The Road to JSF: Forty years of UK ASTOVL work and its impact today

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Abstract
Since 1960 BAE Systems and its predecessor companies have engaged in significant test work in the field of supersonic ASTOVL (advanced short take-off and vertical landing) combat aircraft, in addition to their experience of developing, producing and supporting the Harrier family. This paper seeks to show how this effort has provided deep foundations on which to build their major stake in the JSF project.

The paper provides a brief overview of the tests undertaken in the UK over the last five decades, although it concentrates on two periods of major activity, 1960-65 and 1980-89, with a few of the most significant aircraft projects from those periods looked at. It aims not to present the project design work undertaken on ASTOVL aircraft, but rather to show the significance of the research and technology programmes associated with those designs. The knowledge gained from sub-scale and full-scale model tests is looked at, and the impact and use of this knowledge in the JSF assessed.

Introduction
Testing is central to the successful design and development of all aircraft, from wind tunnel tests to structural and systems tests, as well as flight test. For V/STOL aircraft additional areas of testing are often required, as well as extensions to areas of work common to other aircraft types. This paper will focus on scale model testing in the UK, carried out as part of the design and development of ASTOVL combat aircraft.

Scale model testing can have two main purposes, to evaluate an aircraft configuration or to establish a data base out of which later designs can be used. Perhaps the classic case of the latter is the work carried out in the early twentieth century that led to the evolution of the NACA series of aerofoils that are still widely used. Although much of the NACA wind tunnel design work was carried out using models of particular aircraft types, the data produced on the impact of individual aerofoils could be used much more widely (Ref. 8). The data and the configuration were separable.

It is also possible to carry out scale model tests to help develop a particular configuration where the data produced is not readily separable from the aircraft being modelled. This has proven to be a particularly important aspect of ASTOVL model testing, with the main contribution to other projects being the experience gained of the peculiarities of ASTOVL design problems.

Both approaches to model testing have been used in the UK as part of the decades-long efforts to develop an ASTOVL aircraft to succeed the Harrier.

ASTOVL studies and model testing
Two main areas of effort that were particular to ASTOVL work are of concern here, jet effects in vertical flight and the wind tunnel testing of V/STOL modes of flight. Sub-scale model tests has proven vital to both areas as the highly unstable nature of the hot gas fountain flows produced by jet engines are not amenable to classical analysis. Alternative approaches, such as computational fluid dynamics (CFD) have proven difficult to use to model such flows, both due to their unsteadiness and the resource intensive nature of evaluating multiple data points. Sub-scale models can produce large amounts of data quickly, once they have been set up and calibrated (Ref 4).

Jet effects
In conventional flight the exhaust stream issued from the engine(s) of jet aircraft are left behind. In a hovering V/STOL aircraft the exhaust is pointed downwards and tends to leave the aircraft around the centre of gravity of the fuselage. As it does so it can cause two main problems. Firstly, in close proximity to the ground the highly energetic exhaust impinges directly onto the ground below. If there are a number of separate, spaced out jets the flow from them will strike the ground separately and spread out horizontally. The point at which the

inward horizontal flows meet can produce a strong vertical jet fountain rising back up towards the aircraft. This adds a degree of additional lift where it strikes the aircraft, but it can flow around the aircraft and be recirculated back into the engine inlet, reducing thrust, just when it is needed most, in a phenomenon known as Hot Gas Ingestion (HGI), also possibly causing engine 'surge' and catastrophic loss of power (Ref. 7).

In addition, the outward jet flows that do not meet each other (or all of the flow for a single jet) turn horizontally and flow along the ground in a 'ground sheet' or 'wall jet'. Along the top surface of this wall jet air from above is entrained, flowing outwards and drawing in air from above. This adds to a similar downward entrainment flow acting around the vertical jets themselves. This entrained flow produces a high pressure region above the aircraft and a low pressure one beneath it, creating a phenomenon known as 'suck down' which produces lift losses, increasing the aircraft's rate of descent close to the ground, requiring additional thrust to offset it and prevent a 'hard' landing. This additional thrust can come from the upwards fountain resulting from the use of well-spaced jets if the configuration used produces one, but the overall magnitude of the lift loss encountered is highly dependent on the configuration of the aircraft and the resulting total of suck down forces, HGI thrust losses and fountain lift in combination (Ref. 7). Figure 1 shows these effects on a Harrier.

