The Development and Production of Turbojet Aero-Engines in Britain, Germany and the United States, 1936-1945

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Declaration of Originality

I hereby declare that this thesis represents my own work. Where the work of others has been used, it is appropriately referenced.

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Abstract

The history of the jet engine in Britain, Germany and the United States between 1936 and 1945 has long been recognised by historians as a rich subject for investigating the nature of technological change in comparative perspective. Outside academia, it has captured the public imagination as a story of heroic invention. Both kinds of account have much in common, including a focus on the same successful engines and inventors. This thesis will change both types of accounts by taking a comprehensive and critical approach to reinterpret and broaden the existing history of the jet engine.

This new story of the turbojet is centred on production and on industry, rather than on the work of individual inventors. It brings attention to the extent and significance of jet engine production during the Second World War, and illustrates that production, development and invention – activities often treated as separate – are fundamentally linked. Here, the jet engine is understood as emerging from the existing aero-engine industry rather than as arising outside it. I thus give new accounts of famous institutions outside of the aero-engine industry that made crucial contributions.

Through a detailed study of the work of the main companies and institutions that worked on jet engines during the war, which draws on sources ranging from popular accounts to archival research, this thesis recalibrates our understanding of the importance of different actors in the history of the jet engine, which has been distorted by the greater visibility of particular groups. The necessity of such a re-evaluation is made clear through a historical exploration of how the popular story of the jet engine emerged. In bringing attention to the variety of sources of technical change, this thesis suggests the outlines of a new account of the sources of technical novelty in the twentieth-century.

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List of abbreviations used in the text

ARC	Aeronautical Research Committee
ASM	Armstrong-Siddeley Motors
AVA	Aerodynamische Versuchsanstalt
BMW	Bayrische Motoren Werke Aktiengesellschaft
Bramo	Brandenburgische Motorenwerke GmbH
BTH	British Thomson-Houston Company
EHAG	Ernst Heinkel Aktien-Gesellschaft, founded 1 April 1943
EHFW	Ernst Heinkel Flugzeugwerke
GE	General Electric Company, United States
GTCC	Gas Turbine Collaboration Committee
HMZ	Hirth Motor Company, Stuttgart-Zuffenhausen
ICT	Internal Combustion Turbine
Jumo	Junkers Motorenwerke Aktiengesellschaft
MAP	Ministry of Aircraft Production, Britain
Metrovick	Metropolitan-Vickers
MoS	Ministry of Supply, Britain
RAE	Royal Aircraft Establishment
RAF	Royal Air Force
RAFDEL	RAF Delegation in Washington, D.C.
RCAI	Royal Commission on Awards to Inventors
RLM	Reichsluftfahrtministerium, German Air Ministry
USAAF	United States Army Air Forces

Archives Consulted

AFHR	Air Force Historical Research Agency
BA	Das Bundesarchiv
BL	British Library
BMW	BMW Corporate Archive, Munich
CAC	Churchill Archives Centre, Churchill College Cambridge
DB	Daimler-Benz Corporate Archive, Stuttgart
DM	Archives of the Deutsches Museum, Munich
GOAR	Archives of the Deutsches Zentrum für Luft- und Raumfahrt, Göttingen
IWM	Imperial War Museum
KNA	Kings Norton Archive, Cranfield University
MOSI	Archive of the Manchester Museum of Science and Industry
NA	National Archives, London
NASM	Archives of the Smithsonian Institution, National Air and Space Museum
RR	Archives of the Rolls-Royce Heritage Trust

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Introduction

'Britain can lead in technology, but it must change. We must remember the lesson of Frank Whittle, who invented the jet engine, and let our ideas fly.' So wrote Sir James Dyson in an article in the *Daily Telegraph* on 27 May 2010, in which Frank Whittle featured as the only twentieth-century inventor beside other British inventors who have had 'a seismic impact': James Watt, Michael Faraday, and Isambard Kingdom Brunel.[1] Since 1944, a particular story of the invention of the jet engine has continued to serve as a key example for writers like Dyson belabouring the government's failure to promote invention and recommending how the government should do so. This story of Whittle typifies the popular understanding of the history of one of the century's most important inventions. Dyson, who has made Whittle an icon of his crusade for increased government support for inventors, recounted in his article what was for him a sobering tale:

> [the jet engine could] have changed the course of the Second World War. Yet it was an opportunity missed by the Air Ministry and the government of the time.... Whittle's design pushed the available technology to the limit – too far for the decision-makers at the Air Ministry. Unwilling to invest the time and resources required to realise his idea, they dismissed it. But (a man after my own heart), he didn't give up. He did it himself, taking out a patent in 1930, aged only 21 [Whittle was actually born in 1907], for what he called a "jet engine"....
>
> In January 1935, his patent came up for renewal. The Air Ministry refused to pay the £5 fee and Whittle decided he could not afford it. Unfortunately, the rest is history: the idea found its way to Germany and the Nazis flew the world's first turbo-jet powered flight in 1939.
>
> With prompt backing, Whittle could have helped supply jet planes for the Battle of Britain. But it took the Air Ministry 10 years to recognise his discovery: Britain's first jet-powered flight took place on May 15, 1941, two years after the Germans....
>
> I'm afraid that stories like this are still being written today.... If an idea as brilliant as Whittle's could be achieved with such little encouragement, imagine what would be possible if the Government were to act as a catalyst.[2]

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[1] James Dyson, 'Britain can lead in technology, but it must change,' Telegraph.co.uk, published 5:27PM BST 27 May 2010 accessed on 21 July 2010.

[2] Ibid.

Dyson's account perhaps exaggerates, but does not contradict many other accounts of the invention of the jet engine. Indeed, it is uncomfortably close to some academic treatments. Yet Dyson's story is in nearly every important particular not only misleading but also false, as is clear from the good existing literature on the jet engine, and as this thesis will demonstrate.

Prompted by the hegemony of this particular kind of story of the jet engine in Britain, this thesis is an attempt to write a new history of the jet engine in Britain, Germany and the United States between 1936 and 1945. My argument is not just that we need a better history of the emergence of the jet engine, although there is a lot of scope to add to and reinterpret the existing literature. The repetitiveness and plausibility of existing accounts reveals a great deal about how we think about invention in the mid-twentieth-century. Part of the reason that we don't have a good story of the jet engine's early years is because the typical way of telling invention stories has set up a dichotomy that blinds us to many sources of new things in the twentieth-century, including where the jet engine came from. The typical, mistaken way of thinking about invention has given rise to a pseudo-historical narrative about the place and nature of invention that continues to constrain historical research on invention.

The most significant source of invention is often taken to be the individual, and stories of new things have often been focused around the playing out of genius, the discovery and exploitation of new principles. Opposed to this is a second and particularly twentieth-century source of invention: the corporate research lab, which is generally understood as a laboratory based on an academic research model that carries out scientific research in industry. These limited understandings of where invention occurs, often confounded with value-laden assumptions about how the nature of invention varies in

different places,[3] have been conflated with a story of how invention changed in the early twentieth-century.

This story, which I will refer to as the transition narrative, explains that invention has moved from being overwhelmingly the province of heroic, independent inventors in the nineteenth-century to coming mostly from corporate research labs in the twentieth. Yet there are huge numbers of familiar and important new things that appeared in the twentieth-century that cannot be explained by reference to either of these sources and the limited understanding of technical change that they imply. The Model T, for example, came from industry, but it didn't come from a laboratory.[4]

This thesis, in contrast, relies on an understanding of important sources of novelty that reframes the story of invention in the twentieth-century. It does not think only, or primarily of, independent inventors or corporate research labs and instead directs serious attention to the range of inventive organisations, particularly in industry, that are absent in the standard account. The most important reason to get outside of the standard transition narrative is in order to look at the many, varied places in industry and government where technical novelty emerges, which have been obscured by a historiography focussed on the tension between the individual inventor and the rise of the corporate research lab, which is often taken to represent the broader notion of 'research and development'.

The early history of the jet engine in Britain, Germany and the United States is an important case for rejecting the current understanding of invention and the transition narrative. The jet engine is considered to be one of the most important inventions to have

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[3] Dichotomies have often been drawn between contrasting types of invention, which are each associated with a particular location for invention – in each pair, the first is often associated with the individual inventor, the second with the corporate laboratory: individual/group and sudden/evolutionary (S. C. Gilfillan, *The Sociology of Invention: An Essay in the Social Causes of Technic Invention and Some of Its Social Results; Especially as Demonstrated in the History of the Ship* (Chicago: Follett, 1935)), unpredictable/predictable (Joseph Schumpeter, *Capitalism, Socialism and Democracy* (London: Allen & Unwin, 1943)), revolutionary/evolutionary (Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870-1970* (New York: Viking, 1989)), macro/micro (Joel Mokyr, *The Lever of Riches: Technological Creativity and Economic Progress* (Oxford: OUP, 1990)).

[4] David Edgerton, *Warfare State: Britain, 1920-1970* (Cambridge: CUP, 2006), 246-259.

been made by an independent inventor in the mid-twentieth century. Yet the jet engine represents, not the height of independent invention or corporate research, but a typical product of large-scale, industry-led activity. It was the outcome of huge government investment in the national aviation industries of Britain, Germany, and the United States and of the particular connections of industry with research and with academia, connections that were crucial to the jet engine, but in ways that neither the heroic nor the corporate lab models capture.

Freed from the constraining frame of the transition narrative, the history of the jet engine is transformed. Emphasis on individuals turns into emphasis on the crucial contributions of large-scale organisations, and a whole new set of actors and skills are introduced to the story. The warm glow of early laboratory prototypes as beacons of the future fades in the light of intense industrial activity. The revolutionary nature of the jet engine shrinks beside important continuities with piston engine manufacture. Inevitability turns into conscious choice.

This thesis will use the story of the jet engine – as a typical rather than exceptional example of how new things have emerged - to rethink the importance of industry as a source of inventive activity in the twentieth-century. In this way, the story of the jet engine told here is radically different in scope from existing accounts.

Thesis Structure

The first chapter of this thesis will establish a clearer view of the literature on the emergence of technical novelty by looking at the assumptions that have shaped and continue to shape it. A review of the earliest academic thinking on invention is important both because thought on the subject has not moved very far since that time and because some early ideas still appear in discussions today, although they are never treated as very serious alternatives as they perhaps deserve to be. Revisiting the earliest literature reveals, furthermore, that many of the ideas that are taken for granted today, such as the role of the individual or corporate

laboratory, were quite foreign to early twentieth-century thinkers on invention. Other aspects of more recent work, however, like the combination of technological and social awareness, were present in some of the first works on invention. At stake is both how we think of the emergence of technical novelty generally and the historical narrative of how the sources of technical change have shifted over time.

The latter half of Chapter 1 reviews the perhaps surprisingly extensive existing literature on the jet engine. The literature on the emergence of technical novelty leads less naturally into a review of the jet literature than one might expect of an important twentieth-century machine. The key exception is the work of the American historian Edward Constant, who chose the jet engine as a case study to establish his model of technological revolution. Constant did not however engage with the more recent literature on emergence of technical novelty but chose instead to attack the determinist versus individual debate of early twentieth-century thinkers on invention.

In addition to Constant's academic treatment, there have been two other attempts to tell the overarching story of the jet engine in Britain, Germany and the United States. The earliest and richest account of the jet engine, that by Robert Schlaifer, written just after the jet engine's early years, has been widely used yet overlooked as a serious starting point for later thought. It has, however, shaped this thesis in important ways. The most recent comprehensive account, that by Michael Pavelec, in contrast, is a largely a codification of the previous literature, which was created from an extensive collection of post-war intelligence reports, actor's accounts and popular works. Historians in Britain and Germany have however recently begun to do new research on the jet engine, using archival evidence to add depth to the existing story.

Although the limited and repetitive nature of the information available in existing work on the early history of the jet engine means that much can be done to expand our understanding by drawing on archival sources, the implications of what the literature has

already established remain largely undeveloped. This offers significant scope for reinterpretation, especially in a framework of political, industrial, economic, and social concerns broader than that usually adopted by enthusiasts. The remaining chapters of this thesis combine the existing literature with new archival research to shift the jet engine story in a few important ways. This both produces a dramatically new reading of the jet engine story and contributes to a broader understanding of the sources of technical change.

The first crucial shift is to reverse the order in which the history of the jet engine has been told. Rather than following the traditional order – invention, development, production – this thesis discusses production followed by development and then invention.[5] The standard sequence may seem obvious because it represents stages that a single engine goes through, however iteratively. But in fact, through much of the period covered by this thesis, all three activities occurred concurrently for a given engine, both within a given company and across the entire aero-engine industry.

One advantage of changing the order in which the story is told is that production forms the foundation for this account. By subverting the tendency to view production as a measure of success of other processes, reversing the order actually provides a more compelling account of the jet engine in which production is integral to the creation of the new aero-engine. I am not arguing for replacing one hierarchy with another, but rather for the necessity to view production, development and invention as separate but related

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[5] Thus far I have used the terms 'invention', 'development' and 'production' loosely, using their common definitions and deploying them as descriptive rather than analytical terms. I will continue to do this throughout the text. Several authors have already effectively challenged the often assumed analytical power of these common terms, demonstrating that they are not distinct phases divisible in time or space or according to the people involved. Scranton used the case of early cold war jet engines to describe the inventive process as an 'an a open, iterative, situated process of problem-stating and solving, often with multiple feedback loops that shift the grounds of inquiry, rather than as a series of discrete events.' (Philip Scranton, 'Technology-Led Innovation: The Non-Linearity of US Jet Propulsion Development,' *History and Technology* 22, no. 4 (2006): 338.) In my text I use the actors' language to describe the activities when possible, which serves to demonstrate just how flexible these terms were. Often modified by the actors, they served both prescriptive and descriptive functions.

activities, in which changes in one activity impacted the execution of the others.[6] In the hopes of producing the new jet engines as soon as possible, production plans were put into place in all three countries before development had been completed. This led to a complex interaction between production and development, which was central to how the jet engine was developed. Rather than an afterthought to invention and development, planning for production was integral in all three countries – although earlier in Britain and the United States than in Germany. By 1945, Britain, Germany and America were all producing jet engines, and what each country produced, as well as the scale and timing of production, had a profound effect on what was developed and invented in each country. The mutual influence of production, development and invention during the war, which is emphasised in this telling, made the trade-offs between the activities more pronounced. Under the urgency of war, they competed for the same resources.

Chapter 2 discusses jet engine production. It argues that the jet engine was not produced or deployed primarily because of its superior performance over piston engine aircraft but for reasons of post-war competition, expediency or scarcity. It shows how in Britain and the United States, early interest in production was relaxed when the new jet engines proved unready for production, and attention was refocused on broader development programmes. Looking at the details of production demonstrates the changeability and responsiveness of production planning, the 'concurrency' of development, production and use, which Scranton highlighted particularly well in the case of jet engines during the Cold War.[7] Both the intensity and consequences of the early British dedication to jet engine production must be recognised. The early American programme, meanwhile, needs to be fundamentally understood as a result of a production-driven decision to take

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[6] As Schlaifer described in the context of aero-engines. (Robert Schlaifer and S. D. Heron, *Development of Aircraft Engines* (Boston: Division of Research Graduate School of Business Administration Harvard University, 1950), 25.)

[7] Philip Scranton, 'Turbulence and Redesign: Dynamic Innovation and the Dilemmas of US Military Jet Propulsion Development,' *European Management Journal* 25, no. 3 (2007): 235–248.

over and produce the British Whittle engine in preference to a less developed American design.

The well-known German lead in jet production and deployment was not the natural result of the country's technical lead, nor of the new aero-engine's superiority to existing, out-numbered piston-engines, but rather of the country's desperate position at the end of the war. The jet engines that Germany produced were much easier to build than existing piston engines, requiring only a fraction of the man-hours and material. They were not wonder weapons, but ersatz ones. German jet engine production was not, as some authors have portrayed it, the successful climax to a programme of advanced technological development, but rather the large-scale manufacture of engines of desperation.

This thesis' early focus on production intentionally emphasises the contribution of industry to the jet engine, which is explored in more detail in the third chapter. The range of industrial firms involved in the jet story included many with relevant expertise: engineering consultants, electrical companies and steam turbine builders, automobile companies, fuel companies, metal suppliers, and many different component manufacturers. Yet the central and coordinating actors among these many firms were the firms of the aero-engine industry. Chapter 3 takes the aero-engine industry in Britain and Germany as its main focus, examining how each of the aero-engine industry's firms responded to the new type of engine by deploying their existing skills and resources and acquiring new. It was these firms that did the most work developing jet engines during the war.

The jet engine features in the literature as a revolutionary new power plant, yet focusing on the aero-engine industry stresses the deep continuities between piston engine and jet engine development. Although the youthfulness of many of the teams assembled to work on jet engines contrasted with established piston engine development teams, this was a product of the availability of young graduates during a war in which engineers were in high demand, rather than a reflection of the conservatism of industry. Indeed, jet engine

development teams were led by experienced piston engine and supercharger men. The course of engine development in the new types was similar too. In fact, jet engines took about five years to develop to the point of first production, about the same amount of time as the gestation of a new piston engine, contrary to optimistic, early hopes in industry and government. In this story, it is the continuities of personnel, of method, of resources, and of management that are more important than any major, revolutionary breaks.

The structure of the jet engine fundamentally influenced how its development proceeded, so some technical details are essential for understanding the story. One of the reasons that the aero-engine industry was able to take up the new type of engine so effectively was because the new engines could be designed by combining independent elements – many of which the industry was already familiar with. The simplest early gas turbine, the heart of the jet engine, included three main parts: compressor, combustion chamber, and turbine. The compressor, through which the air entered the engine, increased the pressure of the air stream and thus the amount of air available for combustion in the chamber following it. More air in the combustion chamber meant that more fuel could be burned in the engine, which was converted into additional propulsive energy. On leaving the combustion chamber, the hot and ever faster-moving stream of air impinged on the turbine, which extracted enough energy from the air stream to drive the compressor. The two main types of gas turbine were those with centrifugal and those with axial compressors. Axial engines had lower frontal areas than centrifugal engines and could reach higher compression ratios, but they were more difficult to run at low speeds. (Schematics of both types are reproduced in Figure 0.1.) Any number of variations existed around the gas turbine. In a jet propulsion gas-turbine engine, the remainder of the hot gas was formed into a propulsive jet. The alternative to this was to use a second turbine to extract as much energy as possible from the exhaust stream in order to drive a propeller, leaving only a small propulsive jet. This arrangement was much more fuel efficient at lower speeds than a pure jet.

Industrial experience provided a crucial source of knowledge for jet engines. Superchargers, which allowed piston engines to operate at higher altitudes, were particularly important. In a geared supercharger, an extra compressor, driven directly by the piston engine, compressed the air going into the pistons, where combustion took place. Turbo-superchargers, in contrast, used a turbine that extracted energy from the piston engine's exhaust to drive the compressor. The main components of each jet engine, which were often developed separately, all had different histories.

The minute, even pedantic, attention paid to precision about the different engine layouts and elements discussed in this thesis, to what was made by whom at any given time, is imperative if one wants to understand the full complexity of how and where technical novelty appears. (A reference table is provided in Appendix C to help the reader keep track of the many engines mentioned in the text.) The ambiguity of what an early gas turbine aero-engine consisted of was reflected to some degree in the variety of terms used to describe the early engines, which contrasts with the term 'jet engine' which is today in common use. The new aero-engines were frequently known as 'gas turbine aero-engines', emphasising the engine's central novel element, the gas turbine. Sometimes, the engines were referred to as 'internal combustion turbines', which emphasised continuity with internal combustion engines. Whether or not the gas turbine produced a propulsive jet or drove a propeller was an important distinction. The term 'turbojet', like the ungainly 'gas turbine, jet propulsion aero-engine', referred to a gas turbine that propelled an aircraft primarily through jet propulsion. A 'turboprop', in contrast, used a gas turbine powered propeller.

Looking in detail at the full story of the development of turbojet engines in the British and German aero-engine industries, including both successes and failed or abandoned engine designs, reveals the changing nature of each company and each country's goals, which is also evident in the crucial shifting resources between piston engine and jet engine projects at individual firms. Furthermore, by uncovering a previously hidden world of large-scale

design and development activity off the map of the transition narrative, the industry-centred narrative emphasises the range of skills and expertise that were essential to the jet engine. Examining the full range of development in the British and German aero-engine industries also shows just how wide a range of jet engines was designed and developed during the war.

Understanding development casts the British story, in particular, in a more positive light. The small scale of British jet engine production has often been taken to imply a small-scale development programme. Yet unlike Germany later in the war, Britain deemphasised production in favour of a broad development programme. By the end of the war, despite having produced a smaller number of production engines than the Germans, Britain boasted both the most developed jet engines and the most varied jet engine programme in the world. This encompassed all of the country's aero-engine makers and included the work of Rolls-Royce, which led the world market in large jet engines after the war. So it was that, in contrast to the German V1 and V2 that spawned post-war American military missile and rocket projects,[8] American aero-engine firms did not in the post-war period turn to confiscated German jet engines as a basis for future development but instead licensed British jet engines with wartime heritages.

The literature on the jet engine has overwhelmingly emphasised individuals as sources of creative ideas. Yet these individuals did not work alone, but were members of larger, inventive institutions. Like the creative firms focussed on in Chapter 3, these organisations were not corporate research laboratories. The inventive institutions examined in Chapter 4 designed elements of jet engines but did not themselves produce engines, whether according to or against the organisation's wishes. The influence of these organisations, both government and industrial, on the history of the jet engine and their particular relationships to invention have been entirely overlooked by transition narrative.

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[8] Michael J. Neufeld, *The Rocket and the Reich: Peenemünde and the Coming of the Ballistic Missile Era*, (New York; London: Free Press, 1995).

Chapter 4 explores three inventive organisations that were central in the jet story, two in Britain and one in Germany: Power Jets, the Royal Aircraft Establishment and the Heinkel Aircraft Company. Each is associated with and generally overshadowed by the work of a popular jet inventor, yet each of these organisations was an important source of early jet engine design work in its own right. All three thrived under particular circumstances, which had largely disappeared by the end of the war, when they found their claims to exist as solely design or inventive institutions increasingly ineffectual. Taking the power and impact of these organisations as organisations seriously shifts the discussion from treating institutions as a context for powerful inventors to looking at how the stability of institutions shaped the emergence of technical novelty.

The point of telling the story of the jet engine with these key inventive institutions at the end is to understand invention not as the precursor to development and production, as it is usually treated, but much more broadly as an extended activity in the context of development and production, constantly impacted by development and production decisions. Novelty did not appear through the work of unique inventors in rarefied places, but was carried out in the same kinds of places as and through the work of the same kinds of people who were engaged in development and production.

Chapter 5 extends the historiographical study of the first chapter by looking at the way in which Frank Whittle was constructed as a British inventor-hero from the moment in 1944 when the existence of secret Anglo-American work on jets was first publicly revealed. It shows how the British Government's strict policy on the control of jet publicity created a gap in the public understanding of an increasingly visible and economically significant aero-engine, which was filled by a story of a heroic, individual inventor. This narrative was gradually infused with such wide authority that even professional historical accounts have been shaped by it, and it is still the dominant story of the British jet engine today. The last chapter argues that this narrative, well suited to the post-war needs of a range of groups, set

off a process of forgetting that resulted in the particular understanding of the jet story that inspired this thesis and has obscured the extensive activity of the many different actors discussed below. The construction of the British jet inventor is one persuasive example of how the literature's focus on individuals and corporate laboratories as the most important sources of novelty in the twentieth-century has misled historians.

Because I am concerned with the framing and understanding of the jet story, I do not have space in this thesis to give a detailed account of all of the events and aero-engines mentioned in the text. Much detail on the technical aspects of the work can be found in existing sources, and a few key examples must suffice here as illustrations. Details of the activities of the individuals and companies in this story have been to some extent sacrificed in order to paint a broader picture. In the same way, the approaches of the different jet engine teams mentioned – the differences in the physical, theoretical and mathematical machinery that they used - as well as the evolution of aerodynamics and other sciences relevant to aero-engine development deserve a much more thorough examination and description than can be given here.

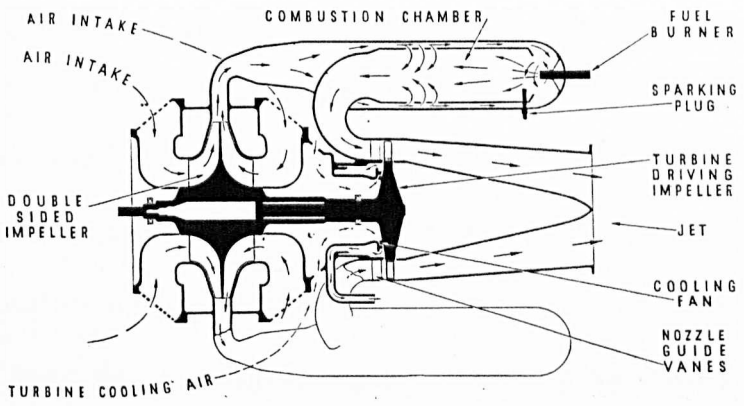
My focus on the aero-engine industry, which has been little studied in the literature, leads me to slight other actors in the story. The role of the government, for example, will not be taken as a guiding frame for this story, although it enters the narrative where relevant. The existing work of several historians can be consulted for more information on different aspects of the role of government in jet engine development.[9] In the conclusion, I will reflect briefly on the government's role in wartime aero-engine development.

By reversing the order in which the story of the jet is related, this thesis shifts the emphasis from familiar individuals to the much less known role of industry and from the

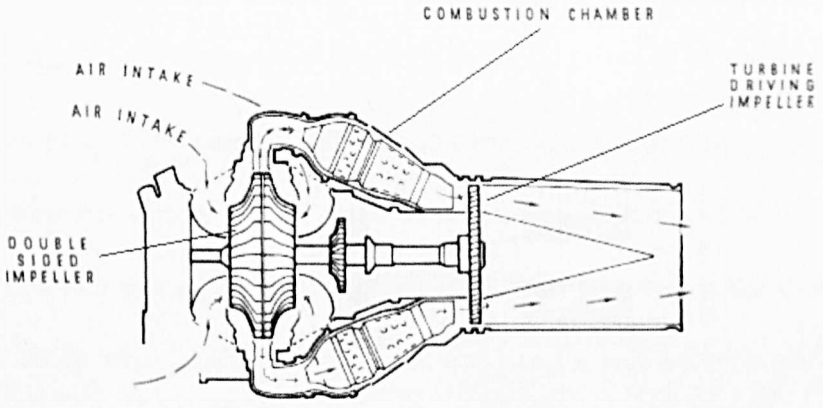
[9] For example: Schlaifer and Heron, *Development of Aircraft Engines*; Ralf Schabel, *Die Illusion Der Wunderwaffen: Die Rolle Der Düenflugzeuge Und Flugabwehrraketen in Der Rüstungspolitik Des Dritten Reiches* (München: Oldenbourg, 1994); Andrew Nahum, *Frank Whittle: Invention of the Jet* (Cambridge: Icon, 2004).

search for revolutionary change to the discovery of the continuities of expertise that made the jet engine a real possibility. Rethinking our basic assumptions about where and how technical novelty emerges produces a wider view of the jet story, which enables us to recalibrate our understanding of the importance of different actors in the process of technical change. The new story told here is not that of a new engine creating a new industry. It is rather of the aero-engine industry creating a new engine.

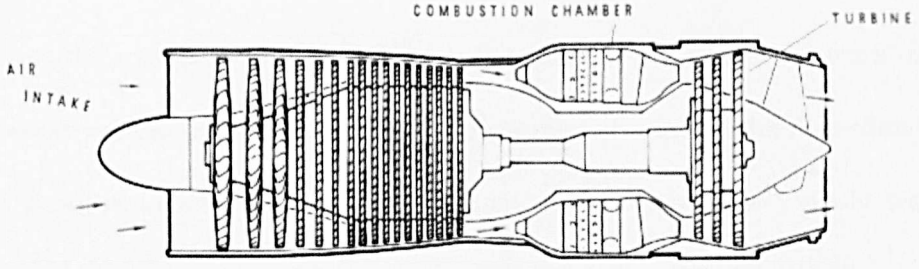
Figure 0.1. Schematics of gas turbine jet propulsion engines



This is the basic Power Jets gas turbine, jet propulsion architecture with its double-sided, centrifugal impeller-compressor and reverse-flow combustion system, made up of individual combustors in which the air's direction is reversed twice, as indicated. This architecture was used in the Power Jets W.2B and Rolls-Royce Welland.



This architecture was used in the Rolls-Royce Derwent; it has a double-sided, centrifugal impeller-compressor but, in contrast to the Power Jets architecture, has a straight-through combustion system.



This axial turbojet architecture has an axial compressor (with multiple stages) powered by three turbines mounted on a single shaft. Airflow is from left to right. Early axial engines included the Metropolitan-Vickers F.2, the Armstrong-Siddeley ASX, the Jumo 004 and the BMW 003. Each had different numbers of compressor stages and turbines; early axial compressors often used a single blade profile for all stages.

Source: Lionel Haworth, *The Rolls-Royce Tyne* (Derby: Rolls-Royce Heritage Trust, 2000), 15; Rolls-Royce, *The Jet Engine* (Derby: Rolls-Royce, 1986), 5.

Chapter 1
The Historiography of the Emergence of Technical Novelty

This thesis will tell a new story of the jet engine in Britain, Germany and the United States. As I will show, this story does not fit either the conventional story of the sources of technical novelty in the mid-twentieth-century, nor even the frame in which the jet story is usually cast, that of the individual inventor. Because this thesis will use the story of the jet engine to revise the conventional story, this first chapter begins by reviewing the existing literature on the emergence of technical novelty before turning to the varied existing literature on the jet engine. Edward Constant's important account of the early history of the jet engine, which is also one of the most significant works in the historiography of technical change, serves as a bridge between the two.

The first part of this chapter will look at what has been written by twentieth-century academics on what has variously been labelled invention, innovation or technical change. [1] It is difficult to describe this as a coherent literature, in part because of the disagreement and lack of clarity about what exactly is being discussed and a lack of appreciation within the literature of its own past. As I show, our understanding of technical change has undergone radical revisions during the twentieth-century, a fact neither well understood nor even acknowledged.

In fact, the sociology of invention from the interwar period and the work of the early post-war period were much richer than later caricatures referring to the discredited 'classical division of innovation into individualistic (heroic) and deterministic'[2] would lead one to

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[1] I limit this discussion to formal academic work, excluding early encyclopaedias of invention and books of machines. Jamison's review includes the latter. (Andrew Jamison, 'Technology's Theorists: Conceptions of Innovation in Relation to Science and Technology Policy', *Technology and Culture* 30, no. 3 (1989): 505-533.) MacLeod has discussed the work of nineteenth-century theorists. (Christine MacLeod, *Heroes of Invention: Technology, Liberalism and British Identity, 1750-1914* (Cambridge: CUP, 2008).)

[2] Charles Susskind and and Martha Zybkow, 'The Argument,' in *Technological Innovation: A Critical Review of Current Knowledge*, ed. Melvin Kranzberg and Patrick Kelly (San Francisco, CA: San Francisco Press, 1978), ix.

believe. I review this older literature, before considering in detail what I call the transition narrative (the supposed shift from individual inventor to corporate laboratory), a powerful narrative that arose in the post-war period and is still pervasive in studies of technical change, even in revisionist narratives, where one would least expect it. It is also an implicit assumption in reviews of the literature on 'technical innovation' from a variety of perspectives, rather than a major feature to be examined.[3] Taking the older literature on invention seriously emphasises the narrowness of the transition narrative and acknowledges productive alternatives to this dominant view. This review will show that in addition to the empirical reasons that will be given in this thesis, there are good historiographical reasons to reject the transition narrative as a guide to technical change.

Because of the importance of precision in understanding the literature on the emergence of technical novelty, this review will pay careful attention to the terms of art used by different authors. 'Invention' was used in the interwar period in the broadest way to refer to the emergence of novelty and the sources of technical change. After the war, however words like innovation, technical change, and research and development came into use. 'Innovation' took on a broad meaning while the meaning of 'invention' became narrower, increasingly relating exclusively to the emergence of novel ideas in particular settings.

A need to revise and clarify was felt by Edward Constant, who explicitly differentiated his work from the narrow, pedantic concerns of earlier authors with invention and patents. In their place, he suggested a new 'model of technological change', which he called the 'technological revolution'.[4] Constant used the jet engine as a central case for revising the common understanding of the emergence of technical novelty. His work is thus

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[3] Jamison used the literature to argue that both the policy and theory of innovation have followed practice. (Jamison, 'Technology's Theorists'.) Susskind and Zybkow drew in their review of the literature on major authors from a range of fields (business, economics, history) who were writing about invention at the time, including the work of Thomas Hughes. They argued that 'the individual inventor-entrepreneur' had given way to 'organized R&D within the Laboratory' – a perfect rendition of the transition narrative. (Susskind and Zybkow, 'The Argument', x.)

[4] Edward Constant, *The Origins of the Turbojet Revolution* (Baltimore: Johns Hopkins UP, 1980), 179.

a contribution to both the literature on the emergence of technical novelty and that on the jet engine. While the main accounts of the emergence of the jet engine are discussed here, I return to the topic in Chapter 5 where I show precisely how certain individual inventors were made central to the story of the jet and the impact that this has had on professional historiography.

Interwar literature on invention

Most famous for inaugurating the formal study of invention in the twentieth-century were a group of American sociologists who expounded what S.C. Gilfillan described as the 'sociology of invention'. Gilfillan was a prominent member of the school of the sociologist William Ogburn,[5] which took up the study of invention as a way to explain a central sociological problem of the day: the observed differences between cultures. They rejected the then popular racialist-biological explanations for cultural differences between Western and 'savage' cultures, arguing instead that humanity had common intellectual capacities. This led them to favour a determinist theory of invention, in which invention occurred everywhere through the combination of elements from a shared cultural base.[6]

The key piece of evidence adduced for this theory of invention was the observation that things were commonly invented by multiple people. Ogburn and Dorothy Thomas argued in a 1922 paper that the frequent existence of 'duplicate inventions or discoveries', which they empirically illustrated with 148 examples from a range of fields, suggested that invention must 'be explained in cultural and social terms, that is, in terms of sociology and not in terms of biology and psychology.'[7] In this way, the authors claimed invention as a

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[5] Ogburn's school also included Kaempffert (editor), L.L. Bernard (sociologist) and Joseph Rossman (chemical engineer). (David McGee, 'Making up Mind: The Early Sociology of Invention', *Technology and Culture* 36, no. 4 (1995): 773-774.)

[6] More subtly than the 'cultural lag' thesis for which he is more generally known, Ogburn argued both that culture influenced invention and that invention influenced culture. (McGee, 'Making up Mind,' 773-801.)

[7] William Ogburn and Dorothy Thomas, 'Are Inventions Inevitable? A Note on Social Evolution', *Political Science Quarterly* 37, no. 1 (1922): 83-98.

legitimate realm for sociological study. The sociologists' belief in a common intellect led them to argue for the non-importance of the individual and to reject the idea of the heroic independent inventor, thus the opposition between the determinism of social need and the heroic individual was established early on. If one man didn't invent something, they argued, then the next man would, motivated by the same social influences.[8]

Gilfillan set out to demonstrate the viability of the determinist thesis by carrying out a detailed empirical investigation of the invention of the ship, 'in her history between floating log and rotorship'.[9] This study formed the companion volume to his more well known publication, *The Sociology of Invention,* of 1935 in which Gilfillan proposed thirty-eight 'social principles of invention' inspired by his empirical work. In fact, his well-considered principles prefigured many of the arguments later made about invention, suggesting that the insights produced by this particular line of exploration were early on exhausted. Gilfillan saw his book as - and indeed it was - a much-needed formalisation of the existing 'intelligent but inconclusive, discordant and scattered writings' on invention, and suggested that using the history of the ship as a case study (a method that 'has hardly been tried before') offered a more satisfying and complete approach to invention than the use of patent statistics or random illustrative examples.[10]

Even if invention required no special skill because it took place through the 'accretion of little details', as the determinist theory held, Gilfillan admitted that 'all our explanations of individual non-necessity have not abolished the great men. There they stick,

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[8] The authors did not assert that all individuals were equally capable of invention, but argued that this was a statistical feature: every population contained a proportion of individuals of 'exceptional native mental ability'. (Ogburn and Thomas, 'Are Inventions Inevitable?', 92.)

[9] S. Colum Gilfillan, *Inventing the Ship: A Study of the Inventions Made in Her History between Floating Log and Rotorship; a Self-Contained but Companion Volume to the Author's "Sociology of Invention"; with 80 Illustrations, Bibliographies, Notes and Index* (Chicago: Follett, 1935).

[10] Gilfillan, *Inventing the Ship*, vii-ix; Robert K. Merton, 'Review of the Sociology of Invention by S. C. Gilfillan,' *Isis* 25, no. 1 (1936): 166-167.

like volcanic peaks above ocean and cloud.'[11] Gilfillan argued that such men could not be denied, but their work, had they not existed, would have been accomplished by other great men or perhaps by a number of lesser men. He posited the existence of an 'inventive class', which responded to the social needs that prompted invention in the determinist view. This 'class of inventors' was an inclusive one, composed of replaceable individuals and containing 'all who invent, not merely the less important group of professional inventors'.[12] The importance attributed to certain 'titular inventors', he said, was a product of recent 'mythology' rather than necessity.[13] Indeed, Gilfillan argued that invention and engineering had only emerged as full-time occupations after the Renaissance, and 'it is only of late that some people, hardly the Historians [sic], have taken to writing down the principal facts of man's technic [sic] progress.'[14] Inventors as individuals, then, were a product of modern times.

To account for the dramatic recent increase in invention in the West, the sociologists identified accelerating and retarding factors. Through science, a common explanation for cultural differences at the time,[15] they argued, the West had escaped the conservatism that held back primitive cultures. Although at first familiar, the sociologists' invocation of science or of theory was unlike its use in more recent work. The importance granted to science in the more recent transition narrative is connected to the perceived emergence of an increasingly 'scientific' technology around the turn of the century, whereas for the interwar sociologists, it represented a new, systematic way of thinking that emerged around the sixteenth-century.

Over time, Gilfillan argued, the inventor had changed from unconscious creator to amateur and then to professional inventor; institutionally, the un-important individual had

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[11] Gilfillan, *Sociology of Invention*, 73.
[12] Gilfillan, *Sociology of Invention*, 79.
[13] Gilfillan, *Sociology of Invention*, 11.
[14] Gilfillan, *Sociology of Invention*, 72.
[15] McGee, 'Making up Mind,' 773-801.

given up solo practice to become part of an organised 'inventing group'.[16] Referring to the distinction between primitive and Western cultures, he noted that invention had moved from being 'empiric' to being 'theoretical'. It had progressed from 'the almost unconscious, mere evolutionism presumed for primitive cultures, thru [sic] the more revolutionary big-ship-building of the 1400s, to the deliberate, scientific research of laboratories today, and farthest of all to the logical, revolutionary invention of a Flettner, who set out to alter the ancient ship fundamentally, and in his rotorship did it.'[17] Anton Flettner, the popular 'inventive genius',[18] whose work Gilfillan identified as the height of marine inventive activity, was an independent inventor who, with the help of others, built the first rotorship in the early 1920s. The rotorship represented the exploitation of a scientific principle to use the wind to propel a ship in a new way. Despite its functionality, rotor propulsion was abandoned around the same time that Gilfillan published his two volumes because it was less efficient than existing methods of propulsion. It is revealing that Gilfillan chose Flettner rather than the 'scientific research laboratories today' as an example of the most modern invention. For Gilfillan the crucial factors were the inventor's foresight and his social context rather than location or means.

The American sociologists of invention were writing in the wake of the emergence of corporate research labs in the United States,[19] yet they saw no great difference between how invention had occurred in the nineteenth- and twentieth-centuries. Waldemar Kaempffert, an important populariser of Ogburn in the interwar period, agreed with Gilfillan that the industrial lab represented the natural progression of invention. Invention had always been a group effort, he argued, because it was based on combining existing ideas. This continued to

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[16] Gilfillan, *Sociology of Invention*, 11 and 68-70.

[17] Gilfillan, *Sociology of Invention*, 66.

[18] 'We can trick the wind into saving billions!' *Popular Science Monthly*, August 1926.

[19] Michael A. Dennis, 'Accounting for Research: New Histories of Corporate Laboratories and the Social History of American Science,' *Social Studies of Science* 17, no. 3 (1987): 479-518.

be true even if, as Kaempffert optimistically wrote in 1930, 'group invention in the industrial laboratory has telescoped time.'[20]

Another well-known history of invention of the interwar period was Abbott Payson Usher's *A History of Mechanical Invention,* first published in 1929. Like the sociologists, Usher came to study invention because it enabled him to address a bigger concern, in this case the general problem of historical change. For Usher, the history of mechanical invention was a particularly profitable focus of study because it could be used to 'securely' establish 'many of the primary features of the process' of 'the emergence of novelty in thought and action'. Mechanical invention, he wrote, was 'broadly representative of every feature of the general process of invention… [and] admits of a more rigorous historical treatment than is possible in many portions of the history of philosophy and the arts.'[21] Usher rejected the heroic view of invention, but he also objected to the determinists' opposing view because it made man 'the passive instrument of cosmic forces'.[22] His history of invention chose instead a middle course, in which building on the work of earlier inventors was fundamental to invention, but in which the individual nevertheless held a crucial place. Invention, which Usher modelled using Gestalt psychology, was not a heroic feat but a 'cumulative accomplishment' that was the result of the 'continuous activity of common mental processes'.[23] Although his work has latterly been attacked for its narrow technical focus, Usher wanted, like Gilfillan, to combine

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[20] Waldemar Kaempffert, *Invention and Society* (American Library Association, 1930), 28; and McGee quoting Kaempffert in 1923 and 1930 (McGee, 'Making Up Mind', 782-783.)

[21] Abbott Payson Usher, *A History of Mechanical Inventions,* Second Edition (Cambridge, Mass.: Harvard UP, 1954), 56-57. Usher's second edition included a much-expanded introduction, which included his detailed theory of history, suggesting the greater interest to him of his larger theoretical project. In a review, White criticised the lack of change in the book's main section in the second edition. (Lynn White, 'Reviewed Work: A History of Mechanical Inventions by Abbott Payson Usher,' *Isis* 46, no. 3 (1955): 290-293.)

[22] Usher, *A History of Mechanical Inventions*, Second Edition, 61.

[23] Abbott Payson Usher, *A History of Mechanical Inventions* (New York: McGraw-Hill, 1929), 5-6.

in his historical account of invention both social context and close attention to technical detail.[24]

Like the sociologists, Usher accepted the importance of science in changing invention, but he viewed science as a leading example of abstract thought in general, which, for him, marked the 'modern' form of invention. Usher located the key shift in the sixteenth century, citing da Vinci, Galileo, and Huygens as examples. Where Gilfillan's example of the peak of inventive capacity was the early twentieth-century Flettner, for Usher it was da Vinci, to whose prowess as 'engineer and inventor' he devoted an entire chapter.[25] For Usher, 'the discoveries of science define[d], or redefine[d], the problems of the inventor... The process of achievement thus [became] conscious and deliberately directed towards its ends in proportion as the pure sciences.' Although they disagreed as to details, Usher's description of how invention had changed over time was very similar to that put forward by Gilfillan. Usher described 'technological improvement' moving from 'empirical' and focused on immediate ends, to the 'more orderly', 'conscious pursuit of relatively remote ends'.[26]

Usher's history of mechanical invention did not venture into the twentieth-century, but he did observe, like the sociologists, that '[i]t is, of course, an error to suppose that the essential quality of the individual innovation is in any way changed by the setting up of a laboratory; and a still greater error to suppose that there is anything new in the development of formal research looking toward technical innovation.' He explained in 1929 that changes over the previous half-century should be understood as the 'completion of tendencies that have been significantly evident since the time of Leonardo da Vinci', the 'accumulated result' of the application to invention of the scientific knowledge and increased imagination born of

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[24] Arthur Molella, 'The Longue Durèe of Abbott Payson Usher,' *Technology and Culture* 46, no. 4 (2005): 781.

[25] Usher, *A History of Mechanical Inventions*, Chapter 7; Molella, 'The Longue Durèe,' 789.

[26] Usher, *A History of Mechanical Inventions*, 21-22.

abstract thinking.[27] Usher did allow that laboratories made invention more 'systematic and regular' but argued that they had not fundamentally altered the process, as the development of science previously had.

Most striking in the early work on invention as compared to later work is the insistence on the continuity of inventive activity over time, place and individuals. The changes in the nature of invention that these authors drew attention to were based on the sociological difference between inventing in isolation or in a group, between immediate and abstract thought. These authors did not see the twentieth-century as being fundamentally different from the nineteenth because they believed that invention had changed fundamentally many centuries earlier. The specificities of the arguments of interwar academics must be remembered, however, for although the language used was similar, the questions that later authors asked about invention were very different.[28]

Robert Merton was another American sociologist working on invention in the interwar period, who was familiar with and inspired by the work of Ogburn. Merton's wide-ranging oeuvre included a 1935 paper on the rate of industrial invention as illustrated by patent statistics,[29] and he reviewed the work of both Usher and Gilfillan for *Isis*, criticising both only for not being sociological enough.[30] After the war, Merton borrowed explicitly from the work of the interwar sociologists of invention in his work on scientific priority and

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[27] Ibid.

[28] In a 1978 paper, Hughes attempted but failed to combine his work with the 'interpretations of invention' put forward by Gilfillan and Usher. Hughes' inability to convincingly apply the earlier work according to a matrix derived from his own thinking to the case of a heroic, a transitional and an industrial inventor reflected the fact that his questions and interests were very different from those of the earlier authors. (Thomas P. Hughes, 'Inventors: The Problems They Choose, the Ideas They Have, the Inventions They Make,' in *Technological Innovation: A Critical Review of Current Knowledge*, ed. Melvin Kranzberg and Patrick Kelly (San Francisco: San Francisco Press, 1978), 166-182.)

[29] Robert Merton, 'Fluctuations in the Rate of Industrial Invention,' *The Quarterly Journal of Economics* 49, no. 3 (1935): 454-474.

[30] The sociologist of science criticised Usher for not spending more time on the collective nature of invention, which Merton claimed was 'widely accepted today'. (Robert K. Merton, 'Review of a History of Mechanical Inventions by Abbott Payson Usher', *Isis* 24, no. 1 (1935): 177-180; Merton, 'Review of the Sociology of Invention,' 166-167.)

attribution, when he extended the determinist argument of multiples to scientific discovery. In a 1961 paper, in which he tried to unify the heroic and determinist views of invention, Merton presented the results of an 'intensive' study of 264 cases of multiple scientific discoveries.[31] Jacob Schmookler and later Edward Constant attacked both Merton's 1961 multiples paper and the work of the earlier sociological school on the grounds that their 'multiple inventions' were not meaningfully equivalent.[32] In their efforts to propound a cumulative view of invention, the later authors argued, the sociologists' disregard for not only historical but also technological specificity had led them to false conclusions about the non-importance of the individual inventor.

Post-war views of invention, research and development

By the 1960s, the long-range, inclusive narratives of the earlier academics had given way to stories that took a shorter view, comparing invention in the twentieth-century to invention in the nineteenth. The corporate laboratory, which had not overly concerned the interwar theorists, now took centre stage in thought about invention, which identified a fundamental transition between the individual invention of the nineteenth-century and the corporate laboratory typical of the twentieth. The notion of a transition in the sources of invention from the individual to the corporate laboratory may well have been influenced by Joseph Schumpeter, who argued that the heroic entrepreneur was being made extinct by the organisation of innovation in the research labs of large corporations. 'Technological

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[31] Robert K. Merton, 'Priorities in Scientific Discovery: A Chapter in the Sociology of Science,' *American Sociological Review* 22 (1957): 635-659; Robert K. Merton, 'The Role of Genius in Scientific Advance,' *New Scientist* 259 (1961): 306-308; Robert K. Merton, 'Singletons and Multiples in Scientific Discovery: A Chapter in the Sociology of Science,' *Proceedings of the American Philosophical Society* 105 (1961): 470-486.

[32] Jacob Schmookler, *Invention and Economic Growth* (Cambridge, MA: Harvard UP, 1966), 189-195; Edward Constant, 'On the Diversity and Co-Evolution of Technological Multiples: Steam Turbines and Pelton Water Wheels,' *Social Studies of Science* 8 (1987): 183-184. Constant later dismissed the determinist argument as 'simply wrong'. (*Origins of the Turbojet Revolution*, 2)

progress,' he wrote in 1942, 'is increasingly becoming the business of teams of trained specialists who turn out what is required and make it work in predictable ways.'[33]

Worried about the fact that economists were drawing starry-eyed conclusions about the rate and sources of industrial invention based on popular notions rather than empirical evidence, three British economists, John Jewkes, David Sawers and Richard Stillerman, set out in the mid-1950s to put to empirical test a range of popular assumptions about the rate and sources of industrial invention. To do this, they assembled and classified a collection of 61 case histories of 'important' inventions according to several criteria, including the independent-ness of the inventor, which they defined according to each inventor's degree of control over problem selection, resources and the results of his work.[34]

Their results, published as *The Sources of Invention*, challenged a range of popular notions of invention. Among them was the set of ideas, which the authors described as the 'modern' view of invention, which drew a 'sharp contrast... between an earlier heroic age of clumsy individual pioneering and a modern age in which highly trained, closely organised teams of technologists, fortified by an easily accessible and constantly expanding body of scientific knowledge, move forward with deliberation to results which can largely be predetermined.'[35] The authors treated this narrative as so common as to need no elaboration.

The Sources of Invention took aim at every aspect of the 'modern' view. The authors' case studies illustrated that companies had produced an increasing number of inventions in the twentieth-century, but also that independent inventors were still crucial sources of invention. Although their emphasis on the continued importance of the individual inventor

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[33] Schumpeter quoted in David Edgerton, introduction to *Industrial Research and Innovation in Business* (Cheltenham: Edward Elgar, 1996), xi.

[34] John Jewkes, David Sawers and Richard Stillerman, *The Sources of Invention,* (London: Macmillan, 1958), 72. The importance of a laboratory for invention was central for those defending the notion of company ownership of inventions made in a company lab. This was a key provision of the very pro-business German patent laws of the early twentieth-century, drafted largely by electrical and chemical industrialists. (Kees Gispen, *Poems in Steel : National Socialism and the Politics of Inventing from Weimar to Bonn.* (New York; Oxford: Berghahn Books, 2002.))

[35] Jewkes, Sawers and Stillerman, *Sources of Invention*, 37.

in the twentieth-century continues to be the most cited aspect of their work, the economists were actually arguing most vehemently against the endpoint exemplified in Schumpeter's argument, namely that the organised research lab represented 'the growing power to invent' and the key to the contemporary 'spurt of technical progress to which no obvious limit is to be seen.'[36] Although they did not explicitly quote Schumpeter, they cited as exemplars of the 'spectacular view of modern invention' work by James B. Conant (1951), J. K. Galbraith (1952), W.R. Maclaurin (1953), Walton Hamilton and Irene Till (1945), W.B. Kaempffert (1930), J.D. Bernal (1953) and A. Hunter (1956). All but two of the quotes were, like *The Sources of Invention,* from the 1950s. These different authors emphasised the increasingly predictable nature of inventive output, the increasing power of scientists and engineers or industry to 'induce technical change', and the disappearance of the 'typical lone inventor of the eighteenth and nineteenth centuries', who had, according to Conant, been replaced by the 'industrial research laboratory' and 'departments of development engineering'.[37]

Against these views, Jewkes, Sawers and Stillerman directed attention to the fact that research labs weren't such prolific producers of novelty that they had entirely displaced independent inventors, as both enthusiasts and doomsayers had argued was inevitable. In fact, the economists argued, corporate labs had not even produced the majority of 'important' inventions in the twentieth-century. The 'spectacular' modern view was wrong because it assumed that the source of invention would shift entirely away from independents, yet their evidence seemed to prove that a complete shift away from independents was not possible. Jewkes, Sawers and Stillerman concluded that large corporate research organisations relied 'heavily' on other sources of creative ideas.[38] To explain this, the authors argued that organised corporate research labs actually restricted invention. Such labs made the process of

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[36] Jewkes, Sawers and Stillerman, *Sources of Invention*, 32.

