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The Development of the Turbojet Engine in Britain and Germany as a Lens for Future Developments

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I. Introduction

THE jet engine is indisputably one of the greatest technological advances to emerge from the twentieth century, both in technical and societal terms. Never before had flight at such speeds been possible, and in time, the jet engine came to connect the world more tightly than ever before. Like many developments that preceded and would follow it, the advance of gas turbine propulsion was spurred by military needs rather than by the investigations of pure science. On the eve of the Second World War, both Britain and Germany (or, more accurately, a few Britons and a greater number of Germans) embarked upon independent courses of research, development, and discovery. Both groups hoped to deliver a decisive wartime tactical advantage to their country's airborne forces, though neither power was able to enjoy substantial (let alone decisive) deployment of the developed technology by war's end. What make the individual stories, compared to each other, so fascinating are their many stark differences, superimposed against their remarkably similar end results. In some key regards, the two histories could not be more different—the two primary inventors received wholly different levels of support from their governments and their nation's industrial establishments, and pursued fundamentally different designs in some regards—yet both nations developed functional jet engines that were deployed in combat roles at roughly the same time. In the retrospective course of any technological development, it is common to speculate as to what might have been if only '*x*' variable had been different, without the ability to actually confirm any hypothesis. The development of the turbojet engine, by contrast, allows for more viable 'what-if' statements due to our ability to objectively compare what happened in each program. Though they certainly do not provide for an omniscient examination, the stories of the first jet engines are an unusually good base

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from which to build such an analysis due to the fact that they happened in almost perfect isolation and with many variables altered.

Development of the turbojet engine carried one other characteristic: speed was understood to be of the essence by both parties, in the interest of wartime necessity. Nearly any idea that is good enough will eventually be taken up and fully developed; the analysis undertaken in this paper assumes that the development in question is under a time constraint. The ultimate goal of this paper is to use the objective comparisons derived from the British and German development histories in order to make generalized recommendations applicable to any new technological development with a bearing on national security and requirement of expedience. More specifically, this paper does not seek to advise on how to make the best or most optimized finished product, but rather on how to use historically demonstrated methods to field a functional device in the shortest possible time frame.

II. Technical Overview

A. General turbojet description

It will serve the following discussion to review the basic components and operation of a subsonic turbojet engine, the simplest and oldest variant of jet engine, which still forms the core of most of our modern 'jet' engines. Air first enters the diffuser, which decelerates the flow, nearly isentropically, prior to its entry to the compressor. In the compressor, the air's pressure is increased, with a corresponding increase in temperature and decrease in volume, and the air is then delivered to the combustor where fuel is sprayed in and the fuel-air mixture is combusted. The hot exhaust gases are passed through a turbine (essentially a compressor in reverse) which extracts the power required to run the compressor at the front of the engine. Finally, the hot gases are passed through a converging-diverging nozzle in which they are supersonically expanded to the design exit pressure. With regard to the thrust equation, $T = \dot{m}(V_{jet} - V_{\infty})$, where V_{jet} refers to the velocity of the air stream exiting the nozzle and V_{∞} refers to the engine's velocity relative to the surrounding air, turbojets generate their considerable thrust by the second term rather than by a high mass flow rate $\dot{m}$ (such as is seen with traditional propeller-driven craft).

While it is natural to envision the components as being arrayed in a linear fashion — diffuser→compressor→burner→turbine→nozzle, such that the flow is always moving in the same direction as it passes through the engine — it is not strictly required. It is actually possible to axially condense the layout such that the flow reverses direction twice as it passes through the engine; such engines are referred to as "reverse-combustion". For the sake of minimizing drag, this is not done today, but the first British turbojet series was designed to do so.

As one might imagine, temperature is one of the most important operational considerations for two engine components: the combustor and turbine. Of these two, the turbine is the more critical due to the more intimate contact that the flow has with the metal elements. While overall efficiency of any engine increases with combustion temperature, the upper temperature bound of a turbojet engine is dictated by the melting temperature of the turbine blades, as they are directly exposed to the hot exhaust gases from the combustor. Those familiar with modern turbines will know that the problem has been ameliorated today to an extent by creative engineering of the blades via both metallurgical processes, such as single-crystal blades, and the use of bleed air from the compressor to form a thin film of (relatively) cool air around the blades, but only the latter technique had begun to enjoy rudimentary use during the Second World War.

B. Main design differences encountered

The bulk of the design differences between the first English and German jets can be summarized in a few binary design choices.