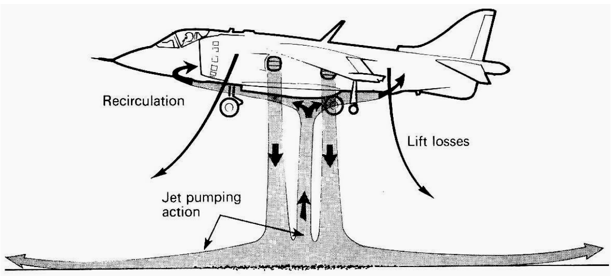


Figure 1.
The 'jet pumping' action of the jets from a V/STOL aircraft can produce lift losses as well as a central fountain that rises up to strike the aircraft. The latter can add lift, as well as reducing thrust by being recirculated into the engine as HGI. Copyright Rolls-Royce PLC.

V/STOL testing

All these jet effects in vertical flight are highly unstable and make additional demands for control of the aircraft in jet-borne flight. In addition, in the transition between jet and wing-borne flight the complex jet flows around the aircraft can reduce wing lift or produce destabilising effects on the aircraft that add to the control difficulties encountered. This has major implications for piloting the aircraft. A well known example is the problem of inlet momentum drag on the Harrier, where the aircraft becomes destabilized over a range of airspeeds between zero and fully wing-borne flight thanks to the effect of a large mass of air entering the intakes effectively being brought to rest ahead of the centre of gravity, producing a force that can be too large for the aerodynamic and reaction control systems to overcome.

The effect of inlet momentum drag was partially explored using low speed wind tunnel tests of the P.1127, in addition to a number of special facilities used by Hawker Siddeley, the company that developed the Harrier, to test other aspects of the design. Two rigs were built in the 1960s at Hawker Siddeley Kingston to test jet effects using sub-scale models. One used a fixed aircraft and a moving ground board to measure lift losses in jet borne flight, while another rig used a mounting for the models that could vary their height over the ground in order to estimate the effects of HGI with height. In both cases compressed air or hot gas was supplied to the aircraft nozzles via pipes around which the model was mounted, with intake flows simulated by using a large pipe to suck air in through the models intakes (Ref. 6). Such pipework is needed on all V/STOL models, but represents features that are not found on actual aircraft and therefore the possible distortions they can introduce to test results need to be understood and allowed for in results.

However, these specialized tests at Kingston, as well as the conventional low speed wind tunnel testing carried out by Hawker Siddeley, could not integrate all the effects of V/STOL flight, which were fully explored only during actual flight tests of the P.1127. In order to explore these areas more fully using sub-scale models, the Britsh Aircraft Corporation (BAC) at Warton built a specialized V/STOL wind tunnel in the early 1960s in which they carried out a great deal of testing on models.

1960s configuration tests at Warton

Recognising that vectored thrust was not the only possible solution to V/STOL, the UK also produced the successful Short SC.1 research aircraft, which utilised multiple lift jets. This led to a number of alternative approaches to ASTOVL aircraft design being explored, such as the number and position of lift jets, in model tests at Warton over many years, as part of their overall ASTOVL design efforts, which began with a joint programme with the French Dassault company.

As a result of a competition to meet a NATO need for a common V/STOL strike fighter Dassault developed the Mirage IIIV, which followed the Short SC.1 approach in using a battery of dedicated lift engines for vertical flight, with a single cruise engine for forward flight. BAC Warton agreed to join with Dassault if the Mirage IIIV won the competition. Although Warton had no direct role in designing the Mirage IIIV they had been busy on exploring the underlying technologies in recent years, and this work was ongoing at the time.

Warton chose to develop their knowledge by using their V/STOL wind tunnel. This was capable of evaluating aircraft throughout their low speed and vertical flight regimes. In addition to exploring purely jet-borne flight Warton also saw the need for research into the effects of the interaction of the airflows from propulsion systems with the ground, ambient air and the airframe of the aircraft. This work had begun in the late 1950s with tests on hovercraft models mounted on a simple frame, with no outside airflows.

These tests were followed with simple tests on a plywood triangle hung from a strain gauge, with tubes passed through it used to simulate jets using compressed air. With these in operation it was possible to measure the 'lift loss' caused by the air flows, and by the variation of the position of the nozzles it was possible to see how these could affect the overall losses. A small fan was then added to simulate the incremental forward flight of transition, and the losses measured. This relatively simple work, similar to the test rigs at Kingston, showed that such variations in the arrangement of the jet nozzles could have significant effects, and encouraged the development of the larger wind tunnel specifically to support project work on V/STOL aircraft (Ref. 3).

