

An Analysis of MH370's Flight Path Between Waypoints IGARI and VAMPI, a Review of Potential Vulnerabilities Specific to Airplane 9M-MRO and a Hypothesis Regarding Possible In Flight Events and an End-of-Flight Scenario

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Introduction

The purpose of this paper is to outline the findings of research into the flight path of Malaysia Airlines flight MH370 between waypoints IGARI and VAMPI and into potential vulnerabilities of the operating airplane, B777-200ER Registration 9M-MRO. Some of the findings support a hypothesis as to the cause of the loss of Malaysia Airlines flight MH370. Other findings contradict or undermine elements of the theory that deliberate and malicious direct action by a member of the flight crew, a "rogue pilot", was responsible for the disappearance of MH370.

Summary of Findings

1. There is no evidence to support the contentions that MH370 flew anything other than a direct route to Penang subsequent to the initial deviation from its planned flight path just past IGARI.
2. 9M-MRO, the Malaysia Airlines' B777 that operated as MH370, was at a significantly increased risk of experiencing a windshield heater fire or failure.
3. The crew oxygen system on 9M-MRO may have been leaking.
4. The initial deviation from the flight plan just past IGARI was consistent with the response to an inflight emergency such as a windshield heater fire.
5. A windshield heater fire can explain both the loss of the transponder signal and the interruption to the satellite communications link.

Discussion

1. There is no evidence to support the contentions that MH370 flew anything other than a direct route to Penang subsequent to the initial deviation from its planned flight path just past IGARI.

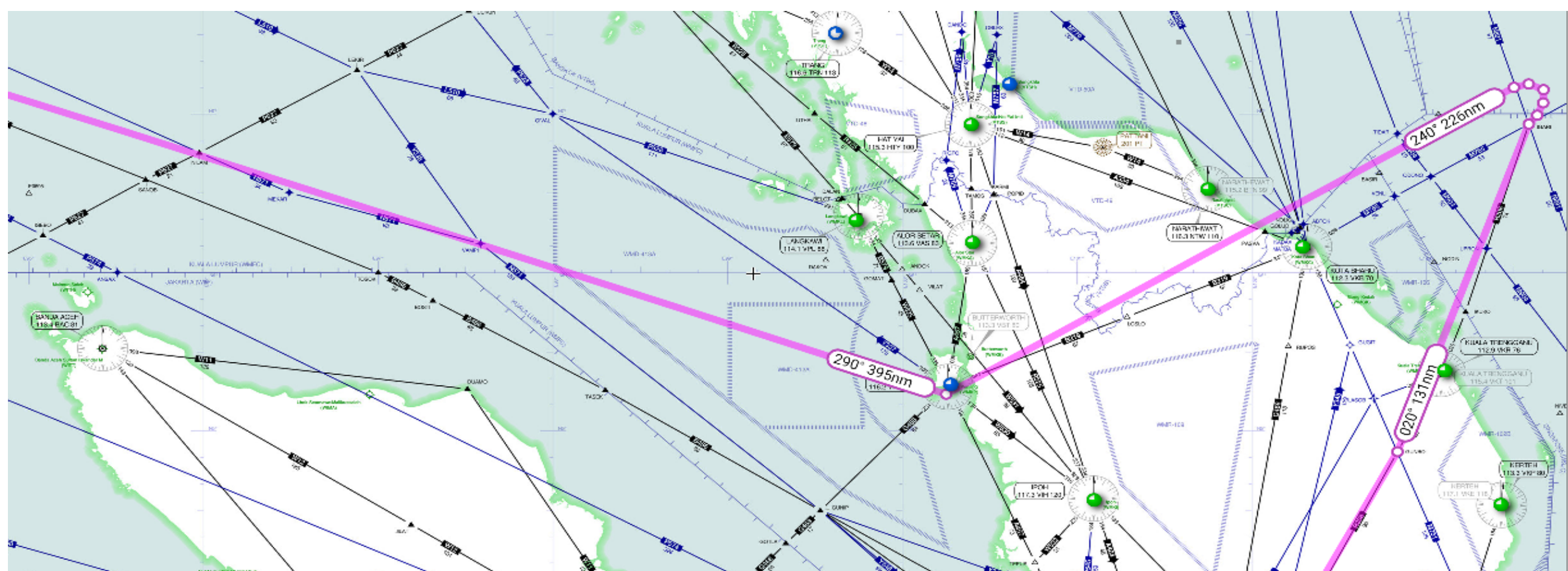
Considerable misinformation abounds regarding the course that MH370 flew after turning back towards the Malay Peninsula. This misinformation together with associated misrepresentations have, to a large extent, guided thinking towards the "rogue pilot" theory.

