freezer from Flat 16. Exhibit JDG/6 was selected to examine the remains of wire segments for this exhibit. No arc damage is observed.

CT Scans: Figures A11-2 & A11-9

On 25 September 2018, a CT scan of Exhibit JDG/6 was performed at X-Tek Systems Ltd (Nikon Metrology UK Ltd). Figures A11-2 to A11-9 show a CT scan of wires for this exhibit. The results of these figures for Exhibit JDG/6 as well as the two figures for Exhibit JDG/5 (Section 3.10) are summarized in the following Table III.

| **Table III. Summary of CT Scans: Exhibits JDG/5 & JDG/6** | | | | | |
|---|---|---|---|---|---|
| | **Exhibit** | **Wire Segment No.** | **No. Strands** | **Approximate Strand Diameter(mm)** | **Based on Strand Count Consistent With** |
| | JDG/5A | Wire 1 | 21 | 0.17 | Power Supply Cord |
| | JDG/5B | Wire 1 | 23 | 0.21 | Internal 5-Wire Cord |
| 1 | JDG/6A | Wire 1 | 24 | 0.17 | * |
| 2 | JDG/6B | Wire 1 | 23 | 0.17 | Internal 5-Wire Cord |
| 3 | | Wire 2 | 14 | 0.17 | Internal 5-Wire Cord |
| 4 | JDG/6C | Wire 1 | 24 | 0.16 | * |
| 5 | JDG/6D | Wire 1 | 23 | 0.16 | Internal 5-Wire Cord |
| 6 | | Wire 2 | 14 | 0.16 | Internal 5-Wire Cord |
| 7 | JDG/6E | Wire 1 | 21 | 0.18 | Power Supply Cord |
| 8 | JDG/6F | Wire 1 | 23 | 0.15 | Internal 5-Wire Cord |
| 9 | | Wire 2 | 23 | 0.16 | Internal 5-Wire Cord |
| 10 | | Wire 3 | 24 | 0.16 | * |
| 11 | JDG/6G | Wire 1 | 23 | 0.16 | Internal 5-Wire Cord |
| 12 | | Wire 2 | 21 | 0.15 | Power Supply Cord |
| 13 | JDG/6H | Wire 1 | 14 | 0.16 | Internal 5-Wire Cord |
| | * Either an internal jumper wire or a run capacitor wire. | | | | |

As noted in Section 3.10, the fridge freezer power supply cord (mains supply flex), which connects to the relay compartment, has three wires each of which has 21 strands. Also, the fridge freezer has an internal five-wire cord that connects to the relay compartment with: (1) three wires each of which has 23 strands; and (2) two wires each of which has 14 strands. Based on strand count, the wire segments in Table III are matched with wires for the power supply cord and internal five-wire cord from the fridge freezer. By process of elimination, each of the wire segments with 24 strands in Table III is ether an internal jumper wire within the compressor relay compartment or a run capacitor wire.

No SEM, X-Ray Maps, or EDS Spectra

Exhibit JDG/6 was not analyzed at NPL.

Summary: Exhibit JDG/6

Exhibit JDG/6 consists of wire segments and wire connectors from the compressor relay compartment of the fridge freezer from Flat 16. No arc damage is observed.

Using a CT scan, thirteen wire segments from Exhibit JDG/6 are identified; (1) two wires with 21 strands that are consistent with one of the wires from the fridge freezer power supply cord (mains flex supply); (2) five wires with 23 strands that are consistent with a wire from an internal five-wire cord to the compressor relay compartment; (3) three wires with 14 strands that are also consistent with a wire from an internal five-wire cord to the compressor relay compartment; and (4) three wires with 24 strands. Both the power supply cord and internal five-wire cord connect to the compressor relay compartment.

By process of elimination, each wire segment with 24 strands is either an internal jumper wire within the compressor relay compartment or a run capacitor wire.

**3.12 JDG/7: Wire Strand**
**From MCL-20 (Debris from Window Area)**
**Kitchen - Flat 16**
**Appendix A12**

Photographs: Figures A12-1 to A12-4

During the 21 September examination at Bureau Veritas, a wire strand with a globule was found in Exhibit MCL-20 (Debris from Window Area – Kitchen – Flat 16). Figure A12-1 shows the wire strand with globule. This wire strand was taken from a 1.1-meter (1.1m) wire section with 32 strands and an approximate strand diameter of 0.18-0.20mm, also shown in Figure A12-1. No other wire strand with a globule was found on this 32-strand wire.

Figure A12-2 shows Exhibit JDG/7 after it had been ultrasonically cleaned. As shown, the globule is coppery in color.