[37] Jewkes, Sawers and Stillerman, *Sources of Invention*, 29-31; Edgerton pointed to the continued presence of the perception in the early twenty-first century that that new things were emerging at an ever increasing rate. (Edgerton, *Shock of the Old*, 3)

[38] Jewkes, Sawers and Stillerman, *Sources of Invention*, 29-31.

invention neither more efficient nor bountiful. In fact, the authors suggested, corporate labs might be inherently conservative.[39] Their main conclusion was that because the sources of invention were so varied, a single outlet could never capture all of the possible inventions.[40] Large industrial research organisations could certainly not be considered a 'sole and sufficient source of inventions'.[41]

Although they effectively demolished the idea that the independent inventor had been eclipsed by highly efficient corporate research labs in the mid-twentieth-century, the broad understanding of technical change that the economists started with gave way to narrow definitions that facilitated their case-study analysis. Their use of the word 'research', for example, referred to 'the attempts on the part of firms consciously to organise for the purpose of increasing the flow of inventions',[42] but the authors narrowly interpreted 'corporate research' to mean only research in corporate research laboratories, implying that this was the only location in industry in which invention occurred. Researchers in academic research labs, in contrast, were considered to be independent inventors. The authors drew a strong distinction between invention and development; the former was a focus of their case study analysis, while the latter was not, although they did devote a chapter to its discussion. The study's conclusions were shaped on one hand by the narrow definition of corporate invention used and on the other hand, by the study's selection of 'important' inventions, which deemphasised by definition the many incremental inventions that improve existing machines, the types of invention that corporate labs are often associated with.

The study's treatment of the jet engine, which the authors firmly classified as a case of independent, individual invention, is illustrative of how their selection criterion narrowed their historical view. Their case study drew on three published sources: the memoir of Frank

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[39] Jewkes, Sawers and Stillerman, *Sources of Invention*, 185.

[40] Jewkes, Sawers and Stillerman, *Sources of Invention*, 246.

[41] Jewkes, Sawers and Stillerman, *Sources of Invention*, 185.

[42] Jewkes, Sawers and Stillerman, *Sources of Invention*, 129.

Whittle, who designed the first British jet engine; the autobiography of Ernst Heinkel, whose firm built the first German jet airframe and engine; and the study of aero-engines by the historian Robert Schlaifer (discussed in more detail below). The three economists reproduced Schlaifer's argument that the development of the jet engine was most successful when established aero-engine manufacturers took it up. But because they had defined their interest as in invention rather than development, they dismissed his emphasis on development and instead argued, in line with Whittle and Heinkel's distrust of the aero-engine industry, that 'one of the most significant facts in the story of this invention' was that 'no suggestion for the invention should have come from aircraft engine manufacturers'.[43]

Not unlike the caution of Jewkes, Sawers and Stillerman to economists, the historian Lynn White issued a warning in 1962 to historians of technology about the dangers of generalisation about 'the act of technological innovation', an abstraction, in the absence of empirical evidence. In a paper on 'the act of invention', White began with a condemnation of the existing literature:

> The rapidly growing literature on the nature of technological innovation and its relation to other activities is largely rubbish because so few of the relevant concrete facts have thus far been ascertained. It is an inverted pyramid of generalities, the apex of which is very nearly a void. The five plump volumes of *A History of Technology*, edited under the direction of Charles Singer, give the layman a quite false impression of the state of knowledge. They are very useful as a starting point, but they are almost as much a codification of error as of sound information. It is to be feared that the physical weight of these books will be widely interpreted as the weight of authority and that philosophers, sociologists, and others whose personal researches do not lead them into the details of specific technological items may continue to be deceived as to what is known.[44]

White's interest in medieval technology gave him a broad understanding of technological innovation, which was notably in contrast to an increasingly narrow use of the word invention, as was demonstrated by the case studies of Jewkes, Sawers and Stillerman. Despite

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[43] Jewkes, Sawers and Stillerman, *Sources of Invention*, 320-321.

[44] Lynn White, 'The Act of Invention: Causes, Contexts, Continuities and Consequences,' *Technology and Culture* 3, no. 4 (1962): 486.

its empirical refutation in *The Sources of Invention*, the story of transition from heroic invention in the nineteenth-century to scientific, corporate-laboratory-based invention (increasingly replaced by a narrow understanding of 'research and development') in the twentieth remained the dominant narrative of how the sources of invention had changed during the twentieth-century. Rather than revising this generalisation, as White had admonished, new empirical studies were fitted into the existing transition narrative, which precisely epitomised a generalised account of technical change created without a firm empirical base.

The transition narrative appeared in textbooks in the 1970s and can still be found there today.[45] Robert Friedel's recent textbook on the history of technology, which impressively incorporates the best of the field's scholarship, began its section on the establishment of permanent research labs in American corporations with the declaration that '[o]ut of the workshops and testing rooms of the nineteenth-century inventor and manufacturer there emerged laboratories of a new kind, later to be dubbed as sites for "research and development," which became the twentieth century's principal sites for technical innovation.'[46]

The transition narrative was also central to new accounts of invention in the 1980s. The sociologist Wiebe Bijker took up the question of invention in his earliest work.[47] His choice of cases of 'sociotechnical change' in *Of Bicycles, Bakelites and Bulbs* fit exactly within the categories of the transition narrative: the bicycle represented the mechanical engineering

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[45] Christopher Freeman, *The Economics of Industrial Innovation* (Harmondsworth: Penguin, 1974); Christopher Freeman, *The Economics of Industrial Innovation*, Second Edition (Cambridge, Mass.: MIT Press, 1982).

[46] Robert Friedel, *A Culture of Improvement: Technology and the Western Millennium* (Cambridge, MA: MIT Press, 2007), 482; Friedel's work on invention has been some of the best to look outside the transition narrative. See for example, Robert Friedel, *Zipper: An Exploration in Novelty* (New York; London: Norton, 1994).

[47] Bijker's first SCOT article was sub-titled 'toward a theory of invention'. His book was subtitled: 'toward a theory of sociotechnical change' - a title more in line with SCOT's interests. (Wiebe E. Bijker, 'The Social Construction of Bakelite: Toward a Theory of Invention', in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, ed. Wiebe E. Bijker, Thomas P. Hughes, Trevor J. and Pinch (Cambridge, MA; London: MIT Press, 1987), 159-187; Wiebe E. Bijker, *Of Bicycles, Bakelites, and Bulbs: Toward a Theory of Sociotechnical Change* (Cambridge, MA; London: MIT Press, 1995)

of the workshop of 1860-1890, Bakelite exemplified chemical engineering in a small industrial lab of 1880-1920, while his third case, the fluorescent bulb, was typical of industrial research in a large electrical company between 1930 and 1945.[48] The earlier tradition of sociology of invention did not figure in this work.

The growing number of empirical studies since the 1980s tended to assume the transition narrative. Studies of inventors (some very good and often critical) overwhelmingly focused on nineteenth-century, American inventors, Edison chief among them (partly due to Edison's extensive archive).[49] This work often attacked the a-historical nature of the lone, untutored, 'heroic' inventor, which some historians, like Thomas Hughes, felt had earlier

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[48] He used each case to develop a different theoretical construct. He used the notion of technological frames, developed using the case of Bakelite, to redefine existing concepts in the invention literature like radical/conservative inventions, outsiders/insiders. (Bijker, *Of Bicycles, Bakelites, and Bulbs*, 12)

[49] Some major works on Edison: Neil Baldwin, 'The Lesser Known Edison: In Addition to His Famous Inventions, Thomas Edison's Fertile Imagination Gave the World a Host of Little Known Technologies, from Talking Dolls to Poured-Concrete House' *Scientific American* 276, no. 2 (1997): 62-67; W. Bernard Carlson, 'Thomas Edison as a Manager of R & D: The Case of the Alkaline Storage Battery, 1895-1915', *Technology and Society Magazine, IEEE* 7, no. 4 (1988): 4-12; W. Bernard Carlson, 'Invention and Evolution: The Case of Edison's Sketches of the Telephone', in *Technological Innovation as an Evolutionary Process*, ed. J. M. Ziman (Cambridge: CUP, 2000), 137-158; W. Bernard Carlson and Michael E. Gorman, 'Interpreting Invention as a Cognitive Process: The Case of Alexander Graham Bell, Thomas Edison, and the Telephone,' *Science, Technology and Human Values* 15, no. 2 (1990): 131-164; W. Bernard Carlson, and Michael E. Gorman, 'Understanding Invention as a Cognitive Process: The Case of Thomas Edison and Early Motion Pictures, 1888-1891', *Social Studies of Science* 20 (1990): 387-430; Robert Friedel, Paul Israel and Bernard Finn, *Edison's Electric Light: Biography of an Invention* (New Brunswick, N.J.: Rutgers University Press, 1986); Myrna Frommer, 'How Well Do Inventors Understand the Cultural Consequences of Their Inventions? A Study of Samuel Finley Breese Morse and the Telegraph, Thomas Alva Edison and the Phonograph, and Alexander Graham Bell and the Telephone' (PhD diss., New York University, 1987); Thomas Hughes, *Thomas Edison, Professional Inventor* (London: H.M.S.O., 1976); Thomas Hughes, *Networks of Power: Electrification in Western Society, 1880-1930* (Baltimore: Johns Hopkins UP, 1983); Paul Israel, *From Machine Shop to Industrial Laboratory: Telegraphy and the Changing Context of American Invention, 1830-1920* (Baltimore: Johns Hopkins UP, 1992); Paul Israel, *Edison: A Life of Invention* (New York; Chichester: John Wiley, 1998); Paul Israel, 'Inventing Industrial Research: Thomas Edison and the Menlo Park Laboratory,' *Endeavour* 26 (2002): 48-54; (Paul Israel is editor of the Edison papers); Reese Jenkins, 'Elements of Style: Continuities in Edison's Thinking,' in *Bridge to the Future: A Centennial Celebration of the Brooklyn Bridge*, ed. M. W. Latimer (New York, N.Y.: New York Academy of Sciences, 1984), 149-181; Andre Millard, 'Thomas Edison, the Battle of the Systems and the Persistence of Direct Current,' *Material History Bulletin* 36 (1992): 18-28; David E. Nye, *The Invented Self: An Anti-Biography, from Documents of Thomas A. Edison* (Odense, Denmark: Odense University Press, 1983); Walter G. Vincenti, 'The Social Shaping of Technology: Real-World Constraints and Technical Logic in Edison's Electrical Lighting System', *Social Studies of Science* 25, no. 3 (1995): 553-574.

dominated and discredited writing about inventors.[50] Exemplary histories of the emergence of technical novelty of the 1980s and 1990s that were based on thorough empirical work included the history of Edison's light bulb written by Robert Friedel, Paul Israel and Bernard Finn and the history of the Wright brothers by Peter Jakab. Friedel, Israel and Finn focussed on Edison, but in a productive and refreshing new way. They used Edison's lab notebooks to give new, historically contextualised empirical data on his work. By looking beyond the light bulb to discuss the entire organisation – from workshops to production machinery - that was developed in order to mass-produce the light bulb,[51] the authors demonstrated how the organisation contributed to Edison's inventive success, and how his inventive success shaped his organisation. Jakab's technically well-informed history of the invention of the aeroplane, while seeming to stray beyond the transition narrative's confines, represented not a new departure, but a way to enable the Wright brothers' work to 'be compared more readily with the work of other aeronautical experimenters, as well as with the achievements of nineteenth-century inventors in other fields.'[52]

The twentieth-century corporate research lab (most often American) too has become a central focus of the literature on technical change in the twentieth-century. However, the industrial labs studied have been overwhelmingly limited to the chemical and electrical industries, the particular 'cutting-edge' 'scientific industries' in which they first appeared.[53]

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[50] In 1979, Hughes claimed that the history of technology had finally overcome the damaging heroic inventor paradigm in writing about invention. (Thomas P. Hughes, 'Emerging Themes in the History of Technology,' *Technology and Culture* 20, no. 4 (1979): 697-711.)

[51] Friedel, Israel and Finn, *Edison's Electric Light.* Friedel's history of the zipper began with an independent, individual inventor but quickly probed beyond this into the production and the commercial context of his invention. (Friedel, *Zipper*) Friedel's earlier work on plastic is also notable for its attention to these contexts. (Robert Friedel, *Pioneer Plastic: The Making and Selling of Celluloid* (Wisconsin; University of Wisconsin Press, 1983)

[52] Peter L. Jakab, *Visions of a Flying Machine: The Wright Brothers and the Process of Invention* (Washington: Smithsonian Institution Press, 1990), xvi.

[53] David Edgerton, *The Shock of the Old: Technology and Global History since 1900* (London: Profile, 2008), 246-249. For example: Reese Jenkins, *Images and Enterprise: Technology and the American Photographic Industry, 1839 to 1925* (Baltimore London: Johns Hopkins UP, 1975); Leonard Reich, *The Making of American Industrial Research: Science and Business at GE and Bell, 1876-1926* (Cambridge: CUP, 1985); George Wise, *Willis R. Whitney, General Electric, and the Origins of U.S. Industrial Research* (New York;

Corporate laboratories in these contexts have been understood as academic-scientific institutions in industrial settings. The fact that the research lab appeared simultaneously in academic, industrial and government contexts is not appreciated, which has hidden the laboratory's continuities with industrial as opposed to academic practice.[54] Rather than being connected to inventive sites in industry like industrial workshops, testing or analysis, work in corporate laboratories has been assumed to be like academic, laboratory-based research.[55] The transition narrative has thus given rise to the intertwined and flawed notions that laboratories represented the chief way that science entered industry and that industry was not in the business of creating new things before such labs were transplanted from their original academic setting.

The transition narrative has also powerfully constrained revisions of standard stories. Paul Israel, for example, argued that the machine shop should not be overlooked as a site for the creation of technical novelty because it was at one point 'the central institution for the development of new technology'.[56] Israel's promising departure, however, ended by inserting the machine shop into the standard narrative as a 'transitional' location between individual and corporate lab. For Israel, the increasing importance of science shifted inventive activity to industrial research labs, which 'wrought a profound alteration in the nature of invention'.[57] Thus the machine shop and plant floor are presented as not-quite-laboratories rather than as

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Guildford: Columbia UP, 1985); David Hounshell and John K. Smith, *Science and Corporate Strategy: Du Pont R & D, 1902-1980* (Cambridge: CUP, 1988); Pap Ndiaye, *Nylon and Bombs: Dupont and the March of Modern America* (JHU Press, 2007).

[54] Dennis, 'Accounting for Research', 505-506; David Edgerton, '"The Linear Model" Did Not Exist - Reflections on the History and Historiography of Science and Research in Industry in the Twentieth Century', in *The Science–Industry Nexus: History, Policy, Implication*, K. Grandin, Nina Wormbs and S. Widmalm ed. (New York: Watson, 2004), 31-57; David Edgerton, *Shock of the Old*, 254; some exceptions are discussed below.

[55] David Edgerton, *Shock of the Old*, 257-258.

[56] Israel, *From Machine Shop to Industrial Laboratory*, 2; Fox and Guagnini echo Israel's argument, arguing that the shop floor was a 'site of innovation in electrical technology'. (Robert Fox and Anna Guagnini, 'Sites of Innovation in Electrical Technology 1880-1914', *Annales historiques de l'électricité* 2 (2004): 159-172.)

[57] Israel, *From Machine Shop to Industrial Laboratory*, 185.

serving as a launching point to rethink what the process of invention in industry looked like.[58]

An important alternative approach to the transition narrative was offered by the literature that explored engineering as an independent form of knowledge. This was developed as an alternative to granting science a causative role in the creation of new machines, an important issue that inspired some of the history of technology's early work on technical novelty, including particularly the work of Edward Layton.[59] Brooke Hindle tried to link novelty with art rather than science, by explaining engineering design as a source of technological creativity.[60] Walter Vincenti has been a vocal advocate of understanding engineering knowledge as an autonomous and creative body of knowledge rather than derivative of science.[61] His key focus, the aviation industry, did not owe anything to the corporate research lab or even academic science.[62] Yet this strand of work on engineering knowledge has not challenged the dominant transition narrative. (Edward Constant's work,

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[58] Hintz offers another promising start, but formulates his challenge in terms of the existing categories, arguing that independent invention and industrial labs co-existed and interacted in 'hybrid innovation strategies'. (Eric Hintz, 'Independent Inventors in an Era of Burgeoning Research and Development,' *Business and Economic History Online* 5 (2007), accessed 25 July 2010, http://www.thebhc.org/publications/BEHonline/2007/hintz.pdf.

[59] Important contributions include Edwin Layton, 'Mirror-Image Twins: The Communities of Science and Technology in 19th-Century America', *Technology and Culture* 12, no. 4 (1971): 562-580; Edwin Layton, 'Scientific Technology, 1845-1900: The Hydraulic Turbine and the Origins of American Industrial Research', *Technology and Culture* 20, no. 1 (1979): 64-89; Hugh Aitken, *Syntony and Spark: The Origins of Radio* (New York: Wiley, 1976); Hugh Aitken, *The Continuous Wave: Technology and American Radio, 1900-1932* (Princeton, N.J.; Guildford: Princeton UP, 1985); Rachel Laudan, *The Nature of Technological Knowledge: Are Models of Scientific Change Relevant?* (Dordrecht; Lancaster: D.Reidel, 1984).

[60] Brooke Hindle, *Emulation and Invention* (New York: New York UP, 1981).

[61] Walter G. Vincenti *What Engineers Know and How They Know It: Analytical Studies from Aeronautical History* (Baltimore: Johns Hopkins UP, 1990). Part of the discipline's attempt to get out from under the history of science's shadow in the 1970s involved the defence of technology or engineering as a unique type of knowledge, led by Edwin Layton's work. This agenda spawned interest in engineers as well as in the cognitive dimensions of engineering and invention. Cf. Thomas Hughes, 'The Science-Technology Interaction: The Case of High-Voltage Power Transmission Systems,' *Technology and Culture* 17 (1976): 646-662.

[62] In contrast to Vincenti's twentieth-century example, Hindle's early work was on eighteenth-century engineering and Layton's on the nineteenth-century. (Brooke Hindle, *The Pursuit of Science in Revolutionary America, 1735-1789* (Chapel Hill: University of North Carolina Press, 1956); Layton, 'Scientific Technology, 1845-1900'.)

which has sometimes been understood as an attempt to do so, is discussed in detail below.) Meanwhile, new work on technical novelty in machine tools in the mid-twentieth century has not been regarded as part of the literature on technical change.[63]

The power of the transition narrative in the historiography of technology was exemplified in the work of Thomas Hughes, surely the most influential theorist of invention in the late twentieth century. In *Networks of Power*, Hughes incorporated the transition narrative into his systems framework. According to Hughes' view, a technical system – his particular example being the electrical systems erected in the late nineteenth- and early-twentieth centuries - progressed through life-stages, each of which was characterised by a particular type of invention and a corresponding type of inventor.[64] The independent inventor was active in the early life of a system, for he could 'choose problems that when solved created the nuclei of new technological systems', while the industrial scientist of the more mature system was limited to solutions that improved and grew the system in which his employers were invested.[65] The independent's 'system-originating' inventions Hughes called radical, whereas the 'system-improving' inventions of the industrial lab he labelled conservative.[66] Hughes' attempt at a theory of how invention happens, his 'reverse salient-

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[63] David Noble ventured into new industries and time periods, but his work on machine tools has not generally been viewed as part of the history of invention, although it rightly should be. (David Noble, *Forces of Production: A Social History of Industrial Automation* (New York: Knopf, 1984).)

[64] Most clearly in Hughes, *Networks of Power*, 13-17. He explained his model again in Thomas Hughes, 'The Evolution of Large Technological Systems,' in *The Social Construction of Technological Systems: New Directions in the Sociology and History of Technology*, Weibe Bijker, Thomas Hughes, Trevor Pinch ed., (Cambridge, Mass.; London: MIT Press, 1987), 74 and Hughes, *American Genesis*, 35.

[65] Hughes, *American Genesis*, 20 and 53; Hughes' reading of Edison as a systems-builder set off one of the few debates in the late twentieth-century history of invention. Friedel, Israel and Finn argued that Edison's work was much less intentional than it had been construed by Hughes. (Friedel, Irasel and Finn, *Edison's Electric Light*, 63; Carlson and Gorman tried in 'Understanding Invention as a Cognitive Process' to unify the two positions by introducing another level of analytical concepts.

[66] Hughes' division of inventive activity into categories fit into the typical taxonomical custom to divide up the field of all inventions mentioned in the introduction. (Hughes, *American Genesis*, 53.)

critical problems method', has proved of little analytical use, for the direction of technological change is rarely singular and well-defined.[67]

Hughes' *American Genesis: a Century of Invention and Technological Enthusiasm, 1870-1970* also centred on the familiar transition narrative, albeit in the guise of a story of the disappearance of the independent inventor. Hughes argued that the failure of independent American inventors to provide useful service to the country during the First World War meant that afterwards 'industrial scientists displaced the independents as the principal locus of "research and development activity," the new name for invention.'[68] As Hounshell has argued, Hughes was deeply hostile to the notion that the industrial research lab was a positive organisational innovation. For Hughes, firms appeared as 'largely unimportant in invention if not outright incapable of truly significant invention... firms exploit creative, inventive geniuses; they neither produce them nor nurture them.'[69] Because he associated revolutionary invention with independent inventors and evolutionary with industrial, Hughes' comment later in *American Genesis* that 'American invention was shifting from a revolutionary to an evolutionary mode', was a dire view of the fate of American invention after the First World War – no less so for its obvious and nostalgic inaccuracy.[70] Hughes synthesised the conflict between individual and determinist views of invention into the lost battle between the free independent and the bound industrial inventor. Although he was aware of the work of interwar theorists,[71] Hughes did not interpret it as an alterative to

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[67] The idea of a 'reverse salient' first appeared in Hughes 1976a and the 'critical problems method' in Thomas Hughes *Elmer Sperry: Inventor and Engineer* (Baltimore: Johns Hopkins Press, 1971). For an example of the concept's recent descriptive use, see the reference to reverse salients in Karen J. Freeze, 'Innovation and Technology Transfer During the Cold War: The Case of the Open-End Spinning Machine from Communist Czechoslovakia,' *Technology and Culture* 48, no. 2 (2007): 249-285 fn 16.

[68] Hughes, *American Genesis*, 15.

[69] David Hounshell, 'Hughesian History of Technology and Chandlerian Business History: Parallel, Departures, and Critics,' *History and Technology* 12 (1995): 217.

[70] Hughes, *American Genesis*, 138.

[71] As is clear in Hughes, 'Inventors'.

contemporary thinking, and he left the transition narrative intact, if reformulated in such a way as to confound the heroic-determinist dichotomy of the early 1930s.

A serious attempt to reformulate thinking about technical change was put forward by Edward Constant in 1980. In his *Origins of the Turbojet Revolution*, Constant attempted to formulate his notion of 'technological revolution' in a way attuned to engineering practice. He defended the independence of engineering knowledge, yet his work drew heavily on ideas from the sociology of science rather than work on engineering, especially on the notion of scientific revolutions developed by Thomas Kuhn (1962).[72] Some reviewers were enthusiastic about the potential of Constant's theoretical model of invention, but it has found little use beyond Constant's own study, which is cited more often as a historical study than as a theory of technological change.[73]

Constant began laying out his notion of technological revolution by defining 'normal technology' as the technology to which a group of technologists were dedicated. Normal technology, like its Kuhnian analogue, was constantly improved through successive series of small changes within the dominant framework. If a 'normal technology' failed, solutions would be sought first within the existing 'normal' system. A 'technological revolution' occurred if a group of technologists became committed to a new technology, based on completely different assumptions, and successfully displaced the old 'normal technology',

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[72] The chief influences on his account were: Thomas Kuhn, Karl Popper and Donald Campbell. (Constant, *Origins of the Turbojet Revolution*, 6.)

[73] Hallion described it as a 'thoughtful model of technological change', Schabel referred to it as an 'excellent model', Nahum a 'compelling model', Aitken praised the 'challenging quality of its theoretical constructs'. (Richard Hallion, 'Review: Aerospace Technology,' review of *Origins of the Turbojet Revolution* by Edward Constant, *Science* 215, no. 4529 (1982): 155-156; Schabel, *Die Illusion Der Wunderwaffen*, 35; Andrew Nahum, 'Two-Stroke or Turbine? The Aeronautical Research Committee and British Aero Engine Development in World War II', *Technology and Culture* 38 (1997): 312-354; Hugh Aitken, 'Reviewed Work(s): Networks of Power: Electrification in Western Society by Thomas P. Hughes,' *Journal of Interdisciplinary History* 15, no. 2 (1984): 350-351.) Hughes identified Constant's 'presumptive anomaly' as a 'presumed reverse salient', but distinguished Constant's concept for its laudable stress on the role of science. (Hughes, 'The Evolution of Large Technological Systems'.) Roland included the notion of 'presumptive anomaly' in his discussion of models of technological change, and grouped it with Hughes' reverse salients. (Alex Roland, 'Theories and Models of Technological Change: Semantics and Substance,' *Science, Technology and Human Values* 17, no. 1 (1992): 79-100.)

founding a new 'normal technology' in its place. To explain the stimulus for a technologist to become committed to a radical, new technology, Constant introduced the 'presumptive anomaly'. This was the prediction, based on scientific understanding, that the normal technology would fail in certain circumstances under which a new technology might perform better. Despite earlier efforts by historians of technology to distance science and technology, a virtue of the 'presumptive anomaly' for Constant was that it represented a direct causal link between 'theoretical science and technological practice'.[74] In this way, Constant's framework neatly explained that radical changes tended to come from 'young outsiders, those who have been recently exposed to the leading edge of relevant science and who are not yet fully committed to the conventional technology'.[75] Through the presumptive anomaly, Constant put science and the individual unreservedly at the heart of radical technological change.

Constant was not bashful about the particular focus and consequences of his model. He admitted that his concept of technological revolution was novelty-centric, interested only in the 'leading edge of technological progress', although he was not interested in ideas so much as concrete realisations of them. His model was only interested in successful, 'discontinuous' technological change, and its focus was early in a new machine's life, emphasising the moment of recognition of 'presumptive anomaly' and the identification of the new 'professional commitment' of a 'significant minority of the relevant community of practitioners' to a new technology, rather than the process of bringing it into use. Patents and increasing industrial investment were of little interest, for he argued that they were the consequences of a successful technological revolution, rather than the indications of an impending one.[76]

One of the greatest successes of the lengthy theoretical reflection on engineering practice that began Constant's study was his formalisation of the characteristics of

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[74] Constant, *Origins of the Turbojet Revolution*, 15.

[75] Constant, *Origins of the Turbojet Revolution*, 17.

[76] Constant, *Origins of the Turbojet Revolution*, 19-20.

engineering communities and engineering practice. Yet despite his early argument for a focus on 'communities of practitioners',[77] Constant argued strongly for the importance of the individual as the cause of technological revolution. This allowed him to challenge the determinists' assertion that inventions were inevitable - virtually his only effort to connect to the existing literature on technical change[78] - yet it severed his careful analysis of engineering communities from his notion of technological revolution, leading him away from transforming standard stories of technical change and causing him instead to reinforce existing heroic accounts.

Constant's work is of particular interest to this discussion because he chose the story of the turbojet aero-engine as a prime example of 'presumptive-anomaly induced radical technological revolution' in Britain, Germany and the United States. Nevertheless, his theory of technological change did not fundamentally reframe the standard turbojet story, or alter its focus on individuals. The book's most original argument about the turbojet was its central thesis: that the timing of the turbojet revolution in Germany, Britain, and America – in that order – can be explained by the character of the study of aerodynamics in each country, where communities were (nationally) variably disposed towards theoretical work on supersonic aerodynamics and practical work on subsonic conditions. But in so far as presumptive anomaly was for Constant the key event to explain, what preceded it technologically and scientifically, which his account described in detail, was more important than what followed.[79]

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[77] Constant, *Origins of the Turbojet Revolution*, 10.

[78] Although one of Constant's reviewers asserted that his work superseded early analyses of technological change by Gilfillan, Ogburn and Schmookler, Constant hardly engaged with the earlier work, spending not more than a single sentence on each author's work. (W. David Lewis, 'Review: The Origins of the Turbojet Revolution,' *Technology and Culture* 23, no. 3 (1982): 512-516.)

[79] Hallion described the book's focus on what came before the revolution as 'structural unevenness'. (Hallion, 'Review: Aerospace Technology.')

Constant's revolutionary framework led him to look in the jet story for radical technological discontinuities rather than emphasise continuities with earlier contexts.[80] Thus existing aero-engine practice formed part of the 'hostile milieu' of piston-engined aircraft that the turbojet revolution had to overcome:[81]

> [t]he turbojet not only would overthrow the piston engine, but also would capture and exploit the vast pool of technological capabilities, the array of production and quality control techniques that were equally essential to high-powered piston engines or to turbojets. The turbojet would usurp and make its own the very institutional structure that had produced aircraft piston engines.[82]

In terms more appropriate to the history of non-technological revolutions, Constant argued that the aero-engine industry was 'captured' by the turbojet revolutionaries, rather than the reverse.

The secondary literature fundamentally shaped Constant's empirical study. It led him (revisionist theory of invention notwithstanding) to create a new version of the familiar heroic story of the turbojet revolution, with the protagonists of the revolution now distinguished by their ability to identify a presumptive anomaly and connect it to the turbojet engine. This was surely reinforced by Constant's correspondence with three of the inventors identified in the secondary literature – Frank Whittle, Hans von Ohain, and Herbert Wagner, while he relied on that same secondary literature for the rest of the story. Interestingly, this was much the same literature that Jewkes, Sawers and Stillerman's account of invention had earlier relied on, and both accounts identified the same few men as inventors of the jet engine.[83]

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[80] Basalla, whose interest was in technological change as a continuous process on the level of the artefact, criticised Constant's model and its arbitrary focus on discontinuity. (George Basalla, *The Evolution of Technology* (Cambridge: Cambridge UP, 1988), 28-30.)

[81] Constant, *Origins of the Turbojet Revolution*, 118.

[82] Constant, *Origins of the Turbojet Revolution*, 129.

[83] Jewkes, Sawers and Stillerman, *Sources of Invention*, 318.

Constant's focus on revolutionary change allowed his narrative to ignore the role of industry in the story of the jet engine, just as Jewkes, Sawers and Stillerman had done, because industry entered the story only after his revolution was complete. It similarly allowed him to avoid engaging with the argument of a key earlier author, Robert Schlaifer (which I will discuss more below), whose 'serviceable' and 'competent', internationally comparative account of the invention of the jet engine, Constant nevertheless used extensively.[84] Both authors agreed that outsiders most often produced radical new engine ideas,[85] but a crucial difference between their accounts was that whereas Constant disparaged piston aero-engine makers for their conservatism, Schlaifer emphasised the decisive importance of the aero-engine industry in the development of the radical new engines.

The historiography of the early jet engine

Constant's account of the turbojet revolution, which was one of the most interesting attempts to reformulate thinking on technical change, was also a notable contribution to the historiography of the jet engine for it appeared at the same time as a new wave of interest in the jet engine. Although the empirical base for late-twentieth century works on the jet engine - Constant's among them - was supplemented by the later testimony of participants, the bulk of the data first appeared in the immediate post-war period. One of the most impressive historical works on the jet engine dates from less than a decade after the war's end and because its richness has not yet been appreciated, it is well worth revisiting.

The scale and importance of the aviation industry in the mid-twentieth-century was recognised by the Harvard Business School, where a research programme on military and civil aviation was instituted in 1942. It undertook a study of aero-engines to contrast the government's role in piston aero-engines - an area in which the United States was ahead of Europe - and jet engines - an area in which it judged Europe had achieved more. The

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[84] Constant, *Origins of the Turbojet Revolution*, 271 fn 2.

[85] A point on which Constant did not cite Schlaifer, although it warranted his single reference to Jewkes, Sawers and Stillerman. (Constant, *Origins of the Turbojet Revolution*, 2.)

connection to early Cold War concerns about leading in weapons development was unambiguous.[86] The historian who carried out the study was a young assistant professor of business administration at Harvard, Robert Schlaifer. After getting a PhD in ancient history from Harvard in 1940, Schlaifer had worked during the war writing technical reports for the American Underwater Sound Laboratory.[87] In his study of aero-engines, Schlaifer had the help of S. D. Heron, a veteran of engine development in both Britain and the United States.

The framing of the study shaped Schlaifer's work in important ways. The Harvard programme's interest in government and industry relations dictated the government programme as Schlaifer's unit of analysis. Thus Schlaifer chose the case studies for his book based on their importance to government policy rather than to the history of aero-engines.[88] Because his study juxtaposed the development of piston and jet aero-engines, it brought out the important industrial continuities between the two engine types. His key argument was that new aero-engines could be most quickly developed by established aero-engine firms because of their wealth of experience and resources. The rapid pace of change in the field of military engines meant that, in his opinion, only private firms, unlike military or government institutions, could act with the speed necessary to develop new aero-engines before they became obsolete. Thus he argued that the aim of government policy should be to maintain a 'sufficient number' of specialised and 'highly experienced' private, aero-engine firms, at which new aero-engine development projects could be placed.[89] Such firms, Schlaifer maintained, would benefit from being responsible for development, production and service.[90]

Completed in late 1949, Schlaifer's academic study was based only on interviews and published documents. A significant part of his account of the British programme was made

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[86] Sponsors' Foreword in Schlaifer and Heron, *Development of Aircraft Engines*, vii-vii

[87] Wolfgang Saxon, 'Robert O. Schlaifer, 79, Managerial Economist,' *New York Times*, July 28, 1994; Stephen E. Feinberg, 'The Early Statistical Years: 1947–1967. A Conversation with Howard Raiffa.' *Statistical Science* 23 no 1. (2008): 136-149.

[88] Schlaifer and Heron, *Development of Aircraft Engines*, 3-4.

[89] Schlaifer and Heron, *Development of Aircraft Engines*, 85-99.

[90] Schlaifer and Heron, *Development of Aircraft Engines*, 25.

up of a detailed financial history of Power Jets, the first British company to develop a jet engine, which was made possible by the generous and open assistance of some of the firm's leadership, who were no doubt eager to get on record after the firm was nationalised in 1944.[91] Schlaifer chose not to reference his sources in the published study, but they certainly included personnel from the war-time Power Jets, the civil servant from the Ministry of Aircraft Production primarily concerned with gas turbine research and development in Britain during the war, and German expatriate engineers who had moved or been taken to the United States after the war.[92] Schlaifer's conclusions are all the more exemplary because his source material was so limited, although detailed archival research has challenged some of his arguments.[93]

Schlaifer's account has been used as a key empirical source by virtually every account of the jet engine both popular and professional that has been written on the British, German, or American programmes.[94] Yet it is also important for its unique problem statement and its thoroughness. Despite its wide use, there is much in Schlaifer's account that has not been given attention by historians, and this thesis will engage in particular with its broader arguments about technical change.

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[91] Cynthia Keppel, research assistant to M.M. Postan, wondered 'why Power Jets gave him so much dope without asking the Ministry'. (NA CAB 103/260)

[92] Schlaifer interviewed Whittle 'at some length' in late 1947. His drafts were commented on by W.E.P. Johnson, Lees, Tinling and Roxbee Cox. (NASMT, Box 1, Folder 12) Whittle was unhappy about an earlier draft, but positive about the published version: 'may I congratulate you on your success in sorting out the wheat from so much chaff.' (CAC WHTL A.320, 9.1.50, Letter Whittle to Schlaifer) Schlaifer's German sources included at least Hans A. Mauch, ex-German Air Ministry, whom he interviewed in Dayton. (DM NL172/2, 29.6.80, Conversation Wagner and Mauch)

[93] For example: Schlaifer used the case of Power Jets to demonstrate the need for government funding in the early stages of an innovation. He argued that Falk and Co would have balked at funding the project if they'd better understood it. Nahum (2004, 33) has persuasively argued that the project was a surrogate official project from the start.

[94] Including Constant, *Origins of the Turbojet Revolution;* Schabel, *Die Illusion Der Wunderwaffen*; Andrew Nahum, 'World War to Cold War: Formative Episodes in the Development of the British Aircraft Industry, 1943-1965.' PhD diss., London School of Economics, 2003; and S. Michael Pavelec 'The Development of Turbojet Aircraft in Germany, Britain, and the United States: A Multi-National Comparison of Aeronautical Engineering, 1935-1946.' PhD diss., Ohio State University, 2004.

An early account of the British jet engine was given in a volume of the British Official History of the Second World War entitled *Design and Development of Weapons*, which was published in 1964.[95] It mostly reproduced an account written by a research assistant to M.M. Postan, Cynthia Keppel, during the war, which was based on official files and wartime interviews with key actors (some of the same men in fact approached by Schlaifer). Keppel, who had worked as a secretary at MI5 before joining the official historians in 1942, was untrained in history or aero-engines.[96] Her narrative was naturally focussed on the British case, and her insubstantial account of German developments was based on British government reports and interrogations.[97] The most important contribution of Keppel's account was its understanding of the views of the British Air Ministry and the Ministry of Aircraft Production, although by the time that the narrative was finally published, it added relatively little to Schlaifer (1950) and Frank Whittle's (1953) work. Keppel had a good grasp of the challenges that the Ministry faced, nevertheless her account of the jet engine came down decidedly in favour of Whittle, arguing that the Air Ministry had failed to support him adequately.

A technical record of the early British jet engines was established in the first decade after the war through an outpouring of technical detail in the journals and lectures of learned societies, which served to inform the wider engineering community of important developments that had taken place in secret during the war.[98] The technical details of work

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[95] M. Postan, Denys Hay and J. Scott, *Design and Development of Weapons: Studies in Government and Industrial Organisation* (London: H.M.S.O, 1964).

[96] She married Postan shortly after the war. (Interview with Keppel, 13.3.09)

[97] Postan edited Keppel's case history, removing its most judgmental passages, before its eventual publication. A draft of Keppel's account can be found in NA CAB 102/393.

[98] A review of current practice was given immediately after the war through a series of articles on gas turbine aero-engines in War Emergency Issue 12 of the *Proceedings of the Institution of Mechanical Engineers*; Other early contributions included: Frank Whittle, 'The Early History of the Whittle Jet Propulsion Gas Turbine,' *Journal of the Institution of Mechanical Engineers* 152 (1945): 419-435; David M. Smith, 'The Development of an Axial Flow Gas Turbine for Jet Propulsion,' *Proceedings of the Institution of Mechanical Engineers* 157 (1947); Eric Moult, 'The Development of the Goblin Engine,' *Journal of the Royal Aeronautical Society* 51 (1947): 655-685. Such work continued to be published throughout the twentieth-century: William Hawthorne, 'Aircraft Propulsion from the Back Room', *Aeronautical Journal*

by aero-engine firms appeared in aviation journals like *Flight*. Gradually actors' accounts and biographies were published as books and articles, which contributed a personal view of the jet engine's early years.[99]

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of the Royal Aeronautical Soceity 82 (1978); Harold Roxbee Cox, 'The Beginnings of Jet Propulsion, the Trueman Wood Lecture,' *The Royal Society of Arts Journal* 132 (1985): 705-723; William Hawthorne, 'The Early History of the Aircraft Gas Turbine in Britain,' *Notes and records of the Royal Society of London.* 45 (1991): 79-108; R.O. Windley, 'Gas Turbine Combustion: A Personal Perspective,' *Proceedings of the Institution of Mechanical Engineers. Part G, Journal of aerospace engineering* 203, no. G2 (1989): 79-96.

Public lectures included: Harold Roxbee Cox 'British Aircraft Gas Turbines. The Ninth Wright Brothers Lecture,' *Journal of the Aeronautical Sciences* 13, no. 2 (1946); Stanley Hooker, 'Cantor Lectures: "High Speed Flight",' *Royal Society of Arts Journal* 94, no. 4714 (1946); Frank B. Halford, 'Jet Propulsion,' *Royal Society of Arts Journal* 94, no. 4724 (1946); MOSI MS0539/39 DM Smith, 'The development of the jet engine,' to the Women's Engineering Society, Manchester Branch, 9.1.1963.

Early textbooks included: J. G. Keenan, *Elementary Theory of Gas Turbines and Jet Propulsion* (London: Oxford UP, 1946); Geoffrey G. Smith, *Gas Turbines and Jet Propulsion for Aircraft*, Fourth Edition (London: Flight, 1946).

[99] Biographical memoirs appeared for engineers who were made Fellows of the Royal Society: A. A. Rubbra, 'Alan Arnold Griffith. 1893-1963,' *Biographical Memoirs of Fellows of the Royal Society* 10 (1964): 117-136; William Hawthorne, H. Cohen and A. R. Howell, 'Hayne Constant, 1904-1968,' *Biographical Memoirs of Fellows of the Royal Society* 19 (1973): 268-279; Owen Saunders, 'David Macleish Smith. 9 June 1900-3 August 1986,' *Biographical Memoirs of Fellows of the Royal Society* 33 (1987): 605-617; G. B. R. Feilden and William Hawthorne, 'Sir Frank Whittle, O.M., K.B.E.. 1 June 1907-9 August 1996,' *Biographical Memoirs of Fellows of the Royal Society* 44 (1998): 434-452; G. B. R. Feilden, 'Lionel Haworth,' *Biographical Memoirs of Fellows of the Royal Society* 51 (2005): 196-220. Book length biographies were written of Whittle (J. Rowland, *The Jet Man: The Story of Sir Frank Whittle* (Bristol: Western Printing Services Ltd, 1967); John Golley, Frank Whittle and Bill Gunston, *Whittle, the True Story* (Washington, D.C.: Smithsonian Institution Press, 1987); John Golley, and Bill Gunston, *Genesis of the Jet: Frank Whittle and the Invention of the Jet Engine*, Second Edition (Shrewsbury: Airlife, 1996)) and von Ohain (Margret Conner, *Hans von Ohain: Elegance in Flight* (Reston, Va.: American Institute of Aeronautics and Astronautics., 2001)). See also D. R. Taylor, *Boxkite to Jet: The Remarkable Career of Frank B. Halford* (Derby: Rolls-Royce Heritage Trust, 1999).

The most influential autobiographical accounts included: J. Grierson, *Jet Flight* (London: Sampson Low Marston & Co. Ltd, 1946); Frank Whittle, *Jet: The Story of a Pioneer* (London: Frederick Muller, 1953); Lancelot L. Whyte, 'Whittle and the Jet Adventure', *Harper's Magazine* 208, no. 1249 (1954); Lancelot L. Whyte, *Focus and Diversions* (London: Cresset Press, 1963); Stanley Hooker, *Not Much of an Engineer: An Autobiography* (Shrewsbury: Airlife, 1984) and George P. Bulman, *An Account of Partnership-Industry, Government and the Aero Engine: The Memoirs of George Purvis Bulman*, M. C. Neale ed. (Derby: Rolls-Royce Heritage Trust, 2002). Such stories often derive their historical authority from the technical expertise of their authors and generally dwell only briefly on personal details, similar to the 'failed autobiographies' described by Oldenziel (Ruth Oldenziel, *Making Technology Masculine: Men, Women and Modern Machines in America, 1870-1945* (Amsterdam: Amsterdam University Press, 1999), 92-123). Walter Boyne and Donald Lopez ed., *The Jet Age: Forty Years of Jet Aviation* (Washington: National Air and Space Museum, Smithsonian Institution, 1979) includes articles by Frank Whittle and Hans von Ohain.

Articles on the jet appeared again in Britain on commemorations of important jet dates: Frank Armstrong, 'The Aero Engine and Its Progress – Fifty Years after Griffith,' *Aeronautical Journal of the Royal Aeronautical Society* 80 (1976): 499-520; A. R. Howell, 'Griffith's Early Ideas on Turbomachinery Aerodynamics', *Aeronautical* Journal (1976): 521-529; Andrew Nahum, 'Origins of the British Jet Engine', *Science Museum Review* (1987): 19-21; William Hawthorne, 'The Early History of the Aircraft Gas Turbine in Britain', in *50 Jahre Turbostrahlflug* (Munich: Deutsche Gesellschaft fur

Details of the German jet programme, in contrast, were recorded in detail in intelligence reports published after the war. Compiled for Allied industry by military and industrial personnel, the reports drew on information extracted from interrogations, tours of German industry, captured artefacts and documents. Because of these reports, which included details of all of the major German jet engine projects, the German wartime jet engine programme was uniquely well technically documented. Supplemented to a certain extent by documents found after the war and by Schlaifer's work, this basis has informed most accounts of the German jet engine.[100] British reports began to build a narrative of the German programme in Britain, but this was largely overshadowed by publicity for the British story (as discussed in Chapter 5).[101] The first accounts by and of participants in the German jet engine programme appeared slowly after 1950 and without much fanfare to inform professionals and jet engineers. [102] When public interest in the history of the German jet

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Luft- und Raumfahrt, 1989); John Golley, 'The Whittle Revolution', *Aeroplane monthly* 19 (1991): 346-351; John Golley, 'Working with a Genius: Engine Pioneer Sir Frank Whittle, Who Died Two Years Ago', *Aeroplane monthly* 26, no. 10 (1998): 18-23; Glyn Jones, 'Jubilee for the Jet Engine: Frank Whittle and the History of the British Jet Industry', *The New Scientist* 130, no. 1768 (1991): 32-35; William Hawthorne, 'The Early History of the Aircraft Gas Turbine in Britain'. The magazine of the Rolls-Royce Heritage Trust, *Archive*, is a good source for numerous articles on engines and individuals.

[100] A good listing of German wartime reports as well as Allied intelligence documents, both sources of information drawn from interrogations, was given in Kyrill von Gersdorff and Kurt Grasmann, *Flugmotoren und Strahltriebwerke: Entwicklungsgeschichte Der Deutschen Luftfahrtantriebe von den Anfangen bis zu den Europaischen Gemeinschaftsentwicklungen*, (Munich: Bernard & Graefe, 1981).

[101] German work was also reported on by British visitors, often members of the British aero-engine industry. Notable among these was the aero-engine designer Roy Fedden, whose reflections were publicised in the trade journal *Flight* in 1945. (Roy Fedden 'Inquest on Chaos.' *Flight* 19 November 1945, 575-578 and 'German Jet Development,' *Flight* 13 December 1945, 626-629.) For more see Chapter 5.

[102] Hermann Oestrich, 'Die Entwicklung Der Fluggasturbine Bei Den Bayrischen Motorenwerken Während Des Krieges 1939/45,' *Flugwelt* 4 (1945): 69-71; S. Decher, 'Die Entwicklung Des Tribewerkes Jumo 004 Bei Den Junkers Flugzeug- Und Motorenwerke in Dessau.' *Flugwelt* 2 (1951): 41-46; W. Gundermann, 'Das Erste Düsenflugzeug Der Welt,' *Zeitschrift Verein Deutscher Ingenieure* 20 (1952): 696-695; Ernst Heinkel and Jürgen Thorwald, *Stürmisches Leben* (Mundus-Verlag, 1953) and *He 1000* (London: Hutchinson, 1956); H. Scherenberg, 'Die Flugmotorenentwicklung Bei Daimler-Benz,' *Flug-Revue* 5 (1964): 59-60; H. Muenzberg, 'Nachruf Auf Hermann Oestrich,' *Jahrbuch der DGLR* (1973): 274-276; Anselm Franz 'Development of the "Jumo 004" Turbojet Engine,' in Walter Boyne and Donald Lopez ed., *The Jet Age*; Anselm Franz, *From Jets to Tanks: My Contribution to the Turbine Age* (Stratford, Conn.: Avco Lycoming, 1985); Max Bentele, *Engine Revolutions: The Autobiography of Max Bentele* (Warrendale, PA: Society of Automotive Engineers, 1991). Bentele remarked that two versions of the jet history were created after the war. The fuller one circulated among professionals and jet engineers but did not reach the public. (Bentele, *Engine Revolutions*, 65)

engine appeared in Germany in the late 1970s, a wide range of information was readily available and many of the actors were still alive. The first German work on German jet engines appeared in 1981 as part of a non-academic study of German aero-engines. The book was impressively comprehensive, including encyclopaedia-like narratives of each German aero-engine company's jet work. Edited jointly by a civil servant and an engineer, much of its information on jet engines was drawn from Allied intelligence and German company reports, and it was written with the help of technicians who had worked with the engines being described.[103] A German book devoted to the world's first jet engines and aircraft, including some new archival information, appeared in 1989. It was written by pilot and aviation journal editor Wolfgang Wagner. Wagner's book claimed to 'prioritize those aircraft designs which actually flew' along with their 'follow-on' developments, including British and American work, but his account included by far the most information on Heinkel (including the first account of the work done at Heinkel-Hirth in Zuffenhausen) and Messerschmitt.[104] Although neither work made explicit claims for the importance of any one company's work on the jet engine, both arranged their entries, not alphabetically by firm, but rather by RLM engine number or chronologically, according to each firm's turbojet accomplishments. Thus both discussed the work of the Heinkel Aircraft Company first. (See Chapter 5 for further discussion.)

Narratives of heroic invention have grown up around some of the jet engine pioneers. As Chapter 5 discusses in more detail, within a decade, a particular story of Frank Whittle had become the predominant popular history of the jet in Britain. Until relatively recently, the average schoolboy in post-war Britain knew of Frank Whittle. In Germany, in contrast, the German pioneers remained unknown to the German public until around 1980.

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[103] The fourth edition of von Gersdorff and Grasmann's *Flugmotoren und Strahltriebwerke*, the second volume in a series on German aviation, was published in 2006.

[104] Wolfgang Wagner, *Die Ersten Strahlflugzeuge Der Welt* (Koblenz: Bernard & Graefe Verlag, 1989) and Wolfgang Wagner and Don Cox, *The First Jet Aircraft* (Atglen, Pa: Schiffer, 1998). Wagner edited numerous periodicals including *Flugwelt*, which he founded in 1949.

The first German publicity for von Ohain as the inventor of the jet engine came when the Deutsches Museum in Munich put on display a reconstruction of the first German jet engine engine to fly, which von Ohain had designed in the late 1930s.[105] In contrast to his obscurity in Germany, von Ohain became relatively quickly known in the United States, where he settled after the war.[106] American supporters promoted von Ohain as co-inventor with Whittle before he was widely known in Germany.[107] The first and only biography of the German inventor, written by an American friend, was published in 2001.[108]

Accounts of jet engines can also be found in some popular books for aviation buffs on specific aircraft. More popular books have been written that focus on jet fighters than on their engines, but some of these do include useful chapters that relate where the aircraft's engines came from.[109] The study of aero-engines as distinct from airframes is essential, however, for the two parts of a finished aircraft proceeded at different rates and were influenced by different considerations.

The bulk of the literature on the jet engine is composed of unadventurous, non-academic works that often recycle anecdotes and details drawn from actors' accounts. The catalogue is a popular format that often includes both successful and failed projects, but its encyclopaedia-like narratives give little of the political, social, technical or economic context

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[105] DM FA001/107, *Frankfurter Allgemeine*, 14.12.81; *Göttenberger Tagblatt*, 5.81; On the fiftieth anniversary of the first German jet flight in 1989, von Ohain was once again singled out in the popular press. (DM FA001/1072, Fritz Janda, 'Oma finanzierte den ersten Jet,' *Abendzeitung*, 14 February 1989.)

[106] Grover Heiman, *Jet Pioneers* (New York: Duell Sloan and Pearce, 1963).

