Journal of the Australasian Society of Aerospace Medicine (JASAM) No.13 (2024) 40-47
10.2478/asam-2024-0007

THE ANATOMY OF A WARBIRD – AN ERGONOMIC STUDY OF THE SUPERMARINE SPITFIRE

(1)

Dr. Anthony Rengel

anthony@rengel.com.au

INTRODUCTION

To achieve the peak performance of a pilot and their aircraft, cockpits need to be designed with optimal integration between human and machine. With any engineering design, there are numerous competing factors, including the aircrafts' role and mission, top speed, range, ceiling and payload. However an often-overlooked area is the ergonomics of the cockpit.

Ergonomics is the field of study concerned with psychological and physiological interaction with engineering and design[2]. Whilst modern aircraft, such as the Airbus family, have thoroughly thought-out cockpit design regarding the pilot operating it[3], traditionally aircraft have been designed with ergonomics as an after-thought. Uncomfortable seating and minimal insulation were provided, with rudimentary control systems and instruments placed without order.

Whilst technology and science have advanced considerably to allow for the design of more comfortable and functional cockpits, there is great value in performing retrospective analysis of vintage aircraft and learning from their development. By taking this approach, we can learn from the iterative processes across many generations of aircraft and examine the impact of evolving cockpit ergonomics on both pilot and aircraft performance.

One of the most iconic fighter aircraft of all time is the Supermarine Spitfire. Seen as the symbol of the Battle of Britain and the fighting spirit of the Royal Air Force (RAF) during the Second World War, it was in service from 1937 to 1958 in multiple countries, operating from the Arctic Circle to the Tropics[4, 5]. It was also universally loved by the thousands of pilots who flew it, owing to its inspired design and graceful handling.

For this paper, the author has drawn on their own personal experience of flying in a Mk IX Spitfire and a Ha-112 Buchon (Spanish-built Messerschmitt Bf-109 variant) at Sywell Aerodrome in 2018[6]. This has been supplemented by previous flight experience in other vintage aircraft including a Beach 18, De Havilland Chipmunk and Tiger Moth. In addition, an assessment of a F.22 Spitfire located at the Bull Creek Aviation Museum in Western Australia[7] was undertaken, as well as a review of modern journal articles and historical documents. The purpose of this paper is to illustrate some of the core aspects of cockpit design of the 1940s and iterate the relevance of the findings based on modern ergonomic knowledge.

HISTORY OF THE SPITFIRE

During the early 1930s, a rapid evolution in aircraft design was occurring. As engine and material technology improved, aircraft were able to fly higher, faster and further than before. In particular, the field of aerodynamics was undergoing a revolution with the advent of wind tunnel testing, allowing designers to test prototype models on the ground prior to production.

Despite these advances, in the early 1930s the RAF was still primarily equipped with biplanes which had only undergone modest improvements since the end of the First World War. With the rise of fascism in Europe and Japan's desire to grow its Empire in the east, the RAF recognised that they were inadequately prepared for a major conflict in the next decade. It was thought that, unlike the First World War, the next major conflict would feature high-speed bombers flying across the continent and bombing cities. Therefore, well-armed interceptors with good rate of climb and level speed would be required.

The initial design for the Spitfire traces back to the Supermarine Type 224, designed by Reginald Mitchell and built to Air Ministry specification F.7/30[4, 8]. This called for a top speed of 250mph, a rapid rate of climb and armament of 4 machine guns. However it failed to reach the desired performance and lost out to the Gloster Gladiator biplane. The Air Ministry later released specification F.5/34, which called for a faster aircraft, armed with 8 machine guns[8]. Hawker developed a submission eventually accepted as specification F.36/34 – becoming the Hawker Hurricane. Whilst faster and more powerful than existing RAF frontline fighters, it was ultimately an evolution of previous aircraft - using a predominately wooden spar and canvas construction and a thick chord wing, combined with modern features of an enclosed cockpit and retractable undercarriage[4, 5].

Supermarine, on the other hand, were developing a more modern design, using their experience with the Schneider Trophy and taking note of the developments in Germany and the USA[4, 5]. They designed a highly streamlined all-aluminium alloy, semi-monocoque aircraft with distinctive elliptical wings. This wing featured a low thickness-to-chord ratio aerofoil, which produced less drag and resulted in higher speeds compared to contemporary designs. This aircraft, designed to specification F.36/34, was to become the famous Supermarine Spitfire[4, 5, 8].