This took the form of an 18 foot square section wind tunnel, opened in 1963, with special support structures that allowed model aircraft to be supported within it and to have compressed air fed to their jet nozzles to replicate the propulsion system of an aircraft. This was later enhanced with the ability to add the functions of engine air intakes to enable the full range of airflows about a model to be replicated, as well as a moving belt on the floor to simulate ground movement during transition, this being necessary as the wind tunnel floor created a boundary layer of air that was not present in the real world, where aircraft moved relative to both the ground and the air (Ref 3).

Tests on ASTOVL models in this tunnel involved the full range of speeds and heights from the ground that would be experienced during hover and transition. This wind tunnel was used in addition to the small scale rig, which was often used for early tests of configurations before larger models were built for the main wind tunnel. These tests during the early 1960s included models of generic, fighter-like, shapes as well as models of proposed BAC aircraft projects. In addition, Warton undertook tests on the positioning of the lift jets of the Dassault Mirage IIIV in support of their own joint bid to meet the NATO requirement. This was as a result of Warton's work indicating that the tight grouping of the Mirage IIIV's lift jets would result in significant lift losses.

Earlier tests at Warton had shown that the existing Mirage IIIV configuration could lead to a lift loss of 50% near to the ground. This was borne out when Dassault tested the Balzac technology demonstrator for the Mirage IIIV, as well as the two prototype Mirage IIIV aircraft built later, when peak lift losses of 55% were experienced. This was a serious problem, effectively halving the aircraft's vertical thrust and leading to a loss of mission performance or, more seriously, a risk of crashing (the single Balzac prototype crashed twice, killing its pilot in each case, and one of the Mirage IIIV prototypes also crashed). In particular, during transition altitude was lost, and it became necessary for the Mirage IIIV to climb to relatively high altitude on its lift engines before carrying out a dive to begin transition.

Tests on a modified Mirage IIIV model in the Warton wind tunnel, with the lift engines in a more spread out configuration, indicated that the lift loss during transition could be reduced to 20%. The Warton project design group, armed with the knowledge they had from the tunnel tests, proposed a modified aircraft, the Mirage 14V, but this was not adopted. However, Warton learned a great deal about how the number and position of jets could affect an aircraft in vertical flight and transition in combination with other factors such as wing shape and position. Figure 2 shows a sample of the configurations tested in the wind tunnel at Warton during the 1960s.

This work led to an important understanding of the effects of nozzle spacing on lift during aircraft transition that static tests had not fully revealed.

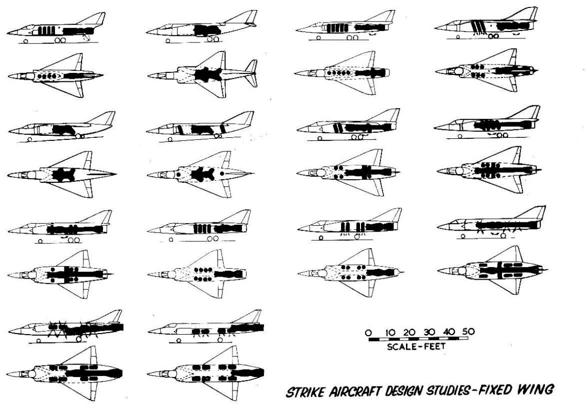


Figure 2.
Warton ASTOVL configurations evaluated during the 1960s. The dark areas show engines, with a variety of dedicated lift and cruise engines, as well as vectored thrust engines, looked at. Ref. 3

Harrier experience

The success of the Hawker P.1127 led to interest in the early 1960s in a supersonic successor design, for NATO and UK-only use. This, the Hawker Siddeley P.1154, was based around the same single-engine vectored thrust concept with the addition of plenum chamber burning (PCB) to boost engine thrust. Although PCB seems like a relatively simple addition to the vectored thrust engine, the use of very hot (1,200-2,000 K) exhausts in place of the Harrier family's relatively cool (400 K) forward exhaust posed a number of problems that took many years of model testing to evaluate, if not to fully solve.

With the political decision to cancel the development of the P.1154 in 1965 and the subsequent development of the Harrier for RAF service, UK work on ASTOVL aircraft focussed on possible successor aircraft. In the 1970s wide-ranging project studies were carried out on projects to meet the RAF's Air Staff Target (AST) 396 and AST.403 requirements, although STOVL was not seen as essential to meet these requirements (Refs. 1 & 2). However, none of these projects progressed beyond the study phase, although some model testing was carried out at Warton and by the Harrier team at Kingston. However, more extensive work was carried out in support of later studies in the 1980s that aimed to develop an ASTOVL aircraft to meet AST.410 and the Royal Navy's Naval Staff Target (NST) 6464 for a Sea Harrier replacement, as well as a joint US/UK ASTOVL research programme.