[107] Walter Boyne and Donald Lopez ed., *The Jet Age*; Frank Whittle and Hans von Ohain, An Encounter between the Jet Engine Inventors: Sir Frank Whittle and Dr. Hans Von Ohain 3-4 May 1978, Wright-Patterson Air Force Base, Ohio (History Office, Aeronautical Systems Division, Air Force Systems Command, 1978); Walter Rathjen,"'Weniger Gerausch, Keine Vibration!": 50 Jahre Strahltriebwerk,' Kultur und Technik: Zeitschrift des Deutschen Museums Muenchen 13 (1989): 206-215; NASM, Golden Anniversary, 1989.

[108] Conner places the invention of the jet at the centre of von Ohain's life story, although he had a long and successful career in the United States afterwards. (Conner, *Elegance in Flight*)

[109] For example, Wagner, *Die Ersten Strahlflugzeuge Der Welt*; David Watkins, *De Havilland Vampire: The Complete History* (Stroud: A. Sutton., 1996); Barry Jones, *Gloster Meteor* (Wiltshire: Crowood Press, 1998).

of aero-engine development.[110] While the first comprehensive catalogue of German aero-engines appeared in 1981, this format was only recently copied for the British jet engine story by Antony Kay as part of an international study of jet engines between 1930 and 1960. It is far less detailed than Kay's previous work on German gas turbines, in part because of the lack of equivalent sources on gas turbine work in other countries, and it is often unreliable.[111]

In addition to popular literature, the jet engine has recently become the focus of renewed archival research by professional historians. The first serious German academic work on the jet's early history, that by Ralf Schabel, was published in 1994.[112] Schabel's study, a political history of wonder weapons, looked at anti-aircraft rockets and jet aircraft, exploring why the Nazis failed to bring these new weapons to the front during the war. Schabel was particularly interested in Messerschmitt's politics, and his account was therefore focussed more on jet airframes than on engines. Nevertheless, he drew attention to the inadequacy of the supply of jet engines in Germany as a key reason for the delay in deploying German jet fighters.

Schabel's account challenged and extended the German historiography of the jet fighter in several important ways. Firstly, he highlighted the fact that the jet was not sought after by the leadership of the German Air Ministry until 1943, after which production problems delayed the last-ditch deployment of Germany's jet fighter, the Me 262. He argued that a split in the German Air Ministry between those knowledgeable about tactics and those conversant with the technical aspects of air armament ('Taktiker' vs. 'Techniker')

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[110] Bill Gunston's *World encyclopaedia of aero engines* (now in its fifth edition) is a good example of this form. It included historical notes on some aero-engines. (Bill Gunston, *World Encyclopaedia of Aero Engines: All Major Aircraft Power Plants, from the Wright Brothers to the Present Day* (Sparkford: Patrick Stephens, 1998))

[111] Antony L. Kay, *Turbojet History and Development* (Crowood Press, 2007). His two volumes treated (1) Great Britain and Germany and (2) the USSR, USA, Japan, France, Canada, Sweden, Switzerland, Italy and Hungary. Both covered 1930-1960 and include aircraft and engines. Other catalogues include: Wagner, *Die Ersten Strahlflugzeuge Der Welt*; Bill Gunston *The Development of Jet and Turbine Aero Engines* (Sparkford: Patrick Stephen, 1995); Anthony Kay, *German Jet Engine and Gas Turbine Development, 1930-45* (Shrewsbury: Airlife, 2002); von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke.*

[112] Schabel, *Die Illusion Der Wunderwaffen.*

undermined the coherence of German development and deployment. Against much German popular literature, Schabel argued that rather than too late, the jets were deployed too early – before they were matured technically. For Schabel, the real tragedy of the German jet was not the failure to win the air war, as nostalgic Luftwaffe officers had argued, but rather the last-ditch deployment of the jet, which served only to increase the war's cost.[113]

The first rigorous British academic research on the early history of the jet engine was the basis of Andrew Nahum's recent book on Frank Whittle, published in 2004.[114] In it, Nahum used archival material and new interviews to challenge the received story of the British Air Ministry's poor treatment of Whittle.[115] Nahum argued that the Air Ministry was more dedicated to the jet engine than is popularly alleged and that it tried genuinely to make use of Whittle's genius and his firm, Power Jets. It was enthusiasm, Nahum argued, that led the Air Ministry to attempt to build jets before the technical capability existed to do so.

A recent important addition to the historiography of the jet engine in the United States as well as the literature on innovation was Philip Scranton's work, which emphasised the complexity of the interconnected development and use of jet engines in the late-war and early-post-war period. Scranton used the jet engine case to decisively reject the standard stories of how innovation occurs, especially the supposed (or wishfully assumed) linear-model of direct reliance on academic science.[116] He called for the need for more contextualised studies of design and production inspired by a more dynamic understanding of the interrelations of development and production. By looking at the British and German stories, this study examines an earlier period in the emergence of the jet engine than

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[113] Schabel, *Die Illusion Der Wunderwaffen*, 289-290; In fact, Göring intentionally promoted the split. (Richard Overy, *Goering: The 'Iron Man'* (London: Routledge & Kegan Paul, 1984): 164-204.)

[114] Nahum, *Frank Whittle*; This book was written for a popular audience, but was based on a chapter of his thesis. (Nahum, 'World War to Cold War', 54-121.)

[115] The only important exception to the received story was the lately published autobiography of the civil servant in charge of engine development at the Air Ministry until 1944, George Bulman. (Bulman, *An Account of Partnership-Industry, Government and the Aero Engine.*)

[116] Scranton, 'Technology-Led Innovation' and 'Turbulence and Redesign.'

Scranton's work, which started with the story of General Electric's I-16, examining how turbojet designs were first created in a production context and highlighting the consequences of the fact that the same companies moved from developing one kind of aero-engine to developing another. This thesis goes farther than Scranton to argue that production concerns actually impacted invention and development from the start.

The most recent account of the jet's early years was written by another American historian, Michael Pavelec. His comparative account did good work putting the jet fighter back into its different military contexts in Britain, Germany and the United States.[117] In so doing, Pavelec reached some of the same conclusions as Schabel with respect to Luftwaffe doctrine, although he did not use Schabel's work. As a story of the development and production of jet engines, however, his account added little to the literature, reproducing its flaws and introducing new errors. Pavelec's overall argument was that Germany was the most successful nation at producing jet aircraft and engines because of its extreme need, while the Allies, lacking that spur to achievement, trailed behind. Yet by building on British and German work, the United States soon took the lead in the new field. Pavelec's account was shaped by a belief in German technical superiority that built on Constant's focus on aerodynamics as the key differentiator in the jet engine revolution.

The jet engine and the historiography of technical change

The jet engine is an important example of technical change in the twentieth-century. Yet the existing literature on the subject offers little help to understand it. Neither the heroic narrative nor the transition narrative satisfactorily explains how the jet engine emerged. In fact, both direct focus *away* from the central locations and actors in the story.

The heroic narrative (similar to the transition narrative's view of nineteenth-century invention), which Constant's model of technical revolution offered in a subtler guise than the popular literature, is unhelpful because its identification of the most important aspect of the

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[117] S. Michael Pavelec, *The Jet Race and the Second World War* (Praeger Publishers Inc, 2007).

story represents only a fragment of the story of the creation of a serviceable jet engine. The model's individualist focus also deemphasises the many 'lesser men' who creatively contributed to the jet engine: designers, fitters, metallurgists, research engineers, workers and managers.

The transition narrative is entirely inadequate to explain the emergence of the jet engine because it ignores the sources of technical novelty most central to that story. Indeed, its is entirely unable to account for a massive inventive effort in precisely the time period that it claims to explain. One would look in vain for an industrial research lab in the aero-engine industry of the 1930s, yet the industry and government establishments played no less a part in the process of invention than the traditionally recognised inventors. Attention needs to be given to the aero-engine industry and its design offices, experimental workshops, test houses, production floors, airfields and flight test hangars, as well as to other institutions of the government and military. Even more than the better-known cases of automobiles and airframes, which both took markedly less time and money to develop and produce, aero-engines were a key example of a large-scale invention, development and production effort.[118] Like the production of the atomic bomb in the United States, another wartime weapons project, the jet engine was a protracted engineering project typical of the mid-twentieth-century, yet remains poorly understood.

As will be shown in the remainder of this thesis, the jet engine offers an empirical case for rejecting the assumption of the transition narrative. In fact, the more wide-ranging thought on invention of earlier thinkers offers a better starting point than the confined transition narrative, because of its willingness to acknowledge inventive activity in all possible places and because of its interest in organisational variety. Constant recognised that the jet engine story could be used to rethink technical change, but he abandoned his most interesting insights into engineering practice in order to explain the wrong thing. With the

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[118] Edgerton, *Shock of the Old*, 258-259.

exception of Nahum and Schabel's work, the literature on the jet engine's earliest years has progressed relatively little since the 1950s, and there is still wide scope to reframe and enrich the existing literature. The following chapters explore different aspects of the jet engine story in order to construct a new, more inclusive and radically different story of the jet engine that enables a re-evaluation of the most important sources of technical change in the mid-twentieth-century.

Chapter 2
Turbojet Production During the Second World War

The resources required for production – by far the most expensive part of creating new machines – make it an important and interesting subject, yet the production of turbojet aero-engines during the Second World War has not been studied in its own right. Instead, it is often used as a proxy for success in invention and development. Approximately 6,600 engines were manufactured in Germany through March 1945. By comparison, to the *end* of 1945 - granting the Allies an additional nine months - the British made just under 750 production turbojet engines, while the United States trailed, having delivered about 300 production engines.[1] For Pavelec, in his recent history of jet aircraft in the Second World War, this proved that Germany was 'the first – and in the end the best – in developing turbojet technology during the war'.[2] Constant concluded based on the number of turbojet aircraft put into service that 'Germany exploited the turbojet most fully and most quickly' and had 'probably… the most comprehensive programme for advanced turbojet development' of Germany, Britain and the United States.[3] On the other side, Gunston claimed that coming second to Germany proved that the British government had failed to sufficiently support its turbojet inventor; for Gunston, Whittle's early start meant that Britain should have been building jets long before Germany.[4] Oddly enough, there are also stories of German failure, likewise based on production arguments. Early post-war German accounts stressed the fact that the turbojet appeared too late to turn the tide of the war - a failure

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[1] These figures do not represent the total number of turbojet engines built in each country because the distinction between development and production engines is not always clear. The focus in this chapter is on production engines, those manufactured in large batches or series and delivered to the military.

[2] Pavelec, *Jet Race*, 154.

[3] Constant, *Origins of the Turbojet Revolution*, 208.

[4] Bill Gunston, *Plane Speaking: A Personal View of Aviation History* (Sparkford: Patrick Stephens, 1991), 159.

caused by those, generally Hitler and Göring, who opposed putting the turbojet into production and thereby delayed the arrival of the decisive weapon.[5]

The biggest flaw of this understanding is that it unproblematically links invention and production.[6] While invention certainly made production possible, it did not make production necessary or inevitable, nor define exactly what would be produced. Production does not necessarily indicate technical achievement, except in a very basic way. As will be shown, during the war, turbojet engines with superior performance were turned down for production, and poor engines better suited to production were accelerated. The German programme explicitly sacrificed engine performance for ease of production, and production numbers notwithstanding, in terms of the quality of engines available at the end of the war, there is little doubt that Britain rather than Germany was ahead.[7]

If one takes production as the focus of study and looks at production *decisions* in each country rather than the number of engines produced, a very different story begins to emerge. Rather than Germany, it was Britain that decided to produce turbojet engines first, in 1940. The United States was second, in 1941, and Germany last, in 1943. Nevertheless, Germany reached by far the highest levels of turbojet production during the war.

Why Germany was so far ahead in production is not properly explained in the literature. Although arguments that emphasise the motivation provided by the Luftwaffe's

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[5] Schabel, *Illusion der Wunderwaffen*, 27-33; Schabel rejected this traditional narrative, arguing that German turbojet production was a failure because the turbojet was not a decisive weapon like the atom bomb.

[6] Using production as a proxy is based on a sequential view of invention, development and production that makes the last a valid measure of the outcome of the entire process. This is however distinct from the fabled 'linear model', which is an argument about science leading to new technology, as described by Edgerton. (David Edgerton, 'The Linear Model'.) Historians have critiqued the proposed sequential or linear features of such models. Scranton challenged such notions when he described the circular nature of turbojet engine development and production in the cold war. (Scranton, 'Technology-Led Innovation'.)

[7] Schlaifer based this conclusion on a discussion of the comparative quality of British and German engines rather than just speed and production numbers. (Schlaifer and Heron, *Development of Aircraft Engines*, 429-439.) Post-war intelligence reports and testing in Britain confirmed the inferiority of German engines to British engines. (NA AVIA 15/2121, 6.45, 205, Edward Pickles (MAP), Note on visit to Germany)

desperate need for turbojet aircraft overestimate the decisive nature of high-performance weapons,[8] the literature is correct that the Nazi leadership came to see the turbojet as their last resort (however unobvious this choice was). Although the turbojet was for some a plausible war-winning weapon, this chapter will show that German production success rested on the turbojet's character as an ersatz piston engine, a cheaper more easily produced aero-propulsion system. The turbojet engine was not an existing machine passively and detrimentally affected by the many material shortages that afflicted Germany. Rather it was material shortages, including of metals and aviation fuel, that made poor-quality turbojet engines an attractive weapon.[9]

In this chapter, I give a very different account of the importance of the turbojet to the Lufwaffe than existing accounts and demonstrate how the jet engine was shaped by the values of the Nazi state. Far from an act of inspired technical brilliance, the design of German turbojet engines was an act of desperation dictated by the production challenges faced by Nazi Germany in its last years. The circumstances of the production of the V2 missile by slave labour in the huge underground factory known as Mittelwerk have been well documented,[10] yet the fact that the turbojet engine moved to the centre of the same production system during 1944 is not appreciated. The steps taken by the Nazi government to accelerate turbojet engine production resulted in the novel engines constituting an

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[8] Pavelec, *Jet Race*, 109; Schlaifer and Heron, *Development of Aircraft Engines*, 438-439; The logic of the decisiveness of superior weapons appears also in arguments for the American failure to invent the turbojet. (I. B. Holley, 'Jet Lag in the Army Air Corps,' in Borowski, H. R., ed., *Military Planning in the Twentieth Century: Proceedings of the Eleventh Military History Symposium, 10-12 October 1984* (Washington, DC: Office of Air Force History, 1984).)

[9] Pavelec mentioned that the engines took low-grade fuel, became easier to make over time, and could use inferior materials, but he didn't connect these facts to a larger argument, as will be done below. (Pavelec, *Jet Race*, 32 and 97.)

[10] Neufeld, *Rocket and the Reich.*

astonishing 20% of German aero-engine production already in December 1944, just months after full scale turbojet production had begun.[11]

Looking at production also alters the stories of Britain and America's early turbojets. In Britain, this chapter shows, there was no evidence of a lack of official interest in turbojet engines or of the absence of a production programme. Indeed, the country's early commitment to production shaped the British turbojet programme and continued to emphasise the production of the country's first turbojet engine design, the W.2B, even as alternatives were developed. Yet over the course of the war, the British programme's focus shifted away from production and towards a massive development programme to produce jets for the post-war period, which is explored in more detail in Chapter 3.

Because the United States deployed no turbojet aircraft during the war, the country's production of turbojet engines is generally dismissed, and its development programme is viewed as a failure.[12] Yet the nature of the American programme was not simply the result of a failure to invent a turbojet in the United States.[13] The decision to produce a British design rather than an indigenous one was made in the hopes that the British engine would offer the fastest route to producing a turbojet in the United States during the war – a production-driven gamble that fundamentally shaped the country's post-war aero-engine industry.

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[11] USSBS, January 1947, Aircraft Division Industry Report, Second Edition, 99; In December 1944, piston engine production was recovering from a trough in October 1944, but as turbojet engine production continued to climb until the end of the war; the proportion of turbojet engines likely continued to increase.

[12] Holley, 'Jet Lag'; James O. Young, 'Riding on England's Coattails', in *Innovation and the Development of Flight*, Roger Launius ed. (College Station, TX: Texas A&M UP, 1999), 263-298; Roland argued that the failure to invent the turbojet engine was the National Advisory Committee for Aeronautics' 'most damaging failure'. Hansen and Dawson echoed his argument. (Alex Roland, *Model Research: The National Advisory Committee for Aeronautics, 1915-1958* (Washington, D.C.: Scientific and Technical Information Branch, NASA, 1985), 187-189; James R. Hansen, *Engineer in Charge: A History of the Langley Aeronautical Laboratory, 1917-1958* (Washington, D.C.: Scientific and Technical Information Office, NASA, 1987); Virginia Dawson, *Engines and Innovation: Lewis Laboratory and American Propulsion Technology* (Washington, D.C.: NASA, 1991).)

[13] Schlaifer disagreed with typical arguments for American failure and offered a number of other reasons that the country did not pursue turbojets earlier than it did. (Schlaifer and Heron, *Development of Aircraft Engines*, 480-493.)

In fact, relatively little is known about the details of turbojet aero-engine production during the Second World War. Accounts of German production mostly emphasise the country's success in overcoming its material constraints in light of the country's high production numbers.[14] Even less has been written about the extent or nature of turbojet production in Britain or the United States, but it is generally assumed to have been less effective than in Germany.[15] This chapter will tell the full comparative story of the wartime production of turbojet aero-engines for the first time. The British and American stories and their interconnections will be assembled from archival sources, while the German story is radically reinterpreted.

In all three countries, the production of turbojet engines needs always to be considered within the context of piston engine production, not least because the most important turbojet engine makers during the war were first and foremost piston-engine producers. Production of both types of aero-engine competed for the same resources. The astonishing scale of piston engine production shown in Table 2.1, suggests the relative place of turbojet engine production in each country, which is given in Table 2.2.

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[14] Pavelec argued that the 'lack of strategically important raw materials' was the 'main problem faced by Junkers'. (Pavelec, *Jet Race*, 120 and 155.) Schabel did not discuss the details of turbojet engine production in any detail, but he did point to the material constraints that delayed engine production. (Schabel, *Illusion der Wunderwaffen*, 182-183.) Constant declared that the German programme was a 'remarkable technical achievement, especially considering wartime privation and near-total lack of strategic materials.' (Constant, *Origins of the Turbojet Revolution*, 208.) Schlaifer argued that bombing and lack of raw materials were significant problems for German production. (Schlaifer and Heron, *Development of Aircraft Engines*, 424 and 439.) Kay was the only author to describe the location and size of the main Jumo and BMW factories. (Kay, *German Jet Engine and Gas Turbine Development*, 78.)

[15] Pavelec claimed that de Havilland was a production failure and understood Rolls-Royce's work as derivative. (Pavelec, *Jet Race*, 118-120.) Constant discussed British production very little and American production not at all. Schlaifer made a few references to British production but did not discuss American production, only the reasons for the country's late entry to the field.

Table 2.1. Aero-engine production in Britain, Germany and the United States, 1939-1945

	1939	1940	1941	1942	1943	1944	1945*
Britain	12,499	24,074	36,551	53,916	57,985	56,931	22,821
Germany	3,865	15,510	22,400	37,000	50,700	54,600	
U.S.A.		15,513	58,181	138,089	227,116	256,912	106,350

* Britain Jan-Aug; U.S.A. Jan-Dec

These figures may or may not include turbojet production; either way, piston engine production far outweighed turbojet production.

Source: Richard Overy, *The Air War* (Dulles, VA: Brassey's, 2005), 150.

Table 2.2 Jet engine production in Britain, Germany and the United States, 1939-1945

Company+	1943	1944*	1945**	Total
Rolls-Royce	9	98	553	660
De Havilland	-	at most 12		85
Total Britain				**745**
Jumo		2,660	3,350	6010
BMW		189	370	559
Total Germany		**2,849**	**3,720**	**6,569**
General Electric				266
Allison	-			22
Allis-Chalmers	-			8
Total USA				**296**

Engine totals of recorded (delivered) production engines only; this does not include numerous experimental and development engines, nor reflect the extent of parts production.

+ Engine Types: Rolls-Royce: Welland and Derwent; de Havilland: Goblin; Jumo 004; BMW 003; GE I-16 marks 1 through 7 (produced 1944-1945); Allison I-16-6 (1944-1945); Allis-Chalmers H.1 (completed by April 1946)

* Germany: up to the end of 1944 including some in late 1943

** Germany: Jan-March 1945; Britain: Jan-Dec 1945

Sources: RRHT; William Hornby, *Factories and Plant* (London: H.M.S.O., 1958), 245; Kay, *German Jet Engine and Gas Turbine Development*; IWM FD 5400/45, Jumo Report, TL-Geräte 004 B-1/4 Neubau und Reperatur; AFHR A2073; AFHR A2072

Allied turbojet engines

Britain was the first country to decide to produce turbojet aero-engines. By the end of the war, three types of turbojet engine had been produced in Britain, of which two were deployed in British aircraft. In addition, British work gave rise to three production programmes in the United States. This section will interweave the American and British stories in order to emphasise the connections between them.

In 1940, with the war against Germany just a few months old, the British Air Ministry decided to pursue the production of turbojet engines. This was an ambitious goal, for the Air Ministry had placed a contract for the first flight turbojet engine only on 12 July 1939.[16] That engine, known as the W.1 (after Squadron Leader Frank Whittle, who designed it), was commissioned from the nominally private Power Jets Ltd., Britain's first turbojet aero-engine research and development company. An experimental airframe to carry the W.1, the E.28/39 (the twenty-eighth experimental airframe of 1939), had been ordered on 30 August 1939 from the Gloster Aircraft Company.[17]

On 26 February 1940, the Air Ministry's Director General of Research and Development, Air Vice Marshal Arthur Tedder, called a meeting to discuss the best way of proceeding with the 'development manufacture' of a Power Jets aero-engine.[18] If the engine was developed from the start with the requirements of production in mind, he reasoned, series production could later be started with the least loss of time. Because Power Jets' engine was at that point more akin to a laboratory apparatus than a flight-worthy jet engine, the Air Ministry provided from the start for both the further development of the engine design and the construction of production facilities. Power Jets remained responsible for the engine's design, but the Air Ministry decided to enlist an existing firm to build development and then production turbojet engines, as well as undertake any alterations to the Power Jets

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[16] Kay, *Turbojet History and Development*, 28.

[17] Tim Kershaw, *Jet Pioneers: Gloster and the Birth of the Jet Age* (Stroud: Sutton, 2004), 14.

[18] NA AVIA 15/2305, 26.2.40, 5A, Minutes of Meeting, Whittle Jet Propulsion Engine; Tedder quoted in Nahum, 'World War to Cold War', 83.

engine that would be required to facilitate production. At the February 1940 meeting, the Ministry proposed the Rover Company, an experienced car manufacturing firm, for the job, and by November 1940, Rover had begun building an experimental engine for Power Jets.[19]

Rover was a respected engineering company and government contractor with experience in aero-engine production, but not design. As part of the government's shadow scheme for Bristol Hercules piston engine production, Rover had already managed government owned factories producing parts for the powerful aero-engine according to Bristol's designs and production methods.[20] The firm had also undertaken on a commercial basis the repair and production of small Armstrong Siddeley Cheetah piston engines, which were used in Oxford trainers and Anson coastal defence aircraft.[21]

By 1940, Rover was carrying out piston-aero-engine production and repair work in six shadow factories. The most recent addition to these was Bankfield Shed, a disused weaving mill in Barnoldswick, which began Cheetah repair during 1940.[22] Bankfield Shed, about twice as large as a normal weaving shed with approximately 165,000 square feet of space, was chosen by Rover as the place where the flow production of turbojet aero-engines would be established, and Mr Poppe, Rover's expert on quantity manufacture, was put in charge of the new factory.[23] Rover decided that it would manufacture the engine's compressor-turbine assembly and build the engines, while it chose to sub-contract the fuel and combustion systems to Joseph Lucas Ltd, a company that manufactured automotive components. Lucas became a key designer and supplier of fuel and combustion equipment

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[19] NA AVIA 15/2305, 26.2.40, 5A, Minutes of Meeting, Whittle Jet Propulsion Engine; David Brooks, *Vikings at Waterloo: The Wartime Work on the Whittle Jet Engine by the Rover Company* (Derby: Rolls-Royce Heritage Trust, 1996), 18.

[20] Sebastian Ritchie, *Industry and Air Power: The Expansion of British Aircraft Production, 1935-41* (London: F. Cass., 1996), 113-146.

[21] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 320.

[22] Brooks, *Vikings at Waterloo*, 15.

[23] NA AVIA 15/1806, 5.1.43, 12A, Notes of a discussion, Rolls-Royce – Rover Organisation

for almost all of Britain's early jet engines.[24] Rover chose a second shadow site, Waterloo Mill in Clitheroe, as the centre of its turbojet engine design and testing work. It was staffed, unusually for a shadow factory, by a number of Rover's permanent staff.

Both the Barnoldswick and Clitheroe factories were, like the Bristol shadow factories, wholly government-owned. Because the expected development tasks were unusual for shadow production, Rover received a slightly higher than usual management fee for the turbojet factories of £16,000 per annum.[25] The government's total expenditure on the two shadow factories was estimated in mid-December 1942 to be £1.5M.[26] At the end of 1942, Barnoldswick had about 1,250 employees and Clitheroe 250.[27]

The Power Jets W.1 flew for the first time on 15 May 1941. It had been confirmed already in February 1941, however, that the Barnoldswick factory should be equipped to produce Power Jets engines at a rate of twenty per week. While this was not an overly high target as compared with piston engine production or later German and American plans, it nevertheless represented an enthusiastic and early investment. At the same time, plans were also approved to provide for the production of an additional thirty engines per week using the maximum amount of subcontracting, which could bring the production total to about 200 engines per month if needed.[28]

The Air Ministry's investment in the turbojet was no idle interest in a new propulsion system, nor a blind devotion to novelty, but part of the Ministry's serious and constant pursuit of and support for improvements in military aviation.[29] The desire to actually deploy

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[24] Brooks, *Vikings at Waterloo*, 13.

[25] NA AVIA 15/1802, 15.12.42, 5A, Interdepartmental note

[26] Na AVIA 15/1806, 11.12.42, 1A, Interdepartmental letter to Freeman

[27] NA AIR 62/608, 5.1.43, Meeting at Brownsover Hall

[28] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 320.

[29] NA CAB 66/15/22, 3.3.41, Memo by Beaverbrook, Minister of Aircraft Production; A dedication to new, high-tech machines was a typical feature of British military planning. (Edgerton, *Warfare State: Britain*; G. C. Peden, *Arms, Economics and British Strategy: From Dreadnoughts to Hydrogen Bombs* (Cambridge: CUP, 2007).)

turbojets was confirmed at the highest levels when on 18 April 1941, the Air Staff noted that they 'regarded the Whittle engine as an essential requirement.'[30]

The turbojet engine design to be produced at Barnoldswick was chosen on 5 March 1941. Known as the Power Jets W.2B, it was a scaled-up version of the W.1. Whereas the W.1 had been designed to produce 1,240 pounds of thrust, the W.2B was designed to reach 1,600. By the time of the first flight of the W.1 in the E.28/39 on 15 May 1941, MAP had already placed contracts for 50 'development engines' from Rover, which were to be used for testing. On 14 February 1941, MAP ordered a mock-up and twelve prototypes of a new twin-engined turbojet fighter airframe, the F.9/40 (the ninth fighter airframe of 1940), from Gloster, which signalled the Ministry's seriousness in pursing the new engines.[31] The contract price was estimated at £200,000.[32]

With the turbojet now being viewed as a serious possibility, enthusiasm for the new weapon spread. In July 1941, Britain's Prime Minister, Winston Churchill, and his advisor, Frederick Lindemann, made Lord Cherwell in June 1941, began to discuss the possible deployment of turbojet aircraft in the summer of 1942. They speculated about the possibility of putting them into production before the prototypes of the Gloster F.9/40 airframe or the W.2B engine were even finished. By accelerating production in this unorthodox way and avoiding delays caused by the 'titivation' of 'perfectionist' technicians,[33] Churchill expected to be able to deploy jet aircraft six months earlier than otherwise. This offered a valuable advantage, since he feared that Britain might come under imminent threat from high-altitude

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[30] NA AVIA 46/234, 18.4.41, Air Supply Board Meeting Summary

[31] Such signals were important: as Ricardo complained, Rolls-Royce deemphasised work on the Crecy because its importance was not made clear through the allocation of an airframe to it. (John Reynolds, *Engines and Enterprise: The Life and Work of Sir Harry Ricardo* (Stroud: Sutton Publishing Ltd., 1999), 210-212.)

[32] MOSI, Tony Butler, 43

[33] NA PREM 3/21/4, 23.7.41, 184, Memo from Cherwell to Churchill; Ronald Clark, *Tizard* (London: Methuen, 1965), 303.

German bombers.[34] Because he had been assured that about 1,000 of the desirable jet aircraft could be produced without adversely effecting the crucial production of piston engine aircraft, Churchill was confident that he could support jet production without sacrificing the country's air defences.[35] The interest from Downing Street contributed to increase pressure on engine development – Whittle recalled feeling 'like a hunted man'[36] – yet the engine was still far from being ready for production: it was still unreliable and lacked power. Nevertheless, preparations for production continued at Barnoldswick through the autumn of 1941 in the optimistic hope that development might solve the outstanding problems with the engine and allow production to proceed as soon as the factory was complete.[37]

MAP's enthusiasm and haste were demonstrated in its willingness to issue full production contracts to industry even before the new engines had been proven. Within six months of the country's first turbojet-powered flight, Rover had already been given a contract for 550 production W.2B engines and investment in production capacity for eighty F.9/40 airframes a month had been authorised.[38] Although MAP's Controller of Research and Development, Air Marshal Francis J. Linnell, was eager to expand Rover's W.2B production capacity beyond the twenty engines a week already agreed on, the Ministry's Deputy Director General for Engine Development and Production, Major George Bulman, cautioned that until the engine made more progress towards production standards, 'it is impracticable... to earmark further productive capacity' for it.[39]

Bulman's scepticism towards the new engines was based on his experience with aero-engines in the First World War, when a novel aero-engine design, the ABC Dragonfly, had

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[34] Turbojets work efficiently at high altitudes where even supercharged piston engines begin to lose power.

[35] Churchill quoted in Clark, *Tizard*, 303.

[36] Whittle, *Jet*, 168-169.

[37] NA PREM 3/21/4, 25.8.41, 177, Letter Cripps, Minister of Aircraft Production, to Churchill

[38] NA AVIA 15/1806, n.d., 24B, Rover Contracts. The engine contract was awarded by 28 October 1941. (RRHT, A-Numbers List)

[39] NA AVIA 15/1509, 14.10.41, Min 8, Minute Bulman to Linell

been ordered in large numbers before it had been built or tested – as Linnell was now proposing for the W.2B. The Dragonfly, when built, had proved so poor that only the end of the war had prevented the 'ghastly tragedy' that would have resulted from outfitting the newly independent RAF with the multitude of inferior engines that had been ordered. Bulman believed that the Dragonfly mess had occurred because the engineers who could have foreseen problems with the engine 'were not strong enough to counter the arguments of the uninitiated enthusiasts.'[40] Bulman, who Power Jets saw as a determined enemy of the turbojet, saw himself as the chief voice of restraint preventing an immature engine from being foisted on the RAF. His judgement proved correct.

The start of production in the United States

While Rover and Power Jets were proceeding with the development and production of the as yet unreliable W.2B, work on a derivative engine was commencing in the United States. The British turbojet engine programme had been revealed in the broadest outlines to the United States during the Tizard Mission in autumn 1940.[41] The British government saw the United States as a potential production centre for British-designed weapons, and the Mission sought to enlist American production help, particularly in the manufacture of microwave radar.[42] It has not been recognised however that some in Britain and the United States saw the latter as a potential production centre for jet engines as well.[43]

One month after the first British turbojet flight, the United States Military Attaché in London requested complete information on the Whittle engine. The next month, the British North American Supply Committee agreed that the design of the Power Jets W.2B could be

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[40] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 319.

[41] David Zimmerman, *Top Secret Exchange: The Tizard Mission and the Scientific War* (Stroud: Sutton, 1996), 94.

[42] Zimmerman, *Top Secret Exchange*, 167-172.

[43] NA AVIA 46/234, Monograph by Adderley (MAP); See also the discussion of the H.1 below. Work on the Whittle engine was not to affect other jet work in the United States. (AFHR A2073, 14.10.41, Doc 16, Letter H.A. Self (British Air Commission) to H.L Stimson (Secretary of War))

shared with the United States Government.[44] This was followed by information about all of the jet engines under development in Britain.[45] The United States was not yet in the war.

In fact, the United States already had a small jet engine programme of its own. At the urging of General Arnold, Commanding General of the United States Army Air Forces (USAAF), and under the guidance of the National Advisory Committee for Aeronautics, three leading American steam-turbine makers had begun to develop designs for axial gas turbine aero-engines in March 1941.[46] (See also Chapter 3.) However it was the possibility of producing the apparently flight-worthy, centrifugal British design that led the USAAF to start speculating about producing and deploying jets during the war. In meetings on 4 and 5 September 1941, the USAAF tasked the supercharger division of the General Electric Company (GE), a trusted contractor, with producing the British W.2B engine. GE received Rover's design drawings for the W.2B in October 1941. Because no W.2B was yet available for shipment, Power Jets' W.1X engine, a non-flight worthy version of the W.1, was sent to the United States along with three Power Jets engineers.[47] GE first built a copy of the W.2B, which was known as the Type I.[48] The firm then went on to make 14 type I-A engines, which increasingly included changes based on GE's supercharger expertise.[49] The USAAF selected Bell Aircraft Company to build an airframe for the GE engine. Bell, which was not a significant American airframe builder, was chosen in part because it had spare capacity and in part because its location in Buffalo, New York was near GE's supercharger division at Lynn, Massachusetts. Bell received a contract for three experimental XP-59A airframes on 3

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[44] NA AVIA 46/234, Monograph by Adderley (MAP)

[45] AFHR A2073, 25.11.41, Doc 25, Letter Caroll (Wright Field) to Echols (Materials Division, Washington); AFHR A2072, Doc 1, Report by Kiern (Power Plant Lab, Wright Field)

[46] Constant, *Origins of the Turbojet Revolution*, 222-223; Hansen, *Engineer in Charge*, 230-232.

[47] NA AVIA 46/234, Monograph by Adderley (MAP)

[48] AFHR A2073, 2.10.41, Doc 14, Letter General Arnold to Col A.J. Lyon (Office of Special Army Observer)

[49] AFHR A2073

October 1941.[50] In the end, adoption of the W.2B was probably not an appreciably faster route to a good jet engine than GE's own work because of the unavoidable delays associated with the firm's need to learn how to design aero-engines, improve the W.2B and build up an aero-engine production organisation.

Competition in Britain

While GE set about copying and improving the W.2B and preparing to produce it, the first W.2B engines built from parts made at the Rover factory in Barnoldswick were put on test. Disappointingly, the engines produced much less than the 1,600 pounds they had been designed for. In order to allow the flight trials that were necessary to improve engine and airframe to begin, Bulman told Rover in mid-November 1941 that the first Rover W.2B engines could be released when they achieved a rating of at least 1,000 pounds thrust (62.5% design thrust).[51] On 31 May 1942, Rover's first under-powered W.2B was dispatched to Gloster for taxying rather than flight trials in an F.9/40 prototype. In order for a single engine to complete the acceptance and final tests necessary to reach these trials (the tests added up to about two and a half hours of continuous running) at around 1,050 pounds thrust without failing, Rover ran five different W.2B engines for 45 hours and 45 minutes.[52] In mid-1942, the W.2B was still unreliable and not yet powerful enough to propel the F.9/40 airframe. Production at Barnoldswick, meanwhile, was limited to a small number of development engines, each varying from the last.[53] Although large-scale production was a far-off possibility, Rover continued to plan for series production of the W.2B, as stipulated in their contract.

Maintaining production facilities for a future production possibility was no inconsequential matter during a war of production, and MAP had to defend themselves in

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[50] AFHR A2073, 4.9.41, Doc 6, Memo Col B.W. Chidlaw to Gen Echols (Fighter Br, Engineering Division); AFHR A2065, 4.9.41, Doc 27, Letter Gen Arnold to American Embassy, London

[51] Brooks, *Vikings at Waterloo*, 50. The next eight engines achieved 1,200 pounds thrust.

[52] NA AIR 62/990, 31.5.42, GTCC Progress Reports

[53] Hooker, *Not Much of an Engineer*, 76.

the face of scrutiny from the newly formed Ministry of Production. In April 1942, Linnell argued that the ability to produce jet engines in the future justified the cost of reserving production capacity for 'an engine we cannot yet produce.'[54] Yet in comparison to the rosy predictions of 1940 that the engine could be developed and produced in much less time than a piston engine, work on the W.2B seemed to be stuck. It was well known in the young British turbojet community – which by no means had uniform faith in the Power Jets design as the best solution[55] - that cooperation between Power Jets and Rover had lapsed into acrimony, and rumours began circulating in mid-1942 that the W.2B engine would be cancelled. Linnell moved to quash the negative speculation, yet he was chary of investing any more in turbojet aero-engines until some progress was demonstrated.[56] In August 1942, Linnell rejected Rover's request to expand the factories at Barnoldswick and Clitheroe, which Rover argued would be necessary to fill the production programme that had been set for the company a year before.[57]

In 1941-1942, a strong competitor to the W.2B emerged: the H.1, or Halford turbojet engine, designed by the independent aero-engine designer Frank Halford. The H.1 was designed to reach 3,000 pounds of thrust, almost twice as much as the W.2B. This performance would allow a jet fighter with a single engine to outperform the contemporary Typhoon and Spitfire - the only way to justify the introduction of a new type during the war.[58] In mid-1942, the H.1 seemed to offer greater thrust, reliability and development potential than the W.2B, despite having been designed less than a year earlier. Bulman, enthusiastic about the engine's prospects and confident in Halford's skill, asked de Havilland

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[54] NA AVIA 9/30, 2.4.42, Linnell to Llewellin

[55] *Archive* 79, 14.1.43, Reprint Letter Lionel Haworth (Rolls-Royce) to Hayne Constant (RAE)

[56] NA AVIA 15/1614, 26.7.42, 26, Intradepartmental Minute Linnell to his Deputy

[57] NA AVIA 15/1614, 11.8.42, 32A, S.B. Wilks (Rover) to Linnell (MAP)

[58] Moult, 'Development of the Goblin Engine', 654-655.

to prepare in July 1942 a preliminary production plan for twenty-engines per week – the same production rate as has been chosen for Barnoldswick.[59]

While de Havilland's engine division set about planning production organisation, the firm's aircraft division designed an unconventional fighter airframe to carry the engine, the DH 100, to MAP specification number E.6/41. Unlike the conventional F.9/40 designed by Gloster, the E.6/41 had a twin-boom tail, which allowed for a short fuselage and thus a short exhaust duct in order to avoid aerodynamic losses and which kept its tailplane clear of the engine's exhaust jet. Taking advantage of the same method that had been applied to the firm's Mosquito and Hornet airframes, the high-speed E.6/41 jet airframe was made using both wood and metal.[60] On 11 April 1942, MAP placed an order for two E.6/41 prototypes at a cost of £40,000; a third airframe, to be built to operational standards including weapons, was added three days later. Permission was given to build the airframe at de Havilland's main works at Hatfield provided that it did not impact production of the hugely important Mosquito.[61]

Delay with the E.6/41 meant that the H.1 was first tested in a F.9/40 prototype, which had been originally intended for the W.2B; in fact, the F.9/40 first flew on 5 March 1943 powered by two H.1s, and for a time, the future of the F.9/40 airframe seemed to be with that engine.[62] While the F.9/40 could fly with two H.1 engines producing 2,000 pounds of thrust or 67% of the H.1's design thrust,[63] it could not fly with the W.2B until the W.2B had been developed to reach 1,450 pounds or 90% of its design thrust. In 1942, Gloster designed a more conventional single-engined fighter for the H.1 engine. The design, to MAP

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[59] NA AVIA 15/1599, 18.7.42, 14a, Letter Bulman to de Havilland

[60] Watkins, *De Havilland Vampire*, 4-5; The switch to all metal aircraft in America, which led Europe in this regard, was more a product of ideology than practical performance. (Eric Schatzberg, *Wings of Wood, Wings of Metal: Culture and Technical Choice in American Airplane Materials, 1914-1945* (Cambridge MA: Princeton UP, 1999).

[61] Watkins, *De Havilland Vampire*, 3-4.

[62] NA AVIA 15/1708, 21.6.42, Letter Linnell to J.J. Lewellin (Minister); AFHR A2072, 2.10.42, Doc 2, Report by Kiern

[63] NA AVIA 31/3, GTCC Meeting Minutes #8

specification E.5/42, was known as the Gloster Ace, but it was never ordered into production.[64] In 1942, Britain already had two jet engine and three jet airframe projects meant for production.

A fear of repeating 'our experiences with the W.2B' guided Linnell's policy on the H.1,[65] and so the bar was set higher for investment in the production of H.1 engines. Only in September 1942, when the second H.1 engine duplicated the performance of the first on test, did Linnell finally agree to Bulman's recommendation that de Havilland be granted a contract for the 'pilot production' of 100 H.1 engines at a rate of five engines per week.[66] After receiving the pilot production contract, development of the H.1 continued at de Havilland in parallel with the construction of the firm's jet engine production organisation, just as had happened with the W.2B at Rover and the Type I-A at GE. In August 1942, Bulman organised for 'engine planning engineers' from Armstrong-Siddeley Motors to help de Havilland plan for the production of a complex, large aero-engine.[67]

At the end of 1942, the H.1 and W.2B programmes were literally competing for the same resources. Barnoldswick's in part idle machinery offered a convenient source of machine tools for de Havilland, and in fact, Rover's factory was already producing some parts for the H.1.[68] MAP's new Deputy Director General of Engine Production, Air Commodore F.R. Banks, who took over some of Bulman's duties in October 1942,[69] informed de Havilland that the firm would get machine tools from Barnoldswick. As long as

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[64] AFHR A2072, 2.10.42, Doc 2, Report by Kiern; Edward Shacklady, *The Gloster Meteor* (London: Macdonald, 1962), 18-19. Contrary to some accounts, the Ace was designed for the H.1 and was never meant for a single W.2B, which would have been too weak to power it. After the war, three prototypes (now E.1/44) flew with the Rolls-Royce Nene. (Shacklady, *Gloster Meteor*, 65.)

[65] NA AVIA 15/1599, 8.8.42, Letter Linnell to Controller General

[66] NA AVIA 15/1599, 1.9.42, 21, Minute Linnell to Bulman

[67] NA AVIA 15/1599, 24.8.42, 20, Minute Bulman to Linnell

[68] NA AVIA 15/1599, 15.9.42, 25, Minute Bulman to Linnell

[69] NA AVIA 15/1599, 3.11.42, 39a, Bulman to Banks

the future of the W.2B's production was in doubt, the Air Supply Board refused to give de Havilland permission to acquire new machine tools.[70]

Abandoning the W.2B

The apparent lack of progress with the W.2B was made more poignant by the flight of the first American jet aircraft, the Bell XP-59A powered by two GE Type I-A engines (GE's Americanised W.2B engine), on 18 October 1942. This was almost six months before the F.9/40, which was ordered to carry the W.2B in 1940, had flown under jet power. Yet despite optimistic plans circulated by the USAAF suggesting the production of up to 1,000 Type I engines per month,[71] the W.2B proved to be further from production ripeness than the USAAF had expected. Indeed, in July 1942, GE's production capacity at West Lynn was only 15 engines per week.[72] Nevertheless, GE's initial success contrasted sharply with what was understood as Rover's inability to produce the W.2B.

This was a serious cause for MAP to abandon the W.2B. On 19 October 1942, Air Marshal Wilfrid Freeman returned to MAP to fill the newly created post of Chief Executive. He soon inquired about progress with the turbojet engine programme, which had begun before his departure from MAP on 5 November 1940 to serve as Vice Chief of the Air Staff.[73] Freeman asked Linnell to establish a clear line on the project's prospects, and on 2 November 1942, Linnell chaired a meeting 'to consider the future of the W.2B design and the possibility of abandoning [it]'.[74] The meeting, attended by MAP and RAE staff closely involved in the programme, judged that the Ministry's gamble on the W.2B had been a failure and that the W.2B production programme should be ended. The W.2B powered Meteor, as the F.9/40 service type was called, was to be reduced to a training role to ease the

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[70] NA AVIA 15/1599, c.11.42, 39b, Report on Development Production of H.1 Supercharger Unit for Air Supply Board

[71] NA AVIA 31/2, 18.7.42, GTCC Report Progress in USA

[72] AFHR A2073, 29.4.43, Doc 56, Progress report for General Arnold Chidlaw

[73] Anthony Furse, *Wilfrid Freeman: The Genius Behind Allied Survival and Air Supremacy, 1939 to 1945* (Staplehurst: Spellmount, 2000), 261-262.

[74] NA AVIA 15/1708, 7.11.42, 15A, Meeting about abandoning W.2B design

Royal Air Force's introduction to jet aircraft. The material already 'under fabrication' at Barnoldswick - estimated as enough for between 150 and 200 engines – was to be finished as 'development and training engines' under an extension to Rover's first development contract for 50 engines, while the later contract for 550 production engines was cancelled.[75] The existing order for Meteor airframes was drastically reduced from 80 a month to 46 total.[76]

This seemed to be the unfortunate end of the W.2B, and Linnell drew conclusions from the case to guide future MAP policy. He wrote in a note to Freeman on 29 November 1942 that '[t]he major causes of our troubles with the W.2B are: (i) undue optimism regarding the capacity of the design; (ii) an attempt to "produce" a completely undeveloped type, and (iii) above all, failure to observe the principle [that the design firm should be the one to carry out initial production]'. The last principle, he said, had been proved by MAP's 'bitter experience' with the Typhoon, which had been designed by Hawker but produced at Gloster, and with the W.2B, which was designed by Power Jets and produced by Rover.[77] As Rolls-Royce's later success attested, however, the division of design and initial production was less problematic than the division of responsibility for the new engine between Rover and Power Jets.

Linnell suggested that the reliable Rolls-Royce Company take over Power Jets Ltd. and that firm's development factory at Whetstone, which would become Rolls-Royce's jet section, leaving the 'salvage of the W.2B engine' at Barnoldswick to Rover. Work on the H.1 would meanwhile continue at De Havilland.[78] Not everyone agreed with Linnell's plan for the redistribution of the country's turbojet development and production resources. Power Jets and its supporters within MAP, particularly the first Deputy Director of Scientific Research, Harold Roxbee-Cox, defended the importance of Power Jets' independence.

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[75] NA AVIA 15/1708, 7.11.42, 15A, Meeting about abandoning W.2B design; 9.11.42, 17, Minute Linnell to Tizard

[76] NA AVIA 15/1708, 9.11.42, 17, Minute Linnell to Tizard

[77] NA AVIA 15/1708, 29.11.42, 20, Minute Linnell to Freeman

[78] Ibid.

Ultimately, it was decided that Power Jets would be left alone and that Rolls-Royce should take over the Rover shadow factories instead.[79]

By the end of 1942, Rover had manufactured just thirty-two development W.2B engines.[80] On taking over the Rover factories in Barnoldswick and Clitheroe, Rolls-Royce decided to finish the W.2B engines then under construction. Completing Rover's W.2B contract would keep the factory busy and thus maintain a claim to the labour and machines that had been assembled in Barnoldswick, preventing them from being reallocated. Work on the centrifugal engine would also serve as an educational order for Rolls-Royce, although the firm showed little interest in the design of the W.2B after finishing the contract. It was MAP's early investment in the factory at Barnoldswick, which was maintained for the eventuality that the W.2B would reach flow production, rather than any strong preference for the engine, that ensured that the W.2B, designated the Welland, was the first turbojet engine produced in Britain.

The change in management at Barnoldswick resulted in the W.2B moving quickly towards production readiness. By 20 February 1943, the W.2B had been put through a 100 hour type test, which included 26 starts, 106 accelerations and 100 hours of running at 1,250 pounds thrust (78% design) without replacing any parts – a significant milestone for an engine that months before had been judged too unreliable for service use. Before the end of February, Rolls-Royce had also put the engine into a flying test bed, a piston-engined Wellington, for a 25 hour flight – another important step considering that the engine had never been airborne.[81]

Production of the Meteor airframe, meanwhile, remained on low priority. Despite earlier planning, the total number of airframes on order was only twenty-seven in January

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[79] NA AIR 62/608, 4.12.42

[80] Brooks, *Vikings at Waterloo*, 72.

[81] NA AVIA 15/1806, 20.2.43, 21A, Letter Hives to Linnell, Roxbee Cox, Freeman

1943, including seven prototype F.9/40s.[82] Until the power and reliability of the W.2B had been proven, there was no hope of resurrecting the pared down Meteor contract at the cost of the production of proven types.[83] If the W.2B continued to produce too little thrust, the Meteor would be slower than existing piston-engined fighters and would offer no advantage over existing types, the production of which was well in hand. At 1,450 pounds thrust, the W.2B-Meteor pair would be good enough for a jet trainer. It would take a full 1,600 pounds to make the Meteor a competitive fighter above 35,000 feet, and 1,750 pounds thrust to make it an 'outstanding' fighter.[84] By 30 April 1943, however, the engine's success had prompted the Air Ministry to increase the order for 27 Meteor airframes to 120; soon after it was raised to 300.[85]

On 12 June 1943 two W.2B engines, each producing 1,450 pounds thrust, powered an F.9/40 for the first time.[86] Rolls-Royce produced 25 development engines before beginning limited production of Welland service engines around November 1943, which were cleared for flight at 1,600 pounds thrust with a very respectable time between overhauls of 150 hours.[87] By the end of November 1944, 100 Wellands had been manufactured.[88] Stanley Hooker of Rolls-Royce later reflected that '[a]lthough this was peanuts compared with our 1,000 Merlins a week, it did at least get the Meteor into the war.'[89]

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[82] NA AVIA 15/1708, 31.1.43, 31, Minute Linnell to Freeman

[83] NA AVIA 15/1708, 30.3.43, 38A, Letter Linnell to Hives

[84] NA AVIA 15/1614, 15.10.42, 39, Notes of meeting between Linnell and Wilks Brothers (Rover)

[85] Postan recorded that a Prime Ministerial directive was responsible for restoring Meteor production in the order for 120 Meteor I's in mid 1943. (Postan, Hay and Scott, *Design and Development of Weapons*, 224.) Power Jets believed that the improvement in engine performance that the contract was a response to 'owes nothing to RR [Rolls-Royce]'. (NA AIR 62/608, 3.5.43, Memo by W.E.P. Johnson)

[86] Kay, *Turbojet History and Development*, 56.

[87] AVIA 46/237, 27.7.44, GTCC Progress Reports; RR HT, Piggott, Development and Production Jets

[88] PREM 3/21/4, 23.11.44, Cripps, Third Two-Monthly Report; Rolls-Royce recorded that they produced 98 Welland engines by the end of November 1944 and an additional 12 before stopping production in October 1945 at Barnoldswick. (RRHT, Piggott, Development and Production Jets)

[89] Hooker, *Not Much of an Engineer*, 81.

