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Loss of an F35 fighter jet – The case for Human Factors Integration

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SUMMARY

An F-35B Fighter Jet belonging to the Royal Air Force ditched in the Mediterranean Sea on 17 November 2021 during an aborted take-off from the aircraft carrier HMS Queen Elizabeth (DSA, 2023). While the aircraft was recovered from a depth of two kilometres, all components were found to be beyond economic repair and the airframe was deemed a total loss. The subsequent safety investigation conducted by the Defence Safety Authority determined the causal factor to be that the left intake blank was at the front face of the engine compressor during the aircraft launch. This paper sets out the latent issues with the design of the intake blank and how they combined with a number of local and organisational Human Factor issues to create the conditions in which this accident occurred.

KEYWORDS

Defence, aviation safety, accident investigation, latent error, Human Factors Integration

Introduction

On Wednesday 17 November 2021 an F-35B Lightning II, designated "BK-18", ditched whilst attempting to launch from HMS Queen Elizabeth. The pilot ejected, due to a lack of engine power, as the aircraft left the end of the flight deck. The pilot landed back on the deck with only minor injuries while the aircraft impacted the sea and subsequently sank.

A technical investigation determined that the lack of power was due to an intake blank being present at the engine compressor (the front face of the engine which draws air into the engine to be used in combustion), resulting in a reduced amount of air flowing into the engine. The blank is believed to have been dislodged and blown down the intake during a period of stormy weather and high winds the night before the incident sortie. This was the first loss of a UK F-35B which came at a cost of £81.8m, with another £2.63m being spent on recovering the wreckage. The incident was also a near miss for the pilot who credibly could have come to serious harm.

Given that aircraft blanks are normally considered a barrier to accidents (MAA, 2023), this incident highlights the importance of Human Factors Integration when designing systems to prevent occurrences in high-risk environments.

Events prior to the accident

At the time of the incident HMS QUEEN ELIZABETH was returning home from its maiden operational deployment known as OP FORTIS, a seven-month deployment to the pacific region. On Tuesday 15 November 2022, the ship was transiting through the Suez canal from the Red Sea to the Mediterranean. Due to the proximity to land, a Government Special-Access-Program Security Officer (GSSO) ordered the engineering personnel on the flight deck to fit blanks to all of the aircraft so that security sensitive areas were covered from observation. There was no flying during the transit period and no maintenance was done on the aircraft on the flight deck.

On the evening of 16 November 2022, two engineers were tasked with conducting a routine before flight servicing on BK18. The task was divided into two discrete activities with engineer 1 (Eng 1) conducting inspections of the engine and ejection seat, and engineer 2 (Eng 2) conducting inspections of the airframe, fluid/pressure levels and the lift fan. Eng 1 started their part of the servicing near the start of their shift, at around 2100. At the same time, Eng 2 was nominated to support an additional task requiring personnel to move storage containers around the hangar and so did not begin their element of the servicing straight away. Eng 2 had a further delay due to a storm warning preventing certain maintenance activities from being conducted. As a result, Eng 2 did not start their part of the servicing until after midnight. At no point were both Eng 1 and Eng 2 working on the aircraft at the same time.

To conduct the engine inspection, Eng 1 removed the right intake blank (Figure 1) and climbed down the intake to gain access to the front face of the engine. On completion of this task, they took the right intake blank down to the hangar for storage. When Eng 2 came up on deck to conduct their element of the servicing, they found the exhaust blank on the deck a couple of metres behind the aircraft. Eng 2 safely stowed this blank and upon completing their servicing took it to the hangar for stowage. The exhaust blank was the only blank Eng 2 observed in or around BK18 that night. Their part of the servicing required climbing into the cockpit which involved considerable activity immediately adjacent to the left intake. Neither engineer reported interacting with the left intake blank during their elements of the servicing.