Figure A12-3 shows Exhibit JDG/7. This photo was taken at NPL on 24 September 2018.

The copper globule and wire strand shown in Figures A12-2 and A12-3 are compared with the fire-heated wires showing globules in Figure 9 [see Section 2.2 of this memo, NFPA 921 Figure 9.10.6.2(b)]. As shown the wire strand and globule in JDG/7 are similar to the fire-heated wires and globules from NFPA 921.

It is concluded that Exhibit JDG/7 is fire damaged, as follows. First, the copper globule and wire strand of JDG/7 are consistent with fire-heated copper wires showing globules in NFPA-921. Second, there is no other globule on any other strand of the 32-strand wire that JDG/7 comes from. Third, there is no identifiable corresponding area of damage on an opposing (neutral) conductor or an opposing grounded metal surface. Arc damage to Exhibit JDG/7 is ruled out.

Figure A12-4 is a microscopic photo of Exhibit JDG/7. Using the microscope, the diameter of the wire section at one location was measured at approximately 0.15mm.

No CT Scans

CT scans of Exhibit JDG/7 were not taken.

SEM Image, X-Ray Maps, and EDS Spectrum: Figures A12-5 to A12-7

Figure A12-5 is an SEM image of the globule on Exhibit JDG/7. EDS analysis was performed within the white line in this figure. JDG/7 was mounted on a carbon sheet.

Figure A12-6 shows the X-Ray maps for the globule on Exhibit JDG/7. The X-Ray maps show (in order of descending amounts) copper (Cu), carbon (C), oxygen (O), sulphur (S), aluminum (Al), chlorine (Cl), and silicon (Si).

Figure A12-7 shows the EDS spectrum for the globule on Exhibit JDG/7. This spectrum shows 55% copper (Cu), 37% carbon (C), 7% oxygen (O) with trace amounts of sulphur (S), aluminum (Al), chlorine (Cl), sodium (Na), silicon (Si), tin (Sn) and zinc (Zn). No significant quantities of melting-point depressant metals are found in JDG/7. As such, alloying damage to Exhibit JDG/7 is ruled out.

<u>Summary: Exhibit JDG/7</u>

Exhibit JDG/7 is a wire strand with a globule, which was taken from a wire section with 32 strands in MCL-20 (Debris from Window Area, Kitchen – Flat 16). No other wire strand with a globule was found on this 32-strand wire.

Exhibit JDG/7 is fire damaged, as follows. First, the copper globule and wire strand of JDG/7 are consistent with fire-heated copper wires showing globules in NFPA-921. Second, there is no other globule on any other strand of the 32-strand wire that JDG/7 comes from. Third, there is no identifiable corresponding area of damage on an opposing (neutral) conductor or an opposing grounded metal surface.

Arc damage and alloying damage to Exhibit JDG/7 are ruled out.

**3.13 RAM/211: Piece of Compressor Mounting Plate**
**Split from BPS/4 (Compressor Unit from Fridge Freezer)**
**Kitchen - Flat 16**
**Appendix A13**

Photographs: Figures A13-1 to A13-3

On 19 June and 20 September 2018, I examined the mounting plate for the compressor for the fridge freezer from Flat 16 at Bureau Veritas. During the 19 June 2018 inspection, a piece on the end of the mounting plate that includes a mounting hole for a run capacitor (to the left of the compressor as viewed from the rear) was cut off the mounting plate and labelled Exhibit RAM/211.

Figure A13-1 shows Exhibit RAM/211. Figures A13-2 (top surface) and A13-3 (bottom surface) show RAM/211 after it had been ultrasonically cleaned. No arc damage is observed on RAM/211 or at any other locations on the mounting plate.

Four sites where surface deposits on Exhibit RAM/211 were observed have been selected for SEM/EDS analysis at NPL. The four selected sites are shown in Figures A13-2 and A13-3.

No CT Scans

CT scans of Exhibit RAM/211 were not taken.

SEM Image, X-Ray Maps, and EDS Spectrum: Figures A13-4 to A13-7

Figure A13-4 shows an SEM image at Site 1 (marked with an "X") on the top surface of RAM/211. Figure A13-5 shows the corresponding EDS spectrum.

Figure A13-6 shows an SEM image at Site 4 (at a "Ridge") on the bottom surface of RAM/211. Figure A13-7 shows the corresponding EDS spectrum.

As shown in the EDS spectra, various elements including iron (Fe), calcium (Ca), zinc (Zn), manganese (Mn), chlorine (Cl), copper (Cu) are identified.