There is a common misconception that MH370 flew along air space boundaries and navigated from one waypoint to another after departing from its planned flight path. This is not supported by the evidence as detailed in the Factual Information Report released by the Malaysian ICAO Annex 13 Safety Investigation Team in 2015. Many people believe that MH370 was tracked continuously on primary radar from when it turned back just past waypoint IGARI to when it was lost from radar at the top of the Strait of Malacca. That is not the case.

The inferred 750 odd kilometre flight path of MH370 after the turn back just past IGARI until radar contact is lost north west of MEKAR is based on seven separate primary radar traces. The longest continuous radar trace by the same radar station was the final 120 kilometres over the Malacca Strait from near VAMPI to past MEKAR. The only waypoint that MH370 *may* have overflown was VAMPI. As detailed in the Factual Information Report, page 7, point 9, MH370 flew about 16 kilometres to the north of MEKAR (although contrary to what is stated, MH370 most certainly did not join Airway RNAV Route N571; if it had of it would have tracked directly to MEKAR from VAMPI). Radar contact was lost well before the airplane approached NILAM however a track from VAMPI to 16 kilometres north of MEKAR will pass about 12 kilometres to the north of NILAM.

Further, and also contrary to popular belief, MH370 did not track or "zig zag" along air space boundaries. After departing from its planned flight path MH370 flew on a heading that took it over, not along, a stretch of about 120 kilometers of the Bangkok (Thailand)-Kuala Lumpur (Malaysia) boundary that traces the Golong River. Subsequently, MH370 remained firmly in the Kuala Lumpur FIR (Malaysian airspace) at all times until it was lost from radar.

The map below illustrates the very simple course that MH370 flew; an initial right turn at IGARI towards BITOD followed almost immediately by a left turn back towards Penang on a heading of 240°. Then from south of Penang a right turn to 290°; this track would take MH370 over VAMPI and to the north of MEKAR.



In short, the evidence indicates that MH370 may have tracked via one waypoint, VAMPI and I would content that this was coincidental.

Importantly, the flight path above does not require programming into the Flight Management System computer (in fact it would be quite laborious to do so), it can be flown very simply using the basic Mode Control Panel autopilot function in Heading or Track Select/Hold.

There have also been a range of misrepresentations about the altitudes flown by MH370 after the turn, ranging from the physically impossible climb to 45,000 feet to a low level, radar-evading run at 5,000 feet across the Malay Peninsula. Of course, none of that is true.

To determine what is true we again go to the primary radar data. Of the seven primary radar traces only three contain altitude data:

- 1730:35 UTC - 1735 UTC, the radar return was at a registered height of 35,700 ft.
- 1736 UTC - 1736:40 UTC, the radar return was at a registered height of between 31,100 and 33,000 ft.
- 1739:59 UTC, the radar return was at a registered height of 32,800 ft.

Allowing for the vagaries of primary radar with regards to determining altitude, that data suggests an altitude below the previously established cruise of 35,000 feet.

Going beyond the radar altitude data, if we assume some consistency with regards to MH370's altitude and air speed from when it turned back until when it disappeared off radar, then we can use the distance flown and the time taken to fly it to do some calculations. Given the known weather conditions, a constant true air speed of 498 knots satisfies the time and distance involved. Based on the known conditions if we convert a TAS of 498 knots to a Mach number we get $M = 0.840$ at FL340 (34,000 feet). M0.84 is not only the last reported speed for MH370 prior to the loss of the transponder signal it is also the typical cruising speed for a B777-200ER. Moreover, if you compare M0.84 at FL340 to the actual radar traces with regards to distance and time you also get a very good fit.