When the first German jet fighter, the Me 262, was spotted on 25 July 1944,[90] which called for a demonstration of Britain's jet capability in return, the Welland powered Meteor was the only British jet that could be deployed.[91] Yet only twenty of the aircraft were predicted to be ready in 1944. These were to be sent not against German jet aircraft but against a new menace closer to home: the flying bomb, or V1, which the RAF had been fighting since June 1944. Cherwell observed that in view of the production record so far, 'the whole of our effort in this field will yield scant results against the flying bomb - which may be the last major opportunity for these aircraft in this war.'[92] The RAF's 616 Squadron flew the first Welland powered Meteors against the V1 on 27 July 1944.[93] Churchill wrote to Cripps on 30 July 1944 saying 'I hope you will make a special drive to turn out as many [Meteors] as you can... If we are caught behind-hand in jet-propulsion aircraft, it will be a serious reflection on MAP.'[94] Downing Street, as much as MAP, wanted to put the new weapons to use. Success against the V1s has been celebrated as one of the major achievements of the early operational Meteors, which did not see action against German jet aircraft during the war. Yet the operational record of the Meteor against the V1 was no better than its piston-engined counterparts. Whereas the few early Meteors eliminated some 40 V1s, (faster) Sabre-engined Hawker Tempests successfully destroyed 'many hundreds'.[95] The V1, however, presented a tactical and propaganda opening for the British jet fighter that was aimed as much at the emergent American turbojet makers as the Germans.

Rolls-Royce's lack of interest in the design of the Power Jets W.2B, which was not only low-powered but was also difficult to produce,[96] became clear when Rolls-Royce

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[90] Pavelec, *Jet Race*, 100.

[91] Postan, Hay and Scott, *Design and Development of Weapons*, 225.

[92] PREM 3/21/4, 26.7.44, 130, Memo Cherwell to Churchill

[93] The squadron had six Meteors. (Golley, Whittle and Gunston, *Whittle, the True Story*, 222.)

[94] AVIA 15/2101, 30.7.44, 1A, Letter Churchill to Cripps (Minister of Aircraft Production)

[95] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 335; Schlaifer and Heron, *Development of Aircraft Engines*, 435.

[96] Schlaifer and Heron, *Development of Aircraft Engines*, 434.

decided not to produce Power Jets' next engine, the W2/500, as originally planned. Instead, Rolls-Royce designed and produced its own centrifugal turbojet, the RB/37.[97] By June 1943, the first prototype had been completed at Barnoldswick.[98] It quickly reached its type tests and MAP built a shadow factory of about 200,000 square feet[99] at Newcastle-under-Lyme (near Stoke, as the factory was often referred to) for production of the Derwent, as the RB/37 was named.[100] The first Derwent engine emerged from the Newcastle factory in November 1944, in time for deployment in Europe.[101] By 30 January 1945, 13 Derwent engines with ratings of approximately 2,000 pounds had been delivered to Gloster for installation.[102] The Newcastle factory produced five hundred Derwent engines before December 1945, after which the factory was closed down. Barnoldswick produced fifty Derwent engines, starting in December 1944.[103]

By the end of the war in Europe, the RAF had 58 active Meteors, 35 of which were Mk Is, powered by Welland engines. The remainder, Meteor Mk IIIs, were powered by Rolls-Royce's second production jet engine, the Derwent.[104]

The decision to give the Barnoldswick factory to Rolls-Royce resulted in the brief series production of the W.2B and meant that Rolls-Royce had a complete jet engine production factory at its disposal, whereas production of H.1, the W.2B's competitor, at de Havilland had a serious delay imposed on it. When de Havilland heard that the Barnoldswick factory had been given to Rolls-Royce in late 1942, the company's general manager

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[97] The 'RB' prefix was already in use when Rover was in charge at Barnoldswick and referred to 'Rover Barnoldswick'. After Rolls-Royce took over the factory, the prefix came to be understood to mean 'Rolls Barnoldswick'. (Brooks, *Vikings at Waterloo.*)

[98] RRHT, Piggott

[99] Estimate based on total floor space added between 1943 and 1944. (Donald Eyre, *50 Years with Rolls-Royce: My Reminiscences*, (Derby: Rolls-Royce Heritage Trust, 2005), 87.)

[100] NA PREM 3/21/4, 27.9.44, Cripps, Second Two-Monthly Report

[101] NA PREM 3/21/4, 23.11.44, Cripps, First Third Two-Monthly Report

[102] NA PREM 3/21/4, 30.1.45, Cripps, Second Third Two-Monthly Report

[103] RRHT, Piggott

[104] Gunston, *Plane Speaking*, 162; Because of Derwent production lagging, the first 15 Meteor IIIs were fitted with Wellands. (Brooks, *Vikings at Waterloo*, 77-78.); NA PREM 3/21/4, 23.10.44, 78, Production of Jet Propelled Aircraft, Supplementary Note

responsible for engines, J.J. Parkes, appealed directly to Freeman to reverse the decision. Parkes argued that '[i]t is generally recognised that the H.1 is appreciably ahead of all contemporary development both in progress, reliability and power output... It would seem therefore to be most unfortunate to lose any advantage and opportunity for its earliest production.' He estimated that the necessity to find replacements for the Barnoldwick machinery would delay de Havilland's production plans by six to twelve months.[105]

However, the H.1 was no closer to production than the W.2B, and may have been farther from it. Continued compressor failure and combustion problems kept the H.1 from reliably achieving its design goal of 3,000 pounds thrust until 1945. The first E.6/41 prototype, which was held up by de Havilland's other airframe work, first flew with an H.1 engine (rated at only 2,225 pounds thrust, or 74% of design) on 20 September 1943.[106] An additional order for 230 H.1 engines was placed by MAP on 25 September 1943.[107]

However in early flight-testing in 1942, the E.6/41 H.1 combination proved to be superior to the Meteor-Welland combination already on order and a better match for the capabilities of Germany's Me 262.[108] Freeman attempted to place a first production order for 120 E.6/41 airframes at English Electric (Preston) on 13 May 1944 (against Linnell's earlier dire warnings as de Havilland could not take on the extra work).[109] Yet the H.1 turbojet had still not reached its design thrust at that time. In July 1944, MAP called for an 'urgent revision' to the H.1 policy, which resulted in a complete redesign of the H.1 engine.[110] The Meteor airframes that had been ordered to carry H.1 engines (Meteor Mk II) were officially

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[105] NA AVIA 15/1599, 31.12.42, 49B, Letter Parkes (de Havilland) to Freeman

[106] Watkins, *De Havilland Vampire*, 6; NA AVIA 31/3, 20.11.43, GTCC Minutes Meeting #11

[107] NA AVIA 15/1708, 19.11.42, 19, Minute Linnell to Freeman; RRHT, A-Numbers List

[108] NA AVIA 15/161, 13.3.44, 86A, Interdepartmental Letter

[109] Watkins, *De Havilland Vampire*, 10.

[110] NA AVIA 15/1599, 22.7.44, Min 54, Watt to Banks

cancelled on 25 July 1944. All H.1 engines were then reserved for the single-engined E.6/41, which however required the engine to produce its design thrust of 3,000 pounds.[111]

Production of the H.1, designated the Goblin in late 1943,[112] and its airframe, ultimately designated the Vampire, were delayed by commitments to other engines and aircraft. Labour was preferentially sent to the new Rolls-Royce jet engine factory in Newcastle-under-Lyme rather than to de Havilland's in Cannons Park, London, and production of the E.6/41 at English Electric was prevented by the firm's commitment to Halifax production.[113] On 20 January 1945, a Goblin engine finally completed a 100 hour service type test at 2,700 pounds thrust (90% design).[114] The first production H.1, originally expected in late 1943, appeared in January 1945. By May 1945, the company had produced 27 engines, fifteen of which were delivered to MAP with a rating of 2,700 pounds thrust.[115] The first production Vampire flew on 20 April 1945,[116] and the Goblin powered Vampire went into RAF service in April 1946.[117]

Production and improvement in the United States

In the United States, GE struggled with the W.2B. The firm's Type I-A produced 1,250 pounds of thrust rather than the specified 1,600. The GE I-16 (later renamed the J31), which did produce 1,600 pounds thrust, was the first engine to contain the company's own design features and the first to be put into production.[118]

Although development of the W.2B in the United States had been slower than hoped for because 'the original drawings did not represent an operable engine and much

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111 NA AVIA 15/1599, 25.7.44, Min 57, Linnell to Banks, Watt; De Havilland, n.d.

112 Watkins, *De Havilland Vampire*, 25.

113 NA AVIA 15/2101, 1.8.44, Min 4, Freeman to Cripps

114 NA AVIA 31/5; At the same time, the Rolls-Royce Nene completed a 100-hour development test at 4,000 pounds.

115De Havilland, 'Development of the De Havilland "Goblin" Jet Propulsion Engine 1940/1945', unpublished, n.d..

116 Watkins, *De Havilland Vampire*, 11.

117 With 247 Squadron. (Patrick Hassel, 'The Halford Jets', n.d.)

118 AFHR A2073, 28.5.43, Doc 60, Letter GE to Col D.J. Kiern (Power Plant Lab, Engineering Division, Wright Field)

engineering has been required to reach the present stage symbolised by the Type I-16 engine', the USAAF still hoped in July 1943 that it would be able to deploy jets in the war.[119] In October 1943, a production contract for 550 I-16 engines plus spares, at a cost of $26,812,500, was added to GE's first contract for 15 Type I engines, which had been approved by the USAAF on 23 December 1941. Before production of the I-16 was stopped in 1945, GE built a total of 266 I-16 engines.[120] Despite the fact that in October 1943, the firm possessed the capacity to allow it to produce 1,000 Type I-16 engines before June 1945, the government ordered only enough engines to 'maintain the facilities', while allowing some skilled labour to be transferred to the pressing development work on the more powerful (4,000 pounds thrust) I-40 (renamed the J33), which was on highest priority by 16 February 1944.[121] Soon however the USAAF was scrambling to add production capacity, which was planned for the I-16 but would be converted to the production of the I-40 as soon as the latter engine was ready. Waiting to build production facilities until the I-40 passed its acceptance tests, the USAAF judged, would result in an unacceptable gap of one to two years before the I-40 could be in production.[122] GE's I-16 contract was initially maintained for the sake of the Bell P-59 programme, but after poor performance consigned the P-59 I-16 combination, known as the Airacomet, to the role of a 'transitional trainer' in early 1944, production of the I-16 was gradually abandoned.

In June 1944, the USAAF chose a second turbojet manufacturer: the Allison division of General Motors.[123] With a slight decrease in production of their piston engines, Allison volunteered to provide 400,000-500,000 square feet of space in its government owned factory for I-40 production. This, it reckoned, would be enough for about 500 engines per

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119 AFHR A2073, 26.7.43, Doc 69, Letter Chidlaw (Chief, Mat Div, Washington) to GE

120 AFHR A2073, Summary, 33

121 AFHR A2073, Summary, 11

122 AFHR A2073, Summary, 15

123 AFHR A2078, 23.8.43, Doc 17, Report by Col. C.D. Gasser (Power Plant and Propeller Section, Mat Div, Washington)

month (a far higher rate than had been catered for at GE).[124] By June 1944, an order for 2,000 engines had been placed with Allison. After the war, GE's contracts for the I-40 were cancelled entirely and production of the I-40 was transferred to Allison. This was a blow to GE, but it freed up the company to develop its more powerful axial engines with which it went on to become a leader in jet engine production in the post-war period.

Prospects for the H.1

While GE was developing its I-16 and I-40 engines, the flight of the first H.1 in Britain in March 1943 drew American attention to the second British jet engine.[125] The H.1 turbojet promised a faster route to a more powerful engine than development of the W.2B, which rumours of German jet and rocket developments made even more urgent.[126] On 14 April 1943, the Bureau of Aeronautics (the United States Navy's aircraft procurement agency), the USAAF, the British Air Commission in Washington D.C., and Bell all agreed that the H.1 should be produced in the United States by Allis-Chalmers, a steam turbine manufacturer, which was producing turbo superchargers for the Navy and which had been working on an axial, ducted-fan turbojet engine design since 1941.[127] By 2 July 1943, Allis-Chalmers had volunteered to abandon its ducted fan in favour of the H.1, as it was no longer interested in turbojet development. It agreed to produce the H.1 on the condition that the engine was already 'technically satisfactory'.[128]

Lockheed started designing a single-engined airframe for the powerful H.1 in May 1943.[129] Designed and built in a rush during 1943, the Lockheed XP-80 nevertheless had to wait for the delivery of an H.1 engine from Britain before it could fly.[130] Following repeated

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[124] AFHR A2078, 20.5.44, Doc 56

[125] AFHR A2072, Summary

[126] AFHR A2072, Doc 12

[127] AFHR A2073, 13.10.41, Doc 17, Letter Hunsaker to Arnold

[128] AFHR A2072, Summary, 1-2

[129] AFHR A2072, 18.5.43, Doc 10, Letter Lt. Col. Thomas Hitchcock (Air Technical Section, London) to Robert A. Lovett (Assistant Secretary of State, Air)

[130] Pavelec, *Jet Race*, 138-141.

appeals by American officials in Britain and a major effort at de Havilland, the first H.1 arrived at Lockheed on 2 November 1943 (producing 2,300 pounds thrust[131]) and a second – necessitated by damage caused to the first engine by the collapse of the intake duct of the XP-80 in which it was being tested - arrived on 8 January 1944.[132] There were so few flight-worthy H.1 engines in Britain that the second H.1 shipped to the United States had actually been intended for installation in the second E.6/41 prototype.[133] Because of the lack of H.1 engines, Lockheed redesigned the P-80, later the Shooting Star, in 1944 to carry the GE I-40 engine. The new airframe flew with GE engines on 11 June 1944.[134]

Given the problems at de Havilland in Britain, the American decision in 1943 to produce H.1 engines appears completely unrealistic. MAP warned in July 1943 that the H.1 was not ready for production, yet on 26 October 1943, Allis-Chalmers submitted a proposal to the Navy for H.1 production that was approved in April 1944, almost a year before de Havilland's production factory finished its first production engine. In order to produce H.1 engines, Allis-Chalmers demanded the 'right to purchase as many rough or partially machined parts from DeHavilland [sic] as the Ministry of Aircraft Production would permit'.[135] This yoked the American production programme to the British programme so that, in contrast to the hopes of those who saw the United States as the only possibility for the engine's large scale production during the war,[136] the American H.1 production (unlike the W.2B-inspired programme) added very little to British work, while suffering from the same delays due to technical setbacks and reduced priority in Britain. Allis-Chalmers had

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131 AFHR A2072, 12.10.43, Doc 25, Report by Brig. Gen. F.O. Carroll

132 AFHR A2072, Summary, 3

133 Watkins, *De Havilland Vampire*, 25-26.

134 Leslie Neville and Nathaniel Silsbee, *Jet Propulsion Progress: the Development of Aircraft Gas Turbines* (New York: McGraw-Hill, 1948), 112.

135 The contract was for 40 H.1 engines. (AFHR A2072, Summary, 2)

136 AFHR A2072, 18.5.43, Doc 10, Letter Lt. Col. Thomas Hitchcock (Air Technical Section, London) to Robert A. Lovett (Assistant Secretary of State, Air)

produced only eight H.1 engines when the cessation in 1945 of reverse Lend-Lease, through which Allis-Chalmers had been receiving H.1 parts, led to the halting of H.1 production.[137]

American jet engines are generally treated as wholly derivative of British design efforts in this period. While this is true for the little-known case of the H.1, it is not true of the Power Jets engine. In fact, as contemporaries testified, collaboration across the Atlantic on the W.2B was 'intimate'[138] – even if both sides had a tendency to defer to their own council and production facilities in the end. Information, engines, engineers, airframes and turbojet engine parts all crossed the Atlantic between 1942 and 1945.[139] In December 1943, testing of a Bell XP-59A airframe with GE Type I-A engines began at the Royal Aircraft Establishment in Farnborough.[140] The first production Meteor Mk I with Welland engines (first flight 12 January 1944) was sent for testing in the United States in exchange. It first flew at Muroc on 15 April 1944.[141] The British and American national turbojet programmes, like programmes in other fields, were closely linked.

Turbojet engine production in Germany

During the Second World War, the German economy was under much more strain than the British or American economies, yet it produced more jet engines and airframes than the Allies combined. This was not because of early production planning, in fact quite the reverse. Although German companies had been developing jet engines from 1938, when at least seven engine designs were already underway, Erhard Milch, the State Secretary of the German Air Ministry (Reichsluftfahrtministerium, RLM) and after November 1941 also the head of the RLM's Technical Office, did not become interested in using jets as a weapon in

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137 AFHR A2072, Summary, 3-4; 20.7.45, Doc 80

138 NASM R Inventory number: A19500082000, 'Whittle W.1X Turbojet Engine.'

139 During the war, the British Gas Turbine Collaboration Committee included a report on American progress at each of its bi-monthly meetings. This stopped at the 19th meeting, on 1 Feb 1946. (NA AVIA 31/6)

140 NA AIR 62/990, 25.12.43, GTCC Reports

141 Peter berry, 'R-R W2B,' accessed on 13 September 2010, http://www.enginehistory.org/r-r_w2b.htm.

the war until early 1943. During that year, the RLM turned desperately to the new power plant because it was cheap to make and easily adaptable to the production system and conditions of scarcity of the last years of the Third Reich. Indeed, unlike piston engines, the new jet engines were designed to be manufactured by unskilled and slave labour. Even in an underdeveloped state, they offered important material and production advantages to the struggling Reich, which will be discussed in detail in the last part of this section.

The RLM Technical Office's section responsible for special propulsion systems (Sondertriebwerke), which included rocket and jet engines, had supported a centrally organised programme of turbojet engine development at all of Germany's major aero-engine companies since 1938. In mid-1942, the head of the Sondertriebwerke section, Helmut Schelp, who in various capacities had shepherded the country's jet engine programme from its inception, decided that two of the engines that had been developed under government contracts - the 109-004 developed by the Junkers Motor Company (Jumo) and the 109-003 developed by BMW - had progressed far enough to initiate a small-scale production programme.

In contrast to the production programme initiated later by the RLM in 1943, Schelp's was a long-term strategy that saw the country's turbojet capability advancing from the simplest turbojets to more powerful turboprops over sixteen years, and he distributed development contracts between the German aero-engine manufactures during the war in what he saw as the most advantageous way for the national programme.[142] Schelp's move towards limited production in 1942 was not a gambit to produce a weapon, but rather to allow the firms to begin to solve the inevitable problems of series production, which he considered to be much farther in the future. In fact, he considered neither of the two simple axial jet engines that he chose for early production - the conservative Jumo 004 engine,

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142 Schlaifer and Heron, *Development of Aircraft Engines*, 402-404; also the testimony of von Ohain (Conner, *Elegance in Flight*, 255). For more on the details of Schelp's long-term programme see Schlaifer and Heron, *Development of Aircraft Engines*, 403 fn 39.

which was close to production readiness, or the more adventurous 003 engine - to be a potential service engine.[143] Both had similar power ratings of about 2,000 pounds thrust – greater than the 1,600 pounds that the British W.2B was aiming for. It was not yet clear that there would be a need for both engines, but pursuing two alternatives was part of Schelp's strategy to reduce the risk of the development programme and to acquire as much experience with the new engines as quickly as possible. Early production, furthermore, would allow the airframe industry to begin to study the problems of high-speed flight and the Luftwaffe to carry out its first flight tests.[144]

When the performance of the Luftwaffe's second-generation piston-engined fighter, the Me 209, was proven to be inferior to that of its long-serving predecessors, the Bf 109 and Fw 190, the RLM decided to switch to jet aircraft earlier than anticipated.[145] This gave the Ministry no choice but to build on the groundwork laid by Shelp's relatively low-level office, and the RLM placed production contracts with Jumo and BMW, the companies with the jet engines closest to production. Nevertheless, both companies struggled to build production organisations.

In addition to the immaturity of the Jumo and BMW engines, the RLM's plan for jet engine production was held up, like the Ministry's 1943 aircraft production programme more generally, by a lack of resources. Herman Göring, Commander-in-Chief of the Luftwaffe, was increasing ineffective in obtaining resources for the RLM in the abiding fight among the leadership of the Reich.[146] During 1943, the Luftwaffe's share of construction projects dropped to half that of the previous four years, despite the increased effort to move aircraft

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143 Schlaifer and Heron, *Development of Aircraft Engines*, 403.

144 BA RL3/1133, 11.6.42, Entwicklung von Luftstrahltribewerken (likely by Schelp)

145 David Irving, *The Rise and Fall of the Luftwaffe: The Life of Field Marshal Erhard Milch (Electronic)*: Parcelforce, 2002), accessed 12 August 2010, http://www.fpp.co.uk/books/Milch/Milch.pdf, 244-245.

146 Adam Tooze, *The Wages of Destruction: The Making and Breaking of the Nazi Economy* (London: Penguin, 2007), 633.

production into new, bombproof factories.[147] In February 1943, Jumo's director Cambeis received an order to plan for the production of the 004 turbojet, reaching a rate of 1,000 engines per month by the end of 1944. But in January 1944, series production had still not begun, largely because the firm was unable to get sufficient resources for the work.[148]

Production of the 004 engine, originally set up at the company's main works at Dessau, finally began at Jumo's large factory at Muldenstein, a few miles south of Dessau, after the firm's main factory was severely bombed in late 1943.[149] Muldenstein, which had been in use producing piston engines, became the centre for the design, development, production and testing of Jumo's turbojet engine. The factory's planned capacity was allegedly 1,200 jet engines per month,[150] but according to production figures its peak output was only 467 engines in December 1944.[151] Nevertheless, the factory's early start meant that it produced the largest number of 004 engines of any German factory during the war: 45% of the total number. Jumo's factories at Köthen (near Muldenstein) and Zittau also began producing jet engines in 1944, and Dessau finally began producing 004 engines in March 1945.[152] The firm made plans to begin production in some of its other piston engine factories, including at Magdeburg and Strasbourg, but neither of these reached production. Magdeburg was put out of action by bombing, and the Strasbourg plant, which was to assemble engines from parts produced by sub-contractors, had not yet begun production when it was taken over by the Allies in January 1945.[153] Some other Jumo factories produced parts for the engines.[154]

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147 Irving, *Rise and Fall of the Luftwaffe*, 233.

148 BA MA N653/4, 18.1.44, GL-Amtschefbesprechung Flugmotoren-Produktion

149 IMW FD 5400/45, Jumo Report, TL-Geräte 004 B-1/4 Neubau und Reperatur

150 NA AVIA 15/2121, 27.7.45, 260, Interrogation of Max Eichler

151 Kay, *German Jet Engine and Gas Turbine Development*, 78.

152 IWM FD 5400/45, Jumo Report, TL-Geräte 004 B-1/4 Neubau und Reperatur

153 NA AVIA 15/2121, 27.1.45, 68, Adderley

154 IWM FD 5400/45, Jumo Report, TL-Geräte 004 B-1/4 Neubau und Reperatur

At BMW, development was some nine months behind the work at Jumo. The firm's turbojet production was initially concentrated in Spandau, where the first series 003 engines were produced, but the factory was bombed with Berlin in late 1943. The firm tried, like Jumo, to set up several jet factories, but only a single factory, BMW's licence production piston engine factory at Zühlsdorf, ever assembled complete BMW 003 engines during the war. The first production 003 engines appeared in October 1944.[155] Production at Zühlsdorf reached a peak of 150 engines in March 1945, although it had been planed for some 1,500 engines per month.[156] Because of its inability to free up its piston engine capacity to produce turbojets, BMW relied heavily on other firms for parts production.[157] While the Zühlsdorf factory made machined components as well as assembled and tested complete engines, for example, all of the sheet metal work for the engines was sub-contracted.[158]

The SS was to be involved in the BMW programme from early on. In mid-September 1943, Schelp approached SS-Obergruppenführer Jüttner, the head of the SS's Main Leadership Office (SS-Führungshauptamt), for assistance in producing parts for BMW 003 engines. Jüttner recommended to Himmler that '[i]n view of the terror raids [Terrorangriffe] by the enemy's air forces, the RLM should be given all necessary assistance' to ensure that the new jet fighters would be deployed in defence of the Reich – the SS was not yet looking to take over turbojet production.[159] The SS agreed to produce parts for the BMW 003 at the SS-Kraftfahrttechnischen Versuchsanstalt in Oranienburg, not far from Zühlsdorf. Before doing so, however, the organisation had carried out tests to make sure that concentration camp inmates could produce the required parts. Although slave labour was typically used for heavy work, the SS had worked out that even for the precision parts required, the slave labourers could in some cases produce parts in half the time that BMW

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155 Kay, *German Jet Engine and Gas Turbine Development*, 118.

156 NA AVIA 15/2121, 27.7.45, 260, Interrogation of Max Eichler

157 BMW FA79, 2.9.43, Letter Zborowski an Himmler

158 NA AVIA 15/2121, 27.7.45, 260, Interrogation of Max Eichler

159 BA MA NS19/57, 15.9.43, Letter Jüttner an Himmler

had calculated. Preparatory work began even before Himmler had given his approval, with the goal of starting parts production by the end of September 1943. Until the end of the war, 1,000 concentration camp inmates produced parts for BMW 003 engines at the SS facility, in addition to the approximately 2,000 workers who eventually worked on turbojets at BMW's main jet engine plants.[160]

During the war, the German turbojet production programme continued to be marked by improvisation borne of the changing realities of production. In December 1943, the RLM decided that it did not need or could not afford two turbojet production programmes, and plans for production of the BMW 003 were cancelled. In January 1944, however, the disorganisation at Junkers, where production had still not begun, led the RLM to worry that the supply of Jumo 004 engines would not be enough for its jet fighter and bomber programmes, and BMW was asked to take up production again.[161] The RLM's plans had expanded to include the Me 262 and Ar 234 airframes, both of which had been commissioned by the RLM's Aircraft Development Group before 1941. The flight-testing of both airframes had been held up by the lack of jet engines. The Arado 234 was redesigned by July 1944 as a jet bomber with four BMW engines rather than the two Jumo engines of the original reconnaissance version,[162] yet the 'development condition' ('Entwicklungszustand') of the 003 soon endangered the bomber programme entirely.[163]

Production underground

The impressive destruction of aircraft factories during 'Big Week' in February 1944, led Milch, with Karl Saur's support, to suggest that an executive committee be formed to rebuild and streamline aircraft production. Milch believed that the only way to increase aircraft

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[160] At Zühlsdorf and Eisenach (see below). (BAMA NS19/57, 15.9.43, Letter Jüttner an Himmler; DM FA001/0323, 29.8.44, Aktennotiz, Meschkat; NA AVIA 15/2121, 27.7.45, 260, Interrogation of Max Eichler)

[161] BA MA N653/11, 5.1.44, FZ-Produktion

[162] Wagner, *Ersten Strahlflugzeuge Der Welt*, 87-90.

[163] Government Report 18.7.44, quoted in Schabel, *Illusion der Wunderwaffen*, 238.

production was to give up control of production to Speer's Armaments Ministry (Reichsministerium für Rüstung und Kriegsproduktion) because he held Speer and his deputy Saur responsible for starving aircraft production of resources.[164] With Speer's approval, a committee, which became known as the Jägerstab (Fighter Staff), was established on 1 March 1944. It was headed by Saur and included Milch;[165] the formation of the Jägerstab marked the beginning of the transfer of responsibility for aircraft production from the RLM to Speer's increasingly powerful Ministry.[166] The Jägerstab's main purpose was to increase the output of fighter aircraft and to protect it from Allied bombing by dispersing production facilities throughout the country. Because of its monopoly over the increasingly indispensible slave labour force of the country's concentration camps, the SS had gained power in armaments production, and it was represented on the Jägerstab by the engineer Hans Kammler, who had earned a reputation for both ruthlessness and competence by accelerating V2 production underground the previous autumn.[167]

After the Jägerstab began its autocratic work, aircraft production climbed steadily upwards; output in terms of airframe weight doubled between February 1944 and July 1944.[168] Yet this was accomplished without any dramatic reorganisation. Speer argued in 1944 that the surge in fighter production came not from the restoration of resources previously denied to the RLM - as Göring and Milch insisted - but rather through the use of the RLM's own reserves.[169] Yet Göring and Milch were correct: the increased availability of resources including 'raw materials, labour, food and transport' allowed the measures that the RLM had earlier put in place to finally take effect. In fact, Speer's 'production miracle' of

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164 Irving, *Rise and Fall of the Luftwaffe*, 301-308.

165 Albert Speer, *Inside the Third Reich* (London: Orion Publishing Group, 1997), 450; Irving, *Rise and Fall of the Luftwaffe*, 301-3.

166 Speer, *Inside the Third Reich*, 450.

167 Michael Thad Allen, *The Business of Genocide: The SS, Slave Labor, and the Concentration Camps* (Chapel Hill, NC: University of North Carolina Press, 2002), 232-239.

168 Tooze, *Wages of Destruction*, 627.

169 BA MA R3/1509, 8.6.44, Führer Besprechung

early 1944 followed the lines laid down in the RLM's 1943 production programme, churning out thousands of out-of-date, single-engined Bf 109 and Fw 190 fighters, which after five years of production had become increasingly inexpensive and quick to produce.[170]

Labour was also crucial in determining which machines were manufactured and which were not. The Jägerstab's executive power and its support for the exploitative labour policies of the SS were as fundamental to the production regime that they initiated as the supply of materials. The apparent success of the Jägerstab in raising aircraft production served as an argument to extend its methods, which brought 'a new measure of coercive violence to the armaments economy', especially to the slave and foreign labour working for the RLM, but also to German workers and even management. Production became defined by the combination of Speer's growing control over material resources and Himmler's ruthless exploitation of slave labourers.[171]

The powerful Jägerstab soon turned its attention to jet engine production, moving it, like aviation production generally, underground. In April 1944, the Jägerstab convinced Hitler that space could be found for production of Jumo 213 piston engines and 004 jet engines in Mittelwerk, an underground factory near Nordhausen that was already producing V2 rockets.[172] The desire to move production of the Jumo 004 into a massive underground factory under the Jägerstab's control reflected not only the requirement for production protected from bombing but also the Jägerstab's despair that Jumo wasn't managing jet engine production correctly. In May 1944, Milch reflected that 'there was complete confusion' at Jumo, '[t]he entire planning for jet engines is a first-class mess' ('eine Schweinerei erster Klasse').[173]

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[170] Tooze, *Wages of Destruction*, 633; In 1944 there was a 'drastic shift of production' to single-engined fighter types. (USSBS, January 1947, Aircraft Division Industry Report, Second Edition, 99)

[171] Tooze, *Wages of Destruction*, 627-634.

[172] Irving, *Rise and Fall of the Luftwaffe*, 308-309.

[173] BA MA R3/1567, 15.5.44, Jägerstab Besprechung

Before it was chosen by the Armaments Ministry as a dispersal site for V2 missile production on 26 August 1943, the underground tunnel complex near Nordhausen had been in use as an oil storage depot. The depot's approximately 1.27M square feet of tunnel space, part of a larger plan that was never realised, was excavated between 1936 and 1942. It was laid out like a ladder, with two long, horizontal tunnels large enough for dual railroad tracks that gave access from the side of the mountain to forty-three internal rungs and three half rungs. (See Figure 2.1.) When the depot was requisitioned for weapons production, the most significant extra excavation required was to extend the second access tunnel to the south side of the mountain and to increase the height of some galleries. Many of the tunnels also needed cement floors to be added; the rungs numbered 17 to 45 had circular cross-sections to accommodate petrol tanks and 'required considerable filling to bring their floors level with those of the main service tunnels'. The galleries numbered 0-16 in contrast, had been designed to house oil tanks and already had flat floors. The work required to convert the depot into a weapons factory was carried out in an amazingly short time by concentration camp prisoners under Kammler's barbaric control, but if the tunnels hadn't been mostly excavated before the site was selected, the factory would not have been able to begin production in less than four months, as it did. The first V2 rockets emerged from the factory on 1 January 1944.[174]

In June or July 1944, Kammler, acting on behalf of the Jägerstab, consolidated V2 production into the complex's southern tunnels (numbers 21-46[175]), known as Mittelwerk, in order to make the northern tunnels, known as Nordwerk, available for the production of aero-engines.[176] Jet engines began to be produced in Nordwerk in October 1944, using some

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[174] CIOS XXXII-17; Neufeld, *Rocket and the Reich*, 200-213; David Irving, *Mare's Nest* (Panther Books, 1985), accessed on 14 August 2010, www.fpp.co.uk/books/MaresNest/index.html, 166.

[175] Neufeld, *Rocket and the Reich*, 230.

[176] Kammler's intention to produce almost all of the country's jet engines and airframes - Jumo 004, BMW 003, Me 262 and He 162 - was symptomatic of the SS's bid to control crucial weapons production towards the end of the war, which began with his take-over of V2 production in Autumn

parts made in the factory and some made by sub-contractors. Jumo jet engine production had already begun at Jumo's factories at Muldenstein and nearby Köthen, but the output from Nordwerk, under the auspices of the Jägerstab and SS, rose much more quickly. (See Figure 2.2.) When output from Muldenstein and Köthen was reduced by bombing in January 1945, production of the Jumo 004 at Nordwerk continued to rise. In January 1945, Nordwerk alone produced more than half of the jet engines that were built that month. Despite beginning production several months after the main Jumo factories, by the end of the war, one third of all Jumo jet engines had been produced at Nordwerk. It was astounding that a factory that began production in October 1944 reached an output of 815 engines in March 1945. The factory's production record was evidence of the grim underground factory's ability to produce weapons.

Nordhausen's underground factories are most famous from histories of the production of the V2. While these accounts often mention in passing that jet engine production occurred beside V2 production, no history of the jet engine shows an understanding of the scale of jet engine production that occurred underground or its significance.[177] That the Jägerstab used valuable underground factory space for jet engine production is crucial to understanding the place of the jet in the German armament effort.

In spring 1944, planning began to provide millions more square feet of factory space for jet engine production in parts of a group of seven more factories planned in the same

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1944. (DM FA001/0832, 8.11.4, Notes of a meeting on 7.11.44 between EHAG and the Nationalsozialistisches Fliegerkorps; CIOS XXIV-6; Neufeld, *Rocket and the Reich*, 245.)

[177] Jet engine production is mentioned in Allen, *Business of Genocide;* Neufeld, *Rocket and the Reich;* F. Ordway and Mitchell Sharpe, *The Rocket Team* (London: Heinemann, 1979); Irving, *Mare's Nest* and in the memoirs of those who worked as slaves on V2 production. See Ralf Bülow, 'Ein Blick in Die Hölle: Die Aufzeichnungen Von Georg Schmertz Uber Die Kriegswaffen-Produktionsstatte Mittelwerk Gmbh,' *Kultur und Technik* 4, no 19 (1994): 38-41 and Yves Béon and Michael Neufeld, *Planet Dora: A Memoir of the Holocaust and the Birth of the Space Age* (Boulder, Colo.; Oxford: Westview, 1997). Kay mentions the factory (Kay, *German Jet Engine and Gas Turbine Development*, 78) because it appears in Jumo 004 production statistics but in no way makes its importance or nature clear. Green notes the dispersal of Junkers engine production to Nordhausen. (William Green, *The Warplanes of the Third Reich* (London: Macdonald & Co, 1970), 13.) Schabel mentions the Mittelwerk only with reference to V2 and planned Me 262 production. (Schabel, *Illusion der Wunderwaffen*, 225.) No professional history of the jet engine mentions production of the Jumo 004 at Nordhausen.

mountain, known collectively as Mittelbau.[178] The new excavations were planned on a scale that dwarfed the existing Nordhausen factory. (See Figure 2.3.) The factories were to have a total of 6.5M square feet of factory space and to house jet engine production, aircraft component production, a liquid oxygen plant (for V2 production), and synthetic oil storage and production facilities.[179] No fewer than *three* of the seven projected factories were meant for Junkers jet engines. The biggest of these, known variously as Project Zinnstein, Bau 12, and Hydrawerk, was projected to reach 2.7M square feet. When the war ended, 134,000 square feet had been excavated for Jumo and a partially completed jet engine assembly line was in place in the factory.

In addition to three of the Mittelbau factories, Jumo jet engine production was also planned for a new factory known as Malachit that was being excavated in a sandstone mountain near Halberstadt-Langenstein. A least 120,000 square feet were already in use by Junkers there at the end of the war, and up to 400,000 square feet might ultimately have been available. All together something like 6.4M square feet were planned for 004 production (of which about 1.31M square feet had been excavated by the end of the war), almost the same amount of factory space as in BMW's main works at Allach.[180] For comparison, Rolls-Royce's total factory space in 1944 came to almost 7.3M square feet. Of this, jet engine production represented only about 730,000 square feet.[181]

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[178] CIOS XXXII-17; The Kohnstein Mountain in which the oil depot was built was composed of anhydrite, dry and strong, which allowed continuous, unlined and extremely high galleries to be dug. The excavated rock was used to manufacture sulphuric acid at I.G. Farben's nearby Leuna Factory.

[179] CIOS XXXII-17; The new factories were designed using a grid layout rather than the ladder layout of the less hastily excavated Mittelwerk, which facilitated faster construction by providing multiple access passages from the side of the mountain through which rock could be removed. The factories were laid out, whenever possible, in collaboration with the firms that were to use them, supporting Allen's argument that industry cooperated in at least or acquiesced to the SS's brutal production regime. (Allen, *Business of Genocide.*)

[180] Constanze Werner, *Kriegswirtschaft und Zwangsarbeit Bei BMW* (Oldenbourg: Oldenbourg Wissenschaftsverlag, 2006), 313.

[181] Eyre, *50 Years with Rolls-Royce*, 87; Roy Fedden reported to the British aviation public in 1945 that 'a big chain of bomb-proof underground factories was being built up when the war ended, but they were earmarked almost entirely for jet and rocket-unit production.' (Roy Fedden, 'German Piston-engine Progress.' *Flight*, 6.12.1945: 602-604.)

While the Jägerstab planned to expand production of the Jumo jet engine on a massive scale, it was also pressuring BMW to disperse its aero-engine production, including its jet engine production facilities. In June 1944, the Jägerstab assigned several potash mines to BMW for jet engine production. Among these was a large underground mine at Heiligenrode, near BMW's piston engine factory at Eisenach. Through the work of the Jägerstab, Organisation Todt and the SS, the mine was prepared for jet engine production by a group of concentration camp prisoners and prisoners of war in March 1945 using methods no less brutal than the well known case of Mittelwerk. As had happened in the tunnels of the earlier factory, large swathes of concrete floor were laid underground at a brutal pace.[182] Despite this, the Heiligenrode plant never produced any jet engines. It was close to commencing engine production in 1945 using about 130,000 square feet of the almost 431,000 square feet available in the mine, when it was captured by American troops.[183] Other smaller mines nearby including ones at Abteroda, Ploernintz, Bad Salzungen were allocated for component production and assembly – the last mine was never used.[184] Production planning for the BMW 003 began to follow the same pattern as for the 004, housed in underground factories manned by forced labourers. Nevertheless, 004 production at the Nordwerk factory was well ahead of 003 production underground.

The output of 004 engines and Me 262 airframes in the last year of the war was extraordinary. Production of the Me 262 peaked at almost 300 airframes in February 1945 – several months after fighter production in general had begun to decline. (See Figure 2.4.) German piston engine production began to decline even earlier, in May 1944.[185] Yet turbojet engine production rose continually from August 1944 until the end of the war. By the end of the war, the pre-eminence of the jet and the shift of resources to its production in the

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[182] Werner, *Kriegswirtschaft und Zwangsarbeit bei BMW*, 329 and 346.

[183] CIOS XXIV-6; NA AVIA 15/2121, 27.7.45, 260, Interrogation of Max Eichler

[184] CIOS XXIV-6

[185] USSBS, January 1947, Aircraft Division Industry Report, Second Edition

regime's planning was complete. Hitler appointed Kammler to be plenipotentiary for jet aircraft ('Generalbevollmächtigte des Führers für Strahlflugzeuge') on 27 March 1945,[186] and on 31 March 1945, Kammler ordered the 'total cancellation' ('restlos Streichung') of all piston-engined aircraft and the cessation of series production of all jet aircraft except the Me 262, the aircraft on which the RLM believed that Germany's fate now depended ('die zur Schicksalsmaschine Deutschlands geworden ist').[187] This extraordinary decision was the desperate climax of the Nazi government's hope to reverse the country's fortunes in the war, and it made sense because jet engines were the easiest aero-propulsion system to produce.

The remarkable production of ersatz aero-engines

Increasing the ease and reducing the cost of airframe and aero-engine production had been a goal of the RLM since the beginning of the war. Already in 1943, the Ministry had made an effort to reduce its requirements for scarce metals through the development of more 'economic manufacturing methods' and the 'rational' usage of materials.[188] Speer's later efforts to streamline armaments production followed a similar logic. In July 1944, Speer announced that no design changes would be allowed to weapons that were in series production unless the changes offered an overwhelming advantage in battle, rectified a flaw that made the weapons useless, or reduced the cost of production by simplifying production, conserving strategic materials or reducing weight.[189] The Volksjäger project, initiated by the Jägerstab not long after, in autumn 1944, demonstrated the Jägerstab's view that the advantages of a being able to build smaller jet airframes using less material and labour than was required for the Me 262 outweighed the serious risk of introducing in the middle of a

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[186] BA RL3/2568, 27.3.45, Letter Führer an Verteiler

[187] BA RL3/2568, 3.4.45, Letter Purucker an Diesing; 28.3.45, Koller (OKL)

[188] BA MA RL3/51, 20.5.43, Report by Milch

[189] BA R3/100, 22.7.44, Speer, Anordnung zum Erlaß des Fürhrers über die Konzentration der Rüstungs- und Kriegsproduktion vom 19.6.44

war a completely new and untested jet aircraft that had been hastily designed and produced.[190]

As the war continued, production savings became as important to the country's war waging and defence capacity as improvements in weapons. As Speer's 'armaments miracle' demonstrated, small improvements were outweighed by the quantity that could be produced if a design remained unchanged in series production. While rumours of wonder weapons were used to fortify the country's will to fight as the war dragged on,[191] production was being shifted to products that were quicker, easier and less costly to make. All of the 'Volks'-weapons produced in the last months of the war - the Volkspistole, Volksgewehr and Volksjäger - were primitive but quick to produce.[192] Large numbers of low quality weapons offered the struggling country an important advantage.[193]

Jumo and BMW's turbojet engines could be made using much less material – whether scarce or plentiful metals - than piston engines of a similar power output. The important Daimler-Benz 603 piston engine, for example, produced 1,750 horsepower for a dry weight of 2,030 pounds; its power to weight ratio was 0.86 hp/lb. The Jumo 004B (the firm's first production version) in contrast, weighed 1,585 pounds (dry) but produced the rough equivalent of 2,580 horsepower when flying at 400 mph. Its power to weight ratio at speed was thus about 1.6 hp/lb.

Much is made of the German replacement of strategic metals in their turbojet engines as a virtuoso technical accomplishment,[194] but efforts to reduce the strategic metal content of piston aero-engines were already standard in the first years of the war. Aero-

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[190] DM FA001/0827, 15.9.44, Memo by EHAG's Technical Directors, Vollmacht für P1073 (production programme for the He 162)

[191] Speer, *Inside the Third Reich*, 549.

[192] Schabel, *Illusion der Wunderwaffen*, 251.

[193] Tooze, *Wages of Destruction*; The RLM's policy shifted from emphasising quality, as favoured by Göring, towards increasingly emphasising the production of a large number of aircraft. (Overy, 1984, 164-204)

[194] For example: Constant, *Origins of the Turbojet Revolution*, 211.

engine production had used about 130 tonnes of nickel a month at the start of 1940 as compared to only around 50 tonnes a month in 1942 – a reduction of almost two-thirds despite an increase in overall engine production over the same period.[195] This was generally not without cost to performance; the replacement of metals that could withstand high temperatures considerably shortened the service life and performance of Germany's turbojet engines, for example.[196]

Part of the reason for the literature's fixation on the reduction of metals in the Jumo engine is because the strategic metals content of the production version was significantly less than in the firm's prototypes and pre-production versions. The first production version, the 004B-0, was about 100 kg lighter than the pre-production version, 004A, and used less nickel and chrome; later production versions had even less.[197] This progression was however, planned from the start. The first Jumo engine was intentionally designed without thought for weight or metal content so that the company could begin testing as soon as possible.[198] The commonly noted reduction in strategic metals, while significant, was a consequence of the way that Jumo chose to develop its engine (quickly), rather than the result of a dramatic change in the country's strategic metals position during 1943-1944. Yet the crucial point made here is not even broached in the literature – the move to turbojets itself saved metal.

In addition to the material advantages of building turbojet engines, the new engines took much less labour time to produce than piston engines. The Jumo 213, Daimler-Benz 603, and BMW 801 piston engines all took approximately 3,000 man-hours to build.[199] In Britain, for comparison, Ford's carefully planned and highly specialised production lines in Manchester allowed the company to reduce the production time required for a Merlin engine

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[195] BA MA RL3/51, 20.5.43, Report by Milch

[196] Constant, *Origins of the Turbojet Revolution*, 208-211.

[197] BA MA RL3/51, 6.42, Jumo Report, Verminderung des Sparstoffgehalts beim Sondertriebwerk 109004 Jumo

[198] Franz, *From Jets to Tanks*, 23.

[199] BA MA N653/104, Mannheim study

from 10,000 hours to 2,727 hours in three years.[200] By the end of the war, the Jumo 004-B-1 (the main production version) required a mere 700 man-hours to build if production was well organised (down from about 980 in May 1943).[201] The RLM required that BMW bring their turbojet production time to 500 hours. This was not an insanely crazy demand, as it would have been for a piston engine, although the BMW engine required closer to 1,000 man-hours to make in practice.[202] The firm reduced its engine construction time largely through the substitution of sheet metal parts for parts that required more time for machining or casting, including its air-cooled turbine blades, which were ultimately folded out of sheet metal.[203] Even at 1,000 man-hours, this production time still represented an important savings over piston engine production that was relatively easy to achieve. In Britain, the Welland took many times longer to produce than the production-optimised, if less reliable, Jumo 004, but only a small number was produced.[204]

The dramatic loss of oil production in Germany during the last years of the war also made turbojets a particularly advantageous type of aero-engine. The Allied bombing campaign against Germany's synthetic oil industry targeted the hydrogenation plants where the country's aviation fuel was produced. Unlike piston engines, turbojet engines could run on less refined and more plentiful diesel oil, a fact that may have influenced Speer's decision in early 1944 not to spend resources on expanding the country's reduced hydrogenation

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[200] 'Packard vs RR,' accessed on 17 January 2011, http://www.ww2aircraft.net/forum/aviation/merlins-packard-vs-rr-2013-8.html; The long production time was due in part to the preference for skilled labour and general purpose machine tools in the German aero-engine industry. The introduction of special purpose machinery at BMW's Augsburg plant in 1944 'cut production costs by half, raw materials used by 49 percent and reduced worktime per engine from 3,150 hours to 1,250 hours.' (Overy, *Goering: The 'Iron Man'*, 187.) There was clearly much savings to be achieved by rationalising piston engine production, yet jet engines still offered production and performance advantages. Rationalisation of piston engine production may have freed up personnel for jet engine production.

[201] Schlaifer and Heron, *Development of Aircraft Engines*, 434; IWM FD 5399/45

[202] BA MA N653/104, Mannheim study; Schlaifer and Heron, *Development of Aircraft Engines*, 416; Kay reported 600 hours. (Kay, *German Jet Engine and Gas Turbine Development*, 78.)

[203] Kay, *German Jet Engine and Gas Turbine Development*, 106; Schlaifer and Heron, *Development of Aircraft Engines*, 416.

[204] Schlaifer and Heron, *Development of Aircraft Engines*, 434.

capacity.[205] The Jumo 004 was designed to burn diesel oil from the beginning, at first for safety reasons, and the BMW 003 was converted to diesel fuel in 1943 without significant problems.[206]

In addition to all these advantages, the turbojet could be adapted to Germany's increasingly dispersed production system, which relied on the extensive use of sub-contracting.[207] The 004's 'unique modular design' allowed various engine components ('compressor/inlet housing assembly, the turbine/combustor assembly, the exhaust nozzle') to be manufactured in different factories, far from the place where assembly and testing took place.[208] The production of both Jumo and BMW engines was simplified, sacrificing performance, so that production could be carried out on standard machines by unreliable and unskilled labour.[209]

That jet engines, unlike piston engines, could be made virtually out of sheet metal should be understood not as resulting in a distortion of the aero-engine type but rather as a reason for the emphasis on their production in a war economy stretched to the breaking point. The turbojet's suitability to the ruthless Nazi production regime is illustrated in the fact that it took the Nordwerk factory only six months during the last year of a hugely destructive war to achieve a numerical monthly output of Jumo 004 engines that was

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[205] USSBS, 1945, Overall Report, European War, 3944

[206] Schlaifer and Heron, *Development of Aircraft Engines*, 416 and 421.

[207] Franz, *From Jets to Tanks*, 29; Kay, *German Jet Engine and Gas Turbine Development.*

[208] Franz, *From Jets to Tanks*, 29; Jumo's Strasbourg plant, for example, was arranged to construct engines from sub-contracted parts and send them to Muldenstein for testing. (NA AVIA 15/2121, 27.1.45, Adderley)

[209] NA AVIA 15/2121, 27.7.45, 260, Interrogation of Max Eichler; The Volksjäger, put into production in January 1945, was similarly designed to fit the existing production realities in Germany. (Daniel Uziel, 'Der Volksjäger: Rationalisierung Und Rationalität Von Deutschlands Letztem Jagdflugzeug Im Zweiten Weltkrieg', in *Rüstung, Kriegswirtschaft Und Zwangsarbeit Im "Dritten Reich"*, A. Heusler, M. Spoerer, and H. Trischler ed. (MTU Aero Engines, BMW Group; Oldenbourg Wissenschaftsverlag, 2010), 63-82.) Many, including Speer, saw in the He 162 a demonstration of what true National Socialist coordination and effort could accomplish. (Alec Cairncross, *Planning in Wartime: Aircraft Production in Britain, Germany and the USA* (Oxford: Macmillan in association with St Anthony's College, 1991), 142.); DM FA001/0827, 29.9.44, Francke) Uziel's work is notable for its interest in aviation production methods. (See also Daniel Uziel, 'Between Industrial Revolution and Slavery. Mass Production in the German Aviation Industry in World War II', *History and Technology* 22, no. 3 (2006): 277-300.)

equivalent to the exceptional monthly output of Merlin engines achieved by Ford in Britain after two years of production.[210]

The rising jet engine production figures achieved at the very end of the war, when production across Germany was faltering, were evidence not of German technical superiority but of the turbojet engine's ability to be mass-produced under conditions of extreme scarcity using brutal labour practices.[211] Rather than faltering as the war drew to a close, more than half of German turbojet engines were produced during the first quarter of 1945. A total of about 6,010 Jumo 004 engines were produced before the end of the war, while BMW assembled approximately 559 production 003 engines. Parts for many more BMW engines were manufactured but never used.[212]

Conclusion

Taking the turbojet engine production story seriously not only reveals important aspects of each country's war effort, it completely transforms the standard story of the turbojet. The story that emerged in this chapter was not one of all parties racing headlong to build turbojet engines, as is generally portrayed in the literature, which treats production numbers as the best measure of success. During the extremity of war, turbojet engines took on changing roles according to each country's military goals, politics, material situation, expertise and expectations about the post-war order. It is impossible to usefully compare them using a single measure.

The British Air Ministry's decision in 1940 to produce Power Jets' engine was an extraordinarily ambitious commitment that tied up valuable British production capacity for more than two years. When the W.2B proved more problematic to produce than expected, the necessity of justifying the resources that had been reserved for turbojet production drove

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[210] Hornby, *Factories and Plant*, 258.

[211] Irving, *Mare's Nest*, 246.

[212] IWM FD 5400/45, Jumo Report, TL-Geräte 004 B-1/4 Neubau und Reperatur suggests that many thousands more engine's worth of parts may have been completed during the war; NA AVIA 15/2121, 27.7.45, 260, Interrogation of Max Eichler

later production and development decisions that reflected the Ministry's continued interest in the engines. Different British engine designs came into favour at different points as their relative performance and reliability changed, and the early British goal of turbojet production was almost given up. The first British jets were deployed during the war, but they were hardly necessary for combat. Britain's modest wartime jet engine production was geared largely toward the post-war market, and the entry of Rolls-Royce and de Havilland into turbojet production during the war helped the firms become post-war leaders.