1) Compressors: There are two types of compressor designs possible: axial and centrifugal. Axial compressors keep the flow moving, as their name describes, axially as it passes through the compressor. They accomplish this by stacking together successive stages, each composed of one rotor and one stator row of blades. The rotor stages are powered by the turbine and all spin at the same angular velocity. When the rotor stages perform work on the flow, it is referred to as impulse, while when the stator stages perform work on the flow, it is called reaction. Centrifugal compressors, by contrast, have flow entering at the axial center and then accelerate it radially by the spinning of the rotor. In contrast to

axial compressors, where the exit flow is at approximately the same radial distance from the engine's central axis as when it entered, the exit flow from a centrifugal compressor is at the (relatively greater) radial extremity of the engine's interior and requires redirection before it can be passed on to the burner. However, centrifugal compressors generally require fewer stages to achieve the same compression ratio relative to axial compressors, as each stage can tolerate a higher stage pressure ratio, making the compressor shorter (albeit fatter). Perhaps most importantly for the purposes of initial development, centrifugal compressors are easier to design and were already well-understood by engineers of the day in the context of aero-engine superchargers. An important corollary effect of the choice of compressor type is the design of the airframe. The engines that result from use of radially-compact axial compressors can generally be slung under a wing without much added design effort, meaning that the only added complexity for a jet-powered airframe design was to make the structure capable of withstanding high-speed flight. In the case of centrifugal compressors, however, the engine bulk is so great that, for drag to not be excessive, an airframe must be designed around the intended engine. Typically, centrifugally-compressed engines are either placed within the fuselage itself with an air intake built into the plane's nose (for a single-engine configuration) or built into the wings (for a dual-engine configuration). As mentioned before, two types of component arrangement are possible: straight-flow and reverse-flow. The choice of compressor type further influences the choice of component arrangement, as discussed previously. The selection of an axial flow compressor invariably dictates a straight-flow configuration in the interest of minimizing frontal area and drag. A centrifugal flow compressor, however, can lend itself to either arrangement; the drag penalty imposed by a reverse-flow arrangement is relatively less if a centrifugal compressor is already present, and the reduced overall length may serve to offset that penalty depending on the engine's intended use.

2) Another design choice regards the type of combustor used. There were two types of combustors available for use: the can-type and the annular-type. A can combustor is composed of a series of cans placed side-by-side in such a manner

as to form a ring around the turbojet's axis. Can combustors are relatively easy to build, test, and maintain, as modifications or maintenance may be performed on a single can at a time rather than on the combustor assembly as a whole. However, the use of a can combustor does create more possible points of failure, since each can is a self-contained combustor with distinct components. The most significant disadvantages of using can combustors are higher weight and greater total pressure loss relative to annular combustors. The higher weight is a result of the greater material cost to construct multiple individual cans versus one annular combustor, and the total pressure loss is due to the inefficiencies inherent in more complicated flow paths. Annular combustors, on the other hand, are axially symmetric and create a single zone for combustion to take place in, with an advantage of more uniform exit flow for the turbine to interact with. They are simpler to initially design, but more difficult to test and maintain. They also tend to be shorter than can combustors, since the continuous combustion zone offers relatively more combustion volume per unit length of combustor; this also contributes to their lower relative weight.

III. Development Paths

Here it is time to delve into the stories of how each country's first turbojet came to be. As mentioned previously, the two developments took place in nearly total isolation from one another.

A. Britain

First, the British development will be considered. The original British turbojet is typically referred to as the 'Whittle engine' or 'Whittle Unit' after its creator, Frank Whittle. It can be fairly said that Whittle pursued the idea for a turbojet engine before anyone else; though impossible to say that he 'had' the idea first, the evidence of patent activity is indisputable.

Whittle first brought his research to the attention of British authorities on aero-engines in 1929, hoping to secure funding for its further development. British interests, immediately prior to the Second World War, may be generally characterized as wedded to the status quo. The governing and influencing bodies of aviation in Britain were reasonably convinced that piston engines were the only viable source of airplane propulsion available at present or in the foreseeable future, in large part because that was all that they were familiar with (and all that had ever worked up until then). The bodies believed, correctly, that improvements could still be made to piston engines, and that is where their attentions were focused. Their bias is, to a degree, understandable, in light of the vast amounts of funding and man-hours of effort which had been dedicated to developing piston engines as the technical standard of aircraft propulsion. However, the men in authoritative positions tended to be unwilling to acknowledge the possibility of jet propulsion as a successor to piston engines; worse, one man may have deliberately diminished the value of Whittle's work in the interest of his own. The greatest weakness of the British air establishment, in the case of the turbojet, was their automatic reliance on 'experts'—not a bad thing, in and of itself, except for when a development is so different from the status quo that there are none or few experts to speak of. The most influential body was the Royal Aircraft Establishment in Farnborough, which advised the RAF on technical matters. The RAE, when initially approached by Whittle in 1929, in turn approached a man named Alan Griffith, who had recently published a paper detailing the use of a gas turbine as an airplane powerplant (in most regards, what Whittle was proposing, and indeed basing his own work off of in part). However, Griffith in 1929 returned an unfavorable review of Whittle's work, citing an error in his calculations, and generally claiming that the design was too simple and too inefficient to be practical. He further dismissed Whittle's design due to its reliance on metals capable of withstanding higher temperatures than could be presently achieved. Whittle, though, was not a fool. He knew that while the materials were not available yet, it was almost certain that they would be developed in the very near future in the course of metallurgical research. Taken by itself, the worst complaint that can be levied against Griffith's report is an abject lack of imagination; he may have legitimately believed that Whittle's work was flawed. Unfortunately, the RAE accepted the opinion of one man at face value and used that as justification to disregard Whittle's work.