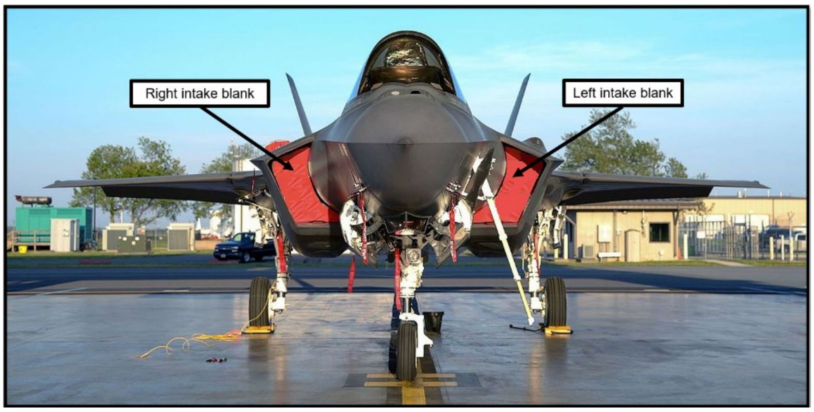

Figure 1: Representative image of an F35 with intake blanks fitted.

By the morning of 17 November 2022, the ship had reached the Mediterranean Sea and preparations were made for flying. The first flight launched at 06:45 and was conducted by a United States Marine Corps F-35B, as it took off it dislodged an exhaust blank from a parked aircraft (DSA, 2022). This blank was quickly recovered, and the second US aircraft was launched. Simultaneously the UK Engineering Officer recalled the night shift and sent them to the flight deck to recover all of the blanks that were still fitted to UK aircraft. As this was occurring, a second exhaust blank was seen to become dislodged at 07:45 and was lost into the sea as it rolled away. By 07:57 it was reported that all blanks fitted to aircraft on the flight deck had been removed and stored in the hangar.

The events of the accident

At 11:00 the pilot of BK18 conducted their pre-flight walkaround of the aircraft which included an inspection of both intakes, the exhaust, and a general visual inspection of the aircraft. An engineering see-off team assisted the pilot with preparing for flight. At 11:37 the pilot taxied BK18 to the runway and converted the aircraft to short take-off mode. At the direction of the Captain of the Flight Deck the pilot conducted engine run up checks, confirmed all engine indications were normal, selected take-off power, 97% Engine Thrust Request (ETR), and released the brakes (DSA, 2022). The pilot reported that the initial acceleration felt normal, but then decreased. On checking the engine displays they discovered that the power was low, at 74% ETR. The pilot then selected maximum power (100% ETR), but the engine continued to deliver lower than expected acceleration. Due to the resulting low speed of BK-18, the pilot attempted to abort the take-off but was unable to stop the aircraft before the end of the flight deck and ejected (DSA, 2022). The ejection was successful, the parachute deployed, and the pilot landed on the flight deck suffering only minor injuries. The aircraft impacted the sea and was seen to be afloat passing down the port side of the ship. The left intake blank was seen to float out of the Auxiliary Inlet of BK18 before it sank (Figure 2). The blank was subsequently recovered by a sea boat dispatched to recover all flotsam (Figure 3).

Figure 2: Left Intake blank floating out of the BK18’s Auxiliary Inlet.

Figure 3: Left intake blank recovered from the sea.

Methodology

The DSA led safety investigation involved several different organisations and multidisciplinary teams. The Service Inquiry panel adapted the Australian Transportation Safety Bureau methodology (Underwood, 2013) to tie together the work conducted by sub-teams and a Sequential Timed Events Plotting (STEP) analysis (Hendrick and Benner, 1987) was conducted to investigate the broader factors influencing the accident. Accident Factors were determined using the standard methodology for UK Service Inquires (MOD, 2008) that assigned factors into the following categories:

- **Causal factor(s).** 'Causal factors' are those factors which, in isolation or in combination with other causal factors and contextual details, led directly to the incident or accident. Therefore, if a causal factor was removed from the accident sequence, the accident would not have occurred.
- **Contributory factor(s).** 'Contributory factors' are those factors which made the accident more likely to happen. That is, they did not directly cause the accident. Therefore, if a contributory factor was removed from the accident sequence, the accident may still have occurred.
- **Aggravating factor(s).** 'Aggravating factors' are those factors which made the final outcome of the accident worse. However, aggravating factors do not cause or contribute to the accident. That is, in the absence of the aggravating factor, the accident would still have occurred.
- **Other factor(s).** 'Other factors' are those factors which, whilst shown to have been present, played no part in the accident in question, but are noteworthy in that they could contribute to or cause a future accident. Typically, other factors would provide the basis for additional recommendations or observations.