The United States, second to decide to produce jet fighters because of the quick route to production seemingly offered by the W.2B design, used the war to build its indigenous turbojet development and production capacity. Yet despite its original optimistic hopes, the United States produced few engines during the war and deployed no jet aircraft. Giving up the jet as a weapon of the Second World War, like Britain, the United States chose to establish a turbojet engine industry premised on the production and constant improvement of rapidly obsolete military engines. It did not produce many engines during the war. However profligate (Britain's production programme, in contrast, became more circumspect after building Barnoldswick), this proved to be a flexible way to combine development with the ability to move improved designs into production as fast as possible. The 'concurrency' of improvement, manufacture and use continued to characterise military jet engine development and production and produce challenging management problems at GE during the cold war.[213] By 1945, the United States was poised for accelerated production of GE's I-40 engine, and by 1950 the American industry had come to seriously challenge Britain's.

In Germany, turbojet engine development work was carried on under government auspices from 1938, but the decision to produce the Jumo 004 and BMW 003 engines as weapons did not come until 1943, well after the flight in 1939 of the He 178, Germany's first

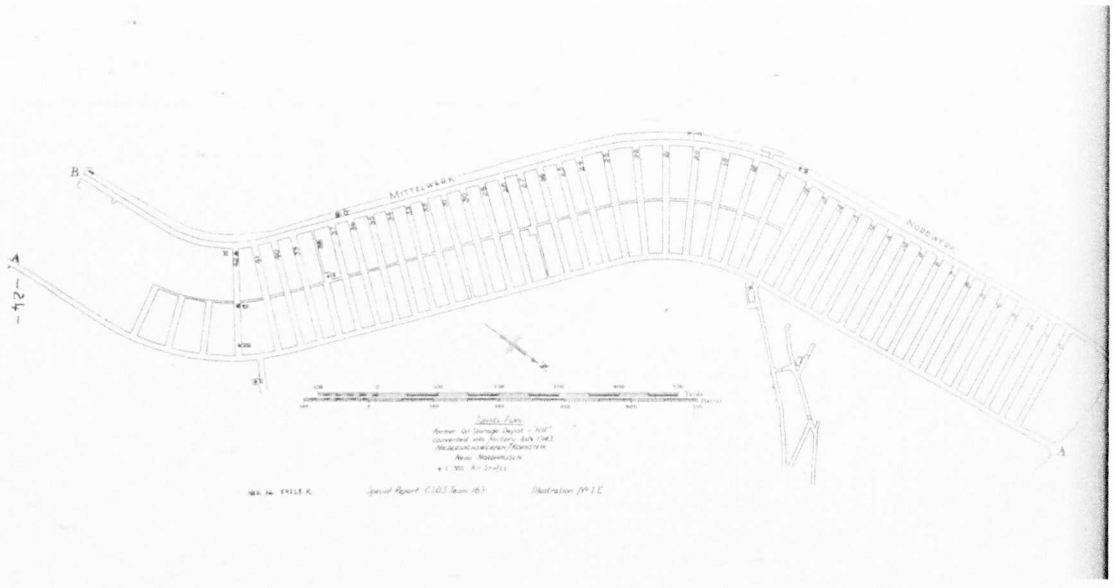
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[213] Scranton, 'Turbulence and Redesign'.

experimental turbojet aircraft. By virtue of Schelp's existing development plan, the RLM was able to consider turbojet production in 1943, but it was the coercion and focus brought to jet engine production by the Speer Ministry and the Jägerstab that resulted in the production of a huge number of poor-quality, virtually obsolete first generation jet engines for the Luftwaffe in the last year of the war.

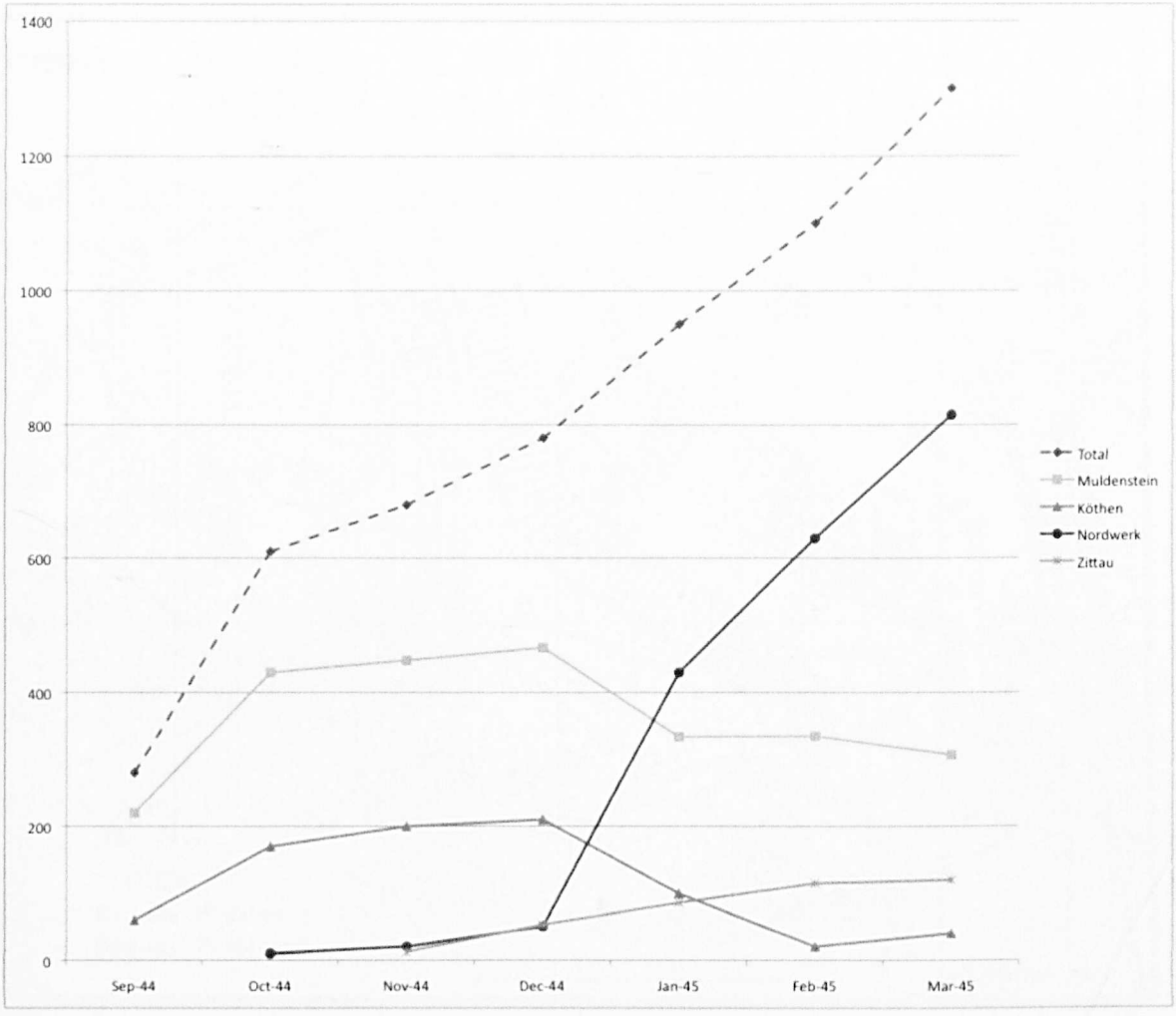
In the context of Nazi Germany's economy of scarcity, the demand for increased turbojet production was not just a matter of building an extra factory or shifting investment between weapons. Rather, it implied engineering and production choices that the Allies neither had to make nor would have made. The extreme nature of Nazi jet engine production repudiates the flimsy universality of a sequential model that allows production figures to be used to compare turbojet programmes. The German programme ultimately sacrificed future development, performance, quality, and safety for production. By the last six months of the war, when German turbojet engine production rose dramatically, the need for production had become as fundamental to the Nazi state as the barbaric cruelty used to achieve it, and the jet engine emerged as an aero-engine as important for its production and material advantages over piston-engines as for any qualitative advantage over enemy aircraft that it could provide.

Figure 2.1. Layout of the Mittelwerk and Nordwerk factories



Source: CIOS XXXII-17.

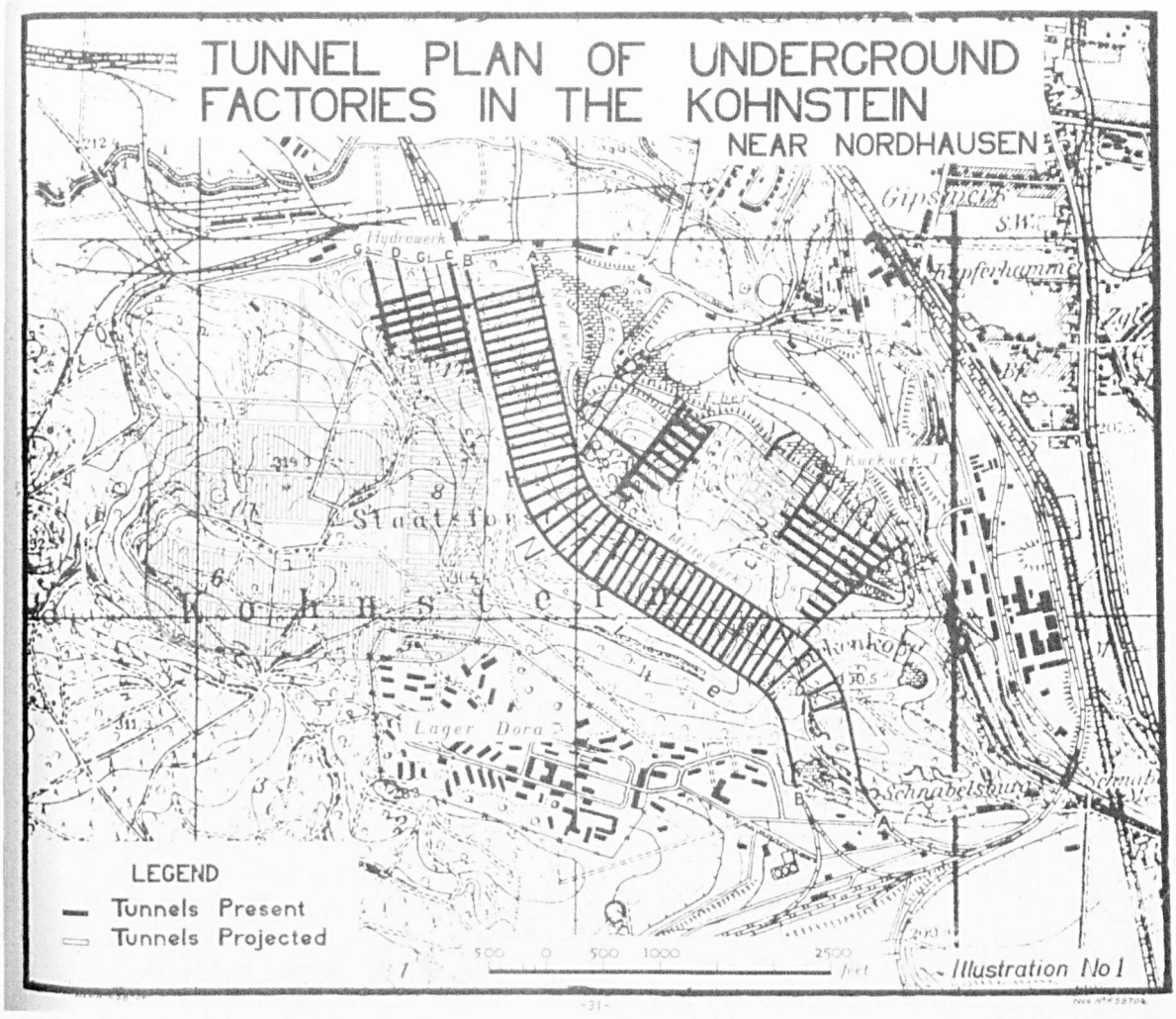
Figure 2.2. Jumo 004 jet engine production by month and factory, 1944-1945



Data is shown for the main production factories. Production prior to September 1944 is not included because detailed monthly information is not available for that period.

Source: IWM FD 5400/45, Jumo Report, TL-Geräte 004 B-1/4 Neubau und Reperatur.

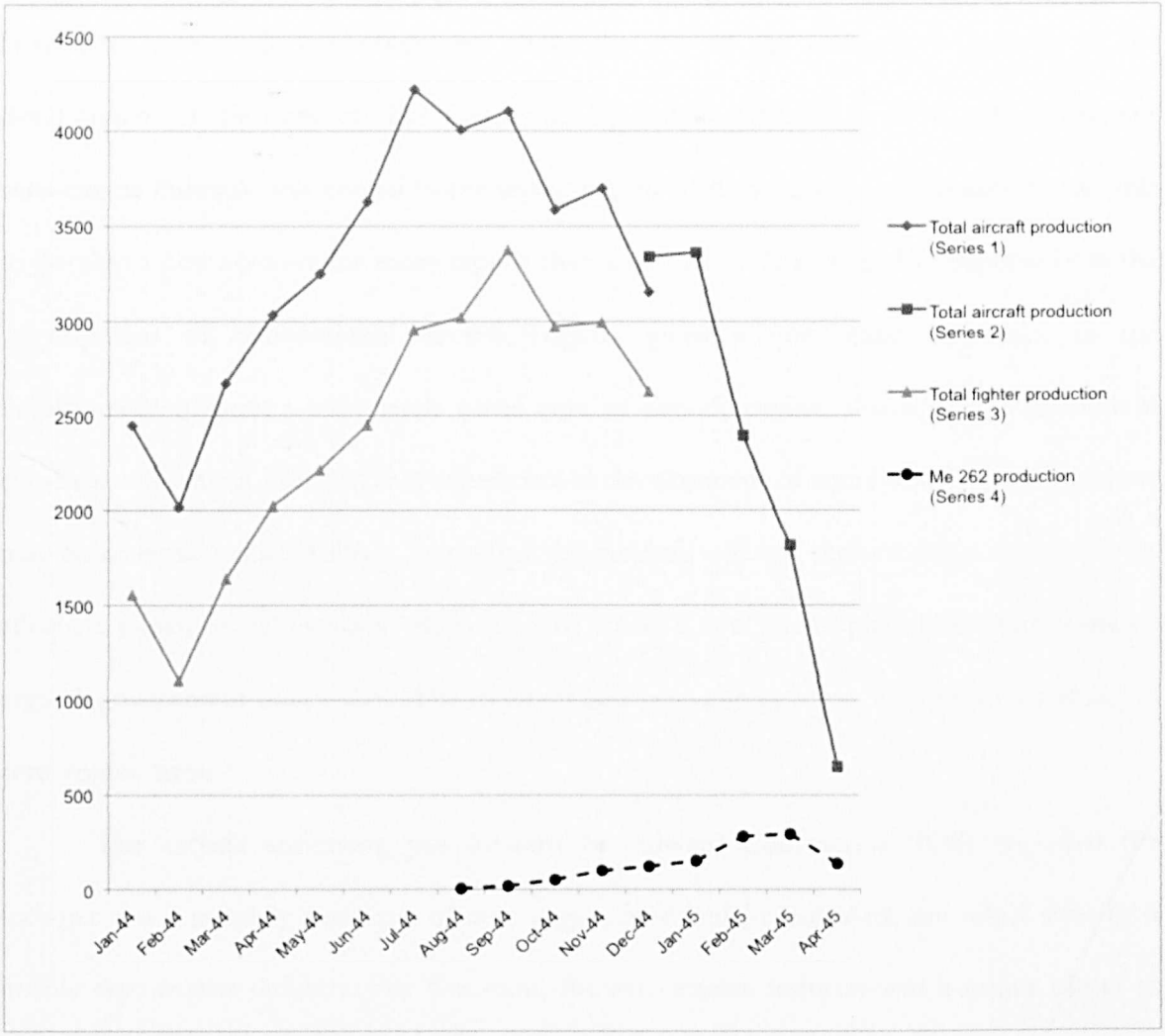
Figure 2.3. Underground factories planned in the Kohnstein Mountain near Nordhausen



Completed (black) and planned (grey) tunnel complexes are indicated. North is roughly vertical. The completed factory running diagonally through the middle of the image is the Nordwerk/Mittelwerk tunnel complex. The Dora concentration camp was aboveground, to the southwest of the Mittelwerk factory.

Source: CIOS XXXII-17.

Figure 2.4. Production of Me 262 airframes compared to production of other German airframes, 1944-1945



The peak of production of Me 262 airframes appears in early 1945, well after the peak in total German aircraft production.

The data series shown here are taken from different original sources reproduced by Vadja and Dancey. Series 1 and 3 are taken from their Table 8-H; Series 2 from Table 8-L; and Series 4 from Tables 8-J and 8-L.

Source: Ferenc A. Vajda and Peter Dancey, *German Aircraft Industry and Production, 1933-1945* (Shrewsbury: Airlife, 1998), 138-143.

Chapter 3
The Aero-Engine Industry and the Turbojet

Historians have made two arguments about the role of the aero-engine industry in the development of the turbojet. The first, made by Robert Schlaifer in 1950, argued that the aero-engine industry was crucial to the development of turbojet engines because it was able to develop a new aero-engine more rapidly than any other.[1] He argued that 'experience in the development of conventional aircraft engines gives a very great advantage in the development of even a completely novel type of aircraft engine, although it is possible in some cases [General Electric] that experience in development of some other type of machine may be of equal value. Brilliant theoretical engineering will not replace either experience or adequate experimental facilities.' Regardless of where a new power plant idea came from, he argued, government policy should be to direct new aero-engine ideas, wherever they arose, to aero-engine firms.[2]

The second argument, put forward by Edward Constant in 1980, was that the turbojet was a radically new type of aero-engine invented by outsiders and taken over by a hostile aero-engine industry. For Constant, the aero-engine industry was a minor player in the 'turbojet revolution', taking up a 'newly established tradition' rather than helping to create it, and his account treated the industry briefly and with some serious omissions – it did not mention Rolls-Royce's involvement with the centrifugal turbojet, for example.[3]

Because the aero-engine industry made its most important contribution to the turbojet through developing turbojet engines, two distinct points are entwined: one is the importance of development to making new machines and the other is the role of the aero-

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[1] Schlaifer and Heron, *Development of Aircraft Engines*, 92-96 and 493. Schlaifer suggested that industry was optimized for the rapid development of aero-engines rather than the search for radical, new ideas. He did not argue that industry had failed by not being first to build a gas turbine engine, an implication of inventor-centric accounts. Cf. Hughes' pro-inventor anti-institution position discussed in Chapter 1.

[2] Schlaifer and Heron, *Development of Aircraft Engines*, 97-98.

[3] Constant, *Origins of the Turbojet Revolution*, Chapter 8.

engine industry. Development has often been overlooked by historians. Constant did not pay much attention to the aero-engine industry because he did not see development as an essential activity in the history of the turbojet.[4] Michael Pavelec's recent account focussed primarily on production and deployment during the Second World War, yet he picked up on Constant's argument, and although he discussed the stories of Whittle and von Ohain, his recent work entirely ignored turbojet development.[5]

When development *is* mentioned in the accounts of the British turbojet by aviation writers like Kay and Gunston, for example, the most extensive if not the only detailed story of any company's turbojet engine bench tests, rebuilds and catastrophic breakdowns is a version of Whittle's account of the work of Power Jets – the story of an outsider and a company that never made a commercially viable aero-engine.[6] This is largely because in his memoir, Whittle offered the most extensive account of development of any actor. Other participants, like Hayne Constant, Eric Moult and David Smith did publish articles that offered accounts of the trials and changes in engine designs at their respective institutions, but these appeared in the journals of technical societies and in the technical press and, as will be discussed in Chapter 5, made little impression on the public or historical understanding.[7] In the German literature, the details of turbojet development in different firms are treated more even handedly, if in significantly less detail than in Whittle's account.[8]

Despite the way that it has been undervalued, development reveals a pivotal aspect of the turbojet story: the continuities between piston engine and turbojet engine practice in

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[4] Constant did, however, offer an interesting, if partial, account of piston engine development between 1915 and 1945. (Constant, *Origins of the Turbojet Revolution*, 118-129.)

[5] Pavelec, *Jet Race.*

[6] Kay, *Turbojet History and Development*, 22-26; Gunston, *World Encyclopaedia of Aero Engines*, 126-128; Whittle's story was reproduced in Golley, Whittle and Gunston, *Whittle, the True Story* and Pavelec, *Jet Race*, Chapter 2.

[7] A review of current practice was given through a series of articles on gas turbine aero-engines in the War Emergency Issue 12 of the *Proceedings of the Institution of Mechanical Engineers* and in public lectures. See Chapter 1.

[8] Von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke*; Wagner privileged some firms, including particularly Heinkel and Messerschmitt. (Wagner and Cox, *First Jet Aircraft.*)

both design elements and personnel. This highlights the crucial contribution that the aero-engine industry made to the turbojet. Schlaifer was unusual in the degree to which he acknowledged obvious connections between piston engine and turbojet practice across firms. He noted, for example, that all of the key parts of the turbojet engine existed in some form before the war, and he emphasised the importance of aero-engine experience generally to developing new types of aero-engine, although he did not pursue the consequences of either claim in detail.[9] Although he dismissed them as incidental to the turbojet story and as less important than the work of his turbojet revolutionaries, even Constant observed generally the existence of continuities in standards, resources and practice between the engine types. He was right to consider precursors to gas turbine components, although his treatment hardly touched on the importance of these continuities.[10]

This chapter challenges Constant's argument for the revolutionary novelty of the turbojet and goes beyond Schlaifer's arguments for the importance of the aero-engine industry to give a much more detailed argument for the continuities that shaped turbojet engine development. With the important exception of combustion, the turbojet was designed to a significant extent using elements that were already in use in piston engines.[11] Turbo-superchargers used centrifugal compressors and turbines;[12] the importance of centrifugal compressors in superchargers, furthermore, meant that centrifugal gas turbines were easier to develop than axial ones. Schlaifer argued that General Electric's expertise in supercharger

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[9] Schlaifer and Heron, *Development of Aircraft Engines*, 92-96 and 493.

[10] Constant, *Origins of the Turbojet Revolution*, 179.

[11] Constant, *Origins of the Turbojet Revolution*, Chapter 3.

[12] Superchargers and turbo-superchargers were, according to Constant in his section on piston engines, 'a unique repository of technical proficiency for the turbojet revolution', although he never returned to this in his account of turbojet. (Constant, *Origins of the Turbojet Revolution*, 125.)

development and production was the reason that the firm was the only company outside the aero-engine industry to successfully become an aero-engine manufacturer during the war.[13]

Within the narrative of any single engine or company, the continuities between piston engine and turbojet practice are often obvious, and many authors have mentioned them, but none of the existing histories of the jet engine have assembled the evidence of the extent of these continuities and acknowledged the importance of the fact that they were general across all of the major aero-engine firms in Britain and Germany. Existing accounts of the turbojet offer only a fraction of this story, yet the important technical continuities between piston and turbojet engines explains important features of development. It explains for example, the fact that, with the addition of General Electric, aero-engine companies were the most successful at developing these new engines. It also sheds light on the emergence of Rolls-Royce as a leader in the turbojet field after the war. This result is particularly striking because almost all of the aero-engine firms and engines involved have been studied to some extent, as will be detailed in what follows. Yet with the possible exception of Schlaifer, no treatments have tried to seriously tell the story of development at the level of the firm.

This chapter will illustrate the important continuities between piston engine and turbojet design and development using details of the firm's expertise, engine designs and resources, which have been gained from a range of sources. The details of the layout of most of the early turbojet engines and the many of the details of the experience of their manufacturers can be found in existing works on the turbojet.[14] Where details were missing in the secondary literature, I first consulted the papers of participants published in the

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[13] Schlaifer and Heron, *Development of Aircraft Engines*, 97; General Electric is an important case of a turbo-supercharger manufacturer outside the aero-engine industry. It is considered with the steam turbine industry below.

[14] In Germany, precise technical details of turbojet design and alterations during development can be found in von Gersdorff and Grassmann's *Flugmotoren und Strahltriebwerke* or in the more recent book in English by the aviation writer Anthony Kay, *German Jet Engine and Gas Turbine Development.* Wagner's account in Wagner and Cox, *First Jet Aircraft* brought attention to numerous important continuities. In Britain, the closest equivalents are the aviation writer Bill Gunston's *World Encylopedia of Aero-Engines* and Kay's recent attempt to compile existing non-archival information on British turbojet work: *Turbojet History and Development.*

proceedings of technical institutions after the war, which included both additional details of company's engine designs and often explained how they came about.[15] Where available, new archival material is adduced to explain particularly the events and concerns that accompanied each aero-engine firm's increasing commitment to turbojet engines, topics that the accounts listed above pay little attention to. The picture of continuity that emerges offers a striking testament to the skill of the aero-engine industry.

We know less about the British industry than its German counterpart because historians interested in the subject must explore British archives to retrieve the information that interrogators, including members of the British aero-engine industry, gathered first hand from German engineers after the war. The nature of the Allied exploitation of the German aero-engine industry meant that a particular type of information was preferentially collected, however – information that could have been valuable to the Allied aero-engine industries. Where wartime intelligence and other sources do not offer enough detail of development activity, the industrial story of the early turbojet is difficult to recover because of the lack of and inaccessibility of many relevant archives and statistics. Industrial archives vary hugely and often suffer by the irrelevance of historical work to a firm's day-to-day business. The industrial archives of German aero-engine firms furthermore were frequently destroyed or lost during the war, although the remaining Daimler-Benz archive yielded some interesting information. In Britain, the unevenness of industrial archives is compounded by the fact that all of the British aero-engine makers were merged into Rolls-Royce during the 1960s, although the firm's Heritage Trust retains branches devoted to the earlier aero-engine companies. The Rolls-Royce archive has a wealth of information, which is however only slowly being organised and exploited.

The first section of this chapter discusses how Rolls-Royce ended the Second World War as unquestionably the most important turbojet company in the world – a surprisingly

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[15] See footnote 8 above.

under-researched topic. The second and third sections use a detailed record of the technical continuities between piston and turbojet engines to explain how all of the major British and German aero-engine companies began developing gas turbine aero-engines by the end of the war. The last section of this chapter examines the role of the significant number of steam turbine companies that participated at different points in the development of turbojet aero-engines. Steam turbine makers are an interesting counter case to aero-engine makers. The gas turbine was and is seen as centred on the turbine, and thus it is accepted that the steam turbine industry should have played an important part in its development. Yet with the exception of Metropolitan-Vickers in Britain and General Electric and Westinghouse in the United States, no steam turbine firm developed a complete gas turbine aero-engine during the war, whereas by the end of the war, all of the major European aero-engine manufacturers had designed a gas turbine engine of some sort.[16]

Rolls-Royce and the turbojet

The history of Rolls-Royce's earliest involvement with turbojet engines is almost entirely absent from the literature.[17] It has been hidden by the Merlin piston engine's dominance in Rolls-Royce's wartime history and by Whittle's dominance in the literature on the turbojet, in which Rolls-Royce appears, if at all, only as the saviour of the Power Jets W.2B engine.[18] Although it gave few details of the firm's turbojets or how these were connected to its piston engine work, the Official British history did acknowledge that Rolls-Royce was an important addition to the national programme as well as 'the only firm who on their own initiative had

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[16] The large turbojet makers were joined by a number of companies that emerged after the war, which developed and produced only small gas turbine aero-engines. (On the North American firms see Richard Leyes and William A. Fleming, *The History of North American Small Gas Turbine Aircraft Engines* (Reston, VA: American Institute of Aeronautics and Astronautics, 1999); on German firms see von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke.*)

[17] Important aspects of the firm's earliest work on gas turbines can be found in *Flight's* account of the Derwent. (*Flight,* 25 October 1945.)

[18] The most recent addition to the literature on Rolls-Royce is unsurprisingly entitled *Hives & the Merlin.* (Ian Lloyd and Peter Pugh, *Hives and the Merlin* (Cambridge: Icon Books, 2004)); Pavelec, *Jet Race*, 118-119.

taken active measures to promote gas turbine development'.[19] Even this crucial fact is not recognised in the few historical accounts of the firm, however. The earliest, three-volume history of Rolls-Royce published in the late 1970s, which covered the period from the firm's founding until 1945, did point to the importance of Merlin development in shaping Rolls-Royce's turbojet work, but its brief account of the firm's turbojet work was marred by inaccuracy.[20] In Peter Pugh's more recent two-volume history, the chapters on the early turbojet are mostly a retelling of the Whittle story.[21] When referred to at all, A. A. Griffith's contra-rotating engine design and Rolls-Royce's early collaboration with Power Jets on the centrifugal WR.1 are both portrayed as failures.[22] This story need to be challenged at many levels to explain just why it was that Rolls-Royce had become the world's most important designer of turbojets by 1945.

By the time that Rolls-Royce took over the production of the W.2B in 1943, the firm had already been involved in turbojet engine development for two and a half years using its own money. It switched quickly from piston to turbojet engines during the war. In 1939, the company was developing five piston engines - the Merlin, Griffon, Peregrin, Exe, Vulture and (two-stroke) Crecy - and had begun the studies that would lead to Griffith's C.R.1 turbojet. All but the Merlin and Griffon became 'casualties of priorities' during the war.[23] At the end of 1945, Rolls-Royce was developing no less than six turbojet engines - the Derwent, Clyde, Nene, Dart, CR.2 and AJ/65 - and only two large piston engines, the Griffon and the 3,500 horsepower Eagle – its last piston engine. During the Second World War, Rolls-Royce

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[19] Postan, Hay and Scott, *Design and Development of Weapons*, 201.

[20] Ian Lloyd, *Rolls-Royce: The Merlin at War* (London: Macmillan, 1978), 131-133.

[21] Peter Pugh, *The Magic of a Name: The Rolls-Royce Story: The First 40 Years* (Cambridge: Icon, 2000), 2000, 268-280. Pugh reduces the firm's wartime turbojet story to the take-over of Barnoldswick. (Peter Pugh, *The Magic of a Name: The Rolls-Royce Story, Part II: The Power Behind the Jets, 1945-1987* (Cambridge: Icon, 2001), 1-13.)

[22] Constant, *Origins of the Turbojet Revolution*, 214; Schlaifer and Heron, *Development of Aircraft Engines*, 355 and 364; Neither is in Kay's recent account of British jet engines. (Kay, *Turbojet History and Development.*)

[23] Pugh, *Magic of a Name: The First 40 Years*, 263-267.

sought to dominate the turbojet field, and the firm triumphed because it had the resources to support several development and design efforts, because it learned from each such effort that it undertook, and because it successfully used its piston engine expertise to develop the new engine type.

Rolls-Royce's first internal combustion turbine

Rolls-Royce's axial turbojet development programme was conceived in 1939 as a long-term programme and staffed with only a few dedicated individuals. In late 1941, the firm's general manager, Ernest Hives, added to this a second strand: the development of a simpler centrifugal engine in collaboration with Power Jets. These two development strands, one based at the firm's main works in Derby and the other at the turbojet factory at Barnoldswick, had very different histories.

In 1939, Hives recruited A.A. Griffith from the Royal Aircraft Establishment (RAE) to begin work on gas turbine aero-engines at Rolls-Royce. He instructed that Griffith should be free, as a 'Senior Research Engineer' at the firm,[24] to continue his theoretical studies of different internal combustion turbine (ICT) and axial compressor layouts.[25] His ongoing support for Griffith's work, which he frequently inquired about, demonstrated Hives' early interest in the new engine type and marked a departure in Rolls-Royce policy; Griffith's concentration on 'advanced ideas' unconnected to any engine under development was unique within the firm.'[26] This was also reflected in Hives' willingness to support the construction and test of Griffith's first scheme, known as the CR.1, which continued for many years during the war. Griffith's design was even shown to the King and Queen when they visited Derby on 8 August 1940.[27]

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[24] He began work on 1 June 1936. Geoff Wilde, 'Dr Griffith's CR.1.' *Archive* 12, no. 1 (1994): 85.

[25] Eyre, *50 Years with Rolls-Royce*, 72; Rubbra, 1964; Lloyd, 1978.

[26] Eyre, *50 Years with Rolls-Royce*, 72-73.

[27] Eyre, *50 Years with Rolls-Royce*, 74-75.

Griffith worked at Duffield Bank House, Rolls-Royce's guest house, to which the firm's non-production staff had been evacuated when the war broke out. In late 1939, he was assigned a personal assistant and draughtsman, Donald Eyre, who was to translate Griffith's elaborate schemes into practical designs for the firm's experimental shop. Eyre, who had worked previously for Henry Royce, a man supremely concerned with detailed design, remembered that Griffith, in contrast, left the practical details of his schemes to Eyre 'with apparent equanimity.'[28] Indeed, Griffith was uninterested in the execution of his ideas and proceeded to elaborate complex schemes in the expectation that they could be realised by Rolls-Royce's famed engineering staff – a faith that would prove to be overly sanguine.

Unlike the design of a new piston engine, where a fund of previous design work could be used for guidance and inspiration, the novelty of the ICT meant that Eyre had to develop the basic design scheme for Griffith's first axial unit from scratch.[29] In early 1940, Eyre's designs for the CR.1 were released to Derby's Experimental Shop, then headed by H.P. Smith, which was busy with piston engine development. Before the construction of the engine was started, four rigs were built, mostly from sheet metal, to test difficult and unprecedented features of the engine and to provide data for design work.[30] Testing on the rigs began in September 1940.[31]

The scheme for the contra-rotating, contra-flow CR.1 engine, the high-pressure section of a larger conceptual engine, was extremely mechanically complex. In order to avoid stalling, its fourteen rotors moved independently of one another, every other one rotating counter to the rotors before and after it (hence contra-rotating). Each rotor carried a compressor stage and, outside and concentric to that, a set of turbine blades. Air flowed into

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[28] Eyre, *50 Years with Rolls-Royce*, 72-73.

[29] Eyre, *50 Years with Rolls-Royce*, 72; In this, Eyre was a great asset; Stanley Hooker maintained that Griffith's complicated work had received so much support because the 'clarity and sophistication' of Eyre's drawings 'sold Griffith's ideas just like Johnnie Walker sold whisky, and with the same soporiphic [sic] effect.' (Hooker, *Not Much of an Engineer*, 101.)

[30] Wilde, 'Dr Griffith's CR.1', 87.

[31] RRL, 20.12.44, Letter Bristol to EJW

the back of the unit, forward through the fourteen axial compressor stages, reversed direction in an annular combustion chamber and then flowed back through the axial turbine stages (thus the engine was 'contra-flow'), whence it left the engine.[32]

Work on Griffith's ideas naturally overlapped with piston engine supercharger work at the firm. Hives assigned a key figure in the development of the Merlin supercharger, Stanley Hooker, to work closely with Griffith when the latter arrived at Rolls-Royce.[33] Hooker in turn assigned Geoff Wilde to supervise the construction and testing of the CR.1 rigs on the pre-war supercharger test rig at Nightingale Road, Derby, which was already in use testing the firm's centrifugal superchargers.[34]

The Nightingale Road test rig became an increasingly scarce commodity as work on the Merlin supercharger increased. Competition between the two development projects became so keen that at one point, Wilde resorted to physically moving the ICT equipment into the courtyard at night so that the supercharger team could use the test rig.[35] In 1941, the urgent need to increase the performance of the Merlin-engined Spitfire over the Bf 109, meant that superchargers took precedence. ICT testing was moved to a hangar at nearby Sinfin, where a new rig was built using a Vulture centrifugal supercharger powered by a Merlin piston engine to produce a stream of compressed air for turbojet testing.[36] Wilde handed over work on the CR.1 work to a new team.

An ICT Section was formed at Derby to take over development of the CR.1.[37] Its first two members, Robin R. Jamison and Douglas Reynolds, were transferred from the cancelled Exe sleeve-valve, piston engine. In June 1941, the ICT section included only four

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[32] Hawthorne, Cohen and Howell, 'Hayne Constant, 1904-1968,' 176-177.

[33] RR HC, 14.6.39, Letter A.G. Elliott to Hives, Re Dr Griffith's department.

[34] Hooker, *Not Much of an Engineer*, 29-30 and 35.

[35] Wilde, 'Dr Griffith's CR.1.'

[36] Donald L. Mordell, 'Better Than a PhD,' *Archive*, 9-11.

[37] Wilde, 'Dr Griffith's CR.1.'

men (as compared to more than 20,000 employed by Rolls-Royce at the time[38]).[39] Under Jamison's leadership it reached about nineteen men by 1944, but by then Rolls-Royce had several design teams working on turbojet engines and the centre-of-gravity of the firm's turbojet work had moved largely away from Derby.[40]

Although Rolls-Royce had funded the CR.1 as a private venture, MAP had been apprised of its progress. On 25 July 1941, Rolls-Royce approached the Ministry for two contracts for the supply and testing of four new contra-rotating, contra-flow turbojet engines. The firm proposed to build two each of two types of turbojet engines. The first type had twenty-two compressor stages and would aim to initially produce 1,200 pounds of thrust. The second was a turbojet/turboprop engine with an unspecified number of stages that would aim to produce 5,000 pounds of thrust. To the latter turbojet engine, the firm proposed adding an additional contra-flow, contra-rotating unit behind the turbo-compressor of the first engine, in which each turbine stage would power both a compressor stage and a contra-rotating airscrew.[41]

Progress on ICT development at Power Jets led Rolls-Royce to emphasise its proposed turbojet unit over the more complicated turbojet/turboprop, which it viewed as a promising post-war engine. The firm 'confidently' presented its new contra-rotating axial turbojet engine as a 'replacement unit' to the Power Jets engine, which would ultimately offer greater thrust, less weight per pound and lower fuel consumption.[42] The turbojet/turboprop engine, meanwhile, was expected to have a much higher power to weight ratio than the contemporary Bristol Hercules XI piston engine. Rolls-Royce estimated a cost of £8,000 per turbojet engine and £21,000 for each turbojet/turboprop unit. Despite the novel aspects of the engine, Rolls-Royce saw it as an outgrowth of piston engine practice. Two

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[38] Extrapolated from Eyre's figures. (Eyre, *50 Years with Rolls-Royce*, 87.)

[39] Mordell, 'Better Than a PhD,' 9.

[40] Wilde, 'Dr Griffith's CR.1.'

[41] Both were contra-rotating, contra-flow engines.

[42] RR HC, 25.7.41, Letter Hives to MAP

representatives of Shorts Brothers, who visited Rolls-Royce on 7 August 1941, reported that '[i]n the view of its designers... the successive banks of contra-rotating airscrews are the natural sequel to the trend towards higher powers and twin contra-rotating airscrews.'[43]

MAP agreed to give Rolls-Royce contracts for the axial engines. In early September 1941, Rolls-Royce further requested that MAP pay for the cost of the development of the CR.1 to date, which the firm had borne, if the company were to release initial data on their work on the fourteen stage contra-flow turbojet in response to American requests.[44] Although MAP was displeased with the firm's request, it nevertheless issued a new contract including the fourteen-stage CR.1 in addition to the four more advanced contra-rotating turbojet engines that had already been approved.[45] (MAP's Director of Scientific Research, David Pye, hoped that providing a research contract, and thus Ministry oversight, for the CR.1 would help to accelerate the project by ensuring that the firm made use of all available research work.[46]) Patent rights on the information shared with the United States were to be covered by the earlier agreement reached for the Merlin 60, Hercules and Centaurus piston engines, in which the British government took responsibility for paying any claims made by British aero-engine firms with respect to contracts placed in the United States.[47]

The CR.1 was completed in September 1941, and its debut on the test stand was unimpressive. Because it was unable to run under its own power, the ICT section fed the engine with a stream of compressed air generated by the compressor of a Power Jets W.2B, which they had earlier been asked to test.[48] Undaunted, the firm continued to develop the

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[43] RR HC, 13.8.41, Report by Keith-Lucas (Shorts Brothers)

[44] RR HC, 21.8.41, Letter Roxbee Cox to Hives; AVIA 15/1201, 13.9.41, 15, Minute by Bulman

[45] NA AVIA 15/1201 13.9.41, 15, Minute by Bulman

[46] NA AVIA 15/1201, 30.10.42, 26, Minute Pye to Roxbee Cox

[47] NA AVIA 15/1201, 5.9.41, 12, Minute Bulman to Linnell; 13.9.41, 15, Minute Bulman; William Ashworth, *Contracts and Finance* (London: HMSO, 1953), 56.

[48] Mordell, 'Better Than a PhD,' 13; The compressor was powered by a 2,000 horsepower Vulture engine, with it rotational speed stepped up from 3,000 to 18,000 using two Merlin propeller reduction gears in reverse. The set up had made it possible to test the full performance of the Power Jets compressor for the first time (Hooker, *Not Much of an Engineer*, 68-69.)

engine until 1944. It finally ran under its own power only in early 1943, after its annular combustion chamber was replaced with four W.2B-type combustion chambers designed by Joseph Lucas.[49]

The Whittle-Rolls-Royce engine

While the ICT Section at Derby struggled to get the axial CR.1 running, Hives moved to broaden the firm's turbojet programme to include a centrifugal engine. Hooker, impressed by what he had seen on his first visit to Power Jets' factory at Lutterworth, brought Hives to see the experimental WU running in August 1940. Compared to the CR.1, the Power Jets WU was a vision of simplicity. The hand-built bench-unit, then sporting the multiple combustion chambers of its third reconstruction, produced about 800 pounds of thrust. Hooker calculated that the Merlin engine produced the equivalent of about 840 pounds of thrust when propelling a Spitfire at 300 mph. 'Compared to the sophisticated design and manufacture of Rolls-Royce, it looked a very crude and outlandish piece of apparatus', Hooker remembered, yet the two men from Rolls-Royce immediately recognised the development potential of the Power Jets scheme.[50] Hives volunteered the Derby Experimental Shop to produce parts for Power Jets, and Hooker was tasked with keeping an eye on the firm's work.[51]

Thus Rolls-Royce's involvement in gas turbine aero-engines began to grow. Because of Power Jets' success with the W.1, which flew in May 1941, Hives had become convinced that the new type of engine was a much shorter-term proposition than he had originally assumed based on Griffith's ideal axial engine. In February 1942, he told the Rolls-Royce Board that the company should not begin to design a new piston engine until the potential of the ICT was better known. He continued to believe that Griffith's design was the most efficient possible ICT layout, but Hives recognised that the CR.1 would require several more

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[49] RRL, 20.12.44, Letter Bristol to EJW; Wilde, 'Dr Griffith's CR.1.'

[50] Hooker, *Not Much of an Engineer*, 63.

[51] Hooker, *Not Much of an Engineer*, 67.

years of development. In the meantime, he wanted Rolls-Royce to become actively involved in the design and development of simpler centrifugal turbojet engines. To this end, he initiated a collaboration with Power Jets to build an engine like the W.2B, which would allow Rolls-Royce to gain 'the benefit of... seven years development work'. The firm's Board authorised £25,000 to 'obtain an interest in Power Jets' in order to secure full and open collaboration with the firm.[52] This was only a fraction of the more than £275,000 that the Air Ministry had invested in Power Jets by early 1942, but it significantly exceeded previous private investment in the firm.[53] Nothing came of this, but the offer illustrated the seriousness of Rolls-Royce's interest and its financial clout.

Rather than a commercial partnership, Rolls-Royce agreed in January 1942 to collaborate with Power Jets as a sub-contractor on the design of a new centrifugal turbojet engine with a power output similar to the W.2B: 2,000 pounds thrust (Power Jets believed that the engine's conservative design could be developed to 3,000 pounds, however).[54] The joint engine would be known as the WR.1 (Whittle-Rolls-Royce). MAP gave its consent to the engine on the condition that the work not interrupt the 'urgent development' of Rolls-Royce's other engines, especially the Merlin Marks 60 and 61, the Griffon, and the Crecy. Rolls-Royce assented to the Ministry's requirement; the firm did not need any additional labour as it had a 'windfall in personnel owing to abandonment of the marine Merlin.'[55] Hives placed Lionel Haworth, who had headed the abandoned project, in charge of the turbojet.[56] Haworth was to become one of Rolls-Royce's eminent turbojet designers.

A research contract for six WR.1 engines wasn't actually issued until early 1943,[57] but work began long before. On 4 February 1942, a technical meeting was held between

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[52] RRDMB #11, 24.2.42

[53] Schlaifer and Heron, *Development of Aircraft Engines*, 345-346.

[54] Whittle, *Jet*, 192.

[55] NA AVIA 15/1607, 27.1.42, Minute Linnell to Pye

[56] *Archive* #79, 'LH and his RCA.3.'

[57] NA AVIA 15/1607, 17.3.43, Memo by Roxbee Cox

representatives of MAP, Power Jets and Rolls-Royce to agree on the specification for the new engine.[58] (In fact, Rolls-Royce was so eager to proceed that they had already ordered some material.[59]) Hives insisted that his firm be responsible for design, manufacture and development of the engines because he wanted Rolls-Royce to use the project to expand its experience in turbojet design and development. The first three WR.1 engines were to be built to the specification agreed with Power Jets and the RAE, but the last three would incorporate modifications by Rolls-Royce based on the performance of the first three engines.[60] Although sub-contractors to Power Jets, Rolls-Royce was clearly the stronger partner and in practice, Power Jets became something of a relay between Rolls-Royce and MAP on the project.

The WR.1 used the same layout as the W.2B, with a double-sided impeller, ten reverse flow combustion chambers and an axial turbine. Because Rolls-Royce engineers created the design, it also included features from Rolls-Royce's work on centrifugal superchargers.[61] Haworth planned to use a scaled up, doubled-sided version of the Vulture supercharger for the engine's compressor, for example, while rotating guide vanes for the compressor inlet were taken initially from the Merlin XX supercharger.[62] To these features were added reverse-flow combustion chambers and fuel nozzles developed by Lucas for the W.2B, a gearbox designed by Rover, and an exhaust cone designed by the RAE.[63]

Early on, Rolls-Royce was an enthusiastic collaborator with other organisations working on turbojets. Following a suggestion made during a meeting at Rolls-Royce on 20 August 1941, Harold Roxbee Cox, the administrator at MAP who remained responsible for

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[58] NA AVIA 15/1607, 9.2.42, 4a, Discussion of Whittle-Rolls-Royce Jet Propulsion unit on 4.2.42

[59] Whittle, *Jet*, 192.

[60] RR HC, 16.4.42, Letter Rolls-Royce to W.E.P. Johnson

[61] NA AIR 62/990, 4.42, GTCC Progress Report #6

[62] RR HT, Exerpt from 17.2.43, Report J.P. Herriot to S.B. Wilks (Rover); AIR 62/990, 11.42, GTCC Progress Report #13

[63] NA AIR 62/990, 4.42, GTCC Progress Report #6; NA AVIA 13/962, 23.2.42, 8A, Minute Constant to Roxbee Cox

turbojet development throughout the war, established the 'experimental' national Gas Turbine Collaboration Committee (GTCC).[64] The exchange of information on gas turbine development facilitated by the GTCC was fully consonant with MAP's expressed desire for the 'rapid development and production of gas turbine engines'.[65] The participating firms submitted monthly progress reports, and problems facing all of the committee's member firms were addressed in sub-committees, which came to include surging, combustion, high temperature materials, patents and production.[66] In contrast with the Ministry's competitive piston engine policy, its gas turbine policy was one of a 'mutual and free interchange of ideas' that went beyond the customary level of informal cooperation within industry.[67] The committee, which eventually included representatives of all of the firms and government establishments working on gas turbine aero-engines, met bi-monthly at different firms, where its members got to see different gas turbines under test. Griffith and Hooker represented Rolls-Royce on the GTCC from its first meeting.

The heavy and relatively low-powered WR.1 engine has been cited as proof of Rolls-Royce's inability to design a centrifugal engine and its reliance on the work of other firms to enter the gas turbine field.[68] But these evaluations do not appreciate the firm's goals in initiating the WR.1 project. Whereas the RAE disparaged the engine's performance as inferior to the W.2B,[69] the WR.1 design was aimed at improving on the W.2B's poor reliability before anything else. Following Rolls-Royce's 'usual practice', the design of the WR.1 was intentionally conservative, sacrificing weight and power for mechanical reliability.

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[64] NA AVIA 46/237, 1.9.41, 3b, Interdepartmental letter

[65] NA AVIA 46/237, 31.7.41, 3a, Gas Turbine Collaboration

[66] NA AVIA 31/3, 1.11.41, GTCC Meeting Minutes #1

[67] NA AVIA 13/935, 20.4.42, 273, Letter Perring to MAP; NA AVIA 43/237, 2.9.41, 3c, Interdepartmental memo; Bulma, *An Account of Partnership-Industry, Government and the Aero Engine*, 327

[68] See Johnson's argument below; Bill Bailey and Ian Whittle, 'The Early Development of the Aircraft Jet Engine,' 2004, 42-43; Interview of James Foulds, 29.3.10

[69] NA AVIA 13/962, 12.2.42, Letter Perring to Griffith; 23.2.42, 8A, Letter Constant to MAP

Once the engine had been proven to be mechanically reliable, the firm would work to improve its performance.[70]

The first WR.1 engine was built, like the CR.1, in Derby's experimental shop. It was completed on 30 November 1942,[71] and the engine ran on the bench for the second meeting of the GTCC on 12 December 1942, by which time it had already done its first acceptance test, a period of continuous running required to fulfil a given government contract (increasingly challenging test parameters were stipulated by the Air Ministry for different turbojet engines).[72] Initial running produced promising readings: a thrust of 1,155 pounds with a compressor efficiency calculated at 76%. By the end of February 1943, the WR.1 had run 18 hours and 7 minutes, and had reached 1,975 pounds thrust.[73] The engine was reliable but suffered from airflow problems, which prevented it from being run at full speed. Two WR.1 engines were built before the programme was abandoned in mid-1943.

During 1943, Rolls-Royce took over development of the W.2B from Rover and gave up the WR.1, but the company undoubtedly benefitted from designing and building the WR.1. During the project, the firm built up its own skills and contributed to its reputation as a 'major influence on gas turbine technique'.[74] One key technical lesson learned, according to Haworth, was how to mount an aluminium rotor on a steel shaft in such a way that the differential expansion and rotation strain would not upset its balance. Work on the WR.1 also resulted in a modification of Power Jets' fir tree turbine blade root to make it easier to produce; the new design was adopted on all of Rolls-Royce's later engines.[75] Because Haworth's design team remained at Derby, like the ICT Section working on the CR.1, the

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[70] RR HC, 17.11.42, Hives to MAP; Lloyd, 1978, 126-133.

[71] NA AIR 62/990, 11.42, GTCC Progress Report #13

[72] NA AVIA 31/2, 12.12.42, GTCC Minutes Meeting #7

[73] NA AIR 62/990, 12.42, GTCC Progress Report #14; 2.43, GTCC Progress Report #16

[74] Roxbee Cox, 1946, 68; Postan, Hay and Scott, *Design and Development of Weapons*, 202; Schlaifer and Heron, *Development of Aircraft Engines*, 364.

[75] Lionel Haworth, *The Rolls-Royce Tyne* (Derby: Rolls-Royce Heritage Trust, 2000), 16.

main contribution of the engine was to future Derby engines rather than to the W.2B project at Barnoldswick.

Another important effect of the WR.1 project was to cement Rolls-Royce's positive relations with Power Jets. Throughout 1941 and 1942, Power Jets came increasingly to see Rolls-Royce as its best partner.[76] In early 1942, it suggested that the latter firm take over flight-testing of the W.2B, a move that MAP supported because it would relieve the over-burdened Gloster Aircraft Company and because it 'would certainly get the most work best done in the shortest time'.[77] The Wellington II bomber allotted by MAP to Rolls-Royce's airfield at Hucknall for flight-testing the W.2B became a mainstay of early turbojet flight-testing.[78] In late 1942, it was Rolls-Royce that Power Jets approached to produce their newest engine design, the W2/500. It was this proposal that led to Rolls-Royce's assumption of responsibility for the W.2B.