Summary: Exhibit RAM/211

Exhibit RAM/211 is an end piece of the compressor mounting plate that includes a mounting hole for a run capacitor (to the left of the compressor as viewed from the rear) for the fridge freezer from Flat 16. No arc damage is observed on RAM/211 or at any other locations on the mounting plate. EDS analysis identified various elements (including Fe, Ca, Zn, Mn, Cl, and Cu) for surface deposits on the mounting plate.

**3.14 SLW/118: Section of Three-Core Stranded Flex**
**(DIAM 0.99 – 1.08 mm, Strand DIAM 0.20 – 0.21mm)**
**From MCL-06 (Remains of Mains Supply Flex Associated with Fridge Freezer)**
**Kitchen - Flat 16**
**Appendix A14**

<u>Photographs: Figures A14-1 & A14-2</u>

I examined Exhibit SLW/118 at Bureau Veritas on 20 June and 26 September 2018. Exhibit SLW/118 is a section of three-core stranded flex that is part of the power supply cord (mains supply flex) for the fridge freezer from Flat 16.

Figures A14-1 and A14-2 show Exhibit SLW/118. This is an approximately 1m (one meter) section of the fridge freezer power supply cord. Although most of the insulation is missing, there are some charred insulation remains at two locations on the exhibit. No arc damage is observed.

As shown in Figure A14-2, one of the wires from SLW/118 has 21 strands with a strand diameter of approximately 0.19 - 0.20 mm, as measured with calipers. Each of the other two wires has a similar stranding.

<u>CT Scan: Figure A14-3</u>

On 25 September 2018, a CT scan of Exhibit SLW/118 was performed at X-Tek Systems Ltd (Nikon Metrology UK Ltd). Using the CT scan, the stranding of SLW/118 was analyzed at a location where the charred insulation continues to surround the three wires.

As shown in Figure A14-3, each of three wires has 21 strands. The approximate strand diameter was measured at 0.15 – 0.16 mm using the CT caliper tool.

<u>No SEM, X-Ray Maps, or EDS Spectra</u>

Exhibit JDSLW/118 was not analyzed at NPL.

Summary: Exhibit SLW/118

Exhibit SLW/118 is an approximately one-meter section of the power supply cord (mains supply flex) for the fridge freezer from Flat 16. The power supply cord has three wires. No arc damage is observed.

One of the wires from SLW/118 has 21 strands per with a strand diameter of approximately 0.19 - 0.20 mm, as measured with calipers. Each of the other two wires has a similar stranding.

Using a CT scan, the strand count of each wire is 21 with an approximate strand diameter is 0.15-0.16mm.

## 4. SUMMARY

A damage assessment summary for the fourteen exhibits reviewed in Section 3 is given as follows.

### 4.1 MJS/1: Section of Electrical Conductor Taken from MJD/32 (Wiring & Miscellaneous) from Flat 16 (also denoted Flat 6, 4$^{th}$ Floor)

Exhibit MJS/1 consists of two stranded copper wire segments approximately 11 cm in length with a separate stranded copper wire segment approximately 5 cm in length. Approximately 15 mm from one end of the two wire segments, there is an apparent fused area approximately 3 mm in length.

Damage in the fused area of Exhibit MJS/1 is arc damage. Both the sharp line of demarcation and missing/melted strands of both wire segments are consistent with arcing from one wire segment ("hot" wire) to the other wire segment (neutral or grounding wire) in the fused area. That is, there is an area of arc damage on one wire segment and an identifiable corresponding area of arc damage on the opposing wire segment. No significant quantities of melting-point depressant metals are found in MJS/1. As such, alloying damage to Exhibit MJS/1 is ruled out.

In the non-fused area, each wire segment has 24 strands with an approximate strand diameter of 0.16 to 0.18mm.

### 4.2 MJS/2: Conductor Removed from BPS3 (Fridge-Freezer Wiring) Kitchen – Flat 16

Exhibit MJS/2 consists of a stranded copper wire segment approximately 2.5 cm (25 mm) in length with possible melting at one end. Wire insulations are missing (except for some charred remains), having been consumed in the fire.

The fusing of copper strands at one end of Exhibit MJS/2 was caused by fire attack aided by large amounts of zinc, which acted on the copper as a melting point depressant (alloying). This end of MJS/1 with possible melting shows a diffused melting region that does not have a sharp line of demarcation between melted and unmelted strands. There is no indication of arc damage at this end.

The rest of the wire segment was damaged by fire attack with no indication of arc damage. There are broken strands at locations along the exhibit, some of which have rounded ends; but there is no indication that an arcing event occurred from these strands to another wire. Corresponding damage on an opposing wire segment has not been identified.

