Metropolitan Police Service
London, UK

HVAC Logic and Functionality Testing

Reconstruction and testing of Grenfell Tower smoke extraction system

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EXECUTIVE SUMMARY

On behalf of the Metropolitan Police Service (MPS), RINA has investigated the functionality of the HVAC fire alarm smoke extraction system, and the interaction between the fire alarm system and lift operation, within Grenfell Tower.

The HVAC system was reported to have two operating modes; environmental and smoke control. It is understood that during the 2017 fire this system was suspected of not functioning correctly and did not therefore extract the smoke effectively, as per its design. The system was designed to open the lift lobby dampers on the floor where smoke is first detected and close all other dampers in the lift lobbies of the other floors. The 2017 fire is known to have started on the floor 4; however, it was found that following the fire, all of the smoke dampers on this floor were closed, and all of the dampers on floor 11 were open. On floor 18 the dampers on the south side were open and the dampers on the north side were closed. The dampers on the remaining floors were closed. It was also suspected that the airflow caused by the system may have resulted in the fire behaving unpredictably.

It is understood that the lifts in the building should have ceased normal operation and returned to the ground floor of the building. However, during the 2017 fire this did not occur, and as a result, residents used the lift to attempt to exit the building.

Analysis of the fire system logic program showed that it would have been capable of managing the smoke extraction system during the 2017 fire, however, there was no reference in the program to control the operation of the lifts. Laboratory testing of the re-constructed system showed that it did behave according to the programmed logic.

It has been identified that the firefighter's override switches (FOS) on each floor in the lift lobbies may have been a weak point in the system. The basic construction of these units left them vulnerable to heat damage, dust and water ingress. It is expected that this allowed for several of the FOS in the hottest parts of the tower to short circuit, sending unintended signals to the logic system, and causing the smoke dampers to close or open unintendedly. It is also considered likely that some of the smoke damper actuators in the tower ceased functioning due to heat damage, preventing operation of the dampers.

It is expected that unintended signals from the FOS would have occurred after the fire had spread considerably and engulfed the floors in question. Therefore, it is reasonable conclude that on the balance of probability the dampers would have operated as designed at the start of the fire, by opening on floor 4 where the fire began and closing on all other floors. Interrogation of the logic program could not determine when unintended signals from the FOS might have occurred.

Product information of the smoke damper actuators and the FOS showed that they had not be designed to withstand exposure to the heat from an ongoing fire. As these units were exposed in the lift lobbies it is likely that the system had not be designed to handle a scenario where significant heat or fire could reach these areas of Grenfell Tower.

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ABBREVIATIONS AND ACRONYMS

HVAC	Heating Ventilation and Air Conditioning
PLC	Programmable logic controller
FOS	Firefighter’s override switch
SDE	Smoke detector
SD	Smoke damper
I/O	Input / output
HMI	Human machine interface
O/S	Outstation
AOV	Automatic opening vent
BMS	Building Management System

1 INTRODUCTION

The Metropolitan Police Service (MPS) approached RINA requesting an investigation into the functionality of the HVAC smoke extraction system, and the interaction between the fire alarm system and lift operation, within Grenfell Tower.

The HVAC system was reported to have two operating modes; environmental and smoke control. It is understood that during the 2017 fire this system was suspected of not functioning correctly and did not therefore extract the smoke effectively, as per its design. It was also suspected that the airflow caused by the system may have resulted in the fire behaving unpredictably.

RINA understands that the lifts in the building were supposed to cease normal operation and return to the ground floor of the building. However, during the 2017 fire this did not occur, and as a result, residents used the lift to attempt to exit the building.

The tower was constructed with ventilation shafts on the south side of the building and on the north side of the building. While these were originally designed only for smoke extraction, they were repurposed during the Grenfell Tower refit for environmental ventilation and smoke extraction when required. During operation in environmental mode, the system was designed to draw in fresh air to the lift lobbies up the south ventilation shafts and expel air from the lift lobbies upwards, out of the north shafts. Airflow into and out of the lift lobbies was controlled by smoke dampers. In the event of smoke being detected in a lift lobby, the system was designed to extract smoke using both the north and south shafts and draw in fresh air from the stairwell. The smoke dampers on the floor where the fire was first detected were designed to open, and the smoke dampers on the rest of the floors were designed to close.

It was found that following the 2017 fire all the smoke dampers floor 4, where the fire started, were closed, and all the dampers on floor 11 were open. On floor 18 the dampers on the south side were open and the dampers on the north side were closed. The dampers on the remaining floors were closed.

MPS asked RINA to try to establish why the smoke dampers on floor 4 were closed and why the smoke dampers on floor 11 were open. MPS also asked RINA to determine why the lifts did not return to the ground floor when smoke was first detected and the fire alarm was triggered.

MPS provided RINA with the relevant electronic and electro-mechanical equipment that was associated with the smoke extraction system at Grenfell Tower. RINA re-assembled the equipment according to the installation details that were gathered during the removal of the equipment from the Grenfell Tower. The equipment was then tested at RINA's laboratory facilities.

2 OVERVIEW OF SMOKE EXTRACTION SYSTEM

The smoke extraction system in the tower was controlled by a programmable logic controller (PLC) housed in a Master panel located in the ground floor Hub room. This system also communicated with the building management system (BMS), situated in the basement. The BMS was responsible for controlling the boiler system.

A human-machine interface (HMI) panel was located in on the ground floor entrance lobby. This was a touchscreen unit which had some control over the ventilation in the building. This was connected to the PLC via Modbus RS485 connection. This is a commonly used communication protocol which supports communication to and from multiple devices.

Directly connected outputs on the PLC controlled a series of 24 V d.c. relays at the bottom of the Master panel which were connected to the auto-dialler, BMS system, and some smoke dampers on the ground and first floor. Directly connected inputs on the PLC received signals from the BMS, HMI, and firefighters override switches (FOS), pressure sensors, and smoke detectors on the ground and first floor.

From floors 3 to 23 at the top of the tower, the PLC was connected to an outstation on each of the floors via a Modbus RS485 connection. These outstations were then connected to the pressure sensor, FOS, smoke detector, and smoke dampers on that floor. Additionally, every odd numbered floor also held a battery back-up unit.

During a fire, the pressure sensors were intended to detect if there was a significant pressure difference between the stairwell and the lift lobby on that floor, which might make the door between the areas difficult to open. To avoid this, the ventilation speed would be reduced. The FOS was to be used if a firefighter wanted to override the automated controls and force the system to extract on a particular floor.

On the ground floor and the roof of the tower, there was also inverter panels which housed inverter units. These inverters provided power to the ventilation fans. The inverters were also connected to the PLC via Modbus RS485 to control the speed of the fans.

Further information about the design of the smoke extraction and HVAC system can be found in BRE reports P109378-1000 [1] and P116337-1001 [2].

3 SMOKE DAMPER OPERATION IN GRENFELL TOWER

One smoke damper was investigated on site by RINA. This smoke damper was located on the floor 6, north side, on the right-hand side. The damper as found, on site, is shown in Figure 3.1. The actuator (Belimo part number BLE24) had been disconnected following the fire both mechanically and electrically from the damper. The actuator is shown in Figure 3.2.