Rolls-Royce at Barnoldswick

In early 1943, when Rolls-Royce took over the turbojet engine factories at Barnoldswick and Clitheroe from Rover, the W.2B was still regarded as far from service use. Emphasising that Rolls-Royce's approach to the W.2B was to be like the firm's approach to any other aero-engine, Hives argued that the W.2B was 'just another way of pushing an aeroplane along except that at the present time it is not as good as with the conventional engine'.[79] Pointing to the engine's reputation in the aero-engine community, Haworth colourfully declared in

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[76] Rolls-Royce also served as a sub-contractor to Rovers, and Derby produced some experimental turbojet parts for Clitheroe starting in 1941. (RR HC, 28.5.41, Letter Hives to Hennesay (MAP)) In early 1942, Rover was also eager to collaborate with Rolls-Royce, but the initiation of the WR.1 project led Hives to refuse the firm's request in January 1942. (RR HC, 11.2.42, Letter Hives to S.B. Wilks)

[77] NA AVIA 15/1607, 10.2.42, Minute Bulman to Linnell

[78] NA AVIA 15/1614, 2.4.42, 14A, A.G. Elliott to Roxbee Cox; RR HC, 25.3.42, W.E.P. Johnson to Linnell; 7.4.42, W.E.P. Johnson to Hives

[79] NA AVIA 15/1708, 27.3.43, 37A, Letter Hives to Linnell

February 1943, that the 'common sense' of Rolls-Royce's engineers would produce a gas turbine to be 'used by ordinary mortals and not by a tribe of scientific dream children.'[80]

Under Rover, Clitheroe had been the W.2B design and development centre, while Barnoldswick had focussed on engine production. Hives immediately turned Barnoldswick from a production factory into a development facility, and some of the factory's valuable machine tools were sent back to the Machine Tool Control for 're-allocation'.[81] He moved Rover's turbojet design team from Clitheroe to Barnoldswick, leaving Clitheroe for administration. It was by now impossible for Rover's 'senior people' to collaborate harmoniously with Power Jets,[82] but in order to avoid disruption at the factory, Rolls-Royce's management was filtered in to replace them over a period of three months. By April 1943, the new company was in full control.[83] Rolls-Royce's management brought with it Rolls-Royce standards, expertise and practices and contributed to accelerating the pace of W.2B development.[84]

Hooker was put in charge of Barnoldswick's technical team. He brought a few key Rolls-Royce personnel with him from Derby. They worked closely with Rover's design team, led by Adrian Lombard, who became a legendary Chief Engineer at Rolls-Royce after the war. The majority of the factory workforce, which was local, remained under the new ownership. Hooker judged that the workforce would need some retraining; wages were

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[80] *Archive* #79, 5.2.43, Letter Haworth to Constant

[81] NA AVIA 15/1802, 24.2.43, 38A, Interdepartmental letter Robinson

[82] NA AVIA 15/1806, 8.44, 11A, Draft memo to Churchill

[83] NA AVIA 15/1802, 7.1.43, 15, Minute Roxbee Cox to Linnell

[84] Hooker, *Not Much of an Engineer*, 80; Hives decided to put Mr Reid, a Rolls-Royce production engineer who had been superintending Merlin production at Packard in the United States, in charge of Barnoldswick. (NA AVIA 15/1806, 11A; 5.1.43, 12A, Notes of discussion held at Power Jets Ltd.) In fact, Reid never worked at Barnoldswick. (Pugh, *Magic of a Name: The First 40 Years*, 317) Hives also assigned Les Buckler from Derby to be works manager at the turbojet factory, where the latter made a crucial contribution to the acceleration of work there. Buckler later became manager of Barnoldswick, when design and development was moved back to Derby. (Pugh, *Magic of a Name: The First 40 Years*, 296.)

increased slightly.[85] Rolls-Royce's intellectual resources, like its material resources, dwarfed Rover's, and this meant that development problems were resolved much more quickly under the new company's control.[86] A new alloy for turbine blades developed by Mond Nickel, Nimonic 80, also helped to speed up the work. Development of the engine was officially ended by July 1944 and production of the W.2B began.

Power Jets and Rolls-Royce disagreed about the latter's contribution to the turn around of the W.2B. Hives held that Rolls-Royce's work was responsible for the improvement in the engine, whereas Power Jets' managers argued that the engine was already on the upswing when Rolls-Royce took over. In an internal memo, dated 3 May 1943, Power Jets' W.E.P. Johnson, recorded that 'up to date RR [Rolls-Royce] cannot point to any technical contribution worthy of note'. Power Jets considered production a derivative exercise rather than a creative one. Johnson pointed to the WR.1 as evidence of Rolls-Royce's lack of design ability with respect to centrifugal gas turbines. The improvements in the W.2B, he argued, were the result of changes made by the Rover design team and of changes in design and testing urged by Power Jets, which the latter firm had not had the influence to force on Rover. Johnson contended that 'it is certainly not to be credited to RR [Rolls-Royce] that they [Power Jets' suggestions] were in due course adopted in substance; if not in detail.' Rolls-Royce's assumption of management undoubtedly had an immediate impact on the work at Barnoldswick. Yet as it would on many occasions, Power Jets discounted this by pointing to ideas rather than their execution as proof that Power Jets deserved credit for their accomplishment.[87] Rolls-Royce recognised that it had much to learn about designing gas turbine engines, as Power Jets had been doing since 1936, but in contrast

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[85] NA AIR 62/608, 19.4.43, Whittle diary, Visit with Hives; Interview with James Foulds, 29.3.10

[86] Interview with James Foulds, 29.3.10

[87] NA AIR 62/608, 3.5.43, Meeting W.E.P. Johnson, J.C.B. Tinling, R.D. Williams and Hives on 30.4.43

to Power Jets, part of Rolls-Royce's success was its ability and willingness to combine their expertise with knowledge gained from other firms.

As Rolls-Royce became more familiar with the centrifugal turbojet engine, it made less of an effort to work with Power Jets. In February 1943, after the first WR.1 had passed its acceptance test, Rolls-Royce told MAP that future WR.1-related contracts should be placed directly with Rolls-Royce.[88] In July 1943, Hives transferred the WR.1 project from Derby to Barnoldswick, and requested that MAP cancel the original contract for WR.1 engines that had been placed through Power Jets.[89] Power Jets was severely disappointed when Rolls-Royce decided not to produce the W.2/500, as had been agreed in November 1942, and chose instead in April 1943 to embark on a new turbojet development, the B/37, which it designed without much consultation with Power Jets, although using some Power Jets drawings.[90]

The quick success of the B/37 demonstrated the power of Rolls-Royce's design and development methods. Eclectic like the WR.1, the engine combined the Power Jets W.2/500 compressor and turbine with the straight-through combustion layout and superior mechanical design of Rover's production-friendly version of the W.2B, the B/26,[91] and with Rolls-Royce's production and supercharger expertise.[92] The first B/37, later the Derwent, ran in July 1943, and its first flight trials were made in an F.9/40 in April 1944. Clearly a point of some pride, by October 1944, Rolls-Royce had completed more hours of bench running and

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[88] NA AVIA 15/1607, 10.2.43, 23, Minute Watt to Roxbee Cox

[89] NA AVIA 15/1607, 17.7.43, 28a, Letter Rolls-Royce to MAP

[90] NA AIR 62/608, 19.4.43, Whittle diary, Visit with Hives; 13.5.43, Whittle diary, 'Phone call with Roxbee Cox

[91] Rover's design team at Clitheroe designed the STX or B/26 to ease the production problems expected to arise if the W.2B were to be manufactured on a large scale, using unskilled labour. The STX used the W.2B's compressor-turbine assembly, but had a completely different, straight-through combustion system. (NA AVIA 13/937, 21.5.42, Meeting at Clitheroe)

[92] Hooker relied on Wilde to use the Vulture test rig at Derby to modify the W.2B diffuser 'on the lines of the Merlin' to increase its airflow. (Hooker, *Not Much of an Engineer*, 82-83.)

flying than all of the other turbojet firms combined: Rolls-Royce had clocked up 14,000 hours as compared to 12,000 for all the other firms.[93]

The design team at Barnoldswick moved swiftly on to a new, more powerful centrifugal engine, the B/41, which would become the Rolls-Royce Nene. The first detail drawings went to the shops on 24 May 1944, the first prototype was completed by 25 October 1944, and the unit ran two days later. On 31 October 1944 the first B/41 had passed its acceptance test. On 9 November 1944, the engine reached 4,500 pounds of thrust, confirming it as the most powerful turbojet in the world.[94] Rolls-Royce's rapid success with centrifugal turbojets at Barnoldswick may have led Hives to consider that turbojet development was straight-forward, but the firm's continuing struggle with the novel axial turbojet at Derby proved otherwise.[95]

Back at Derby

Rolls-Royce's work on axial engines at Derby remained ambitious despite its lack of success. When work on the WR.1 was cancelled, Haworth began work on an axial engine with three concentric shafts, the Rolls-Royce Compound Axial engine known as RCA3.[96] The RCA3 was a three-spool engine, with high, intermediate and low-pressure axial compressors on independent shafts and driven by separate turbines.[97] Because of the failure of the CR.1's annular combustion chamber, the RCA3 made use instead of the reverse flow combustion chambers of the Power Jets engines.[98]

The RCA3 proposal was passed by DSR to the RAE to be 'officially vetted'.[99] The RAE baulked at the engine's mechanical complexity and suggested that Rolls-Royce build a

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[93] RRL 20.12.44, Letter

[94] RRL 20.12.44, Letter; Hooker, 88-89.

[95] Hooker, *Not Much of an Engineer*, 104.

[96] Haworth, *Rolls-Royce Tyne*, 7.

[97] Haworth, *Rolls-Royce Tyne*, 17-18.

[98] RRL, 20.12.44, Letter; Wilde, 'Dr Griffith's CR.1.'

[99] NA AVIA 15/1960, 27.7.43, 7A, Letter Roxbee Cox to Farren; 19.2.43, Letter Roxbee Cox to Haworth

double compound engine before attempting a triple. Yet A.G. Elliot, the company's Chief Engineer, confidently responded to the RAE's objections that 'we are comforted by the thought that our engines have always been more complicated than others without suffering thereby'.[100] Complexity was not only something that Rolls-Royce thought that it could handle – a fact which led the firm astray in some respects - it was a point of pride and the cornerstone of the firm's competitiveness. Hives boasted that the gas turbine was only of interest in so far as it quickly became too complex for most firms to produce.[101]

Construction of the first RCA3 experimental unit began in 1943. The firm began by building a single spool, the engine's high-pressure compressor-turbine unit, RCA1, planning to later add intermediate- and high-pressure axial units to form the RCA2 and finally the RCA3.[102] The programme was discontinued in 1946 after only the high-pressure stage had been built, however, but by then, Haworth and his design team had already learned lessons from creating the RCA3 design and had begun another.[103]

Once the RCA3 design had been sent to the experimental shop, Haworth's team began work on the RB/39, Rolls-Royce's first purpose built turboprop, known as the Clyde. The Derby and Barnoldswick turbojet teams had worked together to successfully design the firm's first turboprop, exploiting continuities with both piston engine practice and the firm's growing turbojet expertise. The firm's first turboprop, the Trent, was a retrofitted Derwent engine. In this turboprop version, the Derwent's compressor diameter was reduced and the extra energy extracted by the turbine was used to power a propeller via a gearbox designed at Derby. Only five Trent engines were built, but the firm nevertheless learned valuable lessons from the turboprop, which proved useful for the firm's later turboprop, the RB/39. The

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[100] NA AVIA 15/1960, 7.10.43, 10A, Letter A.G. Elliott to Roxbee Cox

[101] Pugh, *Magic of a Name: The First 40 Years*, 291.

[102] Haworth, *Rolls-Royce Tyne*, 17-18.

[103] NA AVIA 15/1960, 9.2.46, 16, Minute

Trent demonstrated the importance of using helical rather than toothed reduction gears, for example.[104]

The RB/39 was a product of both Derby and Barnoldswick. Rather than use the axial compressor design of the unproven RCA3 design, as Haworth suggested, Hooker suggested that the new engine use two known compressors: an axial compressor based on Metropolitan-Vickers' axial F.2 followed by a centrifugal compressor based on the Merlin supercharger.[105] Although it abandoned the RCA3's axial compressor, the new engine borrowed one important feature pioneered in the previous design: it used compounding, or a concentric, double shaft to thread the axle powering the propeller through the axle powering the compressor. The design team under Haworth at Derby designed the engine's compressors, while the Lombard team at Barnoldswick designed the combustion system and turbine. The design of the RB/39 started in March 1944, and the engine was built at Barnoldswick.[106] Testing began on 5 August 1945 and development continued until 1949, when the engine was abandoned. No airframe had been foreseen for the engine and Hives, doubting its suitability for production, rejected a Government contract for 100 Clyde engines.[107]

Rolls-Royce did not have an equally good record with all components of the early turbojet engines. The firm struggled with its early axial turbojet designs. In fact, Griffith maintained that the CR.1's failure pointed up the limitations of Rolls-Royce's piston engine

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[104] Haworth, *Rolls-Royce Tyne*, 19; Comments from Max Alderston (RR HT) 10.3.11

[105] The two were good friends. (Hooker, *Not Much of an Engineer*, 101.)

[106] J.P. Herriot managed Clyde development 'almost alone' at Barnoldswick, as the organization had already begun to be moved back to Derby. (Gunston, *World Encyclopaedia of Aero Engines*, 162) After the Clyde, Haworth led the design effort in 1946 on another turboprop, the RB/53, later known as the Dart, which had two coupled centrifugal compressors. Despite the engine's poor initial performance, MAP kept the project going and it eventually became a hugely successful engine. The Dart was in military and civil use for over 40 years. More than 7,000 engines were built. (Roy Heathcote, *The Rolls-Royce Dart: Pioneering Turboprop* (Derby: Rolls-Royce Heritage Trust, 1992), 9 and 21-22; F. R. Banks, *I Kept No Diary: 60 Years with Marine Diesels, Automobile and Aero Engines* (Shrewsbury: Airlife Publications, 1978), 156.)

[107] Heathcote, *Rolls-Royce Dart*, 14; Feilden, 'Lionel Haworth', 200; Gunston argues that the Clyde was superior to the axial turboprops that replaced it. (Gunston, *World Encyclopaedia of Aero Engines*, 162.)

organisation, from which its ICT Section had grown. The company was good at developing known engine types, he argued, but too much focussed on development to succeed with radically new ones. Griffith even considered that the two functions might be mutually opposed; he believed that there were limits to the types of problems to which Rolls-Royce's methods could successfully be applied. 'For the evolution of new and unfamiliar types', Griffith wrote to Hives in February 1944, defending the CR.1 design, 'I believe a leaven of research outlook to be essential.'[108]

Work on gas turbines did lead to changes in how Rolls-Royce made new engines. At first the firm's designers had relied on its Performance and Stress offices for analysis and calculations, which had dictated turbojet engine design to some extent. Haworth, who believed in the primacy of design, resented this impingement on the independence of the designer. Already in Griffith's CR.1, which Haworth had hoped to better with his allegedly more practical RCA3, he had objected to what he saw as the subservience of design principles to the demands of scientific theory.[109] After the war, Haworth began to recruit graduate engineers into his design office to be 'Design Engineers', designers who would be 'self-sufficient in terms of routine technical support and who became intelligent customers for the more complex inputs from the Performance and Stress offices.'[110]

After the abandonment of the CR.1, Griffith submitted a slightly less complex scheme for a new engine, the CR.2, in early 1945. The design of the CR.2 gave up the contra-flow aspect of the CR.1, but it nevertheless called for a four-stage ducted fan and a twenty-row axial, contra-rotating compressor driven by an eight-stage turbine.[111] MAP was as supportive of the new CR engine as it had been of the first. The Ministry argued that the 'CR.2 is a project which, if successfully developed, will be an advance over every other type

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[108] RR HC, 18.2.44, Memo by Griffith

[109] *Archive* #79, Reprint of 5.2.43, Letter Haworth to Constant

[110] Feilden, 'Lionel Haworth', 204.

[111] MOSI, 11.45, MAP turbine engine data sheet

of gas turbine at present envisaged, and we feel that the work should proceed immediately' so long as development, estimated at 4-5 years, would not prejudice 'the simpler and more immediately needed engines' that the firm was working on.[112] The continued faith maintained by MAP and Rolls-Royce in Griffith's theoretically inspired contra-rotating schemes is remarkable. The CR.2 was in fact given up soon after the war, when Hives demanded that Griffith create a more practical axial scheme to take advantage of the higher compression ratios made possible by the axial compressor.

Griffith's next design, the AJ/65 (Axial Turbojet), later the Avon, became the focus of Derby's post-war turbojet work. Although Barnoldswick had no experience with axial compressors, the engine was first undertaken by Hooker's team, then still the centre of Rolls-Royce's turbojet development work. In 1946, however, Hives concentrated turbojet work back at Derby, where the company's two gas turbine design and development strands were finally united.[113] The Barnoldswick factory remains in operation today, supporting Derby's work. The Avon development team at Derby was headed from 1947 by A. Cryil Lovesey, who had headed Merlin development during the war. The Avon was to be the first in a long line of successful axial turbojets from Rolls-Royce, as the firm transformed itself into a maker of gas turbine aero-engines.

The British aero-engine industry

Like Rolls-Royce, the remaining major British aero-engine firms used their piston engine equipment, designs and personnel to develop turbojets during the war, although none was so

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[112] NA AVIA 15/1201, 12.3.45, 48, Minute Watt to Sorley; AVIA 15/1201, 25.3.45, 49, Minute Sorely to Watt

[113] Hooker, *Not Much of an Engineer*, 107; Several of Rolls-Royce's key turbojet engineers left the firm when turbojet work was concentrated back at Derby because they feared they would not find a place in the new turbojet organisation. Hooker famously left Rolls-Royce in September 1948 and eventually became Chief Engineer at Bristol, where he reversed (with Derby's help) the firm's turbojet prospects. (Hooker, 1984, 120) Hooker's leadership later attracted several experienced engineers from Rolls-Royce to join Bristol, including Jamison, Haworth and even Lombard (although he was convinced to stay on at Rolls-Royce). (Hooker, *Not Much of an Engineer*, 131; Lionel Haworth, M. A. Nedham and Geoff L. Wilde, 'Robin Ralph Jamison. 12 July 1912-18 March 1991', *Biographical Memoirs of Fellows of the Royal Society* 40 (1994): 179; Feilden, 'Lionel Haworth', 197.)

ambitious in scope as Rolls-Royce. At the end of the war, the de Havilland Engine Company was finishing the development of its first centrifugal turbojet with 3,000 pounds thrust; Armstrong Siddeley Motors was developing the axial turbojet that it had built during the war, which produced 2,600 pounds thrust, into a turboprop unit; the Bristol Aeroplane Company was developing a turbojet of about 2,500 pounds thrust; and D. Napier and Son was working on turning its turbojet-diesel engine combination into a turbojet that would produce approximately 1,700 pounds thrust.

What we know about the British industry's turbojet development is patchy and in rather less detail than is available for German aero-engine firms. Of all the British firms, de Havilland has received the most attention. This is true in the comparative histories of the turbojet and in the accounts written by amateur historians, although the same details appear time and time again. The latter make much of the Goblin's accomplishments: the fact that the first prototype was built in record time, the Meteor first flew with H.1 engines, the engine's design underwent no major changes, the H.1 was the first to pass the Ministry's new gas turbine type test (in January 1945), and the fact that de Havilland was 'the first company to commence quantity production of a jet engine'.[114] A few details of development can be found in Sharp, Watkins and Taylor's accounts of early engine testing and combustion work,[115] but the most detailed source is the unpublished company history of the development of the Goblin engine.[116]

In comparison to the interest in de Havilland's work, the early work on turbojets at Armstrong Siddeley (ASM), the Bristol Aeroplane Company, and Napier & Sons (Napier) has attracted much less attention. The only existing, popular history of Bristol did not

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[114] Sharp, *D.H.: An Outline of De Havilland History*, 200-205; Philip Birtles *De Havilland* (London: Jane's, 1984), 49-51; Watkins, *De Havilland Vampire*, 22-29; Taylor, *Boxkite to Jet*, 109-121.

[115] Sharp, *D.H.: An Outline of De Havilland History*, 200-202; Taylor, *Boxkite to Jet*, 119.

[116] DeHavilland, n.d.

include the firm's early turbojet work.[117] ASM's aero-engine business after 1939 has been studied only in Roy Lawton's recent amateur history. Lawton gave a general discussion of the firm's gas turbine engines and its internal dynamics (although he was very vague on the details of the firm's collaboration with Metrovick during the war on the F.2).[118] Napier's wartime and post-war aero-engine activity was covered briefly in Wilson and Reader's early history of the firm, which gave an overview of the firm's interest in turboprops for civil aviation and described its early engine projects.[119]

While there are a few individual accounts of the activity of British aero-engine firms, the British literature lags behind the German in terms of accounts of the industry as a whole. The Official History's story of the turbojet, edited by Postan, gave a thorough and matter-of-fact account of how M.A.P. recruited all of Britain's aero-engine firms to turbojet work, although it gave little information on engine designs other than the W.2B and virtually no information about Bristol or Napier's work.[120] The comparative accounts of the turbojet written by historians give a similar impression as the few firm histories. Because its engines reached production during the war, De Havilland's work is described in the most detail, whereas ASM and Bristol's early turbojets are included briefly for completeness's sake, and Napier's work is not even mentioned.[121] The first attempt to compile information on the early turbojets of the entire British aero-engine industry was the recent 2007 book by aviation author Anthony Kay, in which he attempted to extend the comprehensive treatment from his 2002 book on German gas turbines to the Britain gas turbine aero-engine field.[122]

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[117] Derek N. James *Bristol Aeroplane Company* (Stroud: Chalford, 1996); Gunston's biography of Roy Fedden gave some early details, but Fedden left the firm in 1942. (Bill Gunston, *Fedden - the Life of Sir Roy Fedden* (London: Rolls-Royce Heritage Trust, 1998.) Hooker's autobiography gave details after he joined the firm, in 1949. (Hooker, *Not Much of an Engineer)*

[118] Lawton, *Parkside*, 65-84.

[119] Wilson and Reader, *Men and Machines*, 159-165.

[120] Postan, Hay and Scott, *Design and Development of Weapons*, 199-227.

[121] Schlaifer and Heron, *Development of Aircraft Engines*, 355-357 and 374; Constant, *Origins of the Turbojet Revolution*, 216-218.

[122] Kay, *Turbojet History and Development* and *German Jet Engine and Gas Turbine Development.*

He provided a useful compilation of existing information organised by firm and engine, in which he gave the primary details and dates associated with each engine design as well as some anecdotes about development. Like the other histories by amateur historians and aviation writers, he focused on detail and made few arguments.

This section revisits the work of all of these British aero-engine firms and explicitly connects the details of the first turbojet projects taken up by each firm to the circumstances and the piston engine expertise of that firm, regardless of each firm's turbojet production success during the war. Continuities with piston engine practice were important. Two key sources of expertise which British aero-engine firms relied on to augment their own were the Royal Aircraft Establishment's (RAE) expertise with axial compressors and Joseph Lucas's work on combustion. As in the previous section, additions to the existing professional and amateur histories drawn from encyclopaedias of aero-engines and actor's accounts help to elucidate the continuities between piston engine and turbojet engines. Another useful source for the British story has been the periodical *Flight*, which published detailed articles on British turbojet engines after the war and the textbook published for the first time in 1942 (but in its fourth edition by 1946) by one of *Flight*'s editorial directors, G. Geoffrey Smith. The stories in this section are briefer than in the previous one, because most of these firms, in contrast to Rolls-Royce, developed just one turbojet seriously during the war, although their programmes began to branch out near the war's end.

De Havilland

During the war, de Havilland went from being a minor manufacturer of small aero-engines to being a major developer of large turbojet engines. This dramatic transformation was based on the designs of Frank Halford, a successful piston engine designer, who began the war as the firm's aero-engine consultant as well as the head of its propeller development.[123] Both de

[123] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 324; John Brodie, 'Frank Bernard Halford 1897-1955,' *Journal of the Royal Aeronautical Society* 63 (1959): 201; C. Martin Sharp, *D.H.: An Outline of De Havilland History* (London: Faber and Faber, 1960), 201-204.

Havilland and Napier had successfully developed multiple Halford designed engines in the interwar period, but the links between Halford's consultancy and de Havilland deepened after 1937, when the designer's 52-strong company moved into a set of offices built for them in de Havilland's old Stag Lane Works, near Edgware, London, less than fifteen miles away from de Havilland's main works in Hatfield. The establishment on 1 February 1944 of the de Havilland Engine Company at Stag Lane formalised the intimate link between the two firms. The engine company incorporated Halford's engine design team, including his chief engineer, E.S. Moult,[124] and Halford became the new company's technical director and chairman of its board of directors.[125]

At the outbreak of war, Halford's consultancy's work on civil aero-engines was put on hold, which meant that the firm was open to taking on a new project in January 1941, when Sir Henry Tizard, Scientific Advisor to MAP, proposed to Halford that he undertake to design a jet engine.[126] In collaboration with de Havilland's aircraft designers, Halford chose the design goal of 3,000 pounds thrust, a figure almost twice as great as the W.2B.[127] When Halford's design for the H.1 turbojet was completed, de Havilland's engine division was the obvious place to develop it. By August 1941, the first H.1 drawings had been released to the de Havilland engine shops.[128] The first prototype was built largely using existing machines from the production of de Havilland's small Gipsy piston engines, which were in decreasing demand during the war.[129] It was put on test at Hatfield on 13 April 1942,

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[124] NA AVIA 13/934, 23.5.41, Letter E.S. Moult to Hayne Constant

[125] Watkins, *De Havilland Vampire*, 28-29; Sharp, *D.H.: An Outline of De Havilland History*, 207.

[126] Taylor, *Boxkite to Jet*, 106-108.

[127] Pat Hassel, 'Halford Jets'.

[128] Moult, 'Development of the Goblin Engine', 658; Sharp, *D.H.: An Outline of De Havilland History*, 201.

[129] NA AVIA 15/1599, 10.1.42, 1, Minute Bulman to Linnell

in a tunnel that had been converted from Gipsy piston engine testing,[130] and the engine promisingly reached its design thrust of 3,000 pounds for a brief moment.[131]

Halford's confidence in his own design experience was evident, for his design diverged from Power Jets' earlier centrifugal layout in several respects.[132] Before the firm received a research contract from MAP, Halford had to successfully defend each of the H.1's deviations from Power Jets practice.[133] Like Power Jets, Halford preferred a centrifugal compressor to an axial one because it was a familiar component. But instead of Power Jet's double-sided compressor, Halford opted for a single-sided centrifugal compressor with a larger diameter. Halford accepted the challenges of a larger compressor because he could base the design on the tried supercharger of his Napier Sabre piston engine and because he wanted to gain the maximum advantage from the fact that the aircraft's forward speed would increase the engine's power by additionally compressing the incoming air. To aid the adaptation of the Sabre design, high-speed tests were carried out on a Sabre supercharger at Napier. (Napier later lent other equipment for H.1 combustion tests.)[134] De Havilland's propeller division contributed by developing new test methods to determine the vibration characteristics of the H.1's giant impeller.[135]

Halford's design also abandoned the reverse-flow combustion system of Power Jets in favour of a straight-through one. (See Figure 3.1 for a discussion of the two systems.) Halford's previous experience designing crankshafts for piston engines meant that he, unlike

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[130] The firm had to figure out how to measure engine RPM with greater precision than for piston engines, however. (Moult, 'Development of the Goblin Engine', 674-675.)

[131] Sharp, *D.H.: An Outline of De Havilland History*, 201.

[132] Halford received the W.2B drawings from the RAE after 15 May 1941, some time after he had begun his own design. (NA AVIA 13/937, 15.5.41, Letter Hayne Constant for Chief Superintendent RAE to Halford)

[133] NA AVIA 13/937, 15.5.41, Letter Hayne Constant for Chief Superintendent RAE to Halford

[134] Moult worked closely with Napier on the Sabre and with de Havilland on the H.1. (Brodie, 'Frank Bernard Halford', 199; NA AVIA 13/934, 23.5.41, E.S. Moult to Constant; 20.5.41, E.S. Moult to Chief Superintendent RAE; De Havilland, 'Development of the De Havilland "Goblin" Jet Propulsion Engine'.)

[135] Sharp, *D.H.: An Outline of De Havilland History*, 203.

Power Jets, was undaunted by the prospect of a long compressor-turbine assembly. Power Jets had tried to avoid the problematic flexing of a long, thin shaft joining compressor and turbine by adopting a very compact combustion system, which reduced the engine's length but complicated its air path. In order to straighten out the engine's airflow, Halford increased the diameter of the compressor-turbine shaft to make it rigid.[136] The H.1 had an RAE designed turbine nozzle and blades, and a combustion system that used a scaled down version of the chamber-type combustion chambers used for the Power Jets engine, which was the product of work of the RAE, Power Jets and Joseph Lucas.[137]

Using existing design elements had many advantages, but also presented challenges. The Sabre supercharger had to be scaled up and run at a much higher speed in a gas turbine than in a piston engine. The firm's normal practice for bending the vanes of centrifugal compressors into shape could not be used on the H.1 because of the greater accuracy necessary for the turbojet's compressor vane contours on which the engine's efficiency hinged, so new production methods had to be developed.[138] The reuse of the Sabre supercharger design also brought Halford into collision with MAP's policy of open sharing on turbojet engines because he was reluctant to reveal the design – a product of the private interwar piston engine industry - to the RAE or other members of the GTCC. Halford mistrusted the RAE's motives, which he wrongly assumed to be commercial,[139] and he

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136 Moult, 'Development of the Goblin Engine', 657.

137 NA AVIA 13/934, 27.9.41, Comments on DeHavilland-Halford Project (requested 6 Aug); Halford, like Power Jets, chose individual combustion chambers rather than an annular chamber to facilitate testing. (De Havilland, 'Development of the De Havilland "Goblin" Jet Propulsion Engine')

138 In the machining of the impellers, the company called on the expertise and Keller machines of the nearby United Glass Bottle Company. (De Havilland, 'Development of the De Havilland "Goblin" Jet Propulsion Engine'.)

139 It was not until November 1942 that Farren, the Establishment's Director, could convince Halford of the RAE's non-commercial interest in the engines. (NA AVIA 13/935, 5.8.42, Letter Farren to Halford; 10.11.42, Letter Farren to Halford)

believed that de Havilland's competitors on the GTCC would use information gained through turbojet exchange to improve their piston engines.[140]

The unprecedented power and airflow of the H.1 also presented novel problems with testing. The GTCC contributed to the development of the H.1 (and later turbojets) by coordinating the use of powerful state-owned facilities for gas turbine testing. These included the Dartford tunnel compressor, which provided a sufficient volume of compressed air to test the powerful H.1 turbojet, and the Northampton electric power station's steam turbine, which provided enough shaft power to test the large impellor.[141]

As a trusted firm, with 'wide engineering experience and with a sound production background',[142] de Havilland's development of the H.1 was left largely to itself for several years.[143] Yet the Ministry became increasingly wary as H.1 development fell further behind the firm's earlier promises and the work of other companies. In July 1944, MAP abandoned its hands-off policy, which had been inspired by the faith of George Bulman, MAP's earlier Director of Engine Development, in de Havilland and in Halford.[144] De Havilland's experience had brought them a good distance, but Wing Commander Watt, Deputy Director of Turbine Engines at MAP,[145] argued that 'unless we make de Havilland help themselves they will not be able to compete with firms like Rolls Royce for very much longer ... In my opinion the firm are capable of turning out very good work and most of their engineers and technical people are keen. I think it only requires a little pressure from us on the people who are directing their technical policy.'[146]

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[140] NA AVIA 46/237, 22.5.42, 138, Interdepartmental letter; Halford had reluctantly joined when it was established in 1941. (NA AVIA 13/935, 20.4.42, 273, Letter Perring to Roxbee Cox; NA AVIA 43/237, 2.9.41, 3c, Letter Roxbee Cox to Pye)

[141] Sharp, *D.H.: An Outline of De Havilland History*, 202-203.

[142] NA AVIA 15/1708, 29.11.42, 20, Minute Linell to Freeman

[143] NA AVIA 15/1599, 22.7.44, 55, Minute Watt to Banks

[144] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 325.

[145] Watt was Roxbee Cox's deputy until the latter left MAP in 1944.

[146] NA AVIA 15/1599, 16.11.44, 58, Minute Watt to Banks

De Havilland had been slowly developing the H.1 to incrementally higher powers, relying on flight rather than bench testing, and Watt felt that this method, while useful for small piston engines of the sort that de Havilland had worked on before, was ill-suited to larger engines and was largely to blame for the turbojet's slow progress. He advocated the use of extensive bench running to determine as soon as possible whether the engine would fail to reach its design parameters.[147] Watt argued that MAP should intervene to make sure that the H.1 passed a 100 hour reliability test at its rated 2,700 pounds thrust (the 'minimum acceptable thrust' under the company's pilot production contract[148]) as soon as possible. In addition, he wanted to encourage the firm to use components from other turbojet engines to improve the H.1, particularly replacing the H.1's poor combustion system with that of the B/37, which had benefitted from the GTCC Combustion Panel's thorough research.

After MAP's intervention, the firm's development work did begin to move faster. By November 1944, the H.1 had completed 100 hours of running at 2,500 pounds thrust followed by 100 hours at 2,700 pounds of thrust,[149] and in January 1945, it passed the Air Ministry turbojet type test at 2,700 pounds. By 23 November 1944, Halford had already designed a new version of the engine, the H.2 (later the Ghost) with a goal of 4,500 pounds thrust, which dominated the firm's work after the war.[150] Despite the 'almost inhuman pressure' of de Havilland's war work, engine development didn't let up in 1945.[151] The de Havilland Engine Company went on to produce engines for the first generation of post-war British jet fighters, and for the first commercial jet aircraft, the Comet.

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147 NA AVIA 15/1599, 22.7.44, 55, Minute Watt to Banks

148 NA AVIA 15/1599, 7.1.43, 44, Minute Roxbee Cox to Linnell

149 NA AVIA 31/4, 11.11.44, GTCC Minutes Meeting #15

150 NA AVIA 15/1599, 16.11.44, 58, Minute Watt to Banks; PREM 3/21/4, 30.1.45, 95, 3rd Two-Monthly Report from Cripps

151 Brodie, 'Frank Bernard Halford', 201.

Armstrong Siddeley Motors

Armstrong-Siddeley Motors, a second tier British aero-engine firm, began work on an axial turbojet early in the war, and with help from the RAE, designed and developed a moderately successful simple axial turbojet and turboprop engine before the end of the war. In October 1941, ASM agreed with MAP that it would abandon its current piston engine development programmes in favour of a turbojet. The firm had been developing its 1,115 horsepower Deerhound since 1935 and had a planned 3,000 horsepower engine, the Wolfhound, on the drawing board. The Ministry counselled the firm to focus its efforts instead on a single new turbojet engine in order to 'catch up to its rivals'.[152]

MAP believed that ASM's development policy needed to be 'guided', for the firm's large aero-engines had a reputation for low power and reliability, and the disappointing Deerhound engine had made MAP sceptical of the firm's development competence.[153] To help the firm into the turbojet field, the Ministry suggested collaboration with Metropolitan-Vickers (Metrovick), a steam turbine manufacturer that had been working with the RAE since 1940 on a simple axial turbojet now known as the F.2. The Ministry believed that while ASM could learn about the new engines from Metrovick, the promising but over-weight F.2 engine would benefit from ASM's aero-engine expertise and production facilities.[154] ASM was invited to join the GTCC in November 1941.[155]

The collaboration with Metrovick did not work out as ASM or MAP had hoped, however. The steam turbine maker insisted that it retain all technical responsibility for the engine, and crucially from ASM's point of view, that the aero-engine firm was not to

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[152] NA AVIA 15/1509, 6.10.41, Engine Development Policy ASM; 3.10.41, 4A, Meeting at MAP

[153] Hornby, *Factories and Plant*, 259; Gunston, *World Encyclopaedia of Aero Engines*, 19; NA AVIA 15/1509, 6.10.41, Engine Development Policy ASM; 3.10.41, 4A, Meeting at MAP

[154] NA AVIA 15/1509, 10.10.41, 5B, Letter Bulman to ASM with notes of meeting on 6.10.41; NA AVIA 15/1509, 5A; 18.9.41, 1A, Letter Perring to Roxbee Cox

[155] NA AVIA 15/1509, 20.11.41, 25, Minute Roxbee Cox to Linnell, Banks and Pye. Collaboration with Metro-Vick began almost immediately, and the first meeting of the 'Joint Committee on F2 Plant' took place on 18 March 1942. (NA AVIA 15/1509, 18.3.42, 43A, Minutes Meeting #1)

'undertake any redesign or modification work in connection with the actual unit'.[156] This may have led to the failure of the F.2 unit as an aero-engine, as discussed below, but it also prevented ASM from learning about turbojet engine design.

Frustrated with Metrovick's inflexible stance, ASM looked for a way to start its own turbojet project. The firm had previously worked with the Royal Navy on the construction of a Swedish designed gas turbine for a torpedo, and in 1939 it had constructed for the RAE a nine-stage, contra-rotating compressor with independent rotors to the design of A.A. Griffith.[157] Soon after, ASM's chief engineer had inaugurated speculative work on axial ducted fan gas turbines engines at the firm.[158] In late 1941, the ASM Board, particularly two Directors, Frank Spriggs (who was negotiating with Metrovick) and Thomas Sopwith, sought to jumpstart the firm's gas turbine work by hiring Fritz Heppner, a German refugee, who brought an ambitious plan for a contra-rotating, axial turbojet engine with him.[159] Heppner's contra-rotating engine was simpler than Griffith's in that it had only two independent sets of rotors that rotated in opposite directions; the first set was mounted on a central shaft, while the second moved by a rotating external casing.

In November 1939, well before ASM's interest in his work, Heppner had in fact already submitted a patent specification for his turbojet to the Air Ministry's Directorate of Scientific Research, but it had been turned down for being overly complex.[160] In June 1941, the RAE once again reported unfavourably on the short-term prospects of a new Heppner proposal for a contra-flow, contra-rotating engine, which was judged, like other contra-rotating schemes, to have great potential but to be 'a more remote development than the

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[156] NA AVIA 15/1509, 30.7.42, 53, Minute Bulman to Roxbee Cox

[157] MOSI, 10.9.42, Eng/2038.R/HC/21, RAE report by Hayne Constant

[158] The work was done by T.P. de Paravicini and his able assistant Brian Slatter, who eventually moved to the RAE. (Roy Lawton, *Parkside – Armstrong Siddeley to Rolls Royce 1939-1994* (Derby: Rolls-Royce Heritage Trust, 2008), 68-70.)

[159] Lawton, *Parkside*, 69.

[160] NA AVIA 13/911, 5.12.39, Interdepartmental letter Roxbee Cox and Hayne Constant

engines at present under construction.'[161] It was perhaps to be expected that when MAP dispatched Heppner's December 1941 proposal - which had the same structure as his July proposal, but was now under ASM's name - for comment to the RAE, it was once again rejected as impractical for a the firm's first turbojet. The proposed engine was far too complex, and the RAE was sceptical of Heppner's performance assumptions, which far exceeded anything achieved in contemporary practice in Britain.[162]

Criticism of the Heppner proposal from the company's Chief Engineer, Stuart Tresilian, was brought to an end, when the ASM Board used Tresilian's refusal to support Heppner's proposal as a pretext to fire him in January 1942. He was replaced by Dr H.S. Rowell, the firm's general manager, who fully backed Heppner's plans.[163] The firm subsequently submitted an even more complicated proposal, which now included three sets of compressors and a contra-rotating turbine. The revised proposal was, like all of Heppner's previous proposals, rejected by the RAE and MAP in May 1942.[164] The MAP worried that the Heppner scheme 'appear[ed] to have all the earmarks of another Deerhound.'[165]

The Ministry encouraged the firm to give up its complicated Heppner scheme and urged it to begin with a simple engine design that would be relatively quick to develop. ASM slowly came around to the Ministry's position. By mid-August 1942, MAP had finally managed to convince ASM to begin with a simple axial engine, to complement the greater

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[161] NA AVIA 13/911, 26.6.41, Hayne Constant for Perring to Roxbee Cox; Bulman and Ross also had a high opinion of Heppner. (NA AVIA 15/1509, 7.11.4, 18, Minute Bulman to Roxbee Cox)

[162] Heppner claimed to be able to achieve a pressure ratio of 8:1 using a contra-rotating compressor; the highest that had yet been achieved in Britain was a ratio of 3.5:1 (NA AVIA 13/911, 12.12.41, Visit to ASM, Discussion at Coventry on proposed Heppner Turbine)

[163] Stuart Tresilian had been grudgingly installed as Chief Engineer at MAP's request in 1939; he was fired on 19 January 1942. Tresilian took up a position as the USAAF-RAF engine coordinator, which he held from 1942 to 1945. (Richard Hodgson, 'Stewart S. Tresilian – a C.V.,' accessed 17 January 2011, http://www.designchambers.com/wolfhound/TresilianCV.htm.) Tresilian was not the only ex-chief engineer to be given a government post; Whittle and Fedden both benefitted from similar treatment.

[164] NA AVIA 13/911, 5.42, 23, Technical Appreciation of TB Engine (Heppner) from ASM brochure dated 5.5.42; 30.7.42, Hayne Constant / William Hawthorne to Roxbee Cox (revised proposal)

[165] NA AVIA 13/911, 1.7.42, 43a, Notes for discussion with ASM

number of centrifugal engines already under development.[166] The firm's manager, Frank Spriggs, had already written to MAP that the firm's 'development team' was eager to start on an engine; 'they have the facilities, knowledge and enthusiasm, and could have something tangible for test within 6 to 9 months.' Spriggs also volunteered ASM production capacity for the H.1 or any other turbojet that was ready for production.[167] Although the firm was never asked to produce the H.1, MAP did ask it to lend a few of its engineers to de Havilland to help the latter build up its aero-engine production organisation.[168]

The RAE volunteered to assist ASM to design an engine similar to the F.2, which it had helped Metrovick to design, and indeed, MAP relied on the RAE's turbine section to supervise the firm's first steps into the new field.[169] As with the F.2, the RAE provided a basic aerodynamic design based on its unique axial compressor expertise, while ASM was responsible for the layout of the unit.[170] The simple axial engine that the firm designed, the ASX, represented an improvement on the F.2, however, in line with the RAE's continuing axial compressor research. The ASX was designed for 2,500 pounds thrust, whereas the F.2 had been designed for closer to 1,500 pounds; the RAE-designed fourteen-stage axial flow compressor of the ASX had the same nine-stage high-pressure axial compressor as the F.2 plus five additional low-pressure stages.[171] The engine's eleven combustion chambers were designed and manufactured by Joseph Lucas but used a different system of vaporising fuel burners designed by Sidney Allen (rather than the atomising fuel burners used by other

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166 NA AVIA 13/911, 14.8.42, ASM visit to RAE; In an interesting departure from the GTCC's collaborative policies, Roxbee Cox argued that a second axial project, similar to the F.2 would be 'consistent with a policy of competition similar to that existing in the reciprocating engine field'; by mid-1942 neither axial engine was expected to reach production during the war. (NA AVIA 13/911, 1.7.42, 43a, Notes for discussion with ASM)

167 NA AVIA 15/1509, 7.8.42, 56B, Letter Spriggs to Bulman

168 NA AVIA 15/1599, 24.8.42, 20, Interdepartmental minute

169 NA AVIA 13/911, 14.8.42, ASM visit to RAE; NA AVIA 13/911, 5.42, Eng/2038-11/SJH/6S, RAE report

170 NA AVIA 13/911, 14.8.42, ASM visit to RAE

171 NA AVIA 13/911, 15.8.42, 55a, Hayne Constant to Roxbee Cox; Constant, 'The Early History of the Axial Type of Gas Turbine Engine', *Proceedings of the Institution of Mechanical Engineers* 153, no. 12 (1945): 421; Lawton, *Parkside*, 71.

British companies) that was unique to ASM.[172] In order to accommodate particularly long combustion chambers, the firm chose a reverse-flow arrangement for their compressor so that the air flowed through the compressor from back to front – an arrangement that later caused serious aerodynamic losses in the engine.[173]

In October 1942, perhaps after lobbying from ASM engineers, including Pat Lindsey who was a key figure in the firm's turbojet work,[174] the RAE approved the company's engine design and suggested to MAP that an order for six jet engines and spares be placed with ASM on the condition that 'technical supervision of the detail design by RAE should be stipulated'.[175] The contract was granted on 7 November 1942.[176] The first ASX unit ran on a converted Deerhound test bed on 22 April 1943 – a record as impressive as de Havilland's with the H.1.[177] In late summer 1943, MAP gave ASM a second contract to begin research on the ASH, a Heppner inspired gas turbine aero-engine with many 'untried features', however the research project was soon given up.[178]

Instead of pursuing a completely new engine design after the single, experimental ASX that it built, ASM decided to use the turbojet unit as the basis for a turboprop, the ASP. By 20 April 1945, the company had completed 22 hours of test running on the new engine.[179] The ASP was developed into the Python under Ministry contract, and in October 1945, it recorded the highest performance of any turboprop in Britain (and far ahead of any piston engine): 3,656 shaft horsepower plus an additional 1,130 pounds jet thrust.[180] Unlike the

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[172] Kay, *Turbojet History and Development*, 118; Gunston, *World Encyclopaedia of Aero Engines*, 20; Lawton, *Parkside*, 71.

[173] NA AVIA 13/911, 18.6.42, Hayne Constant to ASM

[174] Lawton, *Parkside*, 68-71.

[175] NA AVIA 13/911, 6.10.42, Hayne Constant to Roxbee Cox

[176] Gunston, *World Encyclopaedia of Aero Engines*, 19.

[177] NA AVIA 31/3, 15.5.43, GTCC Minutes Meeting #9; The H.1 took 248 days from first detailed drawing to test bed. (Brodie, 'Frank Bernard Halford', 200); Lawton, *Parkside*, 71.

[178] NA AVIA 31/3, 28.8.43, GTCC Minutes Meeting #10

[179] NA AVIA 31/5, 20-21.4.45, GTCC Minutes Meeting #17

[180] NA AVIA 31/5, 12.10.45, GTCC Minutes Meeting #18

Metrovick F.2, the Python was put into limited military service after the war, a striking success for a firm that had had no experience with axial gas turbine engine design before 1942.[181]

Bristol Aircraft Company

In 1939, the engine division of the Bristol Aircraft Company was, alongside Rolls-Royce, one of Britain's most important and accomplished aero-engine firms.[182] It was reluctant to give up its work on piston engines during the war, despite the fact that the firm was already familiar with gas turbines in 1941, when Bristol's Chief Engineer, Roy Fedden, and the head of Bristol's project office, Frank Owner, visited Power Jets's design office at Sir Henry Tizard's suggestion.[183] Owner had had some gas turbine experience before coming to Bristol,[184] and Fedden asked Owner already in 1924 to carry out an investigation of the potential of a turboprop engine as a replacement for piston engines.[185] Owner dismissed the engine type as much too inefficient. He later evaluated the gas turbine aero-engine proposal of Flying Officer Frank Whittle, who approached the company in February 1931, regarding Whittle's scheme as sound in principle but unlikely to become practical for another decade.[186] In the first years of the war, Bristol collaborated with the RAE in testing a six-stage high-speed axial compressor, which was built for the RAE by Fraser and Chalmers, a company that manufactured steam turbines.[187]

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[181] Gunston, *World Encyclopaedia of Aero Engines*, 19.

[182] The piston engine design, development and production capability of Rolls-Royce and Bristol were by far the most significant during the Second World War. (Postan, Hay and Scott, *Design and Development of Weapons*, 26.)

[183] Owner, '9th Barnwell Memorial Lecture,' 1962; NA AVIA 10/261, 20.10.41, Letter Fedden to Linnell

[184] Owner had joined Bristol in 1922 as the company's first university graduate. While at Manchester University in 1920, he had designed a gas turbine. (Gunston, *Fedden*, 86-90.)

[185] Gunston, *Fedden*, 90.

[186] Owner, '9th Barnwell Memorial Lecture'; Gunston, *Fedden*, 244-245 (reproduction of Whittle's letter, 245).

[187] MOSI, 10.9.42, Eng/2038.R/HC/21, RAE report by Hayne Constant

After seeing the work of Power Jets, Fedden's first proposal for using a turbojet for aero-propulsion was to pair it with a piston engine. In a letter dated 20 October 1941, Fedden proposed to MAP that the W.1A (Power Jets' most advanced gas turbine prototype at the time, which produced around 1,400 pounds thrust) serve as an accelerator or additional power plant for Bristol's most advanced sleeve-valve engine, then under development, the Centaurus (designed to produce more than 2,500 pounds thrust at 300 mph). Bristol submitted a brochure for the accelerator project on 4 December 1941, but the opportunity to develop it was never to arise. War work kept the company firmly focused on piston engines.[188] Nevertheless, Fedden asked MAP whether Owner should join the Ministry's newly established GTCC, and Owner duly attended the second meeting of the Committee on 13 December 1941.[189]

Bristol's first turboprop engine scheme was begun at the request of Owner in May-July 1941, who tasked the firm's project office with preparing a proposal for a 4,000 horsepower turboprop with fuel consumption comparable to that of a piston engine at 300 mph and 20,000 feet.[190] This was a significant condition, not only because of the importance of contemporary piston-engine performance as a point of reference, but also because the high fuel consumption of the early turbojets meant they were ill suited to longer-distance or transport flights. The project office's proposal was completed in May 1942 and the engine design by October 1942, yet it wasn't until 7 April 1943 that Owner finally presented a 'definite proposal' for a turboprop to MAP.[191] The project had been suspended when Fedden was forced to leave his position as Chief Engineer in October 1942.[192]

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[188] NA AVIA 10/261, 4.12.41, 14a, Brochure; AVIA 10/261, 2.3.42, 16A, Letter Linnell to Fedden; 2.10.42, 26, Minute Rowe to Linnell

[189] NA AVIA 10/261,4.11.41, 11B, Letter Fedden to Linnell; 2.3.42, 16A, Letter Linnell to Fedden;

[190] Owner, '9th Barnwell Memorial Lecture'; Gunston stated that Fedden initiated work on a turboprop in May 1941. (Gunston, *Fedden*, 252.)

[191] Owner, '9th Barnwell Memorial Lecture'.

[192] Owner explained to Roxbee Cox that 'various non-technical circumstances' had prevented him from presenting the proposal sooner. (NA AVIA 15/1911, 8.4.43, 2B, Report on Visit to Dr Roxbee

The turboprop proposal that Bristol submitted, scaled down to 2,000 horsepower, included several novel features. The unit combined an axial and centrifugal compressor and had two turbines. A propeller was chosen to achieve higher fuel efficiency on long-distance flights. The centrifugal element and turbines drew on the firm's development of a turbo-supercharger for the Hercules engine, which Owner had led in 1937 and 1938.[193] The firm consulted with the RAE on the novel axial component and with Lucas on the fuel system.[194] The centrepiece of the proposal, however, and unique among British projects, was a heat exchanger, which, through recycling heat that would otherwise be lost, offered a solution to the problem of low fuel efficiency in gas turbines.[195] The use of a heat exchanger was in keeping with Bristol's previous design preferences, which had produced piston engine designs with high power and low fuel consumption that used relatively low supercharger boost pressures. The heat exchanger was the solution to the problem of how to achieve similar characteristics in a gas turbine: low fuel consumption and high power despite a low pressure ratio, which was calculated to keep the unit's internal stresses to a minimum.[196] The engine's overall design was dictated by the inclusion of the heat exchanger. In order to allow the heat exchanger to be placed between the streams of combustion and exhaust gases, its air-path passed through two 180-degree bends. Adding a heat exchanger limited the unit's compression ratio to 5:1 - any higher and the compressed-air stream would be too hot for efficient heat exchanger operation.