The Royal Airforce Centre for Aviation Medicine (RAFCAM) also conducted a HF investigation into the environmental and fatigue factors that contributed to the incident. RAFCAM used their own methodology, known as RAFCAM Accident Route Matrix (ARM), which was developed based upon the systematic and validated framework of the Human Factors Analysis Classification System (HFACS) (DSA, 2016).

Analysis

The panel identified 55 Accident Factors that led to the loss of BK18. The singular Causal Factor was that the left intake blank was at the front face of the engine compressor during the aircraft. A further 26 Contributing Factors were identified that enabled the causal factor to happen. A summary of the key areas of analysis are described below.

Design of the intake blanks

The function of an intake blank is to prevent foreign objects (known as FOD or Foreign Object Debris), from entering the engine when it is not in use and subsequently causing damage to the engine once it is started (MAA, 2023). Human Factors testing by the manufacturer of the blank design was limited to an assessment of the weight of the blank and the height above the ground that personnel would need to lift it during removal and installation. Testing did not consider the ability of engineers to correctly fit the blank so as to prevent FOD, nor to ensure that fitment could be carried out in accordance with a set procedure.

As part of the safety investigation a convenience sample of six engineers was taken as a preliminary test of the possible variance in successfully fitting the left and right intake blanks into an aircraft. Nine other aircraft with pre-fitted blanks were also sampled to account for any changes in the behaviour of the participants as a consequence of being observed (McCambridge et al, 2013). The installation of the blanks was found to vary considerably, with some installations having minimal contact with the aircraft intake's inner surface. The complex geometry of the intake often resulted in the inboard lower corner sitting proud of the airframe. Further engineering investigation determined that this inboard lower corner was a weak point that could cause the blank to rotate and topple (Figure 4) when a force equivalent to a strong breeze was applied (Barua, 2019). Once toppled, the blank was susceptible to further migration down the intake, beyond view, with the equivalent strong breeze force.

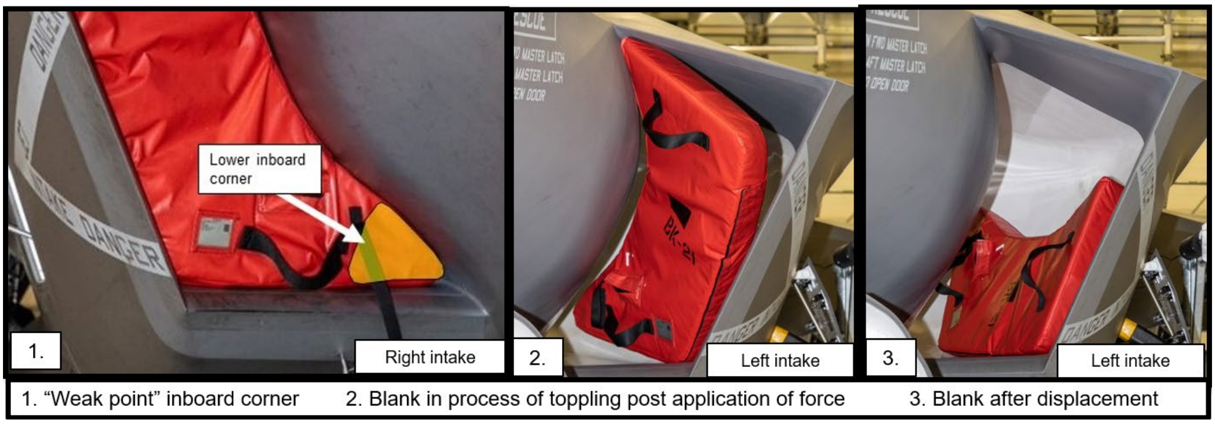

Figure 4: Images from trial demonstrating blank weak point.