I should point out that ground speed conversion calculations are not mine, they were first published by Victor Iannello of Duncan Steel's Independent Group (<http://www.duncansteel.com/archives/1969>)

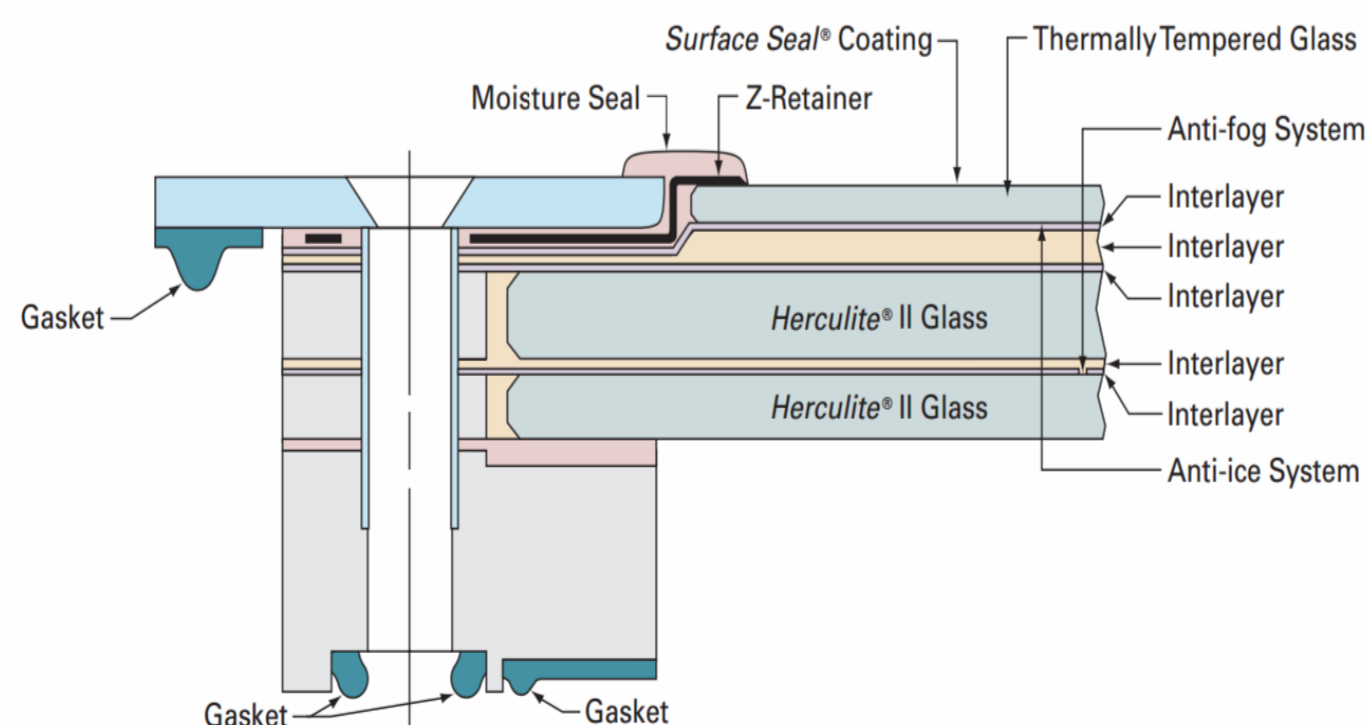
After the initial turn back there were no en route deviations, no zigzagging, no tracking along airspace boundaries, no changes of altitude apart from the initial descent to FL340 (the correct flight level for the westerly heading), and no changes to speed. In short, there were no attempts to evade radar detection or confuse observers.

2. 9M-MRO was at a significantly increased risk of experiencing a windshield heater fire or failure.

The Boeing B757, B767 and B777 all use the same forward windshields; there are two per airplane - left (Captain's) and right (First Officer's). They are manufactured by PPG Aerospace Transparencies of Huntsville, Alabama in the United States.

As illustrated below, the windshield is made up of two inner panes of Herculite (chemically strengthened) glass and an outer pane of tempered glass bound together with urethane interlayers. On either side of the middle pane of Herculite and adjacent to the inner and outer panes are layers of Nesatron film. Nesatron is transparent but electrically conductive and heats up when a current is passed through it - the layers of Nesatron are the windshield heaters. The inner heater prevents fogging of the inner pane and the outer heater prevents both icing and contracting of the outer pane due to exposure to sub-zero air temperatures at altitude. If the outer pane wasn't heated it would suffer a "thermal break" and shatter which would then expose the middle pane.

Main Windshield



In 2007, the cost of each windshield was around \$US100,000.