Whittle was understandably discouraged but remained convinced of the validity of his idea—indeed, he subsequently discovered a second error in his calculations which served to largely cancel the first—and continued to pour effort into his idea for several years in his spare time as he progressed through the RAF officer progam. A fellow officer and friend in the RAF who had formerly been a patent examiner persuaded him to patent his idea in 1930. In 1932, he enrolled in the Officer's Engineering Course per RAF procedure and performed extremely well; his performance was so exemplary what when he requested that he be allowed to study at Cambridge (a customary RAF program for qualified officers which had been recently discontinued) his superiors allowed it. In 1937, he graduated from Peterhouse in Cambridge with first-class honors, a further testament to his ability. Though the program into which he enrolled was nominally two years long, he had been permitted to take an extra year by the RAF to further develop his studies. While at Cambridge in 1935, he had formed an arrangement with Rolf Dudley-Williams and James Tinling in the interest of furthering the development of his turbojet design. At the same time, his original patent came up for renewal at the sum of £5; while this sounds trivial by today's standards, by a reckoning of affordability defined by the average earnings of the day in the UK, this amounted to over £700 in 2010 money, quite a considerable sum for a man who was a university student at the time. Thoroughly unable to pay the fee to renew his patent, and even questioning its worth, Whittle allowed the patent to lapse. However, thanks to the efforts of Williams and Tinling, within the year the investment firm of Falk & Partners met with Whittle and proved willing to back him following a third-party technical review of his design.

By early 1936, Power Jets Limited was created in a power-sharing arrangement with Whittle, Williams, Tinling, the Air Ministry, and Falk & Partners. In July, Whittle graduated from Cambridge and was given permission by the RAF to take a postgraduate year to both continue his studies and further work on his engine. Despite being involved in the arrangement (as a consequence of Whittle still being an RAF officer) the Air Ministry was still unwilling to put forth any funding. The money raised (£2,000) from Falk & Partners proved enough, though, to engage British Thompson-Houston (BTH) to build both a prototype and an associated facility in which to test it in a BTH factory in Rugby. By 1937, development was quite well along and within budget. Concurrent with the agreement which formed Power Jets Ltd, the Air Ministry had once more solicited the opinion of Griffith on Whittle's refined design. However, he did not respond until March 1937; this time, he gave a more favorable opinion, but still failed to recommend the design. As it turned out, Griffith was by that time pursuing a turbojet of his own, which inescapably raises questions regarding a conflict of interest. In any case, Griffith's engine never flew during the war. Unfortunately, despite the unquestionable progress of Whittle's engine by March 1937, the Aeronautical Research Committee (ARC, another advisory body with its own funding to give) decided to fund Griffith's engine rather than Whittle's. This perceived lack of confidence by aero-engine authorities in turn spurred Falk & Partners to refuse funding beyond £5,000 to Whittle. Nonetheless, in April 1937 the prototype engine (dubbed the Whittle Unit or WU for short) ran successfully under its own power. Henry Tizard, the chair of the ARC, was himself impressed and was able to convince the Air Ministry to contribute £5,000 of government money, which was a shot in the arm for Whittle's development. The money proved to be elusive, though, and did not in fact show up until the following year, 1938. This was problematic, since their extant funding from Falk & Partners ran dry in July 1937. The investment group agreed to find more funding, but it failed to materialize and the agreement between Falk & Partners and the other investors fell apart. In default, the investment group's shares went to the other investors, who proceeded on. Work proceeded in Rugby under the joint auspices of Power Jets Ltd and BTH until January 1938, when the combined success and danger of the work merited that it be transferred to an unused BTH facility in nearby Lutterworth. With regard to funding, BTH determined that the enterprise was worth investing £2,500 of its own money, and the promised money from the Air Ministry did at last come during March 1938. Alas, the long-awaited blessing of Air Ministry funding proved to be something of a curse as well, since the government money imposed the Official Secrets Act on the whole enterprise. This, in turn, made it next to impossible to seek out further private funding—quite a problem, considering that the Air Ministry was making no guarantees with regard to the future funding which would be required to develop the engine fully.