Cox) Bristol's reputation was built on Fedden's design skill, and it suffered after his departure. (Gunston, *Fedden*, 86) Fedden became an advisor to MAP in various capacities throughout the rest of the war. (Gunston, *Fedden*, 259 and 266-294.)

[193] Owner, '9th Barnwell Memorial Lecture'.

[194] Smith, 1946, 93-94; 'Theseus Air Testing,' *Flight*, 27 March 1947.

[195] The heat exchanger was designed to recapture energy lost in the exhaust stream and return it to the compressed air stream entering the combustion chambers, thereby transferring energy back to the propeller. It was the most unique and attractive element of the proposal to Roxbee Cox. (NA AVIA 15/1911, 8.4.43, 2B, Report on Visit to Dr Roxbee Cox on 7th April 1943)

[196] 'Theseus Air Testing,' *Flight*, 27 March 1947.

Bristol submitted a brochure for their turboprop engine on 15 April 1943. Five days later, Roxbee Cox promised the firm a research contract for experimental work on a heat exchanger, which because of its novelty and mechanical complexity would require a lot of preliminary development work.[197] Bristol opted instead to accept only a manufacturing contract, which covered material for three turboprops.[198]

After Fedden's departure, Owner became the main force behind the turbojet programme at Bristol. His advocacy resulted in the Board's support for the firm's involvement in 'the design and manufacture of gas turbines' at a meeting on 10 July 1943 (two years after the Rolls-Royce Board had made a similar decision).[199] Despite this support, however, Owner struggled to assemble people and resources for his turboprop project.[200] Several key members of Bristol's leadership were reluctant to support the firm's gas turbine work. According to Owner, it was not Fedden, but the firm's Engine Division's managing director and general manager in charge of production who opposed the switch in emphasis to gas turbine engines.[201]

In January 1944, Roxbee Cox, seeing the delays at Bristol, urged MAP that 'a great firm like' Bristol must be allowed to 'gain the necessary experience of gas turbines if it is to continue to fill its important place in the aircraft engine industry'.[202] In early 1944, Stafford Cripps, the Minister of Aircraft Production, gave the firm permission to build its Theseus turboprop, but only on the condition that the project did not interfere with work on the firm's piston engines, which were still needed for the war. Bristol honoured the undertaking

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[197] NA AVIA 15/1911, 8.4.43, 2B, Report on Visit to Dr Roxbee Cox

[198] NA AVIA 15/1911, 9.8.43, Meeting on Gas Turbine policy held at Bristol 5/6 August 1943

[199] Bristol, 'Short History of Bristol Gas Turbine Project', 1943.

[200] At first he recruited men who had just finished work on the design of Fedden's last piston engine, the Orion. (NA AVIA 15/1911, 8.4.43, 2B, Report on Visit to Dr Roxbee Cox)

[201] Owner, '9th Barnwell Memorial Lecture'; Fedden, became well-known for his opposition to the new gas turbine engines and his defence of the piston engine, although he supported the engines after their worth had been proven. (Gunston, *Fedden*, 244 and 251-252.)

[202] NA AVIA 15/1911, 22.1.44, 29A, Letter Roxbee Cox to Jelfs

to Cripps so 'conscientiously' that the staff doing the detail design for the Theseus engine was made up only of six apprentices and trainees borrowed from the main drawing offices.[203]

By 29 July 1944, fifteen months after its initial proposal to MAP, Bristol had begun testing a section equivalent to one-eighth of its heat exchanger, and was in the midst of manufacturing its first turboprop unit.[204] The engine ran for the first time without its heat exchanger on 18 July 1945.[205] When a complete Theseus engine ran in December 1945, fitted with its heat exchanger, the complex device about which the firm had been so hopeful produced a fuel savings of only 8%, and it was subsequently abandoned in favour of a higher compression ratio.[206]

During 1944, MAP tried to encourage work on gas turbine aero-engines by cancelling its contracts for large piston engine projects at Rolls-Royce and Bristol.[207] This should have freed up resources for gas turbine development. In February 1945, MAP decided that it would allow Bristol to drop a large portion of its remaining piston engine work so that the firm could aggressively pursue a gas turbine design.[208] In addition, in mid-1945, the Ministry approved almost half a million pounds for gas turbine plant at Bristol.[209]

Despite MAP's attempts to shift the balance at the firm, Bristol's management remained firmly focused on the Centaurus piston engine and continued to prevent labour

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[203] Owner, '9th Barnwell Memorial Lecture'; The lack of detail designers on the project not only slowed down the design work on the Theseus but caused problems to appear later in development because the early designs were not as thorough as they might have been. (Banks, *I Kept No Diary*, 145; NA AVIA 15/1911, 7.7.45, 41a, ADTED to ADTE Meeting at Bristol on 6.7.45)

[204] NA AVIA 31/4, 27.9.44, GTCC Minutes Meeting #14; The engine's impeller was set up for test on the Northampton test rig and by 17 February 1945, it had been tested for 22 hours. (NA AVIA 31/5, 17.2.45, GTCC Minutes Meeting #16)

[205] Owner, '9th Barnwell Memorial Lecture'; Gunston, *World Encyclopaedia of Aero Engines*, 36.

[206] While the Theseus design was being completed, Owner diverted an engineer from the already small turbine staff, Charles Marchant, to begin work in September 1944 on a new private venture that would become the Proteus turboprop. Once again, low specific fuel consumption and high efficiently were its key features, but it used a higher-pressure ratio rather than a heat exchanger. (Owner, '9th Barnwell Memorial Lecture'; Kay, *Turbojet History and Development*, 139.)

[207] The cancelled engines were rated between 4,000 and 5,000 horsepower. (Banks, *I Kept No Diary*, 144-145.)

[208] NA AVIA 15/1911, 14.2.45, Minute Watt to Banks; Banks, *I Kept No Diary*, 145.

[209] NA AVIA 15/1911, 25.7.45, Notes

from being transferred to Owner's gas turbine group. In July 1945, for example, personnel which the firm had promised to switch from piston engine to gas turbine work had either arrived late or were not transferred at all.[210] When a significant part of the firm's turboprop staff left the company at the end of the war, Owner lost much of the design expertise that he had managed to build up; the staff members who replaced them had no experience with turbines of any sort.[211] Bristol's reputation for aero-engine design, which had declined with Fedden's departure, was only rebuilt in gas turbines after assistance from MAP and Stanley Hooker, who joined the firm in 1949. In the mid 1950s, Bristol once again passed de Havilland and ASM to become one of Britain's two remaining aero-engine firms.

D. Napier & Son

Napier was, like ASM, one of Britain's second-rank aero-engine firms, and it was the last of Britain's aero-engine companies to enter the gas turbine field. The firm started the war bogged down with Sabre piston engine development and production, which prevented it from diverting resources to any other project, and in December 1942, Napier was taken over by English Electric.[212] During 1944, MAP encouraged Napier to enter the gas turbine field as part of the Ministry's effort to rationalise the aero-engine industry's remaining work on piston engines and to make sure that every one of Britain's aero-engine firm made a 'contribution to British gas turbine progress'.[213] Rather than a pure jet unit, more suited to war than peace-time markets, Napier's proposal was for a power plant that would combine a very high-powered, two-stroke diesel piston engine (English Electric specialised in diesel engines[214]) with an axial gas turbine. Each half of the engine was to drive half of a contra-rotating propeller pair. MAP issued a specification for the engine on 21 August 1944. Known

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[210] NA AVIA 15/1911, 7.7.45, 41A, Interdepartmental note, Meeting at Bristol on 6.7.45

[211] Owner, '9th Barnwell Memorial Lecture.'

[212] The takeover was encouraged by MAP, which was increasingly dissatisfied with Napier's organisation. (Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 345.)

[213] Banks, *I Kept No Diary*, 144; NA AVIA 10/222, 2.5.45, 64, Note by F.R. Banks, Development Plant for Napier E.124/125 Engines

[214] Wilson and Reader, *Men and Machines*, 163.

as the E.124, the engine was projected to reach an impressive 6,000 horsepower (the Sabre produced 3,000 horsepower at its best).[215]

The E.124's design goals reflected the need for a very high-powered aero-engine identified by the Brabazon Committee, which was formed during the war to plan for the post-war needs of British civil aviation.[216] Because of its low projected fuel consumption,[217] which due to the gas turbine element was expected to be lower than for a comparable diesel piston engine, the E.124 appealed to MAP for long-range military and civil aircraft.[218] Indeed, the Ministry saw the engine as a 'most attractive' addition to the national gamut of aero-engine development, which not only would allow the firm to remain competitive with other aero-engine firms, but might prove to be one way that piston engines of higher powers might be able to compete with pure turbojets.[219]

Because Napier planned to use an axial gas turbine in their dual engine, the firm requested and was assured access to all available knowledge on gas turbines and axial flow compressors. By 1944, the provision of such information and assistance to the industry was a matter of course. Napier was also enthusiastic to receive information on Germany's axial gas turbines as it became available.[220] To help the firm start its new work, the government paid for extensive facilities for gas turbine research and development at Napier's Liverpool

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[215] NA AVIA 15/2106, 21.8.44, Specification; By 1946, this had been reduced to 3,000 horsepower. (Charles Wilson and William Reader, *Men and Machines: a History of D Napier & Son Engineers Ltd 1808-1958* (Weidenfeld and Nicolson, 1958), 163.)

[216] Quote from NA AVIA 10/222, 2.5.45, Document 64; NA AVIA 15/2106, 24.8.44, 2, Minute Banks to Sorley; NA AVIA 15/2106, 13.1.45, Letter Curzon to Trend

[217] 0.34 lb/BHP/hr (AVIA 15/2106, 24.8.44, 2, Minute Banks to Sorley)

[218] NA AVIA 15/2106, 13.1.45, Letter Curzon to Trend

[219] NA AVIA 15/2106, 8.9.44, 4, Minute Sorley to Banks

[220] NA AVIA 15/2106, 11.8.44, Conference; 22.8.44, 1a, Letter Napier to Banks

shadow factory.[221] The firm's representatives were included for the first time at the fifteenth meeting of the GTCC on 11 November 1944.[222]

Napier began work on the E.124 in early 1945 with research into two-stroke compression ignition cycles (including both sleeve and poppet valves) and preparing designs for the constituent parts of the gas turbine section of the engine. In fact, the E.124 was never realised. The design – including its axial compressor - evolved however into two post-war engines: a high-economy, two-stroke engine with an axial turbo-supercharger known as the Nomad and Britain's first axial turboprop, known as the Naiad. Neither was very successful commercially; it was only after about a decade of work that the firm produced a competitive gas turbine engine.[223]

The German aero-engine industry

As is well known, turbojet development in Germany was different than in Britain or the United States because the policy of the German Air Ministry dictated that the aero-engine industry should be the main site for that country's development of turbojets.[224] Thus although German piston engine makers were less advanced than their British counterparts in the late 1930s,[225] the entire German aero-engine industry had already embarked on developing turbojets before the start of the war. At the end of the war, both Britain and Germany's entire aero-engine industries were developing turbojets, but in Britain there was a gradual movement of aero-engine firms to work on the new engine type as piston engine development wound down, whereas in Germany the whole aero-engine industry began developing the new engines at the same time and concomitantly with important piston

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221 Wilson and Reader, *Men and Machines*, 162; Early cost estimates ranged from half a million to one million pounds. (NA AVIA 10/222, 2.5.45, 64, Napier development plant for Napier E.124/125 Engines); 4.5.45, 64a, Extracts from Air Supply Board Meeting

222 NA AVIA 31/4, 11.11.44, GTCC Meeting Minutes #15

223 Banks, *I Kept No Diary*, 172.

224 Schelp's testimony. (Joseph J. Ermenc, *Interviews with German Contributors to Aviation History* (Westport; London: Meckler, 1990), 113.)

225 Schlaifer and Heron, *Development of Aircraft Engines*, 387.

engine development. The chief exception to the aero-engine industry's central role was the work of the Heinkel Aircraft Company, which will be dealt with in the next chapter; the airframe company never managed to become an aero-engine manufacturer, even after acquiring a small aero-engine firm, Hirth Motors, in 1941.

A further peculiarity of the German story is that all of the major aero-engine firms ultimately decided to develop axial turbojets, which favoured higher engine powers than centrifugal engines. There was nothing inevitable about the choice of axial turbojets, and several German firms designed alternatives.[226] Yet the ultimate preference for axial compressors is important because whereas many British firms could rely on their own experience with centrifugal compressors, German firms could not exploit as many continuities with piston engine work as their British counterparts. Nevertheless, those firms that made more use of existing expertise – whether in-house or externally - were able to develop turbojets more quickly.

Particularly important in this regard was the Aerodynamische Versuchsanstalt (AVA) in Göttingen, an aerodynamic research institute that moved to the centre of Germany's work on axial compressors. The AVA was reorganised under RLM auspices in 1937, and it carried out extensive research for the aeronautical industry during the war. Its work on turbo machinery primarily included axial compressors for superchargers and gas turbines.[227] During the war, the AVA became Germany's leading source of axial turbine expertise to a greater extent and earlier than the RAE in Britain, where centrifugal turbojets were more extensively developed.

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[226] Schlaifer contradicted the common misconception that the use of axial compressors was dictated by the German government, which has nevertheless continued to circulate. (Schlaifer and Heron, *Development of Aircraft Engines*, 435-436.)

[227] Hirschel, Prem and Madelung, *Aeronautical Research in Germany*, 79-81; In contrast to the work of another research establishment, the Deutsche Versuchsanstalt für Luftfahrt, exclusively on centrifugal compressors. (Ermenc, *Interviews with German Contributors*, 111.)

Despite the leading place of German work in general studies of the turbojet, the history of the development of turbojets in Germany has been only briefly discussed in professional works on the country's aero-engine industry. The historian Lutz Budraß discussed the industry's war record, paying particular attention to Jumo, but spent little time on the turbojet. Excellent company histories of BMW and Daimler-Benz that cover the war period have been written by Werner and Gregor.[228] While Werner discussed the details of the development and production of the 003 at different points in her narrative, using new archival sources to give the view of BMW's administration, Gregor didn't mention Daimler-Benz's work on jet engines at all. A history of Daimler-Benz published by the firm, in contrast, gave the history of the entire aero-engine industry's work on turbojets to set off a brief section on the firm's turbojet work, which defended the superiority of the firm's first engine design over the engines developed by Jumo, BMW and Heinkel.[229]

The literature on the German aero-engine industry and the turbojet is in some ways more detailed than that on Britain. The comprehensive accounts written by von Gersdorff, Grasmann and Wagner, gave detailed descriptions of the different engines developed by each company, although they rarely made explicit arguments.[230] My account relies not only on the details available in existing literature, including Werner's recent historical research, but also on the memoirs of participants like Anselm Franz and new archival evidence from the German national archives and the archives of Daimler-Benz and the AVA.

This section offers a new interpretation of the success of Jumo and BMW. I will show that Jumo was successful because it chose a conservative design that intentionally exploited continuities. BMW, which decided to rely more on building up in-house expertise,

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[228] Lutz Budraß, *Flugzeugindustrie und Luftrüstung in Deutschland 1918-1945* (Droste, 1998); Werner, *Kriegswirtschaft und Zwangsarbeit bei BMW*; Neil Gregor, *Daimler-Benz in the Third Reich*, (New Haven, Conn.; London: Yale UP, 1998).

[229] Harry Niemann, Wilfried Feldenkirchen, and Armin Herman, *Gasturbinen und Flugtriebwerke der Daimler-Benz AG 1952-1960* (Heel Verlag GmbH, 2004), 46-54.

[230] von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke*; Wagner and Cox, *First Jet Aircraft*; Kay, *German Jet Engine and Gas Turbine Development.*

took longer to develop a production turbojet engine. In the case of BMW, my analysis stresses the contribution of Bramo's design team to the firm's turbojet. This continuity has been noted by historians, including Constant and Schlaifer,[231] but neither has emphasised the importance of the ethos of Bramo's programme in shaping the turbojet programme at the piston-engine-centred BMW.

This chapter will also give a new understanding of Daimler-Benz's supposed failure, in contrast to existing historical accounts of the turbojet, which dismiss the firm's turbojet work. Constant disparaged the firm's 'impossibly slow progress' in the fall of 1943, when its 007 engine was cancelled,[232] while Schlaifer characterised the Daimler-Benz project as being practically moribund by 1942. He argued that the firm's interest picked up in 1943, when it was assigned to assist Heinkel-Hirth with their turbojet but only because of the production contracts given to Jumo and BMW.[233]

Junkers Motorenwerke

The first aero-engine firm to begin the series production of turbojet engines was Junkers Motoren. The company's turbojet programme was headed by Dr Anselm Franz.[234] Franz had had an extensive background in turbo-machinery before joining Jumo, and in the late 1930s, headed a small department at the firm, which was in charge of aerodynamics and supercharger development. He also led the firm's efforts to improve piston engine performance by ducting engine exhaust to produce useful thrust.[235]

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231 Schlaifer and Heron, *Development of Aircraft Engines*, 390; Constant, *Origins of the Turbojet Revolution*, 212.

232 Cosntant, *Origins of the Turbojet Revolution*, 213.

233 Schlaifer and Heron, *Development of Aircraft Engines*, 402.

234 Otto Mader, head of development at Jumo until 1944, who put Franz in charge of the programme is often known as a reactionary. Yet he was reluctant to begin work on a turbojet because of the fear that the work would detract from the company's piston engine work. (Franz, *From Jets to Tanks*, 11; DM NL172/2, 8.81, Wagner, Bemerkungen zu Heinkels Darstellung) Franz is one of the few who defended the RLM's policy of placing turbojet contracts preferentially with aero-engine firms. (Franz, *From Jets to Tanks*, 11.)

235 Franz, *From Jets to Tanks*, 16; Wagner and Cox, *First Jet Aircraft*, 235-236; A common idea at the time, directing the exhaust of a piston engine through carefully designed nozzles could add a significant amount of thrust. In 1940, Franz was awarded a PhD by TH Berlin for a thesis on exhaust

Rather than make use of the axial turbojet design that was under private development at the Junkers Airframe Company (which had become allied with Jumo under government ownership),[236] Franz chose to begin his own axial turbojet design, which would stay close to existing expertise. He settled for lower performance goals in order to get the engine to the point of production as soon as possible.[237] Limited time and resources dictated that Franz's group collaborate with outside experts.

Franz chose to use an axial compressor for Jumo's gas turbine, the 109-004,[238] because he considered a smaller frontal area essential for high-speed flight. A centrifugal turbojet would suffer much more drag. Unusually, the firm had some experience with axial compressors, for it had earlier developed an axial flow supercharger with the design help of the Walter Encke of the AVA. The eight-stage axial compressor for the Jumo turbojet was Encke's first multi-stage axial compressor.[239]

Franz's team developed its own combustion system – there was no ready source of expertise with turbojet combustion systems as in Britain - and opted for six individual combustion chambers, which were smaller and easier to test than the annular chamber that Franz might have preferred.[240] Because it had only developed geared superchargers in the

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jet development. (E.-H. Hirschel, H. Prem and G. Madelung, *Aeronautical Research in Germany: From Lilienthal until Today* (Springer, 2004), 232); Jumo had done earlier work on free piston engines, in which a piston engine was used not to produce shaft power but to produce a high-energy exhaust stream. (CIOS XXIV-6, Gas Turbine Development, Franz interrogation)

[236] It has been claimed that Jumo's axial engine came from the work of a turbojet design team led by Dipl-Ing Max Adolf Müller that worked at the Junkers Airframe Company between the mid 1930s and 1939. (For example: Constant, *Origins of the Turbojet Revolution*, 202) Franz consistently contradicted this allegation. (Franz, 'Development of the "Jumo 004" Turbojet Engine'; Franz, *From Jets to Tanks*, 13) Franz did try to convince the members Müller's group to join Jumo. Only the team's skilled materials specialist, Dr Heinrich Adenstedt, stayed on. (DM NL172/2 Franz, Vortrag auf der DGLR-Jahrestagung 1981; Schlaifer and Heron, *Development of Aircraft Engines*, 396) Before the team's departure, Franz did however engage in a four week exchange of information with Müllers' group that was 'intensive and without reservation'. (DM NL172/2)

[237] Franz, *From Jets to Tanks*, 26-27.

[238] The 109- prefix and numbering system was an RLM system that was modified during the war.

[239] NASM VO, Box 16, 463; Wagner and Cox, *First Jet Aircraft*, 31.

[240] Because the firm did not have the necessary power to test the compressor or turbine apart from the engine, it tested its engine (combustion chambers aside) only as a complete unit. Franz attempted

interwar period, and thus had no experience with turbines, the firm called on the help of the steam turbine builders at the Allgemeine Elektricitäts-Gesellschaft to design the 004's turbine. The engine's elaborate jet nozzle, which had a moving centre cone to vary its cross-sectional area - a feature unique in Germany and Britain, was a product of Franz's earlier, detailed studies of piston engine exhaust jet propulsion.[241] The engine's conservative design paid off and the first prototype ran in November 1940, although it was not sufficiently reliable to power an airframe, the Me 262, until 18 July 1942.

Jumo's first turbojet team was small. In the late 1930s, the firm was overwhelmingly committed to piston engine development, and Franz struggled to find people at the company to work on his new project. The core of his early turbojet design group was a few people from his aerodynamics department plus some recent graduates who were gradually recruited from universities and colleges.[242] As in Britain, young recruits were not necessarily favoured because they were better-trained or less committed to piston aero-engines, but because they were available. Franz later praised his youthful team, but insisted on the importance of his group's 'engineering talent and scientific knowledge', which was the product of experience.[243] Although he struggled to find team members, Franz's work was able to proceed thanks to the essential support of the company's experimental shop in building early turbojet prototypes.[244]

During the war, the firm's commitment to the turbojet grew dramatically. From virtually nothing, Franz' team at Dessau grew to about 500 engineers, scientists and mechanics in early 1943 (including staff in the experimental shop).[245] Franz recalled that by

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to carry out scale tests of a model compressor, but this failed spectacularly. (Franz, *From Jets to Tanks*, 21-22.)

[241] Franz, *From Jets to Tanks*, 18-20; CIOS XXIV-6, Gas Turbine Development

[242] Franz, *From Jets to Tanks*, 16.

[243] Franz, *From Jets to Tanks*, 26-27.

[244] Franz, *From Jets to Tanks*, 17.

[245] Franz, *From Jets to Tanks*, 17; Schlaifer and Heron, *Development of Aircraft Engines*, 419.

September 1944, when the firm's turbojet was in production, the opposition that he had initially faced had disappeared.[246] At the end of 1944, the firm's turbojet development section in the Otto Mader Works (where development was separate from production) reported having 580 people on 'pure' development, 134 who were busy on development relating to pre-production, and an additional 70 engaged in development to do with large-series production. For comparison, at the same time, piston engine development engaged 815 on 'pure' development, 186 on pre-production development and only 25 on large series production - a total of 1,026 workers against 794 on jet work. These officially reported figures must be treated with some scepticism, but, however inaccurate, they indicate the shift in the firm's development focus. The different weighting of design and workshop work for the two engine types suggests both the greater maturity of the reciprocating engines and the greater ease of construction and relatively greater amount of design work necessary for the new engines.[247] At the end of the war, Jumo was still developing piston engines on a large scale, but a similarly large team had been transferred to turbojets. The firm's turbojet organisation emerged from a long-standing piston engine organisation, but it reflected the unique problems of the new engines. According to the same company statistics, during the war, the firm's development activity overall increased: the number of people working in the development section at Dessau increased dramatically from around 757 in January 1938 to 1,600 in early 1942 to 2,760 at the end of 1944.[248]

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[246] Franz, *From Jets to Tanks*, 17. Franz, like Hooker at Rolls-Royce and Oestrich at BMW, was most important as a technically adept manager, who guided Jumo's work.

[247] Piston engine design represented 4% of the piston engine development work force, experimental work 34% and the workshop 42%. Jet engine work, in contrast, was about 11% design, 34% experimental, with only 29% in the workshop. These figures include foreign workers, mostly workers from Belarus ('white Russians'). (IWM FD 5400/45, Jumo Report, TL-Geräte 004 B-1/4 Neubau und Reperatur; Vadja and Dancey used the same source, but leaves out foreign workers. (Franz-Antal Vajda and Peter Dancey, *German Aircraft Industry and Production, 1933-1945* (Shrewsbury: Airlife, 1998), 242-243) The use of foreign workers was approximately 28% in piston engines and 21% in jets.

[248] Edward Homze, *Arming the Luftwaffe: The Reich Air Ministry and the German Aircraft Industry, 1919-39* (University of Nebraska Press, 1976), 186.

Because of its conservative design, 109-004's axial compressor needed more stages than other designs to reach its compression ratio of 3.14, but the engine's initial design was never seriously changed.[249] Sacrificing performance for quick development based on existing expertise was a successful strategy that assured the engine's place in the RLM's production planning. Franz was extremely proud that the Jumo 004 was the first German engine to reach production.[250] As the company's production version of its turbojet engine, the 109-004B, went into production, the Otto Mader Works began to develop a range of different versions of its turbojet engine, experimenting with fuel injection, after-burning, and more intense combustion. Free design capacity began work on the design of a more powerful engine, the 109-012, and a corresponding turboprop, the 109-022, although neither was ever built.[251]

Bayrische Motoren Werke

The second German aero-engine company to successfully develop a turbojet during the war was the Bayerische Motoren Werke (BMW). BMW's wartime turbojet programme was formed from two earlier turbojet programmes, that of BMW and that of the Brandenburgische Motorenwerke (Bramo), which BMW took over in 1939.[252] Before the merger, BMW's development section was already the largest of the major aero-engine firms. After taking over Bramo, the number of workers in the firm's development department was more than twice as large as that at either Jumo or Daimler-Benz.[253]

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[249] Bentele, *Engine Revolutions*, 45-46.

[250] Franz, *From Jets to Tanks*, 13.

[251] Franz, *From Jets to Tanks*, 38.

[252] Lutz Budraß, 'Hans Joachim Pabst Von Ohain. Neue Erkenntnisse zu Seiner Rolle in der Nationalsozialistischen Rüstung.' in Friedrich-Ebert-Stiftung, Landesbüro Mecklenburg-Vorpommern (Hg.): Technikgeschichte Kontrovers: Zur Geschichte des Fliegens und des Flugzeugbaus in Mecklenburg-Vorpommern., (Schwerin, 2007), 52-69; Horst Mönnich, Anthony Bastow and William Henson, *The BMW Story: A Company in Its Time* (London: Sidgwick & Jackson, 1991), 232-234; The purchase was encouraged by the RLM as part of its efforts to rationalise aero-engine development. (Homze, *Arming the Luftwaffe*, 27.)

[253] In late 1938, BMW and Bramo's development sections had about 1,794 workers together (1,053 at Munich and 741 at Spandau) against 757 at Junkers Dessau and 441 at Daimler-Benz Stuttgart-Untertürkheim. In 1938, Bramo, which had been taken into government control in 1936, was the

Bramo's turbojet programme was more extensive and ambitious than BMW's. The firm had eagerly accepted a turbojet development contract from the RLM in August 1938, after the Ministry had threatened to stop Bramo's piston engine development funding earlier that year.[254] Bramo's turbojet programme was put under the leadership of Dr Hermann Oestrich, who had earlier worked on both high altitude piston engines and jet propulsion.[255] Based on his previous experience, Oestrich began researching jet propulsion rather than gas turbines. His group first built a motor jet, in which a Bramo piston engine powered a compressor, which pumped compressed air into a combustion chamber where it was ignited to form an exhaust stream. Demonstrating the speed with which such combination of existing parts could be built, the Bramo motor jet was test flown in a biplane at Rechlin before the end of 1938.[256]

Bramo abandoned its motorjet project early in 1939 and focussed on a contra-rotating axial turbojet, which it had calculated would give the best results in a turbojet unit in terms of weight and size.[257] The RLM put the firm in touch with the independent engineer Helmuth Weinrich, who had in 1936 submitted a proposal for a counter-rotating turboprop engine to the RLM, and Bramo's first turbojet design was an ambitious, contra-rotating axial engine to Weinrich's design.[258] In December 1938, it received the government number 109-002.[259] To support the development of the 002, Bramo initiated work on a simpler axial turbojet. The firm's piston engines used centrifugal, geared superchargers, so Bramo like

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smallest of the four major German manufacturers by both employment and market share (12.4%). BMW was just ahead, representing 13.8% of the aero-engine industry. (Homze, *Arming the Luftwaffe*, 186-188.)

[254] Schlaifer and Heron, *Development of Aircraft Engines*, 388-390 and 411.

[255] Wagner and Cox, *First Jet Aircraft*, 244.

[256] Wagner and Cox, *First Jet Aircraft*, 237-238.

[257] Schlaifer and Heron, *Development of Aircraft Engines*, 389-390.

[258] Its contra-rotating blades were mounted half on an internal and half on an external cylinder. After his collaboration with Bramo, Weinrich became a consultant for Brückner-Kanis, a steam turbine company that worked on a marine gas turbine based on Weinrich's ideas. His career indicated the wide interest in gas turbines for air, land or sea traction in Germany, which did not arise in Britain or the United States. (Kay, *German Jet Engine and Gas Turbine Development*, 97 and 179.)

[259] Gunston, *World Encyclopaedia of Aero Engines*, 30.

Jumo relied on the AVA to design the simple axial engine's six-stage compressor and its axial turbine.[260] The firm began developing a unique annular combustion chamber from scratch in 1938, which it continued to develop throughout the war, and which eventually featured in the BMW 003 axial turbojet (the only annular chamber of the war).[261]

BMW began its turbojet programme at the RLM's request in 1938, although the firm's managing director, Franz Josef Popp, made sure that the firm's focus remained firmly on improving its piston engines. Kurt Löhner, who led BMW's early turbojet programme, was the head of BMW's 'research department' and, in contrast to Oestrich at Bramo, was responsible for the firm's studies of both new gas turbine engines and new piston engines. In order to quickly assemble a turbojet engine, Löhner decided to create one from components that BMW was already familiar with.[262] His first plan, known as BMW P.3303, re-used the main components of BMW's earlier exhaust turbo-supercharger: the turbojet had two centrifugal compressors and an axial, hollow-blade, air-cooled turbine based on the work of the firm's turbine expert, Dr Alfred Müller.[263]

At the end of September 1939, BMW purchased Bramo and its turbojet programme.[264] Because Popp wanted to concentrate piston engine development at BMW's main works at Munich-Allach, the firm's small turbojet programme was transferred to join Bramo's group at Spandau, and Oestrich was put in charge of the joint turbojet programme.[265] The single axial jet programme forged from BMW and Bramo's programmes included both the contra-rotating 109-002 (BMW P. 3304) and a simple axial engine, soon

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[260] Wagner and Cox, *First Jet Aircraft*, 239.

[261] Kyrill von Gersdorff and Kurt Grasmann, *Flugmotoren und Strahltriebwerke: Entwicklungsgeschichte der Deutschen Luftfahrtantriebe von den Anfangen bis zu den Internationalen Gemeinschaftsentwicklungen*, Second Edition (Koblenz: Bernard & Graefe, 1985), 195-197.

[262] Schlaifer and Heron, *Development of Aircraft Engines*, 389.

[263] When he left BMW in 1944, Müller began promoting the use of gas turbines for land traction, especially in tanks. (Kay, *German Jet Engine and Gas Turbine Development*, 156-157.)

[264] Wagner and Cox, *First Jet Aircraft*, 237; Schlaifer and Heron, *Development of Aircraft Engines*, 411 fn 47.

[265] Budraß, 'Hans Joachim Pabst Von Ohain'; Schlaifer and Heron, *Development of Aircraft Engines*, 401.

given the Ministry number 109-003. The 003 was based on Bramo's earlier axial design and incorporated some elements from BMW's first turbojet: it combined the AVA designed axial compressor, Bramo's annular combustion system and BMW's air-cooled axial turbine.[266]

In mid-1940, after poor initial results, Oestrich's team decided to redesign the axial turbojet.[267] Because of the combined resources of BMW and Bramo, the group could afford to build up its in-house expertise in order to pursue a more ambitious design, but the decision put the firm's turbojet a year and a half behind Jumo's. In the new design of its axial engine, Spandau expanded its own capabilities and called on additional expertise to augment its own. After relying on the AVA for the design of their first axial compressor, the firm had worked to build up a calculation section to allow it to design its next axial compressor itself. In the redesign, the firm used an axial compressor that it had designed itself using aerodynamic profiles published by the American National Advisory Committee for Aeronautics (NACA) with corrections according to AVA research.[268] BMW's new compressor had a higher-pressure ratio than the AVA compressor it replaced, and it added approximately 300 pounds of thrust to the engine.[269] For this reason one member of the firm could claim in an interrogation after the war that the team had received in the 003 design 'no significant help from national research organisations whose work in this field was considered ineffective.'[270]

BMW developed the fuel burners for its annular combustion chamber at Spandau with the help of Henschel and the Luftkriegsakademie at Gatow, which provided the firm with information about Jumo's fuel-air mixing system.[271] In the interest of rushing the 003

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[266] CIOS XXIV-6, Gas Turbine Development; Schlaifer and Heron, *Development of Aircraft Engines*, 401.

[267] Wagner and Cox, *First Jet Aircraft*, 239.

[268] von Gersdorff and Grasmann, 1985, 197.

[269] Wagner and Cox, *First Jet Aircraft*, 239.

[270] CIOS XXIV-6, Gas Turbine Development

[271] Wagner and Cox, *First Jet Aircraft*, 239.

into production, the RLM later urged BMW to use the superior Jumo fuel regulator rather than its own partially developed system.[272] By the end of the war, the Jumo and BMW combustion systems were similarly efficient, but the lifetime of Jumo's system was much less. BMW's team also worked to improve on the firm's original air-cooled turbine with the help of industrial firms, including the steam turbine makers Brown Boverei Cie and Brückner-Kanis and the mechanical engineering company Maschinenfabrik Augsburg-Nürnberg (MAN).[273]

By mid 1942, the 109-003A-0 design was complete and the firm began developing a production version of the engine.[274] Government demand for production of the 003 virtually halted the firm's work on long-range designs, and kept its attention instead on 'immediate development problems'.[275] In the last years of the war, the turbojet section moved more than once,[276] but after the 109-003 design was reasonably secure, the section turned its design efforts to the new, more powerful engines that the RLM had already asked BMW to design.[277]

By the end of the war, BMW had assembled the largest turbojet development section in Germany. In 1939, about 40 people ('designers and engineers') had been engaged entirely on turbojet work at Spandau, sharing the factory's experimental shops and test facilities with piston-engine development; perhaps half of these were working on the 109-002 and half on

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[272] von Gersdorff and Grassman, *Flugmotoren und Strahltriebwerke*, Second Edition, 200.

[273] Kay, *German Jet Engine and Gas Turbine Development.*

[274] Schlaifer and Heron, *Development of Aircraft Engines*, 413-415.

[275] CIOS XXIV-6, Gas Turbine Development

[276] After Spandau was bombed in late 1943, the firm's turbojet development section was moved to Wittringen (Saarbrücken) and then, after the liberation of France in August 1944, to Neu Staßfurt (code-name Kalag). (CIOS XXIV-6, Gas Turbine Development; Werner, *Kriegswirtschaft und Zwangsarbeit bei BMW*, 347.)

[277] The first was the 109-018, a large turbojet with a twelve-stage axial compressor, annular combustion system with 24 burners, and three turbine stages. In addition, the RLM had contracted for a 018 turbojet outfitted with contra rotating propeller driven by an extra turbine stage (requiring two spools – the country's first compound gas turbine), known as the 109-028. (Oestrich, 'Die Entwicklung der Fluggasturbine bei den Bayrischen Motorenwerken') Neither engine got very far.

Bramo's simple axial.[278] By 1942, the RLM had cancelled the 002 engine and the turbojet staff working on the BMW 003 had grown to about 100.[279] The dedicated turbojet engineering and design team had grown to about 400 by 1945. At the same time, the number of people working on turbojets in the machine shop increased from about 700 in 1942, when piston engine work finally ceased at Spandau, to 1,000 in 1945.[280] Because there were few external sources of trained engineers, the section's growth came largely from the firm's piston engine department.[281]

The RLM came to see the BMW 003 and Jumo 004 turbojets as alternatives. The more technically challenging 003 lagged behind the conservative 004 in readiness for production, but it reached production before the end of the war. The technical sophistication of BMW's turbojet occasionally contributed to the 004, in the latter's hollow turbine blades, for example. By the end of the war, BMW's turbojet team had the most extensive facilities and axial turbojet expertise in the German aero-engine industry.

Daimler-Benz

Despite its limited development capacity, Daimler-Benz undertook research into turbojets, like Jumo and BMW, in autumn 1938 at the RLM's request. One of Germany's most successful aero-engine firms, the company was already developing piston engines for land, sea and air, yet its development capacity was much smaller than that of any of other major aero-engine maker in Germany. In 1938, Daimler-Benz's development section at Stuttgart employed less than two-thirds as many workers on development as Jumo and less than half

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278 Kay, *German Jet Engine and Gas Turbine Development*, 97-98.

279 Wagner and Cox, *First Jet Aircraft*, 239.

280 This was a consequence of the RLM taking over the firm's development programme in 1941 in the wake of a technical crisis at the firm brought on by Popp's handling of the firm's piston engine development. (Werner, *Kriegswirtschaft und Zwangsarbeit bei BMW*, 68; Mönnich, Bastow and Henson, *The BMW Story*, 234.)

281 A significant number of people offered 'miscellaneous help' in the engineering department; a number that more than doubled from 200 in 1942 to 500-600 in 1945. (Wagner and Cox, *First Jet Aircraft*, 241; Schlaifer and Heron, *Development of Aircraft Engines*, 415-416.)

the number employed by BMW (and only a quarter of the joined Bramo-BMW development staff).[282]

After a survey of ramjets and turbojets,[283] Daimler-Benz agreed with the RLM that a high-powered bypass turbojet (Zweikreis-Turbine-Luftstrahl Triebwerk) would be the most appealing addition to the national turbojet programme. The proposed Daimler-Benz engine was to produce 3,000 pounds thrust, in contrast to the simple axial turbojets of the 2,000-pound class under development at BMW, Jumo and Bramo, and aimed to achieve lower fuel consumption than the other axial engines. Choosing a higher-powered engine also made sense according to the master plan devised by man most directly responsible for turbojet development at the RLM, Helmut Schlep (as outlined in Chapter 2), because it would give the busy firm a longer time to develop the more challenging engine; the Jumo and BMW engines would be completed and tested first. Because of Daimler-Benz's many commitments and its small development facilities, the firm devoted relatively little of its limited labour to the project and depended on the development work of outside contractors.

The firm entrusted the design of their ducted fan engine to Karl Leist, who had recently joined the firm from the RLM's research centre in Berlin-Adlershof, the Deutsche Versuchsanstalt für Luftfahrt (DVL), where he had done research on turbine cooling, which the DVL had sponsored as part of its work on centrifugal exhaust turbo-superchargers.[284] Researchers at the DVL had tried two systems for turbine cooling. The first system provided cooling air through hollow turbine blades – as used by BMW and later Jumo. The second was a system of partial-impingement pioneered by Leist, whereby the turbine blades were

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[282] Homze, *Arming the Luftwaffe*, 186.

[283] von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke*, Second Edition, 151.

[284] Ermenc, *Interviews with German Contributors*, 111-112; The DVL's work was directly used by the country's aviation industry: Bramo, BMW, and Daimler-Benz in their own turbo-superchargers. (Hirschel, Prem and Madelung, *Aeronautical Research in Germany*, 244-245.)

only exposed to high-temperature exhaust gases for a fraction of each rotation. When not in the hot gases, the blades were cooled by passing through a stream of cold air.[285]

The complex design of Daimler-Benz's 109-007 was heavily influenced by Leist's work on partial-impingement, which he chose to cool the engine's turbine.[286] The engine's ducted fan provided a stream of unheated air to cool the turbine. The cooling system, furthermore, required an asymmetric combustion chamber arrangement so that the turbine was only subject to hot gas from the combustion chambers, which were built by Henschel, during 70% of its rotation.[287]

To increase the engine's power (in part because only 70% of the turbine was extracting heat from the hot gas flow at any given time) and to decrease the engine's fuel consumption, Leist chose a high compression ratio of 8:1. This was only possible with an axial compressor, and Daimler-Benz consulted, like Jumo and Bramo, the experts at the AVA to design the 007's axial compressor. The two parties met for the first time on 4 October 1939.[288] They settled on a seventeen stage contra-rotating axial compressor to achieve the required high-pressure ratio in a short distance. The compressor was, like Weinrich's compressor, made up of two counter-rotating drums.[289]

On 29 January 1940, Daimler-Benz submitted a scheme to the RLM for its ducted-fan, noting that the provision of labour for design and construction would be decisive ('ausschlaggebend') to the work. On 5 March 1940, the RLM gave Daimler-Benz an intent to

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[285] A third possibility, that of cooling the turbine's surface was used by Sanford Moss at GE. (von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke*, Second Edition, 154-5.)

[286] The engine's complexity is the factor most frequently cited as the reason for its cancellation. (Schlaifer and Heron, *Development of Aircraft Engines*, 387; Kay, *German Jet Engine and Gas Turbine Development*, 145; von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke*, Second Edition, 204-205; Niemann, Feldenkirchen, and Herman, *Gasturbinen und Flugtriebwerke der Daimler-Benz AG*, 50-52.)

[287] CIOS XXIV-6, Gas Turbine Development; BA MA RL3/4399, 5.10.43, Minutes ZTL-Entwicklungssitzung

[288] GOAR 3619, 6.10.39, Letter Daimler-Benz an Betz; 30.10.39, Letter Daimler-Benz an Encke (AVA)

[289] The outer cylinder, geared so as to rotate at half of the speed of the inner one, carried half of the compressor the stages facing inwards and the ducted fan's blades facing outwards. (CIOS XXIV-6, Gas Turbine Development)

purchase ('Vorbescheid') for five ducted-fan turbojet engines, number 109-007, which was confirmed with a contract on 29 July 1940.[290]

On 14 June 1940, Daimler-Benz gave the AVA a contract to build and test a complete contra-rotating compressor; the aero-engine firm was to provide construction expertise, such as that for high-speed gears, which the AVA lacked.[291] However, because the AVA was already over-burdened with its work for other firms and continually losing workers to conscription, the institutions made little progress with the compressor.[292] Further exacerbating the problems caused by lack of labour, the 007's compressor was hugely difficult to manufacture. Each of the seventeen stages of the complex contra-rotating compressor had different blade profiles and between twenty-four and thirty blades each; the entire compressor would require an estimated 3,400 hours of milling time to complete.[293]

Despairing that the AVA would never finish the compressor, Daimler-Benz gave J.M. Voith of Heidenheim, a nearby mechanical engineering company, a sub-contract on 26 March 1941 for the development of an alternate compressor for the 007 engine.[294] Voith designed the compressor but was slow to build it, allegedly because of the delayed delivery of a special blade-milling machine from yet another company.[295] Daimler-Benz continued its work on the remainder of the engine, while pushing its sub-contractor to deliver the compressor. Although several of the main components of the 007 were designed by other firms, Daimler-Benz contributed the constructional know-how necessary to integrate the engine's parts.

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[290] DB Haspel 8.9, 23.10.43, Zeitlicher Ablauf der Entwicklung des ZTL-Triebwerkes

[291] GOAR 3619, 14.6.40, Daimler-Benz Auftrag; GOAR 3619, 1.4.41, Daimler-Benz Aktennotiz

[292] GOAR 3619, 28.6.40, Letter Betz an Daimler-Benz; GOAR 3619, 24.6.40, Letter Daimler-Benz an Bevollmächtigten des RLM für das Luftfahrt-Industriepersonal

[293] GOAR 3619, 1.4.41, Daimler-Benz Aktennotiz

[294] Although none had yet been received, the contract was extended to five compressors on 18 December 1941. (DB Haspel 8.9, 23.6.42, Contract Daimler-Benz und J.M. Voith)

[295] DB Haspel 8.9, 20.7.43, Letter Daimler-Benz an Voith (Heidenheim)

The first prototype of the 007 was completed on 26 March 1943. The engine ran for the first time with external assistance, on 1 April 1943. Throughout 1943, the firm actively tested and developed the engine, focussing initially on the mechanical soundness of the engine. On 2 October 1943, the company's first prototype ran self-sustaining for the first time, and by 19 October 1943, the company had finished the remaining four prototypes initially contracted for – down to their compressors.[296]

The spurt in turbojet activity at Daimler-Benz in 1943, which Constant ignored,[297] was the result of a significant increase in the size of the firm's turbojet workshop in early 1943, which was made possible when the firm's 605 piston engine was launched into production.[298] Yet in mid-October 1943, just at the time that the firm's work on the 007 was picking up speed, State Secretary Milch – whose production-oriented criteria differed from Schlep's - cancelled the engine, arguing that despite four years of development no 'positive results' had been achieved.[299] Milch ordered that the entirety of Daimler-Benz's jet-engine development capacity – all personnel, workshop, machines and test stands - be transferred immediately from work on the 007 to support Heinkel-Hirth's development of the 109-011 engine, which the latter firm was promising was nearly ready for production, a claim which proved however to be overly-optimistic.[300]

Nevertheless, Daimler-Benz collaborated with Heinkel-Hirth on the 011 as the RLM instructed. The two firms agreed that Daimler-Benz should help to produce the turbojet, and

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[296] Another four prototypes were ordered by the RLM on 16 February 1942, showing Schelp's continued interest in the engines despite the delay. (DB Haspel 8.9, 23.10.43, Zeitlicher Ablauf der Entwicklung des ZTL-Triebwerkes)

[297] Constant, *Origins of the Turbojet Revolution*, 213.

[298] DB Haspel 8.9, 21.9.44, Minute Nallinger an Haspel

[299] Schelp's longer-term view prized Daimler-Benz's development record, and he was therefore willing to accept delays in order to benefit from it.

[300] Haspel 8.9, c20.10.43; Milch also ordered, in response to repeated requests from TH Braunschweig, that Leist was to be transferred to the technical university. (Niemann, Feldenkirchen, and Herman, *Gasturbinen und Flugtriebwerke der Daimler-Benz AG*, 42.) Leist's movements, like those of Oestrich and Wagner, demonstrate the high mobility of personnel within the German aviation industry, research establishments and academic institutes.

in June 1944, it took out a license for the engine.[301] Daimler-Benz's involvement with the new engine was limited however by Heinkel-Hirth's desire to remain in control of the work and keep its own production facilities and staff busy.[302] Despite Daimler-Benz's preparations, the early 1944 plan for the firm to produce 150 Heinkel-Hirth 011 engines was put on hold when Heinkel-Hirth decided to retain production entirely at its own works. Daimler-Benz built around twelve 011 engines; the engine never reached series production.[303]

The RLM's Office for special power plants (Sondertriebwerke) continued to give Daimler-Benz, like Jumo and BMW, turbojet development contracts before it had completed earlier ones. Schelp, may indeed have underestimated the difficulty of designing and developing a turbojet,[304] but the effect of these continual demands was that each firm had to make crucial decisions about how to split their resources among many potential aero-engine projects.

Because the 007 project was held up by its lack of compressors, Daimler-Benz actually began work on a second turbojet contract for an even more powerful turbojet before Jumo or BMW. Before the 007 had been cancelled by Milch, Daimler-Benz had already received a contract for an engine numbered 109-016, which was to be one of a family of three geometrically similar, nine-stage axial jet engines ('Einheitstriebwerke'), which were, according to Schelp's ambitious plans, to have thrusts of about 4,400, 14,330 and 28,660 pounds respectively.[305] In September 1943, Fritz Nallinger, Daimler-Benz's head of engine development, ranked the 016 as more important than the continuing production of another batch of 007 engines, and the firm ordered parts to be made for the compressor of the first

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[301] DB Ordner XVIII, 1.6.44, Contract Ernst Heinkel Aktien Gesellschaft und Daimler-Benz

[302] The firm stood to lose around 800 unskilled, foreign workers who could not be used for development. (DM FA001/0323, 10.2.45, Letter Schif an Frydag)

[303] DB Haspel 8.1, 9.2.44, Letter Haspel, Nallinger an Frydag; DB Haspel 6.11, Produktionsstatistiken

[304] Schlaifer and Heron, *Development of Aircraft Engines*, 403.

[305] The project demonstrated the overreaching ambition of the regime and illustrated the way that Schelp sought to reach higher powers quickly through the design of similar units rather than entirely new engines. (Niemann, Feldenkirchen, and Herman, *Gasturbinen und Flugtriebwerke der Daimler-Benz AG*, 53.)

experimental 016 prototype.[306] For the layout of the 016 engine's axial compressor, Daimler-Benz avoided the overloaded AVA, and consulted a different axial compressor expert, Bruno Eckert of the Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren (Research Institute for Motor Vehicles and Engines, FKFS) at the TH Stuttgart, who also advised other turbojet teams.[307]

Despite Milch's order, Daimler-Benz continued testing and learning from its functional 007 prototype.[308] Nallinger came to see the cancellation of the engine and the firm's subordinate role to Heinkel-Hirth as an unfortunate curtailment of its activity in the new engine field. In January 1944, when the firm's directors were undecided, Nallinger argued that while the 4,000 horsepower piston engine already under contract from the RLM should be pursued, the firm had to work on gas turbine engines as 'intensively as possible'.[309] Nallinger first tried to extend Daimler-Benz's remit on the 011 to include design and development in addition to licence production.[310] Schelp agreed in autumn 1944 that the firm should be allowed to use the expertise gained from its work on the 007 to 'more or less independently' develop the 011 turbojet as well as a turboprop version of the unit, the 109-021, which was to be constructed by adding a third turbine stage and propeller to the

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[306] BA MA RL3/4399, 28.9.43, ZTL-Entwicklungssitzung; The engine was never built. (Kay, *German Jet Engine and Gas Turbine Development*, 150.)