The procedure in the maintenance manual for fitting and removing the intake blank was out of date and referred to an older, fundamentally different, blank design. The extant design featured a method of securing the blank to the airframe via a lanyard and pip pin that was not a feature of the design described in the fitment procedure. This meant that there was no method for the engineers to ensure that the intake blanks were fitted in accordance with the manufacturer's intent. The lanyard and pip pin were intended by the manufacturer to be the primary method of preventing the blank becoming dislodged due to weather. However, at the time of the incident the engineering management team had issued an order that the lanyard system should not be used as it was found to cause damage to the aircraft skin. The perception at the time was the risk of not using the lanyard was assessed as low and the possibility that a blank could become a hazard to the aircraft to which it was fitted was not considered since blanks are used to prevent FOD and do not normally cause it.

Blank usage

The dislodging of blanks from aircraft parked on the flight deck had become a normalised event, with intake and exhaust blanks being routinely blown out by modest winds or aircraft launching nearby. Due to the risk that these dislodged blanks could be lost overboard, the engineering management approved another local deviation from procedure that directed that Red Gear, the collective term used for the entire suite of blanks, was not to be routinely fitted to aircraft on the flight deck when the Ship was at sea. The only times it would be fitted were during port visits or if otherwise required for security reasons. This was why the blanks were not fitted to BK18 as the ship entered the Suez Canal, and why a GSSO had to order that the blanks be fitted for security purposes. This meant that the engineering management, who were located away from the flight deck, had no knowledge of the blank fitment. As a result, there was no order made to remove the blanks prior to the first flight of the day, when some became dislodged. This meant that the attempt to gather up all of the blanks was reactive and so, did not involve a full muster to ensure all items were accounted for. In the RAF, the fitment and removal of blanks is normally an engineering function carried out to protect delicate aircraft systems from FOD. The F-35B programme was unique insofar as blanks had another purpose, as a security measure to hide sensitive areas from view. This dual usage led to ambiguity of responsibility between security and engineering personnel, resulting in the installation and removal of blanks not being adequately managed.

Organisational experience

Op FORTIS was both the maiden operational voyage of the HMS QUEEN ELIZABETH and of the UK F35 force on embarked maritime operations. Op FORTIS was also the first operational deployment of a UK fast jet squadron on a UK aircraft carrier since the decommissioning of HMS ILLUSTRIOUS in 2014. As such, there was a lack of organisational experience of embarked operations across the F35 force with 55% of the squadron having some embarked experience prior to Op FORTIS. With the vast majority of the squadrons' experience coming from flying out of a land-based location, it was not until the commencement of Op FORTIS that it was discovered just how much carrier operations increased demands on see-off teams. Aircraft were required to be moved around the deck more frequently than was the case on an airfield, placing an additional demand on the workforce. Also, see-offs required more engineers to conduct additional tasks such as last-minute refuelling and management of the chains used to lash aircraft to the deck of the aircraft carrier. The combined effect of these additional burdens was that a larger engineering workforce was needed when embarked compared to land-based operations. This lack of maritime experience and preparation can be seen by comparing the staffing levels for the two embarked squadrons. The USMC squadron that had a greater experience of maritime operations deployed with 255 personnel while 617 Sqn deployed with only 113 personnel for a comparable number of aircraft. Whilst some of this difference was taken up by support staff there were between 50 and 60 additional engineers in the USMC squadron. 617 Sqn also sustained a high pace of flying throughout the deployment. Flying typically occurred 6 days a week with one day of no flying, scheduled as a rest day. It was also common for engineers to work on the no-fly day, so as to have the aircraft ready for the following day. The RAFCAM HF report determined that it was likely that engineering personnel were experiencing signs of cumulative fatigue after approximately six months of operation at a high tempo.

Blank management

In military aviation it is normal practice to account for 100% of the tools and items of support equipment that are used on an aircraft to prevent them becoming lost and an item of FOD. During Op FORTIS the aircraft blanks were managed using a locally produced log known as the "Red Gear log." Up until September 2021 this log was managed by a senior engineer in charge of manging the maintenance tasks on a day-to-day basis, thus providing a quick reference that blanks would need to be removed before clearing an aircraft for flight. After an amendment to the local procedure in September 2021 this responsibility was moved to the Issue Centre Custodian, a more junior individual responsible for issuing tools to engineers and located in an area of the ship away from the shift supervisors.