It could not have come at a better time. In violation of the Treaty of Versailles, the German Luftwaffe was secretly re-equipping. Bayerische Flugzeugwerkes, with their lead designer Willy Messerschmitt, went on to design the infamous Bf-109 – the most produced fighter plane in history[9]. Shortly after the Spitfire was ordered into production, Nazi Germany shocked the world when it unveiled the Bf- 109 at the Berlin Olympics in 1936[9]. Later equipped with the powerful Daimler-Benz fuel-injected inverted V12 engines, the Bf-109 rapidly went on to break world speed and performance records, as well as bring aerial warfare to the shores of Britain.

Throughout its lifetime, 20,315 Spitfires were produced in 24 major variants as well as various naval carrier variants (known as the "Seafire")[4, 5]. It more than doubled its power output (890hp Merlin I to 2050hp Griffon 65), doubled its maximum take-off weight, tripled its weapon stopping power, increased its top speed from 300mph to 441mph and rate of climb of 2000ft/min to 5040ft/min. It served in all theatres of WW2, acting not just in a land-based interceptor role, but in photoreconnaissance, ground attack/fighter bomber, carrier aircraft and as a trainer[4, 5]. We will now discuss its cockpit and systems in detail.

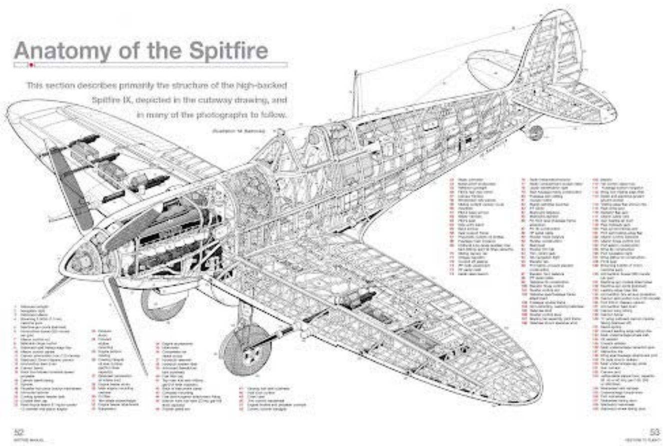

Figure 1. Cutaway of the Mk IX Spitfire (adapted from Price and Blackah, 2007)[5]

GENERAL DESIGN

The overall exterior dimensions of the Spitfire cockpit are approximately 1500mm tall, 800mm wide and 2000mm long. Whilst not particularly spacious by modern standards, this is comparable with other cockpits of the era. Despite the establishment of the Medical Flight in 1917[10], the RAF did not set clear anthropometric limitations on fighter pilots until after the war (following the advent of the ejector seat). As encountered, the author, with his 183cm height and medium waist, wearing a flying suit, boots and modern helmet fit comfortably in the cockpit. In comparison, within a Ha-112 Buchon, the author had their elbows against the fuselage and was restricted to wearing a soft leather helmet as a modern helmet would not clear the canopy.

Image 1. Spitfire F.22 Cockpit entry. Car door, seat, spade grip, landing gear actuator, gyroscopic gunsight and part of instrument panel are seen here.[1, 7]

The seat on the Spitfire was a height-adjustable simple bucket seat, which was standard at the time. RAF pilots were issued and wore the Seat-Type Parachute[11] – which fitted nicely into the seat and provided some comfort to the pilot. They were secured by a standard 4-point Sutton harness, though the model the author flew in featured a modern quick-release harness. Unlike modern ergonomic seats, it does not have sufficient backrest tilt or lumbar support to optimize pilot comfort[12], however the author didn't experience any significant discomfort during a 30 minute flight.

Image 2. Spitfire F. 22 cockpit. Seat (with height adjustment lever and harness), spade grip, rudder pedals, landing gear actuator, trim wheel and part of instrument panel seen. A pillow is provided for comfort in place of the Seat-Type Parachute.[1, 7]

It was noted that throughout the cockpit that there are many exposed conduits, tubes, valves and control linkages. To save on weight and for ease of serviceability, many components in the cockpit are not covered up. This is unlike many commercial aircraft at the time, which featured insulation [Image 5]. As encountered by the author, there are sharp edges in which the pilot could scrape oneself against. In addition, loose items, stones and dirt can easily become lodged amongst the frames and interfere with rudder pedals and control cables.