In the late 1990s and early 2000s, Boeing started to experience problems with windshield heaters either failing or shorting and catching on fire. The problems were encountered initially on the B757 and B767 but eventually the problem manifested itself in the B777 fleet as well. On 17 October 2002, an Air France B777 flying as flight AF062 from Paris to Los Angeles experienced a fire in the immediate area surrounding the windshield heater of the Captain's windshield. It took two fire extinguishers to put the fire out. The outer pane had cracked in a number of places. The crew initiated an emergency diversion and completed a successful landing at Churchill Airport, Canada.

Ten months after the Air France AF062 incident, on 24 July 2003, an Alitalia B777 flying as flight AZ610 from Rome to New York also had an inflight windshield fire that started with the Captain's windshield heater. The fire was extinguished but the outer pane of the Captain's windshield shattered and the crew initiated an emergency diversion to Shannon International Airport, Ireland.

In an attempt to address the problem Boeing had PPG redesign the windshield heater terminal connections, replacing the original screw-in connections with pin-and-plug connectors. In April 2004, Boeing issued a number of service bulletins for the various airplane models impacted - Service Bulletin 777-30-0012 related to the B777 windshield heaters. The bulletin recommended that airlines inspect the electrical connections of the windshield heaters and adjust the connections if necessary or replace the entire windshield assembly with the new design with the improved electrical connections. The bulletin covered all 440-odd B777-200/300 aircraft produced up until 2004. Aircraft built after that time were fitted with the new windshields during production.

It was not until 2007, after investigating American Airlines flight AA1477, a B757 that had declared an emergency on departure from the Dallas-Fort Worth International Airport

because of smoke and a fire near the Captain's windshield heater terminal that the US National Transport Safety Board issued Safety Recommendation A-07-050. That recommendation asked that Boeing and the Federal Aviation Administration require operators to replace the windshield terminal blocks rather than just inspecting them. However, later that year when the FAA issued Airworthiness Directive FAA-2008-0274, which covered B757, B767 and B777 airplanes, it only required operators to comply with Boeing's Service Bulletin(s) with regards to the inspections and adjustments; replacement of the windshields was not required.

Boeing's service bulletins and the FAA's directive were temporarily effective – the incidence of windshield heater related issues fell to zero in the Boeing B777 fleet. But then in 2011, the problem re-surfaced, with two incidents involving B777s in 7 months. On 5 September 2011, an Air France B777 performing flight AF900 from Paris Charles de Gaulle to Yaounde, Cameroon was enroute at FL350 about 270 kilometres south of Paris when the crew experienced a windshield heater failure that led to windshield cracking. Then on 13 April 2012, an Alitalia B777 flying as flight AZ8320 from Rome to Dubai suffered cracking to the First Officer's windshield when the heater failed.

There were also renewed problems with the windshield heaters on B757 and B767. These included a 2008 incident involving an American Airlines B757 operating as flight AA1738 where the inner pane on the First Officer's windshield shattered spraying him with shards of glass and a 2010 incident involving a United Airlines B757 operating as flight UA057 where the Captain's windshield heater caught fire - the Captain emptied two extinguishers onto the fire to put it out, in the process he had his oxygen mask torn from his face twice while retrieving fire extinguishers (the hoses simply aren't long enough for the wearer to move far from their seat with the mask on).

There were at least 39 windshield heater related incidents between 2002 and 2014, eight involving B777s. I say "at least" because, alarmingly, not all incidents are reported through official channels. Boeing concedes that there have been 39 incidents but a review of NASA's Aviation Safety Reporting System database (the ASRS is an external to "official" channels, confidential, voluntary safety reporting system open to flight crew, cabin crew and ground staff) shows a number of incidents that do not tally with NTSB records (a matter that the NTSB acknowledges). The chain of correspondence between the NTSB and the FAA while all of this was unfolding highlights the NTSB's palpable frustration with the slowness of the FAA's initial response and the lack of firm direction regarding windshield replacement.

Analysis of the B777 windshield heater incidents is instructive. The airplane involved in the first incident, Air France F-GSPZ, was production line number 401; the Alitalia B777 involved in the second incident (I-DISU) was number 425. When windshield heater fires re-emerged, the Air France (F-GSPY) and Alitalia (EI-ISB) B777s were line numbers 395 and 426 respectively. All four airplanes – 395, 401, 425 and 426 – came off the Boeing production line in a nine month period from late March to mid-December 2002. Together, that small cohort represents half of the B777s that have experienced windshield heater related incidents.