The actuator was marked with diagrams indicating the position of the damper blade and wiring diagrams. There were two cable tails exiting the actuator, one 3-core cable on which the electrical insulation had been stripped back to attach the conductors to a terminal block, and a 6-core cable, which had be cut flush, within 10 mm of exiting the cable gland. The 3-core cable controls the opening and closing of the damper and it would have been connected to the outstation, while it is understood the 6-core cable was designed to be able to report the open or closed position of the damper, however, this function was not used in the installation.

For testing in the tower, the mechanical linkage was re-attached, and the actuator was held in place as it would have been when installed. The 3-core cable was connected to a 24 V power supply to replicate the supply voltage that would be delivered during normal operation, and the opening and closing time of the damper was recorded at 26 seconds, and the current was recorded at 120 mA. This supported the information found online from the manufacturer’s datasheet [3]. Information printed on the unit and on the manufacturer’s datasheet lists the operating temperature range to be “−30 C to 50 C”. This actuator was removed from the tower and retained by RINA for further testing.

Figure 3.1: North dampers on floor 6 in Grenfell Tower

Figure 3.2: The actuator from the right-hand side north damper on floor 6 in Grenfell Tower

4 LOGIC PROGRAM ASSESSMENT

The Master Panel unit was located on the ground floor Hub Room of the tower. This unit contained the Programmable Logic Controller (PLC), one Modbus board, twelve 24 V d.c. relays, terminal blocks, and the fire service auto-dialler. The Master Panel was delivered to RINA with the PLC removed. The opened Master Panel is shown in Figure 4.1. The empty space in the middle left of the panel was where the PLC was located. The PLC was delivered to RINA as a separate exhibit. The PLC was an IDEC unit consisting of four modules combined together, shown in Figure 4.2 and Figure 4.3. There was corrosive damage to several of the 24V d.c. relays which were located at the bottom of the Master Panel, and that damage was presumed to be as a result of water damage that occurred during the fire. There was no evidence of external damage to the PLC.

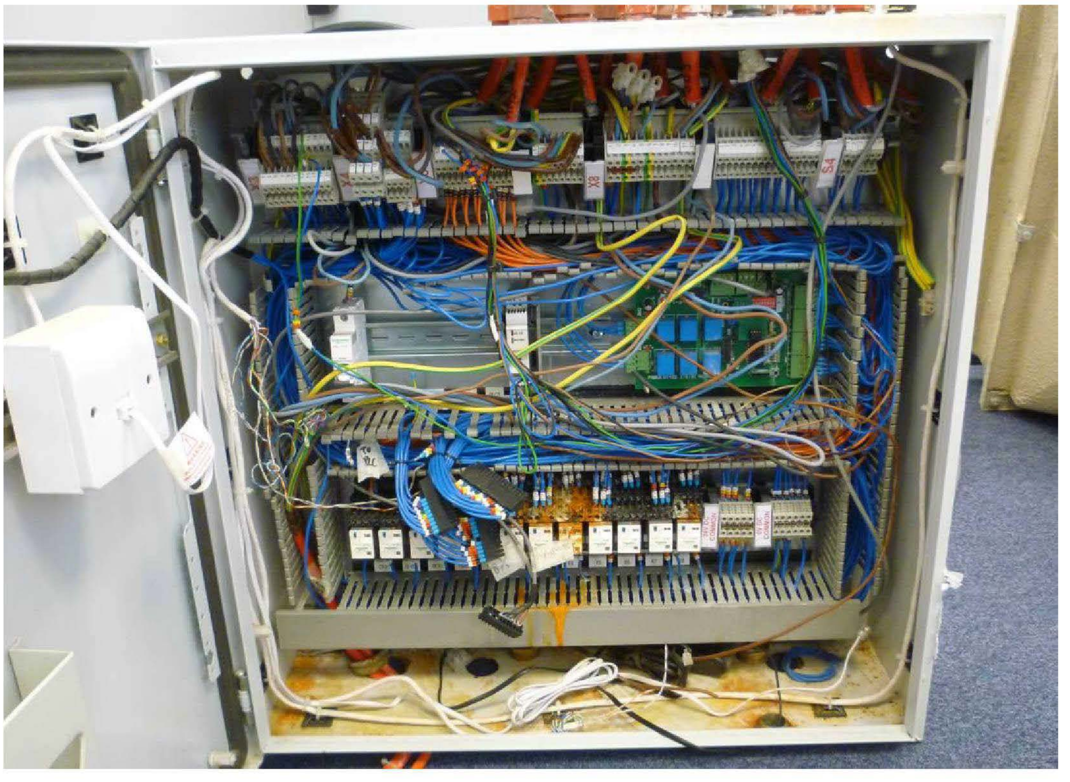

Figure 4.1: Master Panel as received by RINA (opened)

Figure 4.2: Top view of the PLC

Figure 4.3: PLC separated into its modules

The control program on the PLC [4] was provided to RINA and examined using IDEC's WindLDR software. The file properties and folder name suggest that this program was extracted from the PLC on 06.09.2017. The program is a ladder logic system controlling inputs and outputs and communicating to the outstations on each floor using Modbus RS485 protocol.

The program refers to each floor of the Tower as a fire zone. Each fire zone had three inputs, a firefighter's override switch (FOS), a pressure sensor (PS), and a smoke detector (SDE). The fire zones, outstations, and floor numbers were designated as in Table 4.1.

Table 4.1: Outstation location details

Fire Zone	Floor	Panel	Board type	Modbus number
1	Ground	Master panel	Modbus I/O Mk1	1
		Inverter panel 1	Inverter	4
			Inverter	5
			Modbus I/O Mk1	6
-	Roof	Inverter panel 2	Inverter	9
			Inverter	10
			Modbus I/O Mk2	11
2	1	-	-	-
3	2	Outstation 1	Modbus I/O Mk1 v8	31
4	3	Outstation 2	Modbus I/O Mk1	34
5	4	Outstation 3	Modbus I/O Mk1	37
6	5	Outstation 4	Modbus I/O Mk1	40
7	6	Outstation 5	Modbus I/O Mk1	43
8	7	Outstation 6	Modbus I/O Mk1	46
9	8	Outstation 7	Modbus I/O Mk1	49
10	9	Outstation 8	Modbus I/O Mk1	52
11	10	Outstation 9	Modbus I/O Mk1	55
12	11	Outstation 10	Modbus I/O Mk1	58
13	12	Outstation 11	Modbus I/O Mk1	61
14	13	Outstation 12	Modbus I/O Mk1	64
15	14	Outstation 13	Modbus I/O Mk1	67
16	15	Outstation 14	Modbus I/O Mk1	70
17	16	Outstation 15	Modbus I/O Mk2	73
18	17	Outstation 16	Modbus I/O Mk2	76
19	18	Outstation 17	Modbus I/O Mk1	79
20	19	Outstation 18	Modbus I/O Mk1	82
21	20	Outstation 19	Modbus I/O Mk1	85
22	21	Outstation 20	Modbus I/O Mk1	88
23	22	Outstation 21	Modbus I/O Mk1	91
24	23	Outstation 22	Modbus I/O Mk1	94
25 (Community lobby)	Ground	Outstation 1	Modbus I/O Mk1 v8	32
26 (Boxing studio)	2	Outstation 1	Modbus I/O Mk1 v8	33

The program is designed to read inputs from all floors and control the dampers and ventilation fans accordingly.