Indeed, by June of 1939 Whittle's enterprise was once more in danger of financial collapse; thankfully, the work had produced a device impressive enough that the Air Ministry was willing to buy it from Power Jets in the interest of financing a flight-ready unit, the W.1. By April 1940, Power Jets had produced a preliminary W.1 and a followup W.2 and the Air Ministry was enthusiastic enough to request that three companies prepare production lines capable of producing 3,000 engines per month by 1942. Of the three, only Rover accepted the contract. As Power Jets' new air industry partner, they set up a working laboratory in an unused factory in 1941. However, Rover was uncooperative and assumed a general attitude of superiority, while simultaneously failing to deliver parts of sufficient quality. By the end of 1941, it became increasingly clear that the partnership was ill-functioning. Unbeknownst to Whittle, Rover had secretly started work on a W.2 variant of its own—with the Air Ministry's knowledge and approval, no less. By April of 1942, Whittle became aware of Rover's duplicity and the joint project nearly derailed. Despite how incensed he was, along with Power Jets as a whole, cooperation struggled on, in large part due to his conviction that his project was vital to the war effort. Thankfully, in January of 1943, Rolls Royce bought out Rover's involvement in the turbojet project and immediately kicked testing and production into high gear. It is worth noting that Rolls Royce was a more natural fit than Rover for jet engine manufacture, as they already possessed a fully-fledged supercharger division, which lent itself well to turbojet work. By October 1943, production units of the W.2B were coming off Rolls Royce's assembly lines at last, dubbed the Rolls Royce Welland. These engines were placed in waiting Gloster Meteor airframes, and the first British jet squadron was formed in late July of 1944. No jet-to-jet battle was experienced during the war, but they were effective in bringing down V-1 bombs heading for London.

The development timeline of Whittle's engine was not intended to be laborious, but rather to illustrate both the adverse environment his work was subjected to until the latter years of the war, as well as the strength of his perseverance for the sake of a turbojet engine for Britain. While Whittle did have significant technical hurdles to overcome in the course of developing his engine (most notably the burner design) these were secondary to his funding problems. Acquisition of development money was far more of a struggle than it should have been as a result of an unaccommodating institutional system. During the war years, he suffered two mental breakdowns due to stress, one in 1940 and another in 1944. During the war, he would at times maintain 80 hour work weeks, sniffing Benzedrine during the day to stay awake and taking sleeping pills at night. It is worth considering that Whittle was a commissioned RAF officer and could have probably walked away from his project and returned to regular duty; a less-dedicated man likely would have. In time, the W.2B variant originally pursued by Rover in secret, called by Rolls Royce the Derwent, would supplant the Welland, but throughout the war only the Welland engine, a direct product of Whittle's work, would see service in the Gloster Meteor.

B. Germany

The German technological atmosphere prior to and throughout the Second World War, in stark contrast to that of England, was highly favorable to emerging technologies and in many cases able and willing to throw significant amounts of government funding at promising developments such as the jet engine. Indeed, the case has been made that Germany was at the opposite end of the pendulum stroke as England, which is to say that it used too little restraint in the support of new ideas. Historians have often commented on the over-exuberance of German policy on multiple topics, including technical development; the jet engine was no exception to this pattern.

Though the German path to the development of the jet engine differed from that of the British, there was a German inventor who filled a similar role as Whittle. His name was Hans von Ohain, and he was a student at the University of Göttingen in 1935 when he began seriously working on his own ideas of jet propulsion. In 1936, he was granted a patent in Germany for his idea, one year after Whittle's in Britain. From the beginning and throughout his work, von Ohain would enjoy one substantial advantage over Whittle: he had money. Though by no means wealthy, von Ohain did enjoy personal financial security even as a student due to his father's position as a well-to-do businessman in Berlin. Indeed, the first engine produced from his design was built by a garage mechanic named Max Hahn (an automotive and railway engineer), who von Ohain met in the course of having his sports car routinely serviced, from von Ohain's personal money. The engine's manufacture cost nearly 1,000 Marks; using the historic exchange rate for USD and adjusting for inflation, that translates to, *at minimum*, ~$32,000 in 2010 dollars. By contrast, Whittle couldn't hope to afford a patent fee of less than $1,500 in 2010 dollars. It is worth noting that von Ohain, while a brilliant theoretician, was by his own admission "a physicist who really didn't know what nuts and bolts were." Whittle, by contrast, had grown up with access to a machine shop and was quite comfortable with both the design and manufacturing processes. However, von Ohain was lucky enough to have access to Hahn, a superb craftsman.