There was also a 30 July 2008 incident involving an Emirates Boeing B777, registration A6-EMS operating as flight EK006 from London to Dubai where the crew reported smoke in the cockpit and carried out an emergency landing at Budapest Ferihegy airport but I have been unable to confirm that the source of the smoke was a windshield heater. A6-EMS was line number 408.

An inferential statistical analysis of the confirmed windshield heater related incidents involving B777s highlights that 50% of the incidents occurred in less than 5% of the fleet. When adjusted for years of service, the rate of incidence of windshield heater fires/failures by years of service for B777s produced in 2002 is more than 12 times higher than the incidence rate for the entire B777 fleet and more than 30 times higher when compared to the remainder of the fleet (ie the fleet excluding the 2002 sub-group).

9M-MRO was manufactured on 14 May 2002, production line number 404.

If Malaysia Airlines were complying with Airworthiness Directive FAA-2008-0274 and were following the Boeing phased-A check schedule, the flight compartment windows would have been inspected for condition in accordance with the Aircraft Maintenance Manual at every A2 Check. 9M-MRO's last A2 Check was 4 November 2013 and her next A2 Check would have fallen around the end of March-early April 2014.

9M-MRO belonged to a cohort of B777s that were statistically significantly overrepresented in windshield heater related incidents and it is probable that 9M-MRO's windshield heaters were inspected for condition some 4 months before it flew as MH370.

3. The crew oxygen system on 9M-MRO may have been leaking.

The crew oxygen system provides pressurised oxygen to four masks on the flight deck for use in the event of an emergency. Malaysia Airlines B777s are fitted with two cylinders that hold 3150 litres of oxygen each at 1850 psi. This is sufficient capacity to provide 100% pressurised oxygen on demand to two flight crew for 13.5 hours.

Oxygen is drawn off from the system as part of the daily maintenance check; typically this check consists of a 5 second pressure check per mask. Additionally, before each flight, flight crew members check the flow of oxygen to their mask and the function of their mask microphone; these checks are combined into one 5 second test - the mask microphone is selected to INT (for intercom) and the oxygen flow test button is depressed, the oxygen flow can be heard on the flight deck speakers. Further, on the start of the first engine, 25 seconds of oxygen is automatically bled off so that the airplane's sensors can confirm both flow and pressure.

The following information has been sourced from the Factual Information Report, FAA Airworthiness Directives, Boeing Service Bulletins and the operational records for 9M-MRO:

- On 14 January 2014, the crew oxygen system was serviced and topped up to 1800-1850 psi.
- On 17 January 2014, maintenance work was carried out on the crew oxygen system. That work was associated with an FAA Air Worthiness Directive, FAA AD 2012-13-05 (Replacement of Low Pressure Oxygen hose). According to the relevant Boeing Service Bulletin, the replacement job consists of 17.75 task hours and takes 11.2 hours elapsed time for two technicians to complete (that elapsed time does not include set-up, clean-up or independent inspection times). All the work is carried out on the flight deck on the low pressure side of the crew oxygen system and concludes with a simple flow check at the end of the job. The First Officer's seat need to be removed to access the flight deck oxygen system connections.

- 9M-MRO came out of an A4 Check on 16 January and was scheduled to fly from Kuala Lumpur to Melbourne on 17 January 2014 as MH149 departing at 11:45pm MYT. Thus, there was an operational requirement to have 9M-MRO out of maintenance and back on the line by no later than around 8.30-9.00pm local time. Work on the AD task would have occupied much of the day and early evening of 17 January. Given the requirement to first remove and lastly replace the First Officer's seat, the task is not one that can be easily rushed or curtailed.
- FAA AD 2012-13-05 had to be completed before the mandatory completion date of 12 February 2014. 17 January represented the last scheduled opportunity for the AD to be completed on 9M-MRO before the mandatory completion date.
- On 20 January 2014, three days after the work was performed, the First Officer's seat's forward/aft power adjustment was reported as inoperative.
- On 7 March 2014, the afternoon prior to flying as MH370, the crew oxygen system pressure read 1120 psi and was topped up to 1800 psi.
- Between 14 January and 7 March 9M-MRO flew 100 flights and accumulated around 550 airframe hours.

In aggregate, the daily and pre-flight mask checks together with the pressure check bleeds on engine start should have accounted for 5540 seconds or around 315 psi. The drop of 680-730 psi between 14 January to 7 March was about 2-2.5 times higher than what would be expected from the mask checks and start-up pressure check bleeds associated with 100 flights over 52 days.