No inputs, outputs or other references to the lift control were found in the program.

In the heart of the program, the fire zone which detects a fire (i.e. a smoke detector input) is written to the "Activated fire zone" variable. Once this occurs, the other fire zones are unable to write to this variable. This value is copied to the variable "Fire zone status" which controls the operation of the smoke dampers. It is possible for this variable to be overwritten by the FOS input, (but not by other smoke detector inputs). For this to happen, the key operated FOS on the HMI panel must be switched to the "On" position first, and the FOS within a fire zone must switched to the "On" position. Alternatively, once FOS on the HMI panel has been switched to the "On" position the extraction floor can be selected using the HMI's touchscreen, however, this is deactivated if a FOS has been activated on any floor.

In environmental mode, the program opens the dampers on four adjacent floors simultaneously, and it gradually cycles through all floors opening the dampers in groups of four and closing all other dampers.

When a fire is detected, the logic program only allows for the smoke dampers on one floor to open. When the logic program is communicating to the outstations to open or close the smoke dampers, it sends a command every cycle to turn on or off the smoke damper output. During RINA laboratory testing of the reconstructed system the outstations were found to remember the state of the output, and only issue power to the dampers to open or close for the set time (which is adjusted by a potentiometer on the outstation boards) and not repeat the output unless the logic state is switched via the PLC.

Inputs for fire zones 1 and 2, on the ground and first floor, respectively, were connected directly to the PLC. The dampers for these fire zones were controlled directly via the logic program and the relays situated at the bottom of the Master Panel. This allows for the dampers to receive open and close signals for a pre-programmed 38 seconds.

The remaining fire zones were connected via the Modbus system. The RS485 Modbus system also communicated with the HMI panel, Modbus I/O boards in the inverter panels, and directly to the inverters to control the fans and isolation vents.

In the event of a fire being detected by a smoke alarm, the outputs of the logic system:-

- Controlled the ventilation using the Master Panel relays, and over Modbus communication
    - Fan speeds
    - Isolation vents
    - Smoke dampers
- Operated a relay in the Master Panel labelled FDR1 which
    - Activates the auto dial
    - Sends a signal to the BMS
- Activated a high pitch audible signal from the HMI (also activated if an error in the system is detected)
- Displayed scrolling text on the HMI with the location of the smoke

The logic program did not include any references to a lift connection or a building wide audible alarm / siren.

When smoke is reported to the PLC, the fire zone is reported, and the program uses the fan speeds and directions programmed in for each fire zone. For fire zones 1 to 24, these were identical, however, fire zones 25 and 26 did not have values entered into the system for the fan speeds and directions. This could be due to the fact that automatic opening vents (AOVs), akin to windows, were present rather than the dampers and vents present in the lift lobbies. However, in the event that a fire started in one of these zones and the smoke and/or fire subsequently spread to the lift lobby on that floor, the system would not then be capable of turning on the extraction in the lift lobby. This would not have been an issue in the 2017 fire.

There was no reference in the logic program to any smoke detectors other than those listed in Table 4.1, for fire zones 1 to 26. As such, the roof top control room could not be monitored by this system. Additionally, there was no reference to a smoke detector connection in the inverter panel situated in this room.

5 INPUT HISTORY

Examination of the system and logic program did not reveal any intrinsic or deliberate way to capture the input and output history of the system. The PLC can capture some of this information by saving the data between power states, however this is not capable of capturing records of the data being overwritten, or the activation order or time of the inputs. This means that data will have been overwritten as the fire was being extinguished. On powering up, the PLC will also automatically reset the fire signal; as a result, when PLC was powered up to extract the data, much of the information would have been lost. However, if the outstations were not connected at this point, they would not have been able to overwrite the data saved to the PLC. The data would then represent the last communication of the PLC with each outstation. This could have been when an outstation was damaged due to the fire, lost power, or when the system was shut down and removed.

The data register was extracted prior to the delivery of the PLC to RINA and provided separately [5]. File properties suggests that this data was extracted on 19.10.2017.

Due to the system resetting on powering up, extracted data indicated a fire detected in zone 1. This fire zone is reported by a low input on input 3 on the PLC which was unlikely to have been connected at the time of the data extraction. This is the first input registered by the program, and as a result it responds to this input first, regardless of the state of the subsequent fire zone inputs. Many of the data registers would have been overwritten by this action. However, the data inputs from the outstations are likely to have been preserved (for reasons described above). These states are shown in Table 5.1.

Table 5.1: Residual input states of the outstations

Outstation	Fire zone	Floor	Pressure switch	Firefighter's override switch	Smoke detector	Battery backup fault	Notes
1	3	2	off	off	off	-	
1	25	Ground	-	-	Activated	-	
1	26	2	-	-	Activated	-	
2	4	3	off	off	off	off	
3	5	4	off	off	off	-	
4	6	5	off	off	Activated	Activated	

Outstation	Fire zone	Floor	Pressure switch	Firefighter's override switch	Smoke detector	Battery backup fault	Notes
5	7	6	off	off	off	-	
6	8	7	off	off	Activated	Activated	
7	9	8	Activated	off	off	-	
8	10	9	off	off	Activated	Activated	
9	11	10	off	Activated	off	-	
10	12	11	off	off	off	Activated	
11	13	12	off	off	off	-	
12	14	13	off	Activated	off	Activated	Blank input 7 also activated, O/S 22 found to be responding on this address
13	15	14	off	off	Activated	-	Power tracks burnt-out
14	16	15	off	off	off	Activated	Board unresponsive
15	17	16	off	Activated	Activated	-	
16	18	17	off	Activated	off	Activated	Blank input 7 also activated
17	19	18	off	Activated	off	-	
18	20	19	off	Activated	Activated	off	
19	21	20	off	Activated	Activated	-	
20	22	21	off	off	off	off	Board unresponsive
21	23	22	off	off	Activated	-	Board unresponsive
22	24	23	off	off	off	off	Board unresponsive on this address, see O/S 12

During normal operation the pressure switch and firefighter's override switch inputs are low, and the smoke detector and battery backup fault are high. A change in state of these inputs is considered "Activated" in Table 5.1. The blank inputs noted as activated were not connected in the tower, so would have been open circuit. Therefore, on the balance of probability it is considered that these were due to damage to the boards as a result of the fire.

A false activation could occur on the normally low inputs, pressure switch and firefighter's override switch, by a short circuit due to fire or water damage. The smoke detector and battery backup fault inputs are normally high, so activation could occur if these were disconnected.

While being tested at RINA, O/S 12 was unresponsive, and O/S 22 was found to be responding on the O/S 12 address, it is therefore considered possible that the inputs given in Table 5.1 for O/S 12 might have been reported from O/S 22.