As well as lacking insulation, there is no cabin heating system and besides small cabin air vents for cooling, thermal protection was provided by the uniform worn. Most RAF pilots in the Battle of Britain era wore the standard woollen Battle Dress tunic which provided adequate warmth for European theatre operations with some fire protection[11] [Image 3]. In the desert and tropics, the standard Tropical Dress uniform was worn, which provides virtually no fire protection[11] [Image 4]. To improve upon aircrew protection, dedicated flight suits as the Sidcot suit and integrated parachute suits were trialled[11]

Images 3 and 4: RAF Battle Dress (left), RAAF Tropical dress (right).[1, 7]

INSTRUMENT PANEL

Many early military aircraft had no consistency in terms of the choice and placement of instruments within the cockpit. With the development of the artificial horizon, the possibility of flying in poor visibility became possible and further consideration was given to instrument layout. Many US manufacturers during the 1920s started to offer more standardized sets of instruments, grouped together as blind flying panels. Early examples are seen below from Boeing [Figure 2] and Douglas [Image 5].

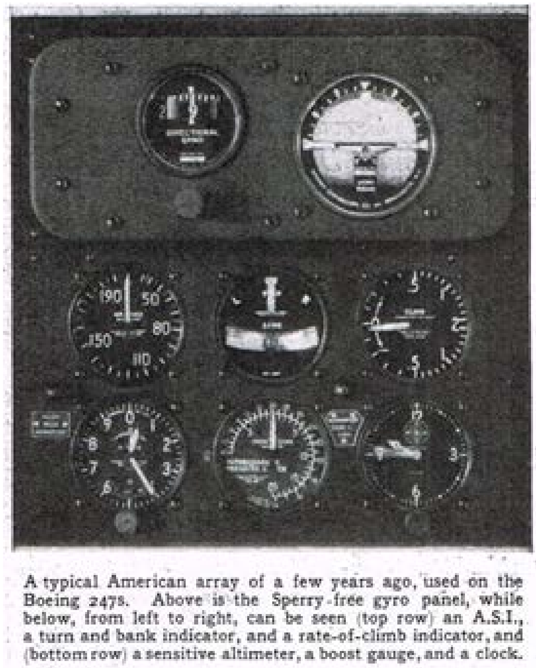

Figure 2. Boeing 247 instrument panel (adapted from Williamson 1937).[13]

Image 5. C-47 Dakota cockpit. Note the central instrument cluster for blind flying. There is also insulation throughout the cockpit for pilot comfort.[1, 7]

One of the unique features of RAF aircraft of the late 1930s and 1940s was that almost all types featured a near-identical and standardized set of primary flight instruments. The Service Blind Flying Panel was introduced in 1937 (Figure 3) and was a standardized unit that could be fitted to numerous types of aircraft[13]. The artificial horizon formed the core of the instrument six pack and allowed the convenient 'T-scan' across the primary instruments – a technique still taught to student pilots today[2].

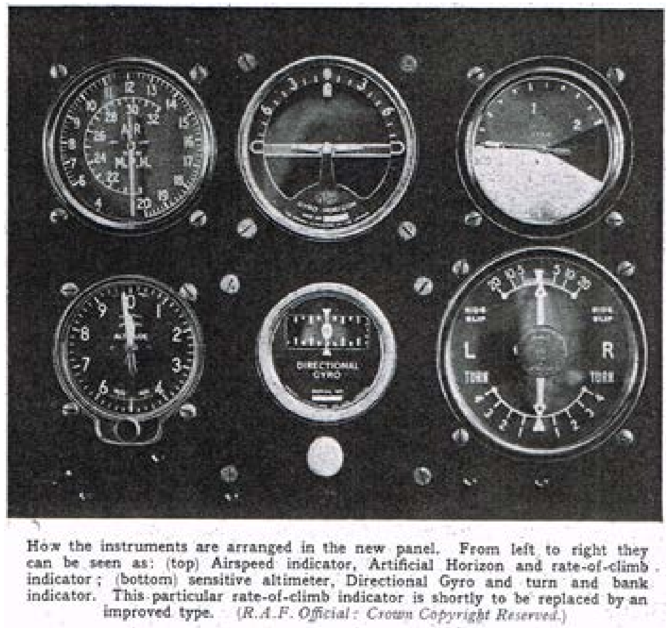

Figure 3. RAF Service Blind Flying Panel (adapted from Williamson 1937).[13]