**4.3 MJS/6: Extractor Fan Motor**
**from Exhibit MCL-20-076029-14062107:**
**Debris from Window Area**
**Kitchen – Flat 16**

Exhibit MJ/6 is the remains of the extractor fan motor from the kitchen of Flat 16. MJ/6 exhibits fire damage only. There is no indication of arc damage or melting of copper motor windings. Also, there is no indication of arc damage or melted copper for the motor circuit board.

It is noted that the extractor fan control board, which is a separate exhibit not included with Exhibit MJ/6, is not evaluated in this memo.

**4.4 SLW/110: Section of Wire Taken from Within**
**BPS4 (Compressor Unit for Fridge Freezer)**
**Kitchen – Flat 16**

Exhibit SLW/110 consists of a stranded copper wire segment approximately 4 cm (40 mm) in length with remains of insulation and/or other debris. The copper strands are separated at both ends of the wire segment.

Exhibit SLW/110 was found by fire investigators to be affixed to the steel mounting plate for the compressor of Exhibit BPS4, the fridge-freezer in Flat 16.

Exhibit SLW/110 shows signs of mechanical deformation only. There is no indication of arc damage or melted copper. EDS spectra with aluminum, carbon, and oxygen removed show up to 38% zinc (Zn), but the morphology of the conductors does not indicate melting of copper either electrically, by alloying or from fire attack.

**4.5 SLW/111: Section of Stranded Conductor,**
**Wire Diameter 1.05 – 1.10 mm,**
**Strand Diameter 0.18 – 0.19 mm**
**from BPS3 (Conductors from Fridge-Freezer Base)**
**Kitchen – Flat 16**

Exhibit SLW/111 consists of a stranded copper wire segment approximately 10 cm (100 mm) in length. Almost all wire insulation is missing, having been consumed during the fire.

Exhibit SLW/111 shows solder remains at the grey/silver end of the wire segment. There is no indication of arc damage or melted copper for this wire segment.

CT scans show a strand count of 24 and an approximate strand diameter of 0.18 mm for this wire segment.

**4.6 JDG/1: Small Section of Wire**
**From MJD/38 (Medium Sized Freezer)**
**Kitchen – Flat 16**

Exhibit JDG/1consists of copper wire segments approximately 4 cm (40 mm) in length with copper beads at one end.

The copper beads of Exhibit JDG/1 are arc damage. The number and volume of the beads indicate that a thermal event caused their melting. Also, the proximity of the copper wire segments to the beads as well as strands affixed to the beads indicate electrical arcing from one wire segment ("hot" wire) to another (neutral or grounding wire). That is, the beads and wire segments indicate arc damage on one wire segment and identifiable corresponding arc damage on an opposing wire segment. Alloying damage is ruled out at three sites on the copper beads. The strand count for each wire segment is 24, and the approximate strand diameter, as measured by Nikon personnel, is 0.16mm.

**4.7 JDG/2: Wire Section**
**From BPS/3 (Conductors from Fridge Freezer Base)**
**Kitchen – Flat 16**

Exhibit JDG/2 consists of a small copper wire segment taken from BPS/3 (Conductors from Fridge Freezer Base). Damage to Exhibit JDG/2 was caused by fire attack aided by large amounts of tin, which acted on the copper as a melting point depressant (alloying).

Exhibit JDG/2 shows no evidence of arc beads. Also, there is no indication that an arcing event occurred from this wire section to another wire. That is, corresponding damage on an opposing wire segment or grounded metal surface has not been identified.

**4.8 JDG/3: Coil**
**From MJD/52 (Miscellaneous Wiring)**
**Flat 16**

Exhibit JDG/3 is a coil from MJD/52 (Miscellaneous Wiring).

At the time of my examination, 21 & 24 September 2018, a "*piece of beading*" that is identified in the 07 November 2017 Bureau Veritas report [MET00007996_0035] for this coil was not affixed to Exhibit JDG/3 and could not be located within MJD/52.

The remains of Exhibit JDG/3 that I examined do not have any arc damage.

The ends of the coil wires for Exhibit JDG/3 have a grey/silver appearance, which is consistent with solder.

**4.9 JDG/4: Wire Strand**
**From MJS/6 (Extractor Fan Motor)**
**Kitchen - Flat 16**

Exhibit JDG/4 is a wire strand taken from MJS/6, the extractor fan motor. A globule was affixed to the wire strand.

The strand diameter was measured at approximately 0.19-0.20mm using calipers, and approximately 0.15mm using SEM. It was verified that this wire strand is likely from one of the wires that connects from the fan control board to the fan motor, and is not a motor winding, whose diameter was measured at approximately 0.26 mm.

It was confirmed that the globule is carbonaceous and <u>not</u> a copper bead. Exhibit JDG/4 is not arc damaged.