6 MODBUS I/O BOARDS

The outstations on each floor consisted of a series of terminal blocks, and one Modus I/O board; expect in the case of O/S 1, which contained three stacked Modbus I/O boards, one for the floor 3 lift lobby, and one each for the for the second fire zones on the ground and second floor. All of the outstations in the tower were delivered to RINA. These arrived with a varying degree of damage from the fire, with the lower floors less affected. A typical undamaged outstation (O/S 5) is shown in Figure 6.1, while a

severely damage outstation (O/S 13) is shown in Figure 6.2. A close-up of the front view of the Modbus I/O board from O/S 5 is shown in Figure 6.3.

Some text was marked on the Modbus I/O boards indicating: inputs and outputs, communication details, and model number and revision of the board. The communication details were: 19200 baud rate, 8 data bits, even parity, and 1 stop bit. Three board revisions were found across the outstations in the tower, these were:

- PSBUK 01422 378131 MODBUS I/O MK1
- PSBUK 01422 378131 MODBUS I/O MK1 v8 (“v8” handwritten)
- PSBUK 01274 694999 MODBUS I/O MK2

Details on which floor contained which of these boards is shown in Table 6.1.

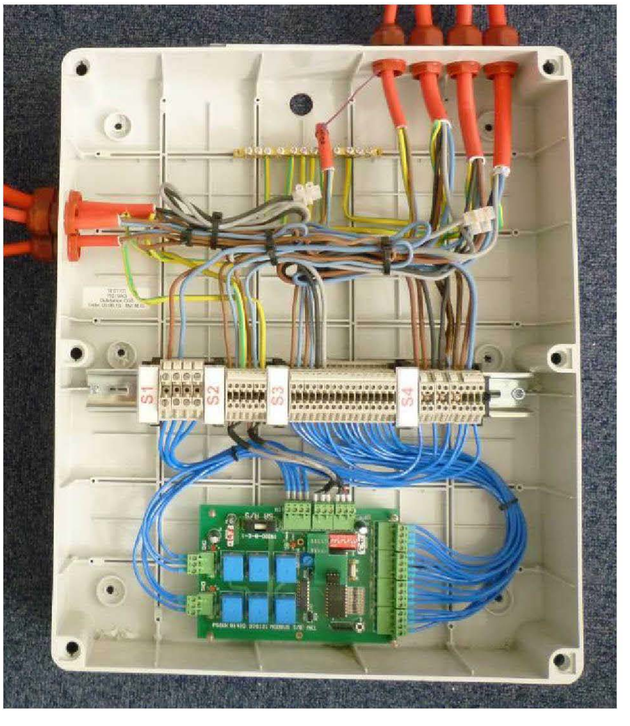

Figure 6.1: O/S 5, a typical example of an undamaged outstation

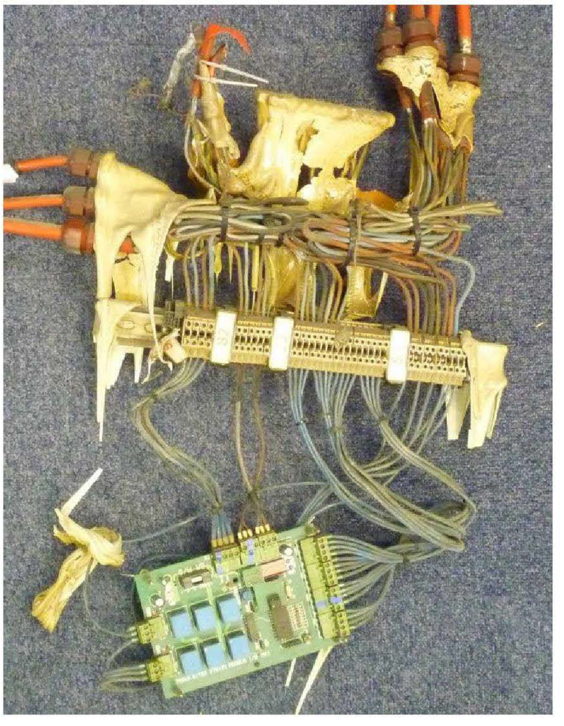

Figure 6.2: O/S 12, a severely damaged outstation

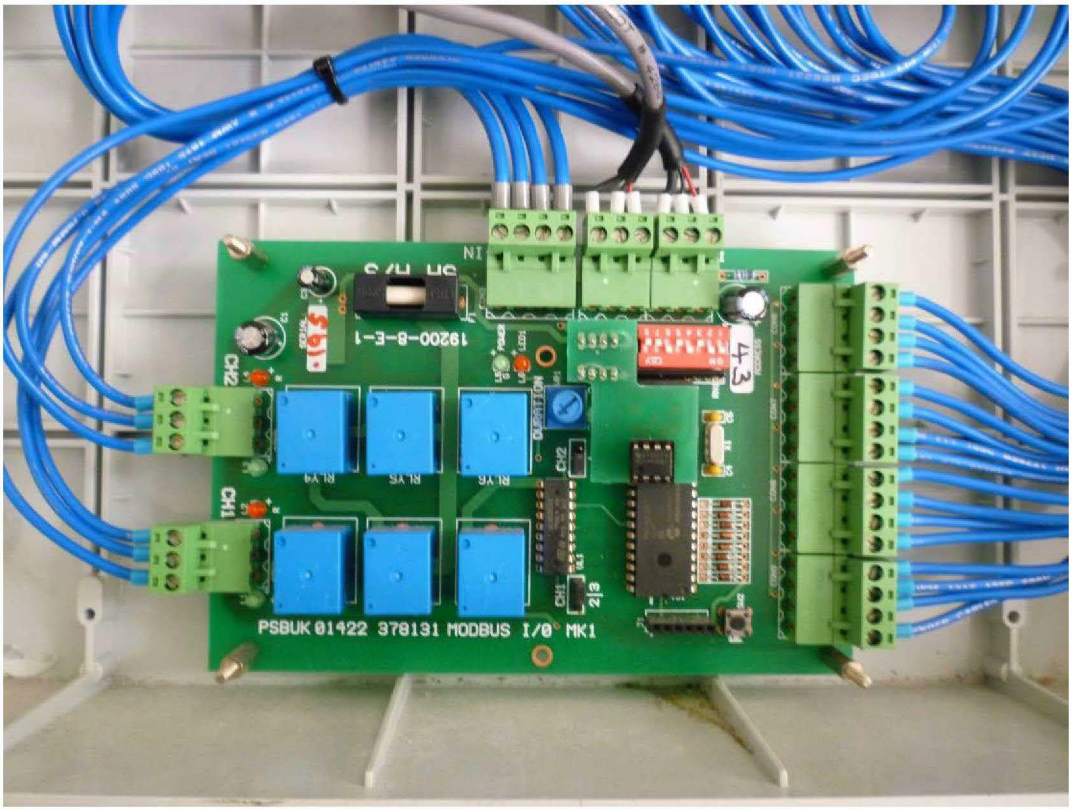

Figure 6.3: Modbus I/O Board from O/S 5

The RS485 communication between the PLC and the Modbus I/O boards was examined. The PLC communicates with the Modbus boards in the order that it has been programmed. The communication system was found to process 20 to 50 commands per second. The commands time out after 0.5 seconds if there is an error, such as if the Modbus board does not respond, or is unreachable. The PLC program will wait for this time-out before continuing with the next command. During the simulated operating conditions, it was recorded that the communications with each outstation occurred approximately every 8.5 seconds.