On the night before the accident, when Eng 2 brought the exhaust blank back to the hangar for storage there was no open entry in the Red Gear Log showing that the blanks had been fitted, with the last entry for BK18 being "blanks removed" on 07 November. Eng 2 concluded that the exhaust blank had been missed during an unrecorded cycle of fitment and removal and so gave no more consideration to the configuration of the Red Gear on the aircraft. On the rare occasions when Red Gear was fitted on the flight deck, failures such as this were so frequent and routine that they had been normalised by the engineers and did not prompt further action by the supervisors or the Issue Centre Custodian. This was partially explained by the fact that the Red Gear Log was not fit for purpose, as it could only account for an entire set of blanks being fitted or removed from an aircraft, when the reality was that there was frequent need for just certain items from a set to be used for certain maintenance activities. This led to the normalisation of maintenance personnel not using the log for all occasions. This explains why a 100% check of all the blanks was not carried out on the morning of the accident after the mass removal of blanks had been completed. This was the last opportunity to notice that the left intake blank in BK-18 was missing.

Safety Management System

Whilst there had been numerous low level occurrence reports involving aircraft blanks on UK F35-B's submitted prior to this incident, none of them occurred in a manner that would have enabled the UK Safety Management System to foresee this accident. However, given that the F-35 was an international programme, UK reporting was but a small piece of the overall global picture and further analysis found four incidents of US F35 aircraft ingesting intake blanks on engine start up. Two of these incidents were very similar to the incident involving BK18 except that they both occurred at land-based, standard length, airfields rather than on an aircraft carrier with a shorter runway and as such they had very different outcomes. In both incidents the longer runway allowed the pilot to compensate for the power reduction by either successfully taking off or aborting. As these incidents only resulted in minor consequences the local investigations did not examine the organisational factors that led to the blank not being removed prior to flight.

The in-service risk to life model used by the UK Platform Delivery team considered loss of thrust caused by a loss of airflow to the engine as a credible risk to the aircraft type. However, the model did not consider that intake blanks could be the cause of an airflow restriction as the assumption was that all maintenance tasks would be done correctly, and so human error was not accounted for.

Recommendations

The panel made 46 recommendations to mitigate against a reoccurrence of a similar accident in the future. Each recommendation was directly linked to an accident factor identified by the analysis, thus covering the full breadth of issues from local factors to organisational issues. Examples of the recommendations made include:

- Ensuring that security considerations are included during engineering planning in order to maintain airworthiness whilst necessary security measures are implemented.

- Ensuring Red Gear is managed in line with extant tool control and aircraft maintenance documentation processes so that its installation on aircraft can be accounted for at all times.
- Ensuring that the blank fitment procedure is clarified and standardised across the F35 force.
- That an assessment be made on the performance of blanks whilst being used in both the land environment and during embarked operations in order to ensure they are fit for purpose.
- That safety reporting from all global users of the F35 is shared between nations.
- To develop a warning to the pilot of a mismatch between commanded and delivered thrust prior to commencing a take-off.
- Ensuring that fatigue management plans are in place for future F35 deployments and that the staffing levels are realistically assessed against the required task output.

Conclusion

This incident highlights the importance of considering Human Factors throughout the lifecycle of an aircraft to create an iterative process of design and in-service review. The initial Human Factors assessment of the blank design only considered the risk to the operative and made no assessment of whether the task could be completed safely, while still following a set procedure and achieving the intended outcome. This allowed a less than adequate design to enter service and without a valid process for removal and installation. Opportunities to identify the inadequacies of the design through in-service occurrence reporting were not acted upon due to the basic level of investigation that was conducted and the lack of data sharing between nations that operated the F-35. Had in-service data from occurrence reporting been factored into the risk to life model used by the UK Platform Delivery team it would have negated the assumptions made regarding perfect human performance and demonstrated a credible route to an alternative loss of thrust on take-off.

The inadequacies of the blank design were a latent error in the system of systems that surrounded the operation of the F-35. As is so often discovered to be the case in accident investigation, it was not until the context of the situation changed that the significance of the latent error became apparent. In this case it was the change of operating environment from land-based airfields to an aircraft carrier that changed the severity of the outcome from low to catastrophic. The lessons identified in this case study have applicability across all safety critical sectors and activities and firmly make the case for Human Factors Integration in system design.

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