**4.10 JDG/5: PTC Component**
**From BPS/4 (Compressor Unit from Fridge Freezer)**
**Kitchen - Flat 16**

Exhibit JDG/5 consists of a wire terminal block from the compressor relay compartment of the fridge freezer from Flat 16. No arc damage is observed.

Using a CT scan, two wire segments from Exhibit JDG/5 are identified; (1) one wire (with 21 strands) that is consistent with one of the wires from the power supply cord (mains flex supply) for the fridge freezer from Flat 16; and (2) a second wire (with 23 strands) that is consistent with one of the wires from an internal five-wire cord to the compressor relay compartment within the fridge freezer from Flat 16. Both the power supply cord and the internal five-wire cord connect to the compressor relay compartment.

**4.11 JDG/6: Wires from Compressor Relay Compartment**
**From BPS/4 (Compressor Unit from Fridge Freezer)**
**Kitchen - Flat 16**

Exhibit JDG/6 consists of wire segments and wire connectors from the compressor relay compartment of the fridge freezer from Flat 16. No arc damage is observed.

Using a CT scan, thirteen wire segments from Exhibit JDG/6 are identified; (1) two wires with 21 strands that are consistent with one of the wires from the fridge freezer power supply cord (mains flex supply); (2) five wires with 23 strands that are consistent with a wire from an internal five-wire cord to the compressor relay compartment; (3) three wires with 14 strands that are also consistent with a wire from an internal five-wire cord to the compressor relay compartment; and (4) three wires with 24 strands. Both the power supply cord and internal five-wire cord connect to the compressor relay compartment.

By process of elimination, each wire segment with 24 strands is either an internal jumper wire within the compressor relay compartment or a run capacitor wire.

**4.12 JDG/7: Wire Strand**
**From MCL-20 (Debris from Window Area)**
**Kitchen - Flat 16**

Exhibit JDG/7 is a wire strand with a globule, which was taken from a wire section with 32 strands in MCL-20 (Debris from Window Area, Kitchen – Flat 16). No other wire strand with a globule was found on this 32-strand wire.

Exhibit JDG/7 is fire damaged, as follows. First, the copper globule and wire strand of JDG/7 are consistent with fire-heated copper wires showing globules in NFPA-921. Second, there is no other globule on any other strand of the 32-strand wire that JDG/7 comes from. Third, there is no identifiable corresponding area of damage on an opposing (neutral) conductor or an opposing grounded metal surface.

Arc damage and alloying damage to Exhibit JDG/7 are ruled out.

**4.13 RAM/211: Piece of Compressor Mounting Plate**
**Split from BPS/4 (Compressor Unit from Fridge Freezer)**
**Kitchen - Flat 16**

Exhibit RAM/211 is an end piece of the compressor mounting plate that includes a mounting hole for a run capacitor (to the left of the compressor as viewed from the rear) for the fridge freezer from Flat 16. No arc damage is observed on RAM/211 or at any other locations on the mounting plate. EDS analysis identified various elements (including Fe, Ca, Zn, Mn, Cl, and Cu) for surface deposits on the mounting plate.

**4.14 SLW/118: Section of Three-Core Stranded Flex**
**(DIAM 0.99 – 1.08 mm, Strand DIAM 0.20 – 0.21mm)**
**From MCL-06 (Remains of Mains Supply Flex Associated with Fridge Freezer)**
**Kitchen - Flat 16**

Exhibit SLW/118 is an approximately one-meter section of the power supply cord (mains supply flex) for the fridge freezer from Flat 16. The power supply cord has three wires. No arc damage is observed.

One of the wires from SLW/118 has 21 strands per with a strand diameter of approximately 0.19 - 0.20 mm, as measured with calipers. Each of the other two wires has a similar stranding.

Using a CT scan, the strand count of each wire is 21 with an approximate strand diameter is 0.15-0.16mm.

## 5. CONCLUSIONS

Laboratory examinations were performed on fourteen exhibits as listed in Section 1 of this memo. Based on the analyses given in Sections 2 – 4; as well as my education, training and experience, I have the following conclusions related to the fourteen exhibits.

(1) Exhibit MJS/1 consists of two stranded copper wire segments with a fused area, along with a separate stranded copper wire segment. Exhibit JDG/1 consists of copper wire segments with copper beads at one end. Both MJS/1 and JDG/1 are associated with wire segments that have 24 strands.

(2) Both Exhibits MJS/1 and JDG/1 have confirmed arc damage.

(3) None of the other Exhibits has confirmed arc damage.

15 October 2018

J. Duncan Glover, Ph.D., P.E. Date