Due to this communication procedure, it is considered very unlikely that the system could be confused by multiple consecutive inputs. In addition, the communication protocol employs a cyclic redundancy check (CRC) which is designed to detect errors in the transmitted data.

Outstation 5 was connected to a USB to RS485 interface and directly controlled using a RINA PC to simulate the PLC commands. Read commands and write commands were successful. Writing to channel 3 turned on the smoke detector output as expected. This stays on indefinitely. Writing to channel 0 turned on the smoke damper output as expected. This could be controlled to "open" and "close". For this outstation the opening and closing time was recorded at 54 seconds (i.e. longer than the 26 seconds that was required to fully close or open the damper that was tested on site at Grenfell Tower).

This opening and closing time was unaffected by commands sent to the outstation during the sequence. Additional open or close commands did not extend this time. Sending an opposing command during a sequence did not interrupt and switch the state, however, the state did change after around 1 to 2 seconds of the sequence finishing.

On power cycling the outstation, the unit would not respond to requests to close the smoke dampers. It would only respond to a command to open. After the open command has been issued, the damper would then respond to a close command. The outstation would not respond to additional open commands after the first sequence had been completed. Likewise, with close commands.

The opening and closing time remained at 54 seconds regardless of the state of the smoke detector on channel 3. It was found that turning on channel 2 set the smoke damper output to open until this channel was manually turned off. Likewise, it was found that channel 1 controlled the smoke detector output in the same timed fashion as the smoke damper on channel 0. Channels 4 to 7 could be written to the board but did not appear to control the outputs. A command to set the dampers to close indefinitely could not be found. If the indefinite open command on channel 2 was on, writing to channel 0, either to open or close did not change the state of the output. These commands were activated (with the timer) after channel 2 was set to off.

The rotary switch (potentiometer) was found to control the on/off time after power cycling the board. This could vary the timer between 2.7 seconds and 2 minutes 59 seconds. This corresponds with what was written on the board, “3 Sec” “3 Min”.

The opening and closing times of each of the operational outstations were recorded and are reported in Table 6.1.

Table 6.1: Set opening and closing times of the damper outputs per outstation

Outstation	Modbus number	Opening time (s)	Closing time (s)	Board version
1	31	68	77	Mk1 v8
1	32	59	69	Mk1 v8
1	33	84	94	Mk1 v8
2	34	58	58	Mk1
3	37	61	61	Mk1
4	40	59	59	Mk1
5	43	54	54	Mk1
6	46	48	48	Mk1
7	49	50	50	Mk1
8	52	48	48	Mk1
9	55	54	54	Mk1
10	58	47	47	Mk1
11	61	94	95	Mk1
12	64	-	-	Mk1
13	67	48	48	Mk1
14	70	-	-	Mk1
15	73	115	124	Mk2
16	76	105	115	Mk2
17	79	67	67	Mk1
18	82	51	51	Mk1

Outstation	Modbus number	Opening time (s)	Closing time (s)	Board version
19	85	58	58	Mk1
20	88	-	-	Mk1
21	91	-	-	Mk1
22	94	54	54	Mk1

The opening and closings times on the Mk1 boards were approximately equal, however, the closing times on the Mk1 V8 and Mk2 boards were ten seconds longer than the opening times. Additionally, the durations set on the Mk2 boards was significantly longer, it is suspected that this is due to the change in orientation of the potentiometer on the board. It is unknown why the closing time would be set to be longer than the opening times on the later board iterations. This could be to ensure that a damper would fully close if not programmed to fully open.

7 TOWER SIMULATIONS

The PLC, the HMI, and the Modbus boards were connected as they were in the tower, based on the removal notes and labelling on the cables [2]. Due to fire damage, six of the outstations were not operational. One of these, O/S 13, did not power up, as the printed wiring board tracks to the power terminal were open circuit. The underside of the O/S 13 Modbus board showing the burned-out tracks compared with a board is good condition is show in Figure 7.1. This appeared to have been caused by an electrical short circuit which on the balance of probability occurred following the fire. To bypass this and power up the board, the cables were soldered directly on to the tracks. Four of the outstations, O/S 12, 14, 20, and 21 appeared to power up, but did not respond to communications. One of the outstations, O/S 22 was responding on a different address (for O/S 12) than specified by the labelling on the board, and the logic program. As the switches on the board were set correctly, it is most likely that this damage occurred as a result of the fire due to damage to the board. A summary of the non-operational boards is shown in Table 7.1.

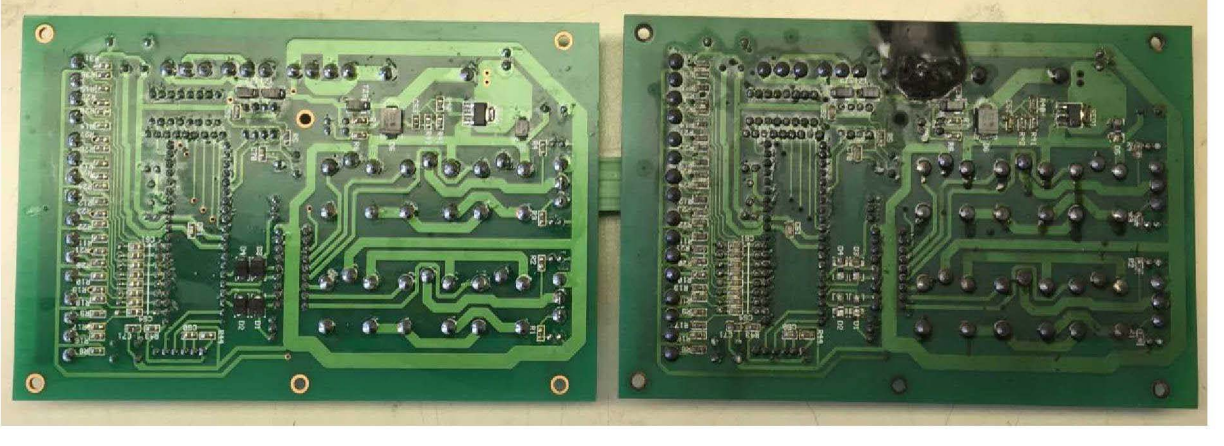

Figure 7.1: Modbus I/O board in good condition (left), O/S 13 Modbus I/O board (right)

Table 7.1: Non-operational outstations

Outstation	Modbus number	Notes
12	64	Board did not respond.
13	67	Board did not power up and was repaired.
14	70	Board did not respond.
20	88	Board did not respond.
21	91	Board did not respond.
22	94	Board did not respond to 94, but did respond to 64. DIP switches correctly position for 94.