The most significant developments in V/STOL model testing techniques were developed during the 1970s as part of the Harrier programme. This addressed the issues combining effects in vertical and transition flight that had been reliant of actual flight testing during the earlier testing of the P.1127.

When the Harrier entered service a number of unexplained crashes occurred. Using a new V/STOL wind tunnel at Hawker Siddeley's Hatfield site a long series of tests discovered that they were caused by the destabilizing effect produced by the jet fountains becoming unstable during transition, striking the wings of the Harrier, which had low roll inertia, leading to an uncontrollable situation rapidly emerging. Although this was done after the Harrier entered service, it was unlikely that an ASTOVL aircraft would be able to proceed into development during the 1980s without extensive V/STOL tests being carried out, as well as HGI and lift loss tests.

Figure 3.
Sea Harrier FRS.2 model in the Hatfield V/STOL wind tunnel. The model is mounted inverted, with the intakes faired over and the nozzles blown via compressed air fed up the central mounting strut. Copyright BAE Systems

1980s ground effects and V/STOL tests

As part of the work started in the 1970s looking at potential Harrier replacements, the UK Ministry of Defence funded a series of full scale tests into PCB-equipped engines, using a modified Harrier airframe and Pegasus engine fitted with PCB burners and nozzles, suspended from a gantry at Shoeburyness in Essex (Fig. 4). This was intended to allow both full scale evaluation of PCB and to allow attempts to be made to correlate scale model tests to full scale, with considerable concern being raised that the 'scaling laws' then in use were inadequate. British Aerospace (BAe) Kingston built a sub-scale model of the PCB test Harrier and tested it on their ground effects rigs, but although a fair correlation between these results and the full scale ones was initially found it was later discovered that the nozzle details of the model differed from the full scale aircraft, making the correlation questionable. Nevertheless Kingston continued to develop so-called scaling laws using sub-scale models of their current ASTOVL project, the P.1216, with further work refining the scaling laws used over subsequent years.

Figure 4.
Harrier PCB tests at Shoeburyness. Copyright BAE Systems.

The P.1216 project was a ‘twin boom’ configuration, with the rear fuselage split into two halves mounted on the wings in order to reduce the effects of engine exhaust gases on the rear fuselage, which had caused problems on the Harrier and promised to be much worse on a supersonic ASTOVL design with PCB. A new test rig was built at Kingston that allowed the effects of HGI and suck down to be tested on the same model, although not at the same time. This new rig was fitted with a pantograph arm that allowed a greater range of movements, including ‘rolling vertical landing’ to be modeled, in comparison to the two old rigs.

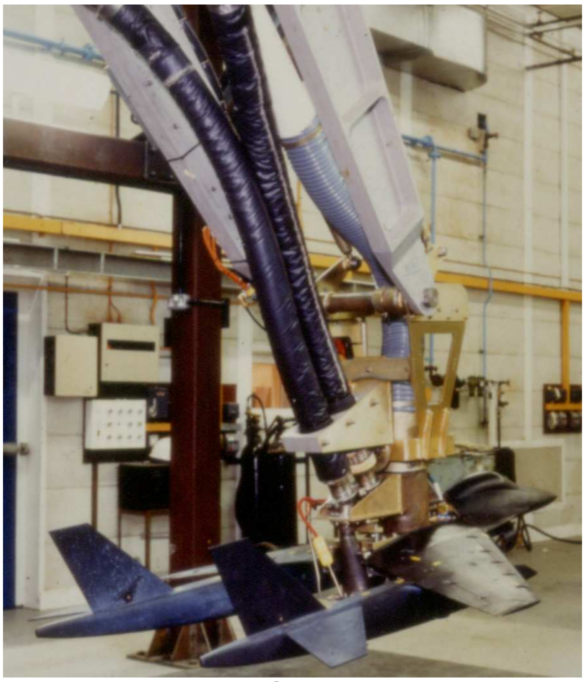


Figure 5.
P.1216 model (modified from an earlier project model) mounted on the new Kingston HGI/suck down test rig. Note the gas supply (air heated to 500 degrees C with hydrogen burners) and intake vacuum pump pipes above the model. Brooklands Museum.