Whilst there were incremental upgrades to the panel with the development of newer instruments, functionally all were identical between aircraft models. This standardization of instruments greatly reduced type training and allowed a consistent approach to teaching recruits. Of note, overall pilot training time did increase from 40 weeks in 1941 to 72 weeks at war's end, however this is attributed to advancing technology and training[14]. Furthermore, it reduced design and production costs, whilst allowing for a surplus of spare parts that can be interchanged between different aircraft (Images 6 & 7).

Image 6. Spitfire F.22 instrument panel, featuring the Blind Flying Panel. Note the ancillary engine gauges to the right, as well as oxygen system controls to the left.[1, 7]

Image 7. Lancaster B2 instrument panel. Despite the vastly different role and configuration of the Lancaster bomber, it features a near identical Blind Flying Panel.[1, 7]

The secondary instruments, including engine RPM, temperature, pressure and boost plus ancillary systems including oxygen are located just outside the blind flying [Image 6]. None of these secondary instruments are obscured by the flight controls however they are not within the normal scanning area. As they ae not considered critical to the safe operation of this aircraft the author believes their placement is adequate.

An important concept of cockpit design is the design eye level [(DEL)(2)]. When seated with head and eyes neutral, the pilots' line of sight should generally site just above the dashboard, allowing them to see to the aircraft's nose. Within 30 degrees of the eye level (which corresponds to eye movement if head is neutral) is the optimal position to place important instruments and warning lights to optimize visual information processing[2]. When we look at the Spitfire cockpit, at the DEL is the reflector gunsight. This is intentional to allow the best possible visual focus for tracking and shooting down an enemy aircraft. However, within 30 degrees inferior of the DEL is the blind flying panel, with the artificial horizon centre.

Image 8. Gyroscopic gunsight of the Spitfire F. 22. This image was taken at the DEL.[1, 7]

During a retrospective video analysis of the authors flight in a Spitfire, it was noted that minimal head movement was required to view the instruments whilst keeping aware of the outside world [Image 9]. When compared to the Ha-112, which features a less orderly panel and with performance instruments below the DEL [Image 10], the author had to keep shifting head position to view all instruments. By having more time looking into the cockpit, this would mean the fighter pilot risks missing the spotting of enemy aircraft outside – which may be fatal.

Image 9. Spitfire Mk IX cockpit. The author is seen here in the rear cockpit. Note that the blind flying panel sits just below DEL and within the 30 degree arc for optimal viewing.[1]

Image 10. Rear cockpit in Ha-112 Buchon. The instrument panel sits well below the DEL and 30 degree viewing arc. Note the tight canopy clearance. (Image adapted from Ultimate Warbirds)[6]

FLIGHT CONTROLS

The Spitfire features a conventional fighter control layout, with throttle, RPM and pitch controlled by the left hand, with right hand to control ailerons and elevators, with feet on the rudder pedals. The main flight control was a unique variant of the joystick known as the spade grip. Whilst still controlling pitch via the X-axis, for roll the grip pivoted half-way along the stick in the y-axis. This allowed for full authority in roll without significant movement in a small cockpit. The grip also featured the trigger button and the main wheel brake lever[5, 15-17]. It is clearly seen in Images 1 & 2.

The Spade Grip also had the advantage in that it allowed pilots to safely switch between flying right and left-handed to free up a hand to perform other tasks. This was done by using the hand-over technique. For example, after take-off the pilot must retract the landing gear[15-17]. They first remove the left hand from the throttle, placing it on the grip before moving the right hand to the landing gear lever[15-17]. One distinct disadvantage was seen in the first 147 models in which a manually pumped gear lever was used. With one hand still on the grip, this often-caused pilot- induced oscillations and resulted in a few accidents until this flaw was resolved[4].

Flying with the Spade Grip was highly intuitive and easy to use as experience by the author, both in level flight and aerobatics. The controls were balance beautifully with responsive roll and solid predictable yaw input. The elevators on the Spitfire were sensitive and hence graceful small inputs were needed to make it respond. Even at higher speeds the controls were easy to use.