The non-operation boards and the inverters were simulated using computer software, "Modbus Slave" by Witte Software. A screenshot of this software is shown in Figure 7.2. This was done to prevent the system from reporting communication errors, and to allow the system function as closely as possible to its condition before the start of the 2017 fire. After simulating these non-operation boards, and the inverters, and connecting the remaining equipment, the HMI was only left with a message reporting that a service was due: "Service Required". If the environmental control input was simulated from the BMS, the HMI panel also scrolled the text: "Environmental Sequence Running". With the environmental sequence running, the system would open and close a selection of dampers every 15 minutes. The control of this sequence is shown in Table 7.2. The dampers in fire zones 25 and 26, on the ground floor community lobby and second floor boxing studio were not programmed into this sequence and did not activate during the simulation.

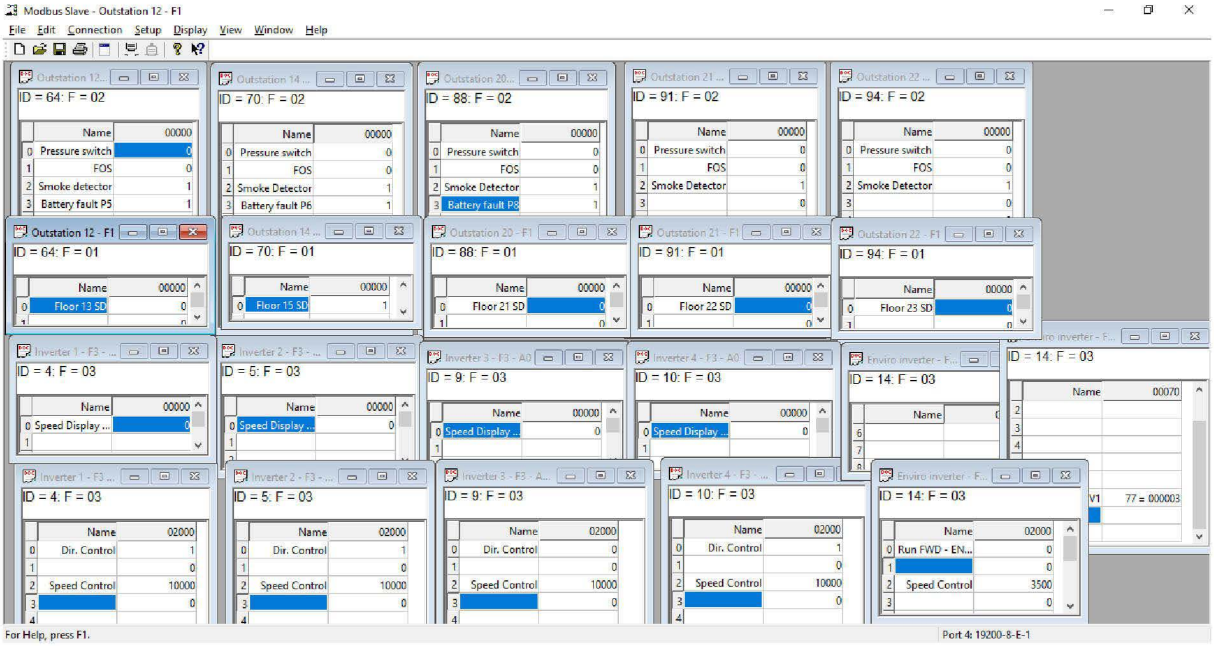

Figure 7.2: Screenshot of the Modbus simulation software

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Table 7.2: Environmental mode damper sequence

Floor	Fire zone	t = 0:00	t = 0:15	t = 0:30	t = 0:45	t = 1:00	t = 1:15	t = 1:30
Ground	1	Close					Open	Close
1	2					Open	Close	
2	3				Open	Close		
3	4			Open	Close			
4	5		Open	Close				
5	6	Open	Close					Open
6	7	Close					Open	Close
7	8					Open	Close	
8	9				Open	Close		
9	10			Open	Close			
10	11		Open	Close				
11	12	Open	Close					Open
12	13	Close					Open	Close
13	14					Open	Close	
14	15				Open	Close		
15	16			Open	Close			
16	17		Open	Close				
17	18	Open	Close					Open
18	19	Close					Open	Close
19	20					Open	Close	
20	21				Open	Close		
21	22			Open	Close			
22	23		Open	Close				
23	24	Open	Close					Open

Damage to the relays and their bases at the bottom of the Master Panel appeared to have been caused by water damage during the fire. In order to simulate the smoke dampers controlled by these relays by the PLC, some relays were moved and re-wired to form an operational pair, one to provide the current, and the other to direct it to either the damper opening contact or the damper closing contact.

Toggle switches and jumper leads were plugged into the outstation boards to simulate the inputs, and 24 V LED lamps were plugged into the outputs on some of the boards to visualise the dampers, however, it was noted that LEDs present on the boards would also indicate the power being directed to the opening and closing contacts of the dampers. After an action, the system was found to take between 9 and 16 seconds to react. This timeframe was not consistent for specific actions. It is expected that the length of time is determined by the "position" of the logic program when the action is made.

Simulating the system confirmed that:

- From environmental or standby mode, simulating smoke detected on a floor would cause the dampers on that floor to open.
- After the first smoke detected signal, additional smoke detected signals for other floors had no effect.
- Removing the smoke detected signal had no effect unless the system was reset from the HMI.
- Intentional operation, or the short-circuit of a lift lobby FOS on any given floor had no effect without the HMI FOS being switched on first.
- FOS activated on a floor would open the dampers on that floor and close the dampers on the floor that the first smoke was detected.
- Further FOS activations had no effect unless all the FOS were deactivated and another was then activated.
- Removing the FOS activated signal had no effect (would not then re-open the dampers on the floor where smoke was detected or on any other floor where smoke had been detected).
- On the deactivation of the HMI FOS switch, the system would revert to opening the dampers on the first smoke detected floor at the start of the fire, and close the remaining dampers.
- Activation of a pressure switch would reduce the extract fan speed from 100% to 50%.
- Extraction override controls on the HMI would be deactivated if a FOS had been activated on any of the floors.
    - The visual appearance of the HMI screen would not change.
    - The screen would not show any error messages in this scenario.
    - The buttons would be present but pressing them would not result in any changes on the screen or in the lift lobby dampers.
- The HMI control to power off the system would close all lift lobby dampers.
- The HMI control to then restart the system does not reset the smoke detected signal.

An example test run is shown in Table 7.3.