This two-person team was enough to get Germany's turbojet program underway to such an extent that it was noticed and championed by the head of von Ohain's department at the university, Dr. Robert Pohl. This first engine, largely made of sheet metal and generally dubbed the 'garage engine', suffered from several problems (it never ran under its own power and had a tendency to throw flames almost ten feet out the back) but was still a compelling demonstration. Pohl wrote to Ernst Heinkel, head of the Heinkel aircraft company, in 1936 in support of von Ohain's work. Both von Ohain and Hahn were soon employed by Heinkel, where they worked to further develop the turbojet. The two men's previous joint working arrangement split to a degree, with von Ohain being assigned an aircraft engineer to help him translate his ideas into munfacturable designs and Hahn being made head of the manufacturing team. Heinkel quickly produced the HeS 1 (Heinkel-Strahltriebwerk, or Heinkel Jet Engine) which was, like the garage engine prototype, made largely of sheet metal, although this time with the addition of final machining. It ran on hydrogen in March 1937 and on gasoline in September of the same year (Whittle's had ran on gasoline in April). It is here worth reflecting on the considerable benefit conferred on von Ohain's work by his financial ability: Whittle had agitated for his design in Britain since 1929, while von Ohain had only began seriously thinking about his in 1935. Yet, both designs reached their first great milestone, that of running under their own power, within a few months of each other in 1937. From here, Germany's program would generally overtake Britain's due to greater funding and industry support. By 1939, an He 178 (the first flying turbojet-powered plane) demonstrated the feasibility of turbojet propulsion to an audience of Nazi officials including Hitler. Now convinced of the utility of turbojets, the German equivalent to the British Air Ministry the Reichsluftfahrtministerium (RLM) began an active effort to recruit established engine manufacturers to further develop the concept, including BMW, Daimler-Benz, Bramo, and Junkers Motoren (Jumo). It is interesting to note that Junkers had already made an abortive effort in secret to develop a turbojet at about the same time Heinkel's program was getting underway. Faced with failure, by 1939 they had already decided to return to the drawing board, taking with them the lessons already learned. Beyond engine developers, the ministry sought manufacturers to develop airframes suitable for turbojets, including Messerschmidt, Heinkel, and the airframe division of Junkers.

Regarding engine development, Heinkel had been at an early disadvantage due to a lack of engine manufacture and testing facilities (indeed, turbojets were the company's first foray into engine manufacture) and found itself pressured by the RLM to either divest itself of the turbojet work or acquire a company with experience; the RLM did not favor supporting a company lacking prior experience developing engines (similar in some ways to the position of the RAE regarding Whittle's work). Fortunately, it was able in 1939 to acquire the Hirth-Motorenwerke engine manufacturing firm and proceed ahead. Of the other engine manufacturers approached, BMW and Jumo took up the call initially. Fittingly, the first engine to receive an official RLM number was a Heinkel, the HeS 8. It became known as the 109-001 in the Nazi numbering scheme. Other engines among the first to be christened by the RLM included the BMW 109-002 and 109-003 as well as the Jumo 109-004. Fully discussing the developments of each of these engines would be laborious, if instructive, so rather the focus will be on the overriding difficulties which presented themselves to the German developers.

Where Whittle's greatest source of trouble had been the acquisition of funding, the Germans found themselves troubled by technical issues, often relating to their choice of axial compressors. This was generally insisted upon by the RLM, with some reasonable logic behind it. The demonstrator aircraft, the single-engine Heinkel 178, had virtually no room for payload due to its bulky centrifugal compressor design. This is much the same as the Gloster E.28/39 testbed used by Whittle. However, for some reason the Germans do not appear to have considered the British solution of building a centrifugally-compressed engine into the wings themselves; rather, they intended to build twin-engine fighters with engines suspended from the wings. On multiple occasions, German designers struggled with vibration issues emanating from axial compressors. The problems were often not truly able to be solved during the war, but merely minimized. Six months were spent on partially rectifying vibrational issues for the compressor of the Jumo 004 alone in 1941, and such work would continue intermittently through 1944. BMW's 003 suffered less from specifically vibration issues, but its compressors still had their own problems; the first prototype Me 262 flown on BMW 003's was nearly lost on its maiden flight due to dual compressor failure. Entirely separate from vibrational considerations, the axial compressors suffered from an additional problem in practice: since the rotational moment of inertia was relatively small, if the throttle was ramped up too quickly the compressor could stall itself. The combustion chambers could then overheat for lack of cooling airflow, and the engine would be destroyed. This limitation meant that only highly-experienced pilots were able to fly German turbojet-powered planes.