VISIBILITY, PROTECTIVE SYSTEMS AND EMERGENCY ESCAPE

The Spitfire features a blown Perspex canopy, with a framed armour glass windscreen[5]. Earlier model Spitfires featured a high-backed fuselage, which when coupled with an armoured headrest, does obscure part of the rearward view[5]. This was overcome by the placement of a rear-view mirror. Later models, such as the Mk XIV and Mk XVI, introduced a bubble canopy, which gave fantastic 360-degree view [Image 11]. When compared to the Bf-109, which features a thick framed canopy[9] [Image 10], the Spitfire has great visibility.

Image 11. Bubble canopy feature on the F.22 Spitfire, showing rear armour plating and fantastic all-round visibility.[1, 7]

As the service ceiling of most models exceeded 35,000ft[15-17], the carriage of oxygen was a must. In early models, this was provided by high-pressure bottled oxygen that was fed into the pilot's mask via a regulator on the left of the instrument panel[5, 15-17]. The disadvantage of this system is that it flowed regardless of the stage of the respiratory cycle. When fully open, the system would deplete the supplies quickly, requiring the additional weight of more bottled oxygen[11]. The Royal Aircraft Establishment had already developed an economiser to reduce oxygen use[18], which connected to the low-pressure line from the regulator and featured a flow-sensitive valve that was triggered from negative pressure due to inhalation[18]. This was retrofitted to earlier models[11] and made standard from the Mk V onwards[19].

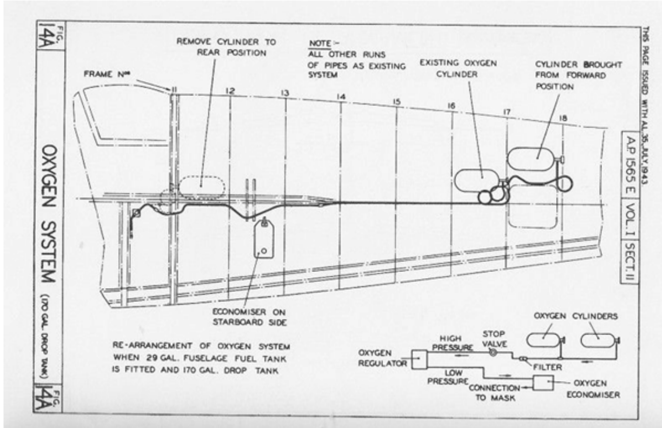

Image 12: Oxygen system of later Spitfires modified with the economiser.[19]

In the early model Spitfires, 100% ethylene glycol coolant was used, which was highly flammable and due to the design of the main return pipe and engine water jacket, a common cause of engine fires[4, 5, 15]. The two main fuel tanks were in front of the cockpit, and neither were armoured or self-sealing in early models[4, 5, 15]. Therefore, cockpit fire was an ever-present threat and the pilot had to bail out quickly to survive.

To escape, pilots had to open the canopy, underdo the Sutton harness, disconnect the oxygen mask and communications[4, 15-17]. Then they must either a) open the car door to go bail out over the wing, b) invert the aircraft to fall out, or c) push the aircraft into a negative G dive and jump[4, 15- 17]. Sadly, one of the early design faults of the Spitfire was the slide rail often jammed and latching mechanism required two hands to operate – which proved difficult if the aircraft was in uncontrolled flight. Many pilots burnt to death or drowned during ditching as a result[4]. In later models, including the Mk IX and F. 22 examined, a simpler one-handed ball-toggle mechanism was used to release the canopy [Image 12]. In addition, armoured and self-sealing fuel tanks were added, with coolant changed to a non-flammable 60:40 ethylene glycol to water mixture[4, 5].

Image 13. Spitfire Mk IX rear canopy. Excellent rearward visibility is seen here (even with the high rear fuselage), as well as the later model ball-toggle canopy release. (Image adapted from Ultimate Warbirds)[1, 6]

CONCLUSION

Overall the Supermarine Spitfire is a product of its time, however it highlights the best of the innovation of the era. The use of a standardized instrument cluster in the Service Blind Flying Panel echoes modern human factors theory that advocates for easy-to-read, well laid out instruments to reduce cognitive workload during the demands of instrument flying – particularly for pilots who operate across different aircraft types. The Spitfire also features a degree of the automation that we have become familiar with today, with retractable undercarriage and pneumatic flaps. The Spade Grip was a unique British feature, yet it demonstrated to the author how intuitive and easy it was to use, particularly with the hand-over technique.