Based on the above I'm led to believe that 9M-MRO had an oxygen leak, probably from one of the cockpit mask hoses given the nature of the work performed on 17 January. The leak may have resulted from the work associated with AD 2012-13-05 being rushed. The task may have been rushed because the maintenance crew would have been under pressure to complete the AD task on 17 January and operational requirements meant that they were afforded virtually no extra time to complete the task in the event of unforeseen delays or difficulties. The subsequent failure of the First Officer's seat's power adjustment may have been the result of the seat being hurriedly replaced.

Dangers associated with oxygen-enriched atmospheres

While oxygen itself is not flammable when the concentration of oxygen in the atmosphere rises by just 2%, from the usual 21% to 23%, the chemistry of fire changes and it changes dramatically; materials that do not normally burn become flammable and normally flammable materials ignite at lower temperatures and burn faster and hotter. Fires in oxygen-enriched atmospheres are extraordinarily difficult to extinguish.

The photograph below is of the flight deck of an EgyptAir B777 that suffered an oxygen fire whilst on the ground at Cairo International Airport on 29 July 2011. It took less than 4 minutes for the fire to cause that damage. (As a matter of happenstance, the work that was done on 9M-MRO's crew oxygen system under FAA AD 2012-13-05 was a result of the findings and recommendations arising from the Egyptair B777 oxygen fire.)



A contributory factor, perhaps the major one, to an oxygen-enriched atmosphere may well have been a flight crew mask. The crew's initial reaction to a windshield issue or smoke, fire or fumes in the cockpit is to don their oxygen masks, select 100% oxygen and select emergency mode on their mask. The combination of 100% oxygen and emergency mode ensures that oxygen is delivered continuously to the mask at a positive pressure to ambient; this is to ensure that smoke or fumes cannot be drawn into the mask. The cockpit fire extinguisher is behind the Captain's seat and while it can be reached by the Captain while seated it is easier for the Captain to retrieve it and use it by getting out of his seat. However, doing so would tear the mask from the Captain's face in much the same fashion as the UA057 incident mentioned above. 100% oxygen would flow from his mask into the flight deck at the rate of 30 litres per minute at around 14-15 psi. Had the Captain elected to don portable breathing equipment (a smoke hood with its own oxygen supply, that is stowed right beside the fire extinguisher) instead of trying to refit his mask then his mask would continue to vent oxygen.

Moreover, the air flow on the flight deck is such that oxygen venting from the mask would most likely be drawn towards the forward instrument panel and the fire.

4. The initial deviation from the flight plan just past IGARI was consistent with the response to an inflight emergency such as a windshield heater fire.

In the event of an inflight emergency such as windshield cracking or a windshield heater fire, the crew would divert to the nearest airport. A list of the four nearest airports in

terms of ETA can be quickly accessed via the Flight Management Computer. If an emergency were to present itself approaching or just past IGARI the two nearest airports were Kota Bharu (about 10 minutes flying time away) and Penang (about 30 minutes flying time away). However, Kota Bharu is not a 24 hour airport and was closed when MH370 was flying; its runway is also on the short side for a B777 at MH370's weight. A diversion to Penang, however, would have taken MH370 past Kota Bharu therefore providing an option if the emergency progressed rapidly to the point where an immediate landing was required.

MH370's change of direction back towards Penang on a heading of about 240° and its descent to FL340 just past IGARI were entirely consistent with a response to an inflight emergency.

5. A windshield heater fire can explain both the loss of the transponder signal and the interruption in the satellite communications link.

There are two transponders on the B777; left and right. In normal operations one transponder is active and the other is in standby mode. If the active transponder fails there is no automatic fail-over to the standby transponder, it needs to be selected manually. I have not been able to determine what Malaysia Airlines' procedures are for selecting the active transponder when crew are undergoing training but under normal circumstances the left transponder is active and the right is on standby.

The circuit breakers in airplanes are thermal-magnetic; they are designed to respond to the heat generated by an electrical overload or the magnetic flux associated with a short circuit. Because they are sensitive to heat, external heat will trip a thermal-magnetic circuit breaker.

There are two overhead circuit breaker panels on the flight deck that hold, amongst others, the circuit breakers for the transponders. Heat rises and, in the case of a windshield heater fire, would roll across the flight deck ceiling and over the circuit breaker panels. Heat from a windshield heater fire, particularly if it was in an oxygen-enriched atmosphere, may have started tripping some of the lower rated thermal-magnetic circuit breakers in the overhead panels. The right and left transponder circuit breakers are rated at only 5 amps. Further, the left transponder circuit breaker is located at the A3 position on the left panel, placing it closest (bar two) to the potential heat source, the Captain's windshield.