While British support for Whittle was halting, it did at least abstain from backtracking. The Nazi Reich, however, was personality-driven and, as a result, at times capricious. Early in the war in 1940, when optimism for victory verged on absolute certainty, the head of the Luftwaffe Hermann Goering commanded that all military development projects which would not reach completion within one year be discontinued immediately in favor of pouring extant resources into the production of mature aircraft designs. In 1941, Hitler himself repeated the demand, shortening the timeframe to six months in the future. Clearly, turbojet developers quietly ignored these decrees, perhaps having a clearer idea than the Fuhrer of the future requirements for the war. However, it can hardly have been beneficial for development; it was likely not easy to procure additional funding for projects that were supposed to have been canceled. Thankfully, by late 1942 it was again permissible to perform long-term experimental development work, likely due to the loss of German forward tactical momentum and concurrent desire for stronger weapons. Later in the war the RLM itself began to waffle between different funding priorities. The Messerschmitt 262 had been selected as the jet fighter to pursue rather than the Heinkel 280 owing to its superior combat qualities. Unfortunately, Messerschmitt was also arguably the premiere manufacturer of piston-powered fighter planes; even in-house, these dual designs competed for resources. In the larger world of RLM funding, there emerged wavering behavior over which plane to prioritize—the revolutionary and powerful Me 262, or the pinnacle of conventional piston-powered engineering, the Me 209. In June 1943, the RLM agreed to Willy Messerschmitt's suggestion that the Me 262 be made the top production priority and dropped Me 209 development. Yet, a mere two months later in August, the RLM decided that both planes should be produced and ordered a ramping-up to produce Me 209's as well. At last in November 1943, the Me 209 plans were scrapped altogether, but at a cost of misdirected resources that should have went to the Me 262 program.

IV. Retrospective Analysis

With the forgoing descriptions of the respective development processes in mind, we will here consider what each nation did well and poorly. The analysis will be restricted to institutional-level decisions, since the goal of the paper is to identify courses of action by government and industrial bodies. Certainly, individual men played crucial supportive roles in each nation, but it is impossible to predict where or when such persons will fortuitously interact with a project.

A. Britain

The fortunes of Whittle and his project were largely determined by two British bodies: the Air Ministry and the RAF. In fairness to the Air Ministry, it was focused on winning the first war in which air superiority was a decisive factor. The body, though, was far more often an obstacle than a help to Whittle, withholding funding based on the opinion of one man, failing to prevent Rover's obstinacy and arrogance from badly delaying development, and being generally slow to respond. The Ministry's support was so meager that it is to a degree miraculous that Whittle did not abandon his idea altogether in the early 1930's.

The RAF, on the other end of the spectrum, deserves a great deal of commendation for the quiet but huge role which it played in the turbojet's development. Though it never contributed funds or directly supported the engine in any way, it did an outstanding job of supporting Whittle himself; he spent the war engrossed in development and never saw combat, yet retired an Air Commodore, having been promoted several times and continually permitted by his superiors to continue work on what they recognized as a worthy project. Even prior to the war, the RAF allowed and paid for Whittle to take a two-year engineering course at Cambridge, identifying his substantial talent.

Somewhat confoundingly, when Britain nationalized Power Jets nearer to the end of the war (March 1944) they also forbade the company from producing any more jet engines; though this is explicable by pressure from the air industry, it still smacks of poor decision-making. Many engineers simply left Power Jets at this point, seeing no point in continuing work there. While the war was functionally over by that point from a research and development perspective—no new work undertaken then would have reached combat by the war's end—this still very likely set back further turbojet development.

B. Germany

Subjecting German institutional behavior to the same analysis, it is harder to find either overriding excellence or grounds for condemnation; rather, German industry can be generally described as good but over-optimistic. It is more interesting to look at the various aspects of the German government's involvement, particularly compared to the British government. While Whittle's greatest obstacle was getting government funding, the Nazi government funded every production engine developed during the war, as well as several that did not reach production; in the RLM numbering system, which implied use of government funding, at least sixteen numbers were used. The technology had had to be first demonstrated to be viable under efforts funded by private companies, but once that hurdle was passed, public funds were quickly made available and an overall development scheme established (notwithstanding the issues with administrative waffling discussed earlier). Indeed, speaking to the optimism of the Nazis, a classification system was implemented in the late 1930's concerning turbojet engines. It possessed four classes, with the second class roughly twice the power of the first, the third class roughly thrice the power of the first, etc. By the end of the war, only two engines had reached production, the BMW 003 and Jumo 004; both were merely Class 1. Development had only begun on Class 2 engines. In fairness, the creation of the classification system did not imply that the Nazis intended to produce a Class 4 engine by the end of the war, but only indicated that they had the planning outlook of long-term development—a full sixteen years, to be exact, rather longer than turned out to be available. This mentality is quite logical from an R&D standpoint (and is in excellent agreement with the stereotype of Germans as methodical and efficient pseudo-machines). However, this forward-thinking mentality arguably hindered the turbojet program's combat-effectiveness, by spreading resources too thin and taking the long view too often. Only in the latter two years of the war was the design process frozen for the sole viable production engine at the time, the Jumo 004. By that point, German industry actually began evincing a great deal of practical strategic ability, prioritizing output over optimization. The Jumo 004 was simplified as much as possible to accommodate severe shortages in alloying metals such as nickel and chromium which were necessary to produce heat-resisting steel; the final war production model used heat-resisting steel in only the turbine blades and nozzles, and could in fact be assembled by unskilled labor.

V. Conclusions

Viewing the two histories of turbojet development can lead to some generalized conclusions regarding how industry and government should pursue groundbreaking technological developments which also require expedience.