Table 7.3: Example test run of the logic simulation

Action	Damper status	HMI Status	Time to react
System initiated	No change	-	-
Smoke on floor 4	Dampers begin to open on floor 4	Fire reported on floor 4	9 – 16 seconds
FOS activated on HMI	No change	HMI screen changes to firefighter mode	-
FOS activated on floor 11	Dampers begin to close on floor 4 and open on floor 11	Screen updates to show extracting floor	9 – 16 seconds
FOS deactivated on floor 11	No change	No change	-
FOS activated on floor 18	Dampers begin to close on floor 11 and open on floor 18	Screen updates to show extracting floor	9 – 16 seconds
FOS activated on floor 11	No change	No change	-

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Action	Damper status	HMI Status	Time to react
FOS deactivated on floor 18	No change	No change	-
FOS deactivated on floor 11	No change	No change	-

8 FIREFIGHTER'S OVERRIDE SWITCHES

The FOS on the HMI panel was recorded in-situ after the fire with the key present in the device, and turned to the ON position, with the touch screen of the device showing it having switched to the override mode, and dampers open on the 18th floor [2]. Information from MPS was also received that none of the FOS in the lift lobbies were activated by the firefighters. Despite this, the records from the PLC show that it had received input from the FOS on serval floors. Examination of a FOS from the second-floor lift lobby showed simple construction, with a key operated switch (Figure 8.1). A sticker on the back of the unit identified as a "KAC Alarm Co. Ltd K21SYS-11". A datasheet found online from the manufacturer lists electrical and environmental specifications [6]. The electrical properties were suitable for its application. The environmental properties specified an operating temperature of "−20 °C to 55 °C", and an ingress protection of "IP24". An x-ray image of the FOS from floor 2 is shown in Figure 8.2 and the red arrow in this x-ray image indicates the spacing between the contacts.

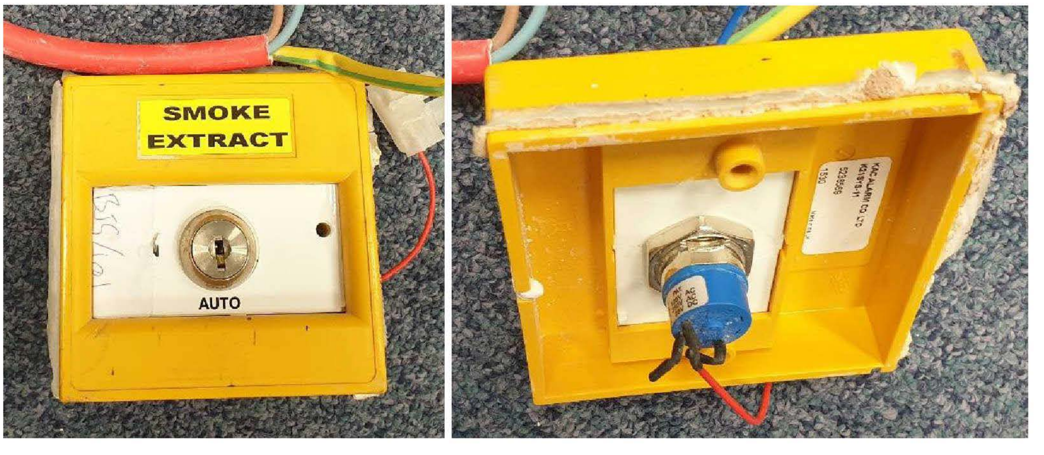

Figure 8.1: Firefighter's override switch from floor 2

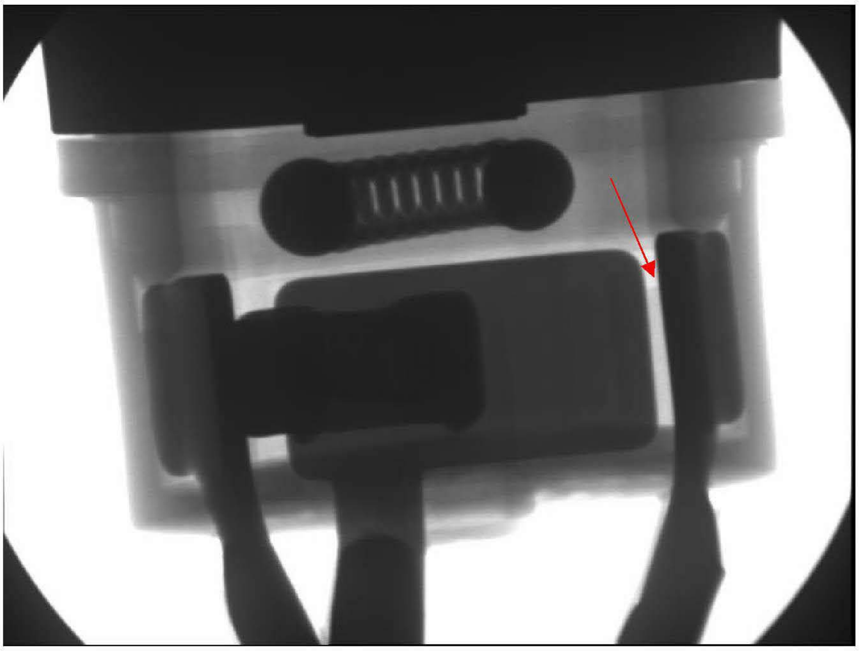

Figure 8.2: X-ray of the FOS from floor 2 set to the auto (off) position

Severe fire damage to the FOS on floor 11 had caused the casing to melt (Figure 8.3). This was taken by RINA to be x-rayed, but it was found that the switch components were not within the melted casing.

Figure 8.3: FOS from floor 11

9 INSPECTION PROCEDURE

RINA received extracts from a document titled "ESTATES SERVICES MONTHLY CHECKS AT GRENFELL TOWER" dated 16th November 2016. This document details monthly inspection procedures to be carried out at the tower. The fire alarm system is listed in this document to be tested; however, the procedure is limited, and only checks if smoke detection is working before the system is manually reset.

There does not appear to be any procedure for checking the operation of the dampers. Additionally, the procedure does not specify if the test should be conducted on any particular floor, or if there is a set rotation to follow.

10 DISCUSSION

During laboratory testing of the reconstructed smoke extraction system, it was found to operate as expected with respect to the control of the smoke dampers on floors 4 and 11, in the event that a fire was first detected on floor 4.

There were some inconsistencies noted during the examination of the system. These are listed below, however, they are not considered to have affected the performance of the system during the 2017 fire.

- The Modbus input and output terminals in outstation 15 were transposed compared with other boards. This is not likely to have affected operation.
- Fan speeds and directions for the smoke extraction system were not programmed into the PLC for fire zones 25 and 26. This would not have caused an issue in the case of the 2017 fire, however, this would have prevented smoke extraction if a fire was detected in these zones first.
- The FOS for zones 25 and 26 were not programmed to prevent further recognition of the other FOS switches. However, due to the order of the logic, only the FOS in fire zone 25 could be overwritten by the FOS in fire zone 26. This would not have caused an issue in the case of the 2017 fire.
    - It is unclear to RINA where the FOS in fire zones 25 and 26 were physically located, however, they were referred to in the logic program, and connections were present in the outstation with cables exiting out of cable glands before being cut away.
- The X4/12 cable output to the first floor lift lobby smoke damper was found to resting inside the terminal X4/11 terminal. From the photos in the BRE report [2], shown in Figure 10.1 below, it appears that this was as in-situ on site. This would have prevented these dampers from opening.