With regards to the failure of MH370's satellite communications, the Satellite Data Unit is powered by the left AC bus. In the event of a fire, smoke or fumes in the cockpit, the B777 Quick Reference Handbook checklist states the objectives are; To remove power from the ignition source, and To land the airplane as soon as possible, if needed. The checklist states that if the source of the fire is obvious, power should be removed from any affected equipment. If the fire originated in the Captain's windshield heater the approach to removing power from it would be to first turn off the windshield heaters and then fully isolate the Left AC bus. The latter is accomplished by selecting the Left Bus Tie Breaker to ISLN, selecting the Left Backup Generator to OFF, and selecting the Left Generator to OFF. This would have the effect of cutting power to the SDU.

Hypothesis

While the following is speculation on my part it is to a large degree based on research and precedent accidents.

As alluded to above, I believe that MH370 suffered a windshield heater related incident involving the Captain's windshield shortly before arriving at waypoint IGARI. At the first sign of smoke, a burning smell or a fire, the crew's initial reaction would have been to don their oxygen masks. In keeping with prior windshield heater fire incidents the fire most likely would have broken out around the frame of the Captain's windshield. The Captain would have ordered the First Officer to identify the nearest airport and initiate a diversion. There would almost certainly have been some initial confusion/discussion regarding the choice of diversion - Kota Bharu, which was closer but closed, versus Penang, which was further but open. That delay may well account for the initial right turn at IGARI as the Flight Management System would have commanded a right turn to 059° to track towards their next waypoint, BITOD. Having decided on Penang the First Officer would have taken the autopilot out of LNAV mode and into Mode Control Panel Track Select and selected 290° to take them back to Penang; the airplane would have stopped the right turn and then turned left. The First Officer would have also commanded a 1,000 descent to Flight Level 340 to put them on the correct level for a westerly heading.

I suspect that the Captain got out of his seat to retrieve the cockpit fire extinguisher and fight the fire (a small fire burning directly in front of him may have also prompted him to leave his seat). That would have meant either taking his mask off or having it torn off when the hose reached full extension. He would have then either donned the PBE (which was right beside the fire extinguisher and designed for just such a situation) or donned one of the observer's oxygen masks at the rear of the flight deck.

If the Captain had donned the PBE he was now out of communication with the First Officer; this would have left the First Officer to work the Smoke, Fire or Fumes checklist. A mayday call does not appear on the checklist and, moreover, as the Captain had been handling the radios for the flight up till this point, making a mayday call may not have been front of mind for the First Officer. Having identified the source of the fire as the Captain's windshield the First Officer would have first turned the windshield heat off on the overhead panel and then isolated the Left AC Bus; in doing so power to the SATCOM would have been cut. The oxygenation of the flight deck would cause the fire to flare, tripping the transponder circuit breaker and possibly injuring either or both the pilots.

The fire would have then propagated rapidly possibly forcing one or both pilots from the flight deck. However, it would have only burned for only a few minutes and then the Captain's windshield would have failed. When the windshield failed initially shattered glass and windshield debris would have been blasted into the cockpit at about 500 km/h. That would have been immediately followed by a rapid depressurisation. The depressurisation would have extinguished the fire. If anyone was still on the flight deck when the windshield failed it is difficult to see how they would not have been seriously, if not fatally, wounded.

The basic autopilot function is highly protected and runs on redundant systems and would have kept MH370 tracking towards Penang on 240° at FL340.

Within 20-25 minutes of the depressurisation event, 5-10 minutes before reaching Penang, just about everyone on board would have been dead. The passenger oxygen system uses chemical oxygen generators and continuous flow masks that have inhalation and exhalation

check valves. Because the inhalation check valves on the masks dilute the supplied oxygen with the ambient atmosphere, at 34,000 feet the passenger oxygen generators cannot provide sufficient partial pressure of oxygen in the lungs to maintain consciousness without considerable conscious respiratory effort. People unfamiliar with hypoxia would have simply lost consciousness and died after 20-22 minutes when the oxygen generators burned out. A flight or cabin crew member may have recognised the early symptoms of hypoxia and started deep, forceful breathing and remained conscious. The PBE, which provides unpressurised but undiluted 100% oxygen to the wearer, would have offered the best chance of remaining conscious after the depressurisation.