A. Technological leaps

The first conclusion is to restrain the number of individual technological leaps as much as possible. Whittle's design was groundbreaking—no one before him had seriously advocated the use of a gas turbine power plant in an aircraft—yet in manufacture, he used an assemblage of relatively conventional components to achieve his goal, innovating on a component level only when necessary. Ohain, too, understood how to simplify a design to the bare minimum in required complexity; his first prototypes were made largely of sheet metal. However, the larger German industry took up his work so broadly that his influence could not reach all developers, and the industry forgot his example of simplicity in the pursuit of a functional end product. Expediency demands that conservative approaches be taken wherever possible but German industry neglected this consideration in their use of axial compressors. They were absolutely correct that an axial compressor was (and is generally to this day) a superior design choice for a turbojet. However, they failed to adequately estimate the extra research and development which would have to be poured into the overall project as a result. Whittle's original patent even called for an axial compressor, but he gave it up when faced with funding limitations, settling reasonably on what amounted to a modified supercharger. Both countries' turbojets were the culmination of design concessions for the sake of deployment; some key differences in finished quality result from the fact that Britain's engines were designed from the beginning with a sense of expedient technical compromise, while German engineers realized only later in the war that they would not have the time they expected to perfect their designs, or even the materials they had taken for granted.

Framed a different way, this point could be defined as ‘minimize the number of variables that must be arranged.’ Britain’s centrifugal compressors were machines whose manufacture and operating characteristics were generally understood already; if some operating parameter needed to be changed, it is likely that redesign was a relatively minor issue (though the compressor itself did have to be replaced entirely). By contrast, Germany’s use of axial compressors stepped into the metaphorical deep end of design variables, for merely one component. The interaction of rotor and stator blading was not yet understood—the one engine which used a 50% reaction design was discarded—and many problems regarding the blades themselves were encountered, usually due to harmonic vibration issues which caused the failure of many compressors. As earlier referenced, the first Me 262 test flight was nearly a disaster due to simultaneous compressor failure in both turbojet engines (fortunately, the craft was a testbed that still had a piston engine installed in the nose).

B. Use of panels for funding decisions

The second conclusion is to never allow new ideas which reach government funding agencies to have their fate determined by the opinion of one ‘expert’. If an idea is truly groundbreaking, it’s possible that no true expert may exist at all (as was the case in Britain) or, as is the case with anything human, that there may well be a personal bias. This problem does not, in truth, exist so much today as it did then. Between the wider availability of experts via ease of modern contact and the general use of committees or panels to determine project funding, it is unlikely that such a blunder as the Air Ministry’s 1929 refusal to support Whittle’s work based on one expert’s opinion would be repeated today. However, it is such a painful error that the caution bears repeating; had Britain possessed a functional turbojet engine during the early war period, years of bloodshed could likely have been avoided due to the Allies’ crushing air superiority.

C. Intra-institutional support

The third conclusion is to ensure that personnel within organizations or services are supported in their development work, as Whittle was supported within the RAF. Such tacit support of an inventor can be crucial, particularly in the early stages when no explicit funding is available for their work; some 3 years passed between Whittle's initial enrollment in Cambridge (funded by the RAF) and the first receipt of official government funding for his work. Once Whittle completed his post-graduate year at Cambridge in 1937, he remained on the Special Duty List by permission of the RAF until his retirement in 1946, solely for work on the turbojet engine. Despite not being on active duty for eleven years, the RAF wisely supported him continuously throughout, recognizing his superior potential.

D. Support of original developer(s)

The fourth conclusion is to support the person, group, or company that originally develops an idea, regardless of whether or not they possess prior experience in the field their development falls into. Britain failed to do this for Whittle on several occasions, first by dismissing his design in part because he lacked design experience for any kind of engine, then by tacitly allowing Rover to steal one of Whittle's designs and secretly modify it for their own use, and finally by nationalizing Power Jets and subsequently prohibiting the company from further engine manufacture. Germany, too, nearly did the same thing to Heinkel; despite the fact that they were the first company to enjoy successful development of a turbojet engine, they were solely an established airframe manufacturer. Had Heinkel been unable to acquire an engine manufacturer, RLM funding would likely have been cut off to the first group to actually succeed in Germany.

If an inventor has the wherewithal to strike out in a new direction (and it works), they must be accorded respect enough that their development isn't taken out of their hands and given to 'more qualified' groups for further growth.

E. Consistency in administrative course

The fifth conclusion is to maintain commitments to funding and official support. While Britain never reversed an official decision of support, Germany did so on several occasions. Even if the project itself lives through the uncertainty, it stands to reason that its quality will suffer regardless; those working on the project are unlikely to maintain morale and, consequently, quality of work between the ebb and flow of purpose. In the case of Germany's wavering between support for experimental development of turbojets, resources were unquestionably squandered on further production of defunct piston-powered engines.