In direct comparison to the Bf-109, two different design philosophies are seen. Whilst in many aspects the Bf-109 was technologically superior, particularly its engine and management systems(9), the cockpit is cramped with instruments not placed within the DER nor thought given to the workflow and cockpit scan of the pilot. Whilst a fantastic aircraft to fly in its own right, the design approach is more clinical compared to the almost organic, pilot-orientated design of the Spitfire. Whilst the protection and escape systems seem wanting when compared to modern fighter aircraft, the evolution and design changes seen during the Spitfire's service life recognised the importance of developing more robust escape mechanisms. The experiences of those brave fighter pilots during the War that lead to the eventual development of the ejection seat(20).

As experienced by the author, the Spitfire was a graceful aircraft to fly with well-balance controls and a reasonably well-thought-out cockpit layout. It was no surprise that this aircraft was loved by the thousands of pilots who flew it across its service life. It stands today as a testament to British aircraft design and as a historical highpoint in the development of modern aircraft.

Image 13. The author in Supermarine Spitfire Mk IX ML407 – known as the Grace Spitfire, following a 30-minute sortie.(1)

REFERENCES:

1. Rengel A. Personal Photographs. 2021.
2. Robson D. Human Being Pilot: Human Factors for Aviation Professionals. Huntingdale, VIC: Aviation Theory Centre; 2008.
3. Cockpits: Airbus; 2021 [2021-Oct-30]. Available from: https://www.airbus.com/aircraft/passenger-aircraft/cockpits.html.
4. Nichol J. Spitfire: A Very British Love Story. UK: Simon & Schuster; 2018.
5. Price A, Blackah P. Supermarine Spitfire 1936 onwards (all marks) Owner's Workshop Manual. Somerset, UK: Haynes Publishing; 2007.
6. Ultimate Warbird Flights 2021 [2021-Sep-30]. Available from: https://www.warbirdflights.co.uk/.
7. Aviation Heritage Museum 2021 [2021-Sep-01]. Available from: https://aviationmuseumwa.org.au/.
8. Meekcoms KJ, Morgan EB. The British Aircraft Specifications File. London: Air Britain; 1994.
9. Blackah P, Lowe MV. Messerschmitt Bf109 1935 onwards (all marks) Owner's Workshop Manual. Somerset, UK: Haynes Publishing; 2009.
10. Hopson JA. R.A.F. Medicine—The First 50 Years. BMJ. 1968;4(5622):48-50. doi: 10.1136/bmj.4.5622.48.
11. Rood G. A Brief History of Flying Clothing. Journal of Aeronautic History. 2014;1:3-54.
12. Goossens RHM, Snijders CJ, Fransen T. Biomechanical analysis of the dimensions of pilot seats in civil aircraft. Applied Ergonomics. 2000;31:9-14.
13. Williamson GW. Instrument Planning. The New Service Blind Flying Panel Described. Flight. 1937;Aug-19:193-5.
14. Royal Air Force Museum. Pathway to Pilot: Second World War 2022 [2022-May-12]. Available from: https://www.rafmuseum.org.uk/research/online-exhibitions/taking-flight/pathway- to-pilot/second-world-war/.
15. Air Ministry. Pilot's Notes The Spitfire I Aeroplane Merlin II or III Engine. A.P.1565A Vol I. Air Ministry, 1941.
16. Air Ministry. Pilot's Notes Spitfire VA, VB and VC Aircraft and Seafire IB, IIC and III Aircraft. A.P.1565E Vol I Sec I. Air Ministry, 1943.

17. Air Ministry. Pilot's Notes for Spitfire IX, XI and XVI. A.P.1565J 3rd Edition. Air Ministry, 1946.

18. Royal Aircraft Establishment. Oxygen Economiser Apparatus. Test of Economiser Unit Mask Valve RAE Inst. Tech Note 413. Farnborough: Royal Aircraft Establishment, 1940.

19. ir Ministry. Spitfire VA, VB and VC Aircraft and Seafire IB, IIC and III Aircraft Maintenance and Descriptive Manual. A.P.1565E Vol I Sec II. Air Ministry, 1943.

20. History & Founders United Kingdom: Martin-Baker Aircraft Co Ltd; 2021 [2021-Oct-30]. Available from: https://martin-baker.com/about/history-founders/