Central to the tests of the P.1216 was a desire by Kingston to optimize two main features that were seen as being able to ameliorate the effects of PCB on HGI and suck down. One was the use of Cushion Augmentation Devices (CADS) under the aircraft fuselage, to capture the jet fountain flowing up from the ground to enhance lift and offset the suck down effect, as well as directing the fountain away from the intake as much as possible to reduce HGI. The other feature was the use of a ‘toe-in’ angle on the two front PCB-equipped engine nozzles to suppress the fountain until low altitude was reached (about 10 feet/3 metres) where the CADS would become effective.

It was BAe Kingston’s aim to achieve the right balance of these effects to allow the P.1216 to carry out successful landings. Kingston focussed on establishing the best layout of CADS for the P.1216 project, having decided that a maximum of ten degrees of ‘toe-in’ was desirable, as greater levels led to a loss of thrust, both from the angle of the nozzles reducing vertical thrust and from the loss of lift caused by elimination of the hot gas fountain.

Establishing these highly configuration dependent features took several years of testing, but from this a number of general features emerged. One was that it was not possible to establish precise results for the temperature and pressure distortion that HGI caused at the engine face. Rather, trends were seen as being more accurate. Despite the large amount of testing done on the new rig it was found that it was not the average maximum from the tests that were significant but rather the maximum effects of a one in ten thousand occurrence that even an extensive series of model tests may not uncover. This was derived from statistical analysis of the test results rather than experiencing them during the tests (Refs 5, 6 & 7).

Similarly, precision in the exact nozzle toe-in angle that would produce the minimum HGI or suck down was also not predictable from model tests. Rather, it was established that the trends given by varying nozzle angles were of use, while the exact numbers produced by the test may not read across directly to a full scale aircraft. One key discovery was that small changes in the aircraft configuration could require the CADS and other features to be re-optimised, requiring considerable further testing to establish their effectiveness.

In order to establish the transition characteristics of the P.1216 a 1/10 scale low speed model of the design (Fig. 6), originally used only for testing in wing-borne flight, was converted to do V/STOL testing. This was not ideal as the wind tunnel used (at BAe Woodford, now moved to Manchester University) was small, and the model could not carry the jet thrust on the balance, requiring two larger pipes feeding a blowing box to be built, with the live model wrapped around it, but not touching it. Attempts to seal the gap with soft seals were abandoned, with the test results adjusted using empirical factors instead.

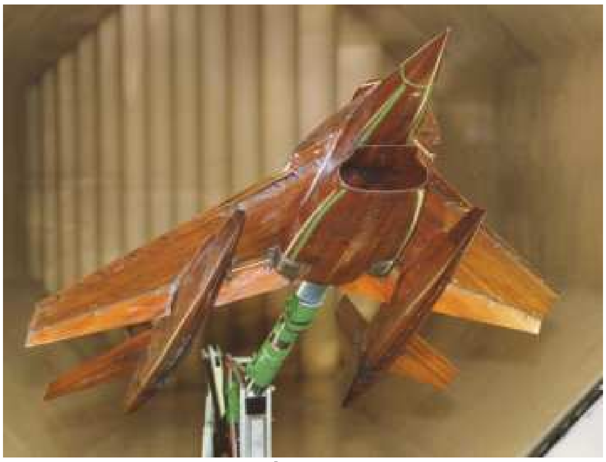


Figure 6.
P.1216 low speed model in a Warton wind tunnel, during conventional flight tests in the late 1980s. Copyright BAE Systems.

Although this modified low speed model allowed relatively quick and cheap results to be obtained it was less than ideal for testing V/STOL effects. In order to do this properly a considerably more expensive V/STOL model of the P.1216 was built in the mid-1980s, taking several years to be finalised due to the expense involved. Further large sums were spent during the second half of the 1980s trying to get this model working in the Hatfield V/STOL tunnel. This model was designed like the successful Harrier one, with live nozzles, testing with jet blowing on and off for various configurations, including the effect of stores being carried, flaps settings etc. However, it was discovered that the need to model the effects of a PCB-equipped engine, of higher basic technology than the Pegasus, had a significant impact on the tests.