I believe that one of the flight crew survived the fire and depressurisation event, possibly because they had donned the cockpit PBE, possibly because they were out of the cockpit retrieving an extra fire extinguisher when the windshield failed, possibly both.

The cockpit would have been reduced to something akin to the EgyptAir B777 photograph with the additional problems of being both incredibly noisy and extremely cold (around -30°C). The cockpit displays are liquid crystal and quite vulnerable to heat damage, in all likelihood they would have all been destroyed. There are no analogue back-up instruments. Moulded plastics such as keypads and switches together with oxygen masks, headsets and microphones would have been burned or melted. An unused crew oxygen mask would probably have still been usable but with two destroyed masks venting the oxygen supply would be depleted very quickly. There would be effectively no visibility from the cockpit - it would be almost impossible to look through the open section left by the failed windshield and all the other windows would have been covered with soot from the fire and would also be rapidly accumulating frost.

For someone to get back to the cockpit would have taken considerable effort. First of all, they would have needed to retrieve one of the portable walk-around oxygen bottles - one bottle would give them 15 minutes of oxygen - or one of the extra PBEs. Then they would need to brave the cold and the noise.

On approaching Penang the surviving pilot would have come to the realisation that he had no means of communication; radio communication panel keypads, microphones and headsets would have been melted by the fire. He may have tried using the emergency locator beacon stowed in the cabin but trying to get line of sight to a satellite through a window would be problematic and the battery would have been short-lived given the freezing temperature (the batteries will not function in temperatures below -20°C). He may have tried mobile phones (there were reports of the First Officer's mobile phone trying to log on to a Penang cell tower) but the altitude would have made a connection unlikely and the batteries would have quickly succumbed to the cold.

The pilot would have also realised that there was no reasonable chance of manually flying the airplane; he had no instruments, it was night, there was no moon, he could only occupy the cockpit for short periods of time and oxygen supplies were dwindling. Any attempt to take manual control of the airplane would almost invariably end with loss of control and there could be no guarantee that he could re-engage the autopilot if he disengaged it.

Just off the starboard wing was Penang; population 1.65 million. Immediately ahead and stretching 900 kilometres from the north-west to the south-east was the world's second busiest shipping lane, the Strait of Malacca, the conduit for trade from Europe and the Middle East to South East Asia. There would have been ships - tankers, chemical ships, container ships, bulk carriers and cruise liners - about every 5-6 kilometres along the Strait. 20 minutes ahead lay nearly five million people, the inhabitants of the North Sumatra

province of Indonesia and that country's third largest city, Medan.

Given the situation I believe that the pilot then elected to do what many pilots in stricken airplanes have done in the past; steer it clear of populated areas. He turned up the Strait of Malacca running parallel to but to the north of the shipping lane. When he reached the top of the Strait I think he then made a last ditch effort to regain communications or some additional flight functions and reconnected the Left AC Bus. This had the effect of reconnecting power to the SATCOM which then rebooted and started the sequence of satellite handshakes that allowed MH370 to be eventually tracked to the Southern Indian Ocean. Then, with very little oxygen remaining, I believe that the pilot simply pointed the airplane due south, using Track Select onto 180°, turning it away from India directly ahead.

Moving to the end of flight, I believe that MH370 ran out of fuel on the 7th arc near 34° 12' S, 94° 30' E, about 695 kilometres north east of the ATSB hot spot and about 200 kilometres outside the current search area. The ATSB modelling assumed an undamaged, intact airplane and favours flight paths to the 7th arc that are consistent with a normal fuel burn. Factoring in the additional drag from the failed windshield makes shorter paths that use more fuel over the same period of time more likely. A southerly track on 180° gives a final leg that is 360 kilometres (or nearly 10%) shorter than that modelled as most likely by the ATSB.

34° 12' S, 94° 30' E is interesting in another regard also; it sits right on the north-western edge of aerial search zone of 2-3 April 2014. A debris field would have drifted more than 100 kilometres north-west by the time the aerial search reached that location on 3 April. The aerial search may well have found the debris field if search efforts had have been continued in that area as originally planned. Regrettably, on 4 April 2014 all the search assets were redirected about 1,500 kilometres to the north chasing what turned out to spurious underwater acoustic signals.