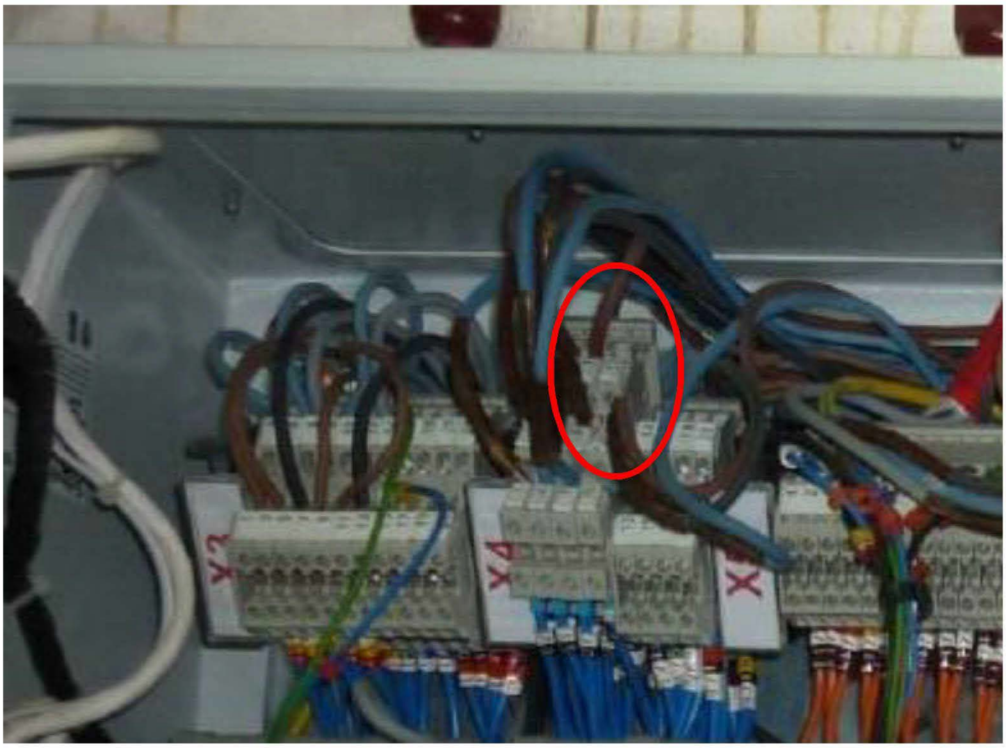

Figure 10.1: Master panel photographed in-situ [2], wiring error circled in red

The installed system was not programmed to provide any control or signal to the lifts in the tower in the event of a fire. However, the system did have the capability to operate smoke extraction system as intended in the case of the 2017 fire. The logic system was capable of recognising the inputs from the outstations and sending outputs to them. The system was set-up correctly such that the dampers would open on the floor where a fire was first detected, and close on the remaining floors. The programming allowed adequate time for the dampers to fully open and close.

Firefighter's override switches (FOS) were present in the lift lobby of each floor. The logic system was programmed to recognise only the first of these switches activated and would only reset after every switch was deactivated. The dampers would open on the floor where the FOS was activated, and close on the floor where the fire was first detected. Unintended activation of the FOS inputs are considered by RINA to be the most likely reason for the unusual operation of the smoke dampers in the tower during the 2017 fire. Table 5.1 shows that seven of the outstations were reporting activation of the FOS, despite reports from the firefighters on scene that the key switches were not activated. This indicates that false activation of these FOS was a likely occurrence during a severe fire. Additionally it was noted that the activated FOS were in the upper parts of the tower where the fire damage was reported to have been the greatest [1]. It is also considered likely that some of the smoke damper actuators in the tower ceased functioning due to heat damage, preventing operation of the dampers. It is apparent from the product information of the smoke damper actuators and the FOS that they had not be designed to withstand exposure to the heat from an ongoing fire.

In addition to the floor 4 dampers found to be closed, and floor 11 dampers found to be open after the fire, it was also found that the dampers on the north side of floor 18 were found open, according to BRE's report [1]. A possible scenario for this to occur is as follows:

1. Smoke was detected on floor 4, where the fire started;
2. The dampers opened on floor 4, and closed of the remaining floors;
3. As the fire progressed, the FOS on floor 11 melted, shorting the contacts;
4. The dampers closed on floor 4, and opened on floor 11;
5. Fire damaged the cable junctions or all four actuators on floor 11, preventing them from moving;
6. The FOS on floor 11 fell away from the casing, causing it to deactivate;
7. Fire damaged the cables, cable connections, or both actuators for the dampers on the north side of floor 18;
8. The FOS on floor 18 melted, shorting the contacts;
9. The dampers remained open on floor 11 due to damage;
10. The dampers opened on floor 18 (south side only due to damage on the north side);
11. FOS switches on other floors melted or short circuited due to fire damage;
12. Dampers remained in this position for the remainder of the fire.

11 CONCLUSIONS

Analysis of the logic program showed that it would have been capable of managing the smoke extraction system during the 2017 fire, however, there was no reference in the program to control the operation of the lifts.

Physical simulation of the reconstructed system showed that it was likely to have operated according to the programmed control logic.

The system was configured correctly with respect to the control and operation of the smoke dampers on floors 4 and 11.

Some faults were noted which would not have influenced the performance of the system during the 2017 fire. Fire zones 25 and 26 appeared to be “half-programmed”, such that while as fire could be detected in these zones the FOS and fan speeds were not set-up correctly for these zones. In addition to the wiring errors already reported to MPS, a loose wire was noted in the master panel which would have prevented the first floor lift lobby smoke damper from opening.

It was identified that the firefighter’s override switches (FOS) on each floor in the lift lobbies may have been a weak point in the system in the event of a severe fire. The basic construction of these units left them vulnerable to heat damage, dust and water ingress. On the balance of probability this allowed several of the FOS devices in the hottest parts of the fire to short circuit, causing the smoke dampers to behave unpredictably. Damage from the fire to the smoke damper actuators would also have prevented them from operating correctly, which led to some smoke dampers being unable to either open or close in response to the (unintended) FOS inputs. It is expected that this would have occurred after the fire had spread considerably and engulfed the floors in question. Therefore it is reasonable conclude that the dampers would have operated as designed at the start of the fire, by opening on floor 4 where the fire began. Interrogation of the logic program could not determine when this switch-over to unintended operation of the smoke extraction system might have occurred.

In RINA’s opinion, based on product information, the smoke damper actuators and the FOS were not designed to withstand exposure to the heat from an ongoing fire. As these units were exposed in the lift lobbies it is likely that the system had not be designed to function reliably in a scenario where significant heat or fire were present in these areas.

12 REFERENCES

[1] BRE Global Ltd, "Grenfell Tower Fire Investigation - On-Site Investigation," P109378-1000 Issue: 2, 2019.

[2] Building Research Establishment Ltd., "GT site report," P116337-1001 Issue: 1, 2020.

[3] Belimo, "Technical data sheet BLE24," 2018-08-14.

[4] Grenfell USB 1 MPSA22491266, Grenfell Tower 6-9-17, "75019AG Grenfell Tower PLC Rev06.pjw," 2007.

[5] Grenfell USB 1 MPSA22687128, "Data Registers from PLC- Binary.csv," 2017.

[6] KAC Alarm Company Ltd, "Indoor Specialist Activation Devices Single Pole Keyswitch Devices," SP-KEY Rev. No. 3, July 2019.

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