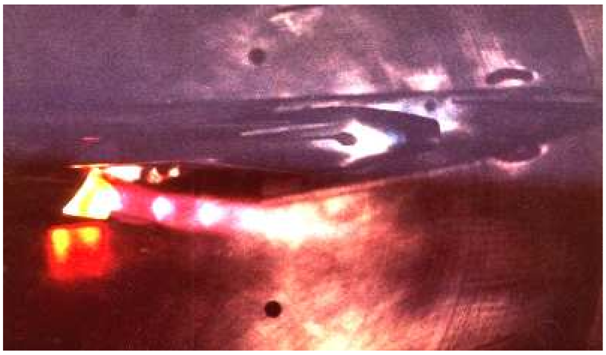
The jets on the Harrier model were just subsonic, whereas on the P.1216 model they were supersonic. One result of this was that the model 'screamed like a banshee', being audible across the Hatfield site. A more significant effect was that the results obtained from the model tests were highly questionable. It was soon realised that the effect of supersonic jets on lift loss was significant, which would require accurate nozzles that were shaped as closely as possible to those that were to be used on a full scale aircraft. As the P.1216 was still at the project design stage no definitive nozzle design was available, hence generic nozzle shapes were used on the model, with various fixes attempted to get different nozzle pressure profiles. However, it was recognised that these results had no basis in reality, despite the high accuracy of the overall model.

Other testing

While ground effects and V/STOL testing were perhaps the most significant areas of testing undertaken in the UK, other techniques have also provided experience relevant to the JSF.

One of particular note is acoustic testing. The effects of sound and heat on airframe structures and stores was recognised as potentially very serious, especially with the more powerful engines needed for ASTOVL aircraft and the lack of experience with new structural materials, such as composites, for areas of the airframe exposed to hot jet impingement. In order to explore these areas, a number of testing activities were carried out from the 1980s in the UK.

The Shoeburyness Harrier was used to test the effects of heat and noise on airframe and wing mounted stores, while a special test rig and subscale model tests at Warton were used to systematically explore heat and noise effects (Ref. 5). However, scale models were also used. At British Aerospace Brough the effects of PCB engines on ASTOVL project aircraft were explored using steel ‘half’ models with engine flows simulated with hot gases. These models were placed in the high speed wind tunnel at Brough to explore the overall effect of heat and noise on the fuselage in high speed flight (Fig. 7 & 8).



Figures 7 & 8.

BAe P.1230 ‘half’ model tested in the BAe Brough high speed wind tunnel, late 1980s. This was a four poster PCB vectored thrust design, with the lower image showing the front nozzle at full thrust. Thermocouples and acoustic sensors measured the effects on the rear fuselage. Copyright BAE Systems.

The data from all this work was analysed in order to determine if rear fuselage sections of ASTOVL aircraft could be built from composite materials, with a full scale composite fuselage test section built at BAe Kingston in a related programme.

This acoustic and thermal test work has led to the development of a significant facility at BAE Systems Brough for the measurement of thermal and acoustic effects in vertical flight that has been extensively used on the JSF programme (Ref. 4).

Summary and Conclusions

One key lesson emerges from this brief overview of the UK’s work on ASTOVL testing from the early 1960s to the late 1980. This is that experience of modelling, and of interpreting the results produced, is more valuable than the precise numbers produced. This is shown in a number of areas:

Firstly, the absence of highly accurate, scaleable data from model tests of V/STOL aircraft means that judgement was key to making use of the results obtained, rather than the direct application of the data produced. It was also important for the teams to become adept at explaining this to potential customers, who may wish to use exact data to prove if a design was viable or not.

Secondly, an understanding of how relatively small changes to a configuration could have a major impact of the results, and that certain design features, such as nozzle design, were fundamental to establishing if an ASTOVL design could be considered to be viable. This understanding emerged from the experiences obtained over a number of years and test programmes in the UK.

Thirdly, the fact that the different aspects of V/STOL specific testing had to be carried out separately meant that integrating the results from the different tests was vital to allow any degree of confidence in a design. This was made harder by the fact that solutions in one area can affect other areas adversely. For example, changing a nozzle design to improve HGI effects may worsen the lift loss experienced in transition. Learning how to integrate the results of all tests, and to compromise in ‘fixes’ to accommodate them, required considerable experience.

It is this range of experience that is one of the key contributions made by BAE Systems to the JSF. The test facilities at Warton, including the V/STOL wind tunnel and the jet effects rig that has been moved form Kingston to Warton, now constitute the only specialized V/STOL model testing facilities in the world, with similar facilities at Boeing and Rolls Royce having been demolished. In alliance with the acoustic testing facility at BAE Systems Brough, the experience of the small team of staff that operates these facilities, gained over many decades, form a vital contribution the F-35B, with many thousand of hours of testing having preceded the full scale testing of that aircraft that is about to commence.

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