Appendix

Following this paper are photographs of relevant museum exhibits encountered while on research travel in the UK and Germany.

References

Anderson, J. D., *Aircraft Performance and Design*, McGraw-Hill, Boston, 1999.

Anderson, J. D., *The Airplane: A History of it's Technology*, AIAA, Reston, VA, 2002, pp. 283-359.

Golley, J., *Jet*, Datum Publishing Ltd., Fulham, UK, 2010.

Hardman, R., "The genius who shrank the globe: Why after 70 years we should celebrate jet engine inventor Frank Whittle," *Daily Mail*, 22 Apr. 2011.

Hill, P. G., and Peterson, C. R., *Mechanics and Thermodynamics of Propulsion*, 2nd ed., Addison-Wesley, Reading, MA, 1992.

Kay, Antony L., *German Jet Engine and Gas Turbine Development, 1930-1945*, Airlife Publishing Ltd., Shrewsbury, UK, 2002, pp. 9-155, 289-292.

Kay, Antony L., *Turbojet History and Development 1930-1960*, The Crowood Press Ltd., Ramsbury, UK, 2007.

Lawrence H. Officer and Samuel H. Williamson, "Purchasing Power of British Pounds from 1245 to Present," MeasuringWorth, March 2013.

Pavelec, S. M., *The Jet Race and the Second World War*, Praeger Security International, Westport, CT, 2007.

"Power Jets: A Brief Biography," *The Sir Frank Whittle Commemorative Trust*, URL: http://www.frankwhittle.co.uk/content.php?act=viewDoc&docId=6&docFatherId=1&level=sub [cited 3 January 2013].

"Rolls-Royce Derwent," *Flight and Aircraft Engineer*, Vol. 48, 25 Oct. 1945, pp. 447-450.

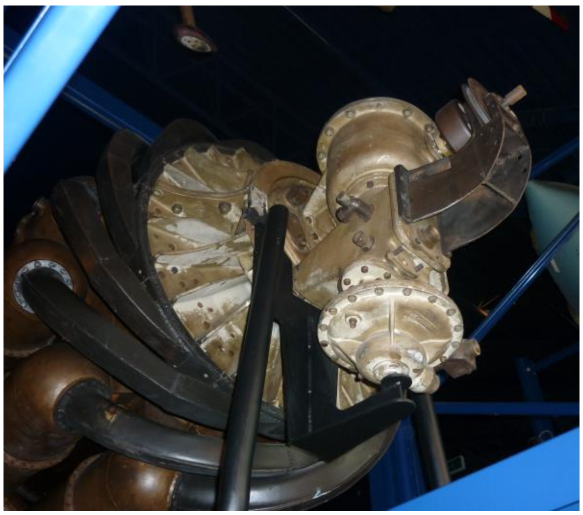
Samuel H. Williamson, "Seven Ways to Compute the Relative Value of a U.S. Dollar Amount, 1774 to present," MeasuringWorth, April 2013.

Sears, W. R., "Hans J. P. von Ohain: 1911-1998," *Memorial Tributes: National Academy of Engineering*, Vol. 10, 2002, pp. 234-239.

Whittle, F., British Patent Application for "Improvements relating to the propulsion of aircraft and other vehicles," Number 347,206, filed 16 Jan. 1930.

Whittle, F., "The Papers of Sir Frank Whittle," Archives Center, Churchill College, Cambridge University, Cambridge, UK (unpublished).


Rear view of Whittle Unit (WU) first-ever turbojet


Front view of WU


Rear view of W.1 turbojet

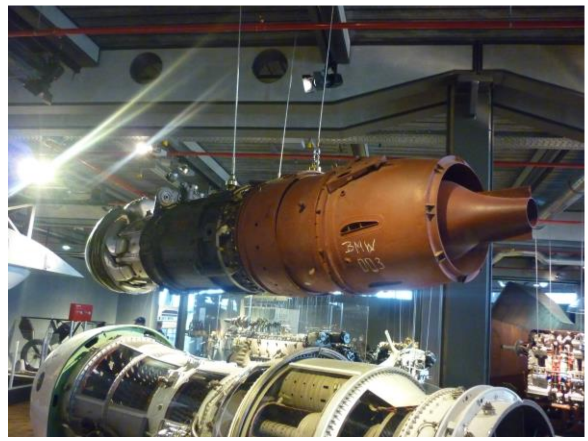

Front view of W.1 turbojet


Gloster E.28/39, single-engine testbed for W.1

W.2B/500 engine, powerplant for Gloster Meteor

Front view of BMW 003 turbojet

Gloster Meteor, sole British jet fighter of WWII



Rear view of BMW 003 turbojet

Junkers Jumo 004B turbojet, first-ever to see service and typical powerplant for Messerschmitt Me 262

Messerschmitt Me 262, first operational jet fighter, powered by either Jumo 004 or BMW 003 engines