[307] Eckert worked on a compressor for Daimler-Benz's large 016 engine and may have been consulted on the layout of Voith's compressor for the 007. (BA MA RL3/4399, 9.11.43, Besprechung im Forschungsinstitut für Kraftfahrwesen und Fahrzeugmotoren Stuttgart; Niemann, Feldenkirchen, and Herman, *Gasturbinen und Flugtriebwerke der Daimler-Benz AG*, 44-45; BA MA RL3/4399, 8.10.43, Company Minutes 60KR-Notiz)

[308] It had run for 152 hours by March 1944. (von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke*, Second Edition, 205; Kay, *German Jet Engine and Gas Turbine Development*, 150); This chimes with Gregor's argument for the firm's active independence in defending its own interests. (Gregor, *Daimler-Benz in the Third Reich.*)

[309] DB Haspel 8.1, 3.2.44, Aktennotiz Betr. Besprechung in Untertürkheim am 22.1.44

[310] DB Haspel 8.9, 22.9.44, Niederschrift; This agrees with Schlaifer's assertion that the firm was 'extremely anxious to catch up in the new field'. (Schlaifer and Heron, *Development of Aircraft Engines*, 405.)

turbojet unit. Twenty 021 turboprop engines were ordered from Daimler-Benz, but none was ever built.[311]

Nallinger's decision marked a change in strategic focus at the firm, and led to an increasing commitment of resources, even at the cost of piston engine work, to develop in-house design expertise with the new engines. In September 1944, Nallinger appealed to the chairman of the board, Wilhelm Haspel, for more resources for turbojet work. He argued that a lack of labour had led to the 'failure' of the 007, and it would be unbefitting a leading aero-engine firm to make the same mistake again. If the company failed to invest in the new field, he argued, 'we will not be a party to these developments for many years to come'.[312]

Steam turbine makers and the turbojet

Although the majority of turbojet development work was centered in the aero-engine industry, that industry does not exhaust the firms that undertook to organise turbojet development during the war. Steam turbine makers were another important group of firms to undertake turbojet projects, although their roles were very different in Britain, Germany and the United States. German policy initially avoided steam turbine makers, while the United States' wartime policy gave turbojet development contracts *only* to steam turbine manufacturers (although General Electric was chosen for its turbo-supercharger experience). Britain's turbojet programme, both centrifugal and axial, at first relied entirely on steam turbine makers, but by the end of the war privileged aero-engine manufacturers.[313] Steam turbine makers are mentioned in the historical literature, although their failure to succeed is not adequately explained. Schlaifer argued that in a fast changing industry like the aero-engine industry, in which delay was tantamount to failure, private firms that lacked

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311 von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke*, Second Edition, 205-206; DB Haspel 6.11, Produktionsstatistiken

312 DB Haspel 8.9, 21.9.44, Nallinger an Haspel

313 Schlaifer and Heron, *Development of Aircraft Engines*, 492-493; Development of the two-stroke Crecy showed the Air Ministry's preference to place new engines at aero-engine firms when possible, however. (Nahum, 'Two-Stroke or Turbine?', 321.)

experience in aero-engine development and production were at a strong disadvantage.[314] This chapter strengthens the argument of the previous sections that the aero-engine industry was the most appropriate place to develop turbojet engines because of its ability to exploit a range of continuities with piston engine practice, by arguing that while some firms in the steam turbine industry proved to be effective developers of gas turbine aero-engines, they were, because of their lack of aero-engines experience, much slower and less successful at turning them into viable power plants.

Two British steam turbine manufacturers, the British Thomson Houston Company (BTH) and Metropolitan-Vickers (Metrovick) were critical in the early stages of British turbojet development. Both continued to develop turbojets more or less seriously until the end of the war, yet neither managed to put a gas turbine aero-engine into production. Metrovick is known for its work on if not its contributions (as opposed to the RAE's) to the axial turbojet,[315] but the firm's failure to enter the aero-engine industry after the war is not understood. Roy Lawton's account of ASM's takeover of Metrovick's last axial turbojet, for example, offers an impressionistic explanation for Metrovick's failure, which does not however consider the implications of the firm's wartime work.[316]

No German steam turbine firm received a development contract for developing a turbojet engine during the war, despite the fact that Brown, Boveri & Cie (BBC), a steam turbine company, was the earliest company in Germany to build a gas turbine engine (albeit a stationary one). German steam turbine makers were however much more active than their British and American counterparts in producing gas turbine engines for land and sea applications.[317]

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[314] Schlaifer and Heron, *Development of Aircraft Engines*, 13-14.

[315] As in Constant's account. (Constant, *Origins of the Turbojet Revolution*, 215-216); Schlaifer gave Metro-Vick more credit (Schlaifer and Heron, *Development of Aircraft Engines*, 256.)

[316] Lawton, *Parkside*, 76-77.

[317] Kay, *German Jet Engine and Gas Turbine Development.*

The United States was the only country where steam turbine makers played the central role in turbojet aero-engine development throughout the war. Yet as in Britain, steam turbine manufacturers struggled to develop and produce turbojets competitive with the output of the aero-engine industry. The great exception was the General Electric Company (GE), the only steam turbine maker to successfully join the aero-engine industry. GE's previous experience with turbo-superchargers gave them an advantage over other steam turbine makers, but the company's struggle on the way to success bespeaks the disadvantages that even GE had to overcome.

Britain's steam turbine companies start it off

Because it was afraid that the established aero-engine industry would steal its ideas, Power Jets chose a steam turbine maker, the British Thomson-Houston Company in Rugby, to build its first turbojet unit. BTH was unique among steam turbine makers for working on centrifugal rather than axial turbojets. In a contract signed with BTH on 4 March 1936, Power Jets promised the steam turbine maker the right to manufacture the first 100 Power Jets production turbojet engines. One argument against BTH's involvement in quantity production in 1940, however, when the Air Ministry decided to put a Power Jets engine into production, was that the firm lacked aero-engine production facilities. The firm's director, H. N. Sporborg, judged that the firm could have assembled the plant given enough time, especially because, from his point of view, a significant amount of experimental work remained to be done before production could be contemplated.[318] BTH was busy with other war work and did not in the end pursue its claim to produce Power Jets' engines. It did, however, ask to be allowed to continue to play a role – if a less central role one - in turbojet development. Its request to continue to make experimental units was granted in order that the experience that BTH had built up during its first four years of collaboration with Power

[318] NA AVIA 15/2305, 5.3.40, 7B, Letter Sporborg to Power Jets; 13.3.40, 8B, Memo of discussion between Director of Contracts and Sporborg

Jets would not be lost to the national programme.[319] A few of the firm's most enthusiastic turbojet engineers, who had worked closely with Power Jets, including L. J. Cheshire, left BTH to join Power Jets.[320]

BTH remained involved in building experimental turbojet engines until the end of the war – to Power Jets' designs until 1943 and then according to their own development programme.[321] Long after its sub-contract with Power Jets had expired, BTH continued to be a member of the GTCC, and the committee's fifteenth meeting was hosted at Rugby on 11 November 1944.[322] The firm's representatives attended GTCC meetings until at least 29 October 1947, although the firm stopped giving a report of its progress after the meeting on 12 October 1945 and had had nothing to comment on for several meetings prior.[323] Despite its long running interest in gas turbines, BTH never attempted to enter the aero-engine industry.

Metrovick, like BTH, began working on a turbojet as a sub-contractor, but in contrast to BTH, in 1940 it took the lead in the design of a turbojet aero-engine, the F.2, which was based on an axial compressor design by the RAE. Metrovick assembled a top-class design team to work on the engine, led by David M. Smith. The combination of steam turbine experience, aerodynamic research, mathematical analysis and skilful design that characterised the fruitful partnership between Metrovick and the RAE created a first axial gas turbine bench unit that was powerful but heavy; closer to steam turbine practice than

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[319] NA AVIA 15/2305, 13.3.40, Memo of discussion between Director of Contracts and Sporborg; 14.3.40, 8, Minute Director of Contracts

[320] NA AIR 62/1023, 7.1.44, Whittle address to Power Jets

[321] Whittle, *Jet*, 120; NA AVIA 15/2305, 13.3.40, Memo of discussion between Director of Contracts and Sporborg

[322] BTH hosted the meeting; no aero-engine was displayed. (AVIA 31/4, 11.11.44, GTCC Meeting Minutes #15)

[323] AVIA 31/5, 12.10.45, GTCC Meeting Minutes #18; AVIA 31/6, 1.2.46, GTCC Meeting Minutes #19; AVIA 31/7, 29.10.47, GTCC Meeting Minutes #25

aero-engine design. (More details of the collaboration with the RAE are given in Chapter 4.) An F.2 prototype ran for the first time in December 1941.[324]

MAP viewed the F.2 as a promising alternative to the languishing W.2B. In October 1941, the Ministry considered the engine to be a 'second string' engine for the F.9/40. In order to accelerate its progress towards flight status, the Ministry arranged for collaboration between the steam turbine firm and Armstrong-Siddeley Motors (ASM), as described above.[325] Metrovick refused to let ASM have input into the engine design, however. In December 1941, the manager of ASM, Sir Frank Spriggs, despaired that Metrovick 'still fail to realise that while we all recognise their experience and ability in what they term the "rotating plant" they do not realise how much they do not know about aero-engines.'[326] On 30 July 1942, four months after technical collaboration had begun between the two firms, their relationship had not changed. MAP's Director of Engine Development, Bulman, agreed with Spriggs that '[b]y themselves, M-V in my view will never achieve that aero engine standard, anymore and for much the same reasons, than I would expect the B.T.H. Co. to produce an effective aero engine.'[327]

The F.2 had reached an impressive 2,160 pounds thrust in bench testing by the start of May 1942 – well ahead of the W.2B,[328] yet the F.2 began gradually to fall farther behind its competitors. Whereas in March 1942 it was still unclear 'whether the de Havilland H.1. or a cleaned up Metropolitan Vickers F.2. is likely to be the first to reach that combination of reliability, weight and performance to make it suitable as an operational engine,'[329] by autumn

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[324] Gunston, *World Encyclopaedia of Aero Engines*, 117.

[325] AVIA 15/1509, 14.10.41, 8, Minute Bulman to Linnell

[326] AVIA 15/1509, 8.12.41, 30, Minute Bulman) to Roxbee Cox quoting letter from Spriggs

[327] AVIA 15/1509, 30.7.42, 53, Minute Bulman to Roxbee Cox

[328] AVIA 31/2, 2.5.42, GTCC Meeting Minutes #4

[329] AVIA 15/1614, 9.3.42, 11, Intradepartmental minute

1942 the F.2 had dropped after the H.1 in the Ministry's priority ranking.[330] The F.2 powered an F.9/40 prototype on 13 November 1943, eight months after it flew with H.1 engines.

By the end of the war, Metrovick had embarked on a new, improved axial design, the F.9. Yet in the 1940s, aero-engine firms put more and more turbojets into production, and the slow speed of Metrovick's aero-engine development work resulted in the firm surrendering the F.9 design to ASM, an aero-engine firm, in the late 1940s rather than produce it themselves. Despite its successful design, Metrovick never entered the aero-engine industry.

German steam turbine makers help out

German steam turbine makers did not design complete turbojet engines until relatively late in the war, and none of these was ever developed. Nevertheless, they were looked to to collaborate with aero-engine firms on turbojet development. In 1941, when Junkers ran into trouble with their AVA designed axial compressor, the RLM turned to Brown, Boveri & Cie (BBC), which had begun developing axial gas turbines for industrial use in the inter-war period,[331] to develop, build and test an axial aero-engine compressor. By the end of 1942, when BBC had finished developing an axial compressor for the 004, Junkers had however solved its own compressor problems, and was not interested in the steam turbine maker's design.[332] In 1944, the RLM once again voiced interest in the BBC compressor, hoping to use it now in the BMW 003 rather than in the Jumo 004. Nothing came of this plan either, however, for the experimental compressor had suffered damage during testing and was not

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330 AVIA 15/1509, 7.8.42, 56B, Letter Spriggs to Bulman; AVIA 15/1614, 12.5.42, Jet Engine Propulsion Panel 5th Meeting and 8.10.42, 10th meeting; AVIA 31/3, GTCC Meeting Minutes #8

331 For example in power generation, waste heat capture, foundries and wind tunnels. BBC produced the turbine for the Herbitus high altitude test facility at Munich. BBC earlier designed and supplied the compressor and power system for wind tunnels across Germany, including a wind tunnel for Reichlin and a supersonic wind tunnel at the Luftfahrtforschungsanstalt Braunschweig. (BMW FA 50, 1.2.71, testimony of BBC and MTU leaders; CIOS XXVII-22, Gas Turbine and Wind Tunnel Activity, BBC, June 1945; Hirschel, Prem and Madelung, *Aeronautical Research in Germany*, 220-221.)

332 Franz later described cooperation with BBC instigated by the RLM as 'fruitless.' (CIOS XXIV-6, Gas Turbine Development); BMW FA 50; 1.2.71 testimony of BBC and MTU leaders

repaired before the war ended.[333] Although neither of the aero-engine compressor designs completed by BBC during the war made it into an aero-engine, the firm's expertise in compressor design was clear in the impressively high 90% efficiency of the second compressor.[334]

In 1943, with production tying up the development resources of BMW and Jumo, the RLM asked BBC and the Allgemeine Elektricitäts-Gesellschaft to design complete turbojet aero-engines with required performances and efficiencies well beyond anything achieved by German turbojet designers at that point, but none of these got very far.[335]

American steam turbine manufacturers take the lead

In the United States, responsibility for turbojets and piston engines was neatly divided. The United States Army Air Forces (USAAF) and the National Advisory Committee for Aeronautics (NACA) selected the country's steam turbine industry as the best place to develop the new engines, leaving the aero-engine industry to produce piston engines for the war.[336] In 1941, General Arnold, head of the USAAF, asked Vannevar Bush, chairman of the National Defense Research Committee and NACA at the time, to organise a group of scientists to investigate the problem of jet propulsion. The special NACA committee that Bush created, headed by Dr William Durand, included politicians, scientists, NACA researchers, representatives of the Army and Navy, and the country's leading makers of steam turbines: Allis-Chalmers, Westinghouse and General Electric.[337] The special committee asked each steam turbine firm to submit a proposal for a gas turbine engine. Three schemes were agreed on, and in 1941, Allis-Chalmers embarked on designing an axial ducted fan,

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[333] BMW FA 50, 1.2.71, testimony of BBC and MTU leaders

[334] Kay, *German Jet Engine and Gas Turbine Development*, 125; CIOS XXVII-22, Gas Turbine and Wind Tunnel Activity, BBC, June 1945

[335] CIOS XXVII-22, Gas Turbine and Wind Tunnel Activity, BBC, June 1945

[336] In the 1930s, there were scattered turbojet projects in the American aviation industry, without much success, and the NACA had begun studying jet propulsion seriously in February 1939, based on the work of Eastman Jacobs. (NACA TR 802, 491)

[337] Hansen, *Engineer in Charge*, 230-231.

Westinghouse began work on an axial turbojet, and the steam turbine division of General Electric Company (GE) set about making an axial turboprop.[338]

Allis-Chalmers developed their ducted fan gas turbine engine until 1943, when they happily dropped it in exchange for licenced production of the de Havilland H.1. With the failure of H.1 production, Allis-Chalmers left the aero-engine industry.

Westinghouse was more successful. It developed a small axial turbojet, the 19A, as a booster for the Navy's piston engines during the war.[339] The firm founded its Aviation Gas Turbine Section in 1945, but the new section struggled to design a more powerful turbojet aero-engine than its 19A and 19B (J30) engines. In an attempt to catch up with GE, the firm signed an eight-year collaboration contract with Rolls-Royce in 1953.[340] Nevertheless, the firm failed to collect the staff, facilities, and experience to develop a complex turbojet engine, and the failure of its J40 axial turbojet development resulted in the firm giving up aero-engines all together in 1960.[341]

GE was the only American steam turbine manufacturer that was successful with turbojet development. During the war, the firm began two turbojet programmes. The firm's steam turbine division developed its own axial turboprop design, while the firm's turbo-supercharger division, which had been producing superchargers for the Army since the First World War, was chosen by the USAAF in autumn 1941 to undertake the country's development of a centrifugal engine based on Power Jets' W.2B.[342] Because there was no pressure to get an American jet into the war, GE had the time necessary to undertake the

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338 AHFR A2073, 13.10.41, Doc 17, Letter Hunsaker to Arnold

339 Constant, *Origins of the Turbojet Revolution*, 22-23.

340 *Flight*, 11.5.56, 'Aero Engines 1956…'

341 Paul Lagasse, 'The Westinghouse Aviation Gas Turbine Division 1950-1960: A Case Study in the Role of Failure in Technology and Business,' MA diss., University of Maryland, 1997.

342 Sanford Moss was a key pioneer of centrifugal superchargers and turbo-superchargers at General Electric. This was a key consideration in choosing GE to take on the W.2B. Constant and Nahum have noted that General Electric knew of the turbojet work through connections at BTH. (Nahum, *Frank Whittle*, 98-100.)

'slow and expensive' business of creating an efficient aero-engine development and production organisation.[343]

The distinction between GE's two programmes is essential. During the war the turbo-supercharger division worked on centrifugal engines while the steam turbine division worked on an axial engine. For centrifugal engines, experience with aviation turbo-superchargers was directly relevant, whereas the firm's axial compressors were developed anew. GE succeeded in producing centrifugal turbojets during the war despite taking up the development of the W.2B more than a year after Metrovick began the F.2. It did not however produce axial engines before 1945.

In fact, delays with development and production of GE's centrifugal turbojets led to Allison being brought in to produce engines to GE's designs during the war, which left GE to focus on development. This was not entirely unlike Metrovick give up its F.9 to Armstrong-Siddeley, a firm with piston engine production experience, although GE continued developing turbojets after losing control of its engine. The war and Allison's participation in production gave GE and its steam turbine division time to develop aero-engine design and development experience – including, crucially, in axial engines.

It was only after the war that the main American aero-engine manufacturing firms entered the turbojet field, initially by licensing British turbojet designs. Curtiss-Wright, which continued to produce huge numbers of piston engines into the 1950s, tried to start developing turbojets in 1950 by taking out licenses for the Armstrong-Siddeley Sapphire (ASM's development of the Metrovick F.9) and Bristol Olympus turbojets. The firm successfully produced many Sapphire engines but was overcome in its attempts to develop the immature Olympus engine, and it gradually faded from the aero-engine industry. Pratt and Whitney was pressured by the government to enter the field soon after the war, and took out a license for the Rolls-Royce Nene. The firm successfully transitioned to the new aero-

[343] Schlaifer and Heron, *Development of Aircraft Engines*, 97.

engines, and relatively quickly joined GE as one of the world's major turbojet engine development and manufacturing companies.[344]

Conclusion

The turbojet did not create a new industry, although it presented a chance to alter existing relations within the aero-engine industry, as the expertise, resources and personnel used for piston engines were gradually transferred to gas turbines.[345] By the end of the war, all of the major pre-war aero-engine companies in Britain and Germany had entered the new field and had begun designing turbojets. In Britain, Metrovick was the only firm from outside the aero-engine industry still developing a turbojet. In the United States, GE and Westinghouse were in 1945 still struggling to develop competitive turbojets.

Schlaifer argued that the aero-engine industry was better suited to quickly develop a radically new type of aero-engine than any other type of firm. Analysis has shown that it was the continuities between piston engine and turbojet aero-engine practice that were essential for success. Where new expertise had to be acquired, as with axial compressors, the old provided a scaffold for the new. Firms that took up turbojet engines did change to meet the challenges of the new engines, but this gradual shift was less important than the strong continuities between piston engine and turbojet engine practice.

Being a successful aero-engine firm was not a guarantee of success in developing turbojet aero-engines, but it helped. As illustrated by tracing the elements of early gas turbine aero-engines, most aero-engine firms had some specific design experience that touched on aspects of gas turbine design: whether compressors, turbines, or exhaust nozzles. Those that

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[344] Hooker, *Not Much of an Engineer*, 141; Jack Connors, *The Engines of Pratt & Whitney: A Technical History* (American Institute of Aeronautics and Astronautics, 2009); Louis R. Eltscher and Edward M. Young, *Curtiss-Wright: Greatness and Decline* (New York: Twayne; London: Prentice-Hall International, 1998).

[345] This contrasts with the literature on the emergence of the American automobile industry from the bicycle and carriage industries, in which the latter two industries provided elements, skills and concepts that shaped a new transportation industry, consisting of newly founded firms. The development of the turbojet did not correlate to the emergence of a new industry, rather it took place within and was achieved by an existing industry.

undertook entirely new axial engines had a fund of aero-engine design and development experience, including relevant plant and skilled personnel, to fall back on. It was from the aero-engine industry that the most ambitious and elaborate gas turbine schemes emerged, and these projects represented an immense creative effort. Competition and war exigency favoured quick development and led firms to abandon more complex – and perhaps advantageous – schemes in favour of simpler turbojet engines. By the end of the war, the profusion of early designs had given way to a smaller range of basic types.[346]

Being an aero-engine firm had distinct advantages. Metrovick, a steam turbine company, successfully developed an axial gas turbine during the war, yet the firm struggled to produce a unit that would meet the strict requirements for an aero-engine. By rejecting the assistance of ASM, an aero-engine firm, Metrovick contributed to the further delay of its turbojet programme. Rolls-Royce, in contrast, brought to the turbojet an extensive knowledge of aero-engine design and manufacturing, and while it failed to develop a successful axial compressor, it was eminently able to produce the new type of aero-engine. In the end, ASM took over Metrovick's F.9 design. Rolls-Royce ultimately benefitted as well because it was able to use part of Metrovick's compressor design in its first successful commercial axial aero-engine, the Avon.

It was not impossible to create a new aero-engine firm, as GE's success attested, or new expertise, as BMW's attested. But creating a new firm and building up expertise in development was expensive in terms of time and money. Schlaifer suggested that the creation of a new company to exploit an invention should be a government's last resort for development because it was a relatively slow way to develop a new aero-engine.[347] Existing aero-engine companies represented reservoirs of skills and resources for developing new aero-engines.

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[346] 'Britain's Power Units,' *Flight*, 8 September 1949.

[347] Schlaifer and Heron, *Development of Aircraft Engines*, 97-99.

A major advantage of calling on the aero-engine industry was the availability of existing elements that could be included in turbojet engines. The major disadvantage of involving them, which the American policy avoided, was competition with piston engines for resources. So long as piston engine development had priority, turbojet programmes struggled to recruit personnel and obtain test and manufacturing facilities. Despite being two of the world's strongest aero-engine firms, at Bristol and Daimler-Benz, a commitment to piston engines seriously delayed achievement with gas turbine engines. Contrary to what historians like Constant have suggested, it was not when the turbojet was proved to be possible but when piston engine production was well in hand that the aero-engine industry embraced the new engines.

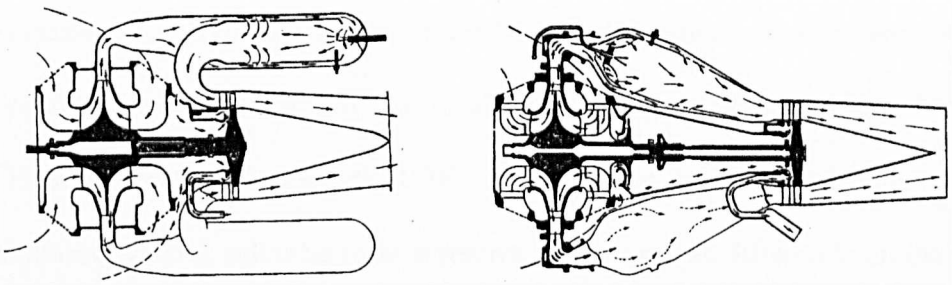
Overlaps between piston engines and early turbojet designs allowed aero-engine firms to successfully take up the new type of aero-engine. The most successful firms were the best at exploiting these overlaps. Sometimes taking advantage of continuities meant integrating outside expertise, especially from research institutions, into a full engine design. In the odd conditions of Germany's war years, Jumo's work demonstrated that emphasizing continuity could quickly yield results, whereas BMW's decision to build up new in-house experience ended up with an aero-engine that was later to production yet technically superior to Jumo's. Producing a good result quickly required striking a balance between the two approaches. Rolls-Royce and de Havilland were successful in striking this balance and both produced powerful turbojets by the end of the war. Even though it lacked experience in gas turbine elements, ASM nevertheless successfully exploited continuities in aero-engine design method in its work and reached production sooner than Metrovick.

In retrospect, it seems obvious that the aero-engine industry was the right place to develop turbojet engines and that firms would deploy as much experience as possible in tackling the new challenge, as the existing accounts of individual firms often make clear. Yet the vision of the turbojet as a revolutionary technology has obscured the vital importance of

the engine elements and expertise already available in the aero-engine industry. Turbojet aero-engines were not that different from piston aero-engines, just as turbojet companies were not that different from companies that made piston engines. Jet engines were aero-engines before gas turbines, and expertise with the former proved to be more difficult to build up than the latter.

In addition to aero-engine companies and steam turbine companies, however, there was another important group of institutions that contributed to the early history of the turbojet, even if none of them ever produced a series turbojet. The next chapter looks at three inventive institutions that used the turbojet to forward their interests. As in this chapter, an evaluation of the resources that each was able to martial and an understanding of what each institution was trying to do begin to explain the aero-engine designs that each produced and their ultimate success or failure in forwarding their turbojet designs. In fact, because the literature pays more attention to invention than development, the work of the institutions discussed in Chapter 4 has gotten much more attention in the literature than the remarkable stories of the firms discussed in this chapter, most of which successfully moved from developing piston engines to developing turbojets.

Figure 3.1. Comparison between reverse-flow and straight-through combustion on double-sided impeller turbojet engines



	Reverse-Flow Combustion System			Straight-Through Combustion System
1.		+	-	Requires a longer shaft, involving a third bearing and a flexible coupling
2.	Permits automatic compensation of expansion without special joints	+	-	Requires expansion joints to allow differential expansion
3.	Is such that the turbine stator and rotor blades are shielded from direct high-temperature radiation from the flame	+	-	Subjects turbine stator and rotor blades to direct high temperature radiation from the flame with possibly higher metal temperatures
4.	Involves two 180° bends in the path of the gas	-	+	Involves no bends and so has the lower pressure loss
5.		-	+	Allows the greater cross-sectional area for combustion within a given overall diameter
6.		-	+	Is the simpler manufacturing proposition
7.	Allows easier location and inspection of burners and easier assembly and removal of combustion chambers	+	-	
8.		-	+	Should provide the more even air distribution.

Reproduction of Figure 33 and Table 1 from Roxbee Cox's lecture on British aircraft gas turbines given in December 1945, showing one example of the design trade-offs inherent in choosing any engine component. The weighting of advantages and disadvantages depends on a company's expertise and changes over time.

According to Roxbee Cox, if the points in the table 'were of equal weight, the merits of the two systems would be evenly balanced. Item 5... however represents a preponderating design advantage in the larger engines, and the disadvantages noted against the straight-through system have with development, shrunk in importance.' Frank Halford's 1941 H.1 engine used straight-through combustion and a single-sided impeller. All of the engine designs developed by Power Jets during the war used reverse-flow combustion.

Source: Harold Roxbee Cox, 'British Aircraft Gas Turbines. The Ninth Wright Brothers Lecture,' *Journal of the Aeronautical Sciences* 13(1946): 66-67.

Chapter 4
Inventive Institutions

To the companies discussed in Chapter 3 must be added another group of institutions that were also centrally involved in the early years of turbojet engine, which included Power Jets, the Ernst Heinkel Aircraft Company (EHFW), and the Royal Aircraft Establishment (RAE). These institutions, which I will refer to as inventive institutions, all differed from the firms of the aero-engine industry in important ways. Although all three developed turbojet engines, none of them manufactured them. Like most steam turbine makers, they did not benefit from the technical continuities with piston engines. The only exception was the RAE's Engine Department, which although it had no production expertise, did have technical responsibility for piston aero-engines in the interwar period. To differing degrees, each defined itself as an institution specialising in novelty, and the turbojet took a central place in that identity. Of all of the institutions associated with the turbojet's early years, the three given in this chapter are the best known as turbojet pioneers, although those discussed in the previous chapter did on average more development work.

The story of the institutions grouped together in this chapter presents a challenge to the transition narrative's account of the sources of technical change in two important ways. Firstly, it directly challenges the heroic inventor accounts of the early history of the turbojet and secondly, it contradicts the story of the centrality of the industry laboratory in the process of invention in the mid-twentieth-century in new ways.

This chapter is concerned with three institutions that were central to the work of the men who figure most prominently in the literature as independent inventors of the jet engine: Frank Whittle (Power Jets), Hans von Ohain (EHFW) and to a lesser extent Arnold A. Griffith (RAE). In fact, the significance of these inventive institutions has been overshadowed by the claims made for the inventors that worked at them. While there is no doubt that these individuals were important, all of them were also employees (Whittle was

employed as an officer in the Royal Air Force, RAF), and it is therefore not helpful to think of them as independent inventors. Yet inventors they were, and they and the inventions that their institutions made were promoted by their institutions. Each institution did this in a different way, based on its own goals, institutional security, and the availability of resources for turbojet work. In this, Griffith's institution was the most successful, Whittle's second and von Ohain's least successful. These judgments are not reflected in the claims made for these individuals in the literature, however, nor in the claims that have been made for the institutions, which will be discussed at the start of each section below. We know much more about the less successful institutions, Power Jets and EHFW, which both had a strong identity as pioneering turbojet firms, than about the RAE, which promoted the axial gas turbines inspired by Griffith's early work long after the ideas of Whittle and von Ohain had ceased to shape industry practice. The significance for our understanding of invention of taking these institutions seriously is indicated by the distance between the familiar account of Whittle's success as an independent inventor, which would fit into a heroic story or the transition narrative, and the new account given in this chapter of the failure of his invention through the failure of his institution.

The stories of these inventive institutions also challenge the transition narrative's second pole: its emphasis on the industrial research laboratory as a source of novelty. None of the inventive institutions in this chapter could be described this way. None of them was an industrial laboratory, attached to a large industrial firm. One was a peculiar venture capital funded start-up, which developed the work of an RAF officer. Another was the newly established aero-engine division of an airframe company. The last was a very large government establishment devoted to research rather than invention, and to helping rather than competing with, the aviation industry.

This chapter is the first account of these institutions as inventive institutions in their own right, an approach that changes not only how we understand them as organisations, but

also how we evaluate the work of the inventors associated with them. It takes the stories of these institutions farther by looking beyond the inventors traditionally associated with them, and looks too at their later lives, once their inventors had left or become less central, in the case of Power Jets and the RAE. Examining the blind spots in the standard story's account of these institutions reveals that the trajectories of the work of three most famous turbojet pioneers was very different from what the standard story implies.

Earlier histories of the jet have made much of firsts, whether first flights, first production, or first deployment. Being first was important and was taken to be a measure of technical advance. Furthermore, an assumption was often made that there were obvious and close connections between being first to fly and first to produce. Thus, the claim for German superiority has been made on the basis of large-scale wartime production, first deployment and first flight. In this thesis, all these assumptions have been called into question. This chapter focuses on institutions associated with important firsts, yet the two most important, as I show, failed to get their engines into the air in substantial numbers. Furthermore their engines were of a type, which in Germany were never put into production at all and in Britain did not prevail long after the Second World War. In the third case, that of the axial gas turbine, where the long-term effects are most apparent, the claims to invention are the weakest.

This chapter will give a new account of these inventive institutions' effectiveness and of how that influenced the success of their inventors. Power Jets failed to become a commercial enterprise during or after the war, and this chapter will argue that the institution's weakness, a product of its wartime history, contributed to the abandonment of Whittle's ideas by the British aero-engine industry. In addition, this discussion moves the RAE from the sidelines to its place as a central driving force in British turbojet development. Emphasising the Establishment's role as a turbojet developing institution for the first time, it will show how the RAE's success as an institution contributed to the propagation of the axial

gas turbine in Britain. In the last section, I will argue that the nature of EHFW was the major reason that von Ohain's wartime work had no lasting result on turbojet design.

Inventors

This chapter is not concerned with how the turbojet first emerged, but some comments on the claims made for the three key figures that feature in this chapter are necessary to highlight the unfamiliarity of this chapter's results and to put the work of these individuals and institutions into perspective with the work discussed in the last chapter. The prominence and number of accounts of Whittle written by historians, enthusiasts and aviation writers speak to his status as the British inventor of the turbojet.[1] This claim rests on the argument that his proposal for a gas turbine jet propulsion engine was the first practical proposal for a turbojet (supported by a patent), that he inspired work on turbojets in Britain, and that he was the first to run a centrifugal turbojet aero-engine, which burned kerosene, on 12 April 1937. As is shown below, claims to the significance of Whittle's work were central to the policies and practices of Power Jets.

Due largely to American advocacy (as discussed in Chapter 5), von Ohain has joined Whittle as a co-inventor, who independently and simultaneously invented the turbojet aero-engine. For von Ohain the claim is that he was the first to run a radial turbojet unit using hydrogen gas in March 1937 – just before Whittle's first prototype ran.[2] The two men's early engines were in fact notably different – not only in terms of fuel but also in their layout: von Ohain's engine had a centrifugal compressor (like Whittle's) but also a centrifugal (rather than axial) turbine.

In terms of putting engines into the air, both men were pioneers. Von Ohain designed the first turbojet in the world to power an experimental aircraft, the HeS 3 that

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[1] Postan, Hay and Scott, *Design and Development of Weapons*; Boyne and Lopez, *The Jet Age;* Constant, *Origins of the Turbojet Revolution*; Golley, Whittle and Gunston, *Whittle, the True Story*; Nahum, *Frank Whittle*; Pavelec, *Jet Race*; Kay, *Turbojet History and Development.*

[2] The exact date is unclear, but von Ohain's HeS 1 ran in late February or early March. (Constant, *Origins of the Turbojet Revolution*, 198.)

powered the He 178 on 27 August 1939; and his HeS 8 engine powered the He 280 fighter prototype on 31 March 1941. Whittle's first engine to fly, the W1, powered the E.28/39 for the first jet flight in Britain on 15 May 1941.

Griffith, the least acclaimed of the three, is generally not seen as a gas turbine inventor in his own right and tends only to be mentioned in an obligatory nod to a pioneering 1926 paper, in which he made the first detailed proposal to use a gas turbine in an aero-engine, or to his Department's subsequent early gas turbine experiments.[3] Constant explicitly dismissed Griffith's claim to invention based on the fact that he did not consider jet propulsion.[4] Yet before plunging into the Whittle story, Postan laconically remarked in the British Official History that 'he [Griffith] and his department at the R.A.E. can claim to have been solely responsible for the development and eventual success in this country of... the axial-flow compressor.'[5] As we have seen, this was to be the compressor of the future in Britain and the main type of compressor used by the Germans during the war in operational engines.

Whittle and von Ohain were initially a few years ahead of the competition; by 1940, however, they were in competition with other engine designers. In Germany, the first axial turbojets ran during 1940: a precursor to the BMW 003 ran in spring 1940 and the Jumo 004 ran for the first time in October 1940.[6] The first axial turbojet in Britain, the Metrovick F.2, designed with the help of the RAE, ran in December 1941.[7] Although Herbert Wagner of the Junkers Airframe Company was the first to develop a scheme for an axial turbojet in 1935-1936, the engine built based on his designs by Max Adolf Müller did not run until 1942 (at EHFW). Within three years of the experimental operation of the very first Whittle and

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[3] Schlaifer and Heron, *Development of Aircraft Engines*, 332-333; Postan, Hay and Scott, *Design and Development of Weapons*, 177; Constant, *Origins of the Turbojet Revolution*, 110-111; Kay, *Turbojet History and Development*, 12.

[4] Constant, *Origins of the Turbojet Revolution*, 218.

[5] Postan, Hay and Scott, *Design and Development of Weapons*, 177.

[6] Wagner and Cox, *The First Jet Aircraft*, 230 and 239.

[7] Gunston, *World Encyclopaedia of Aero Engines*, 117.

von Ohain units there were thus many competitors, a point central to the history of all the institutions we will discuss.

Power Jets

Because of the fame of its chief engineer, Frank Whittle, Power Jets is the best-known institution associated with the turbojet in Britain. As is clear from its central role in accounts like that of Postan, Kay and Nahum, the firm is considered to have been central to turbojet development in that country. Despite the surfeit of accounts that discuss Power Jets, however, we know very little about the company apart from Whittle. Indeed, the firm is often treated as an extension of the officer, whom it was founded to support. Yet their stories are not identical, which becomes especially clear after Whittle's involvement in the company began to lessen in 1942, while the company's turbojet activity continued to grow. Nor was Power Jets able to supply everything that Whittle needed – many other firms were involved, from the earliest days.

There are two reasons that we know so much about the short-lived company, and in much greater detail than about any other company that made gas turbines during the war. The first is because Whittle's own account of the firm in his memoir (1953) was so detailed and so widely known, indeed it is an important source in this account. The second is because the company's end in 1946 allowed its senior figures to discuss the intimate details of the firm's finances with the business historian Robert Schlaifer, which resulted in a detailed financial history of the private company featuring in the latter's 1950 history of the turbojet - the only such section in his account. Despite the fact that Power Jets' story represented a disproportionately large part of Schlaifer's account, however, the firm's work didn't carry an excessive weight in his analysis, which was concerned with development.[8] Other historians like Postan, Constant and Pavelec, treated the firm's financial circumstances in less detail, but

[8] Schlaifer and Heron, *Development of Aircraft Engines*, 336-348; Whittle's memoir commented on the firm's labour and space problems and the lack of machine tools, but Whittle denied any real knowledge of the firm's finances or administration. (Whittle, *Jet.*)

all emphasised the company's private status and its difficulty in attracting funding.[9] All of the major historical accounts of the turbojet and some others by enthusiasts make clear Power Jets' antagonistic relationships with MAP and the firms chosen to produce its engines, BTH and Rover.[10]

The standard story of Power Jets jumps from the time when it gave up on collaboration with Rover in 1942 to the moment of its nationalisation in 1944 – an event which has been confused with the nationalised company's being turned into a government research establishment in 1946.[11] This corresponds roughly to Whittle's visibility in the story. The new story told here makes clear not only the meaning and relation of these events, but also what the company was doing when it slips out of the historiographical lime light.

The firm's nationalisation was undoubtedly a key event in its short history. According to the standard account given by Whittle and Golley, in nationalising the company, MAP opportunistically took advantage of the firm.[12] Schlaifer and Postan treated the nationalisation of the firm as a move that ended the company's freedom.[13] Pavelec argued that the transfer was justified because the company was for all intents and purposes government owned at the time of nationalisation.[14] In his recent book, Nahum argued, in

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[9] Constant, *Origins of the Turbojet Revolution*, 187-188; Pavelec, *Jet Race*, 45-46; Kay, *Turbojet History and Development*, 21-22; The official history discussed the firm's financial arrangements in brief detail, contrasting Power Jets' hardship particularly to the easy financial situation of the Heinkel Aircraft Company. (Postan, Hay and Scott, *Design and Development of Weapons*, 191-192.) Similarly, Kay, *Turbojet History and Development*, 21-22 and Golley, Whittle and Gunston, *Whittle, the True Story.*

[10] Schlaifer and Heron, *Development of Aircraft Engines*, 359; Kay, *Turbojet History and Development*, 59; Pavelec, *Jet Race*, 58 and 114; Postan, Hay and Scott, *Design and Development of Weapons*, 215-217; Whittle, *Jet.*

[11] Golley gives a dire view of the treatment of Power Jets, which confuses the company's nationalisation (1944) and its conversion to a national research establishment (1946). Whittle was unhappy about the nationalisation, but much more upset by the firm's conversion into a national establishment. Golley quoted Whittle in his section on the nationalisation of Power Jets, but used a quote that Whittle originally made in reference to the conversion of the government company into a research establishment. (Golley, Whittle and Gunston, *Whittle, the True Story*, 217; original quote in: Whittle, *Jet*, 283.)

[12] Ibid.

[13] Postan, Hay and Scott, *Design and Development of Weapons*, 228-230; Schlaifer and Heron, *Development of Aircraft Engines*, 369-371.

[14] Pavelec, *Jet Race*, 126.

contrast, that the Government was more supportive of Power Jets than it is given credit for. Nahum interpreted the nationalisation as a good faith attempt, particularly by the Minister of Aircraft Production, Stafford Cripps, to make use of the company's unique skills despite its peculiar position.

Building on Nahum's interpretation, this section will make clearer than heretofore that Power Jets was hardly isolated or ignored by the government. I show very clearly the reliance not only on MAP support but also on the assistance of other firms into 1941. It was only from 1940 onwards, with government funding, that the firm built up a huge staff and significant facilities, reaching almost 1,000 employees in 1943. In so doing, it increasingly found itself in an atypical position with regard to the aero-engine industry and the RAE, a fact which was intensified by the firm's failure to get a second Whittle engine into production.

In a significant recasting of the nationalisation story, I go farther than Nahum to argue that nationalisation served to preserve the company as an operational unit rather than eliminate it, and that this allowed the firm briefly to expand its capabilities and stretch the boundaries of what an inventive institution could be. We have seen the story of Power Jets too much through Whittle's eyes, with the assumption that the firm deserved special treatment because of its role as a pioneer. I will argue that Whittle and Power Jets' extravagant moral claims for their right to be free from oversight alienated the government and the aero-engine industry. The firm's uncertain institutional position and its clumsy attempts to advance its commercial interests were its undoing in a context where, as we have seen, it was very far from being the only institution able to develop a turbojet in Britain.

Small beginnings

Power Jets was established on 27 January 1936 by an agreement between Flight Lieutenant Frank Whittle ('The Inventor'), the President of the Air Council, Rolf Dudley Williams and James Collingwood Burdett Tinling ('The Vendors', Whittle's representatives), and Oswald

Toynbee Falk and Partners ('The Firm').[15] The Air Ministry was a party to the agreement because Whittle was a serving RAF officer, and for that reason the Air Ministry retained crown user rights to all of Whittle's patents, which made them useless as commercial tools during the war.[16] Williams and Tinling, both ex-RAF, were instrumental in helping Whittle to find finance to exploit his ideas. In recognition of their support, Whittle granted each a 22.5% interest in his patents, which became the new firm's sole initial assets. O.T. Falk and Partners, a branch of the investment-banking firm O.T. Falk and Company that made high-risk investments in new companies, was responsible for the firm's finance. It pledged an initial £2,000 to the firm and undertook to raise more funds for Power Jets from its own capital and from interested investors.[17]

On 19 March 1936, when it was officially registered, Power Jets consisted only of a board of four directors and one alternate director. At the company's first meeting on 26 March 1936, Whittle was named its honorary chief engineer and technical consultant (seconded from the RAF).[18] The firm's board of directors consisted of two members of Falk and Partners, Lancelot Law Whyte and Maurice Bonham Carter, and the neophyte business partners, Williams and Tinling, who were both nominated by Whittle. M.L. Bramson served as Bonham Carter's alternate and the firm's technical advisor.[19] Bonham Carter, a Partner at O.T. Falk, held a number of business directorships in addition to Power Jets, including several in the aviation industry.[20] Along with Whyte, who became the first managing director

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[15] NASM T, Box 1, Folder 8, Agreement

[16] If the patents had been declared secret the Ministry would have retained all rights; since they were not, the government retained the right of free use and Power Jets retained the commercial and foreign rights on the patents, for which they were required to pay a fraction of their royalties to the government. (Schlaifer and Heron, *Development of Aircraft Engines*, 339.)

[17] Schlaifer and Heron, *Development of Aircraft Engines*, 337.

[18] BL Add 61931, Board Meeting 26.3.36; Certificate of Incorporation No 211791

[19] Bramson was a pilot, engineer and aeronautical consultant. He had put Williams and Tinling in touch with O.T. Falk and Partners and wrote the technical report on Whittle's ideas that secured the bank's support. Bonham-Carter cancelled Bramson's nomination on 25 January 1940. (Whittle, *Jet*, 45; Schlaifer and Heron, *Development of Aircraft Engines*, 337; BL Add 61931, 25.1.40)

[20] BL Add 61931, 26.3.36

of Power Jets, Bonham Carter was also a director of an equally promising company to Power Jets, Scophony Limited, a firm founded in the early 1930s with O.T. Falk's help to develop a mechanical television based on the patents of George William Walton.

Power Jets was initially funded by venture capital, and between 1935 and 1939, the firm's shareholders came to include friends, family and Power Jets employees as well as experienced investors, industrialists and private companies. (Appendix A gives a list of the firm's shareholders.) The Weir brothers were the firm's largest shareholders, investing £5,000 between November 1937 and spring 1939.[21] Shares were accepted in lieu of cash payment by the firm's management and by its key sub-contractors. By May 1939, the British Thomson Houston Company (BTH), the company's first major sub-contractor, held £4,500 shares, making the later maligned company second largest shareholder in Power Jets after the Weir brothers.[22] In July 1939, the company's total income (including shares granted for services) since March 1936 came to £19,880. Of this, £16,640 was from private sources, while 16% of the firm's income had come from Air Ministry contracts paid in 1938 and 1939. In addition to these early contracts, the Air Ministry supported the firm by paying Whittle's salary and sponsoring his education (including a post-graduate year) at Cambridge, where the Flight Lieutenant studied from July 1934 to mid-1937. His studies at Cambridge culminated in first class honours in the Mechanical Sciences Tripos in 1936, and his post-graduate year, which was largely dedicated to working on his turbojet engine, was supervised by the head of the University's Aeronautics Department, Melville Jones.[23]

Although Power Jets did raise an additional £3,830 privately after 1 July 1939 (largely through additional purchases by its original investors since its fundraising was now limited by the strictures of the Official Secrets Act), funding from the Air Ministry quickly overtook the

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[21] William Joseph Reader, James Kenneth Weir, Elizabeth McClure Thomson, *The Weir Group: A Centenary History* (London: Weidenfeld and Nicolson., 1971), 117-119; BL Add 61931

[22] BL Add 61931; Schlaifer and Heron, *Development of Aircraft Engines*, 344-345.

[23] Whittle, *Jet*, 50-51; Arnold Hall and Morien Morgan, 'Bennett Melvill Jones. 28 January 1887 -- 31 October 1975,' *Biographical Memoirs of Fellows of the Royal Society* 23 (1977).

amount of private capital invested in the firm.[24] This was no surprise to O.T. Falk and Partners and its investors, most of whom had understood that 'the entire undertaking would ultimately have to be a partnership with the state'.[25] The company's official blessing and the extent of indirect government support from early on suggest, as Nahum has argued, that the company was 'a surrogate official venture' from the start.[26]

Fearing the loss of independence that might result from enlisting the help of an established aero-engine company,[27] the fledgling Power Jets turned to the British Thomson-Houston Company in Rugby, one of Britain's major electrical engineering firms and steam turbine makers to undertake the design drawings and construction of its first experimental turbojet engine, known as the Whittle Unit or WU. In a contract signed on 4 March 1936, Power Jets promised BTH production rights to its first production engine, implying not only confidence in their success but also the expectation that Power Jets would not make them.[28] (See also Chapter 3.) The small firm relied on the expertise and facilities of other companies during the 1930s, but as it began building up its own skills and capabilities, it became increasingly dismissive of the competence of its earlier collaborators.

In addition to BTH, Whittle consulted numerous leading British firms on aspects of each of the unit's main components. Laidlaw Drew and Company of Edinburgh designed its single, elongated combustion chamber. Whittle consulted the Hoffman Company in Chelmsford about bearings, Alfred Herbert of Coventry about machining the WU's rotor shaft, High Duty Alloys in Slough about the unit's compressor-impeller and Firth-Vickers of Sheffield about forging the turbine from its Stayblade alloy with integral blades, disc and shaft.[29]

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[24] Schlaifer and Heron, *Development of Aircraft Engines*, 345-346; BL Add 61931, 20.12.38

[25] Schlaifer and Heron, *Development of Aircraft Engines*, 341.

[26] Nahum, *Frank Whittle*, 31-33.

[27] Whittle, *Jet*, 98.

[28] Whittle, *Jet*, 120; NA AVIA 15/2305, 13.3.40, Memo of discussion

[29] Gunston, *Development of Jet and Turbine Aero Engines*, 123.

Whittle's contacts outside of industry were also important. The compressor rotor of the WU was designed with the help of Arnold Alexander Hall at Cambridge.[30] From late 1936 or early 1937, Whittle initiated contact with Hayne Constant and Arnold A. Griffith at the RAE, whose support was crucial in securing government funding for Power Jets in 1937.[31] Power Jets' contacts with the RAE were typical, for one of the Establishment's chief functions was to assist industry with aeronautical design work. Based on its work on centrifugal exhaust gas turbines and combustion, the RAE had in fact a reservoir of knowledge relevant to the design of a centrifugal gas turbine aero-engine, despite the fact that it was busily designing axial gas turbines. Indeed, according to Hayne Constant, the Establishment was then engaged in research on 'the same problems as Whittle was attacking from the design point of view'.[32] Whittle also travelled frequently to London to consult with Bramson and Power Jets' Directors.[33]

A year into its existence, Power Jets still had neither employees nor facilities. Whittle, still Power Jets' only technical member, designed the company's first experimental unit from an office at BTH. The tiny firm continued to rely on BTH's engineering and drawing staff until well into 1940.[34] So close was Whittle's control of the work done by the sub-contractor, that all of the design drawings required his signature before being sent to the shop.[35] The resulting experimental gas turbine was much lighter and more precise than anything BTH

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[30] Gunston, *Development of Jet and Turbine Aero Engines*, 123; After leaving Cambridge, Hall embarked on a distinguished career in aeronautics. (Anthony Tucker 'Sir Arnold Hall,' accessed 17 January 2011, http://www.guardian.co.uk/news/2000/jan/11/guardianobituaries2.)

[31] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §28, Interview with Constant 14.12.49; The reports by Constant and Griffith, RAE Note #E3546 and Report #3545, can be found in NA AVIA 46/234

[32] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §28, Interview with Constant 14.12.49; NA AIR 62/10, 22.12.37, Whittle diary, Long 'phone call to Dr. Griffith

[33] Whittle, *Jet*, 50-51.

[34] Postan, Hay and Scott, *Design and Development of Weapons*, 191.

[35] Whittle, *Jet*, 56.

was accustomed to building in the course of steam turbine manufacture.[36] It ran for the first time at Rugby on 12 April 1937.[37]

In August 1937, BTH's director, H.N. Sporborg decided that the jet unit could no longer be safely tested directly outside the firm's turbine factory.[38] Power Jets consequently negotiated with BTH to rent part of its disused Ladywood Ironworks in Lutterworth, and it was there that Power Jets began in early 1938 to establish its first factory.[39] In September 1937, expenditure on the firm's first significant items of equipment and testing apparatus were approved by its Board at a cost of £156.11s.5d, and in December 1937, the firm hired its first employee, Victor E. Crompton.[40] The government's first payment to the firm was £1,000 in May 1938.[41] By December 1938, the company had five employees, none of whom, however, were engineers.[42]

Power Jets received a government contract for a flight engine, the W.1, in August 1939, and it once again sub-contracted the construction to BTH. In June 1940, the company designed a test engine from un-flight-worthy W.1 parts, which was known as the W.1X. It was also built by BTH. Power Jets had a range of test rigs designed and built by its growing staff, but until the W.1X arrived from BTH on 11 December 1940, the firm had only one complete engine to use for testing. After its arrival, the firm used the W.1X for experiments including installation in the Gloster E.28/39 airframe.[43] Remarkably, the firm continued to modify and test the WU until 22 February 1941. The W.1 was delivered to Power Jets by BTH in February 1941 as a group of sub-assemblies, but the company did not assemble it

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[36] Whittle, *Jet*, 66.

[37] Whittle, *Jet*, 57.

[38] Whittle, *Jet*, 52-62.

[39] BL Add 61931, 10.2.38

[40] BL Add 61931, 2.12.37

[41] Schlaifer and Heron, *Development of Aircraft Engines*, 344.

[42] Two night-watchmen, an office boy, Mary Phillips (Whittle's secretary), and Victor Crompton. (Whittle, *Jet*, 80.)

[43] Whittle, *Jet*, 128-129.

until they were confident that they had learned enough from the experimental W.1X. The W.1 ran for the first time in April 1941.[44]

When the Air Ministry decided to put a Whittle designed turbojet into production after seeing the reconstructed WU running at Lutterworth, Power Jets had a staff of not many more than twenty-five and had never entirely manufactured even a single engine. Whittle, no matter how gifted, was young and inexperienced, and he could not be given the time to learn the skills needed to run a production organisation. Furthermore, it was impossible to put him in a position of authority over an established engineering firm. If Power Jets' early success meant that the engine was 'a production job' as Tizard announced in January 1940, it meant that production had to go to an experienced company.[45]

The very optimism of the Air Ministry about the aero-engine's prospects dictated that it should turn to industry for production, while Power Jets continued doing 'research work'.[46] When Power Jets realised that it would not be given its own production organisation, it put forward Rover as a likely collaborator,[47] suggesting that a joint manufacturing company be established. Later, Power Jets urged the Air Ministry to grant contracts directly to itself. Power Jets would then sub-contract the work to Rover in an arrangement similar to that which had held with BTH, allowing the small firm to retain control over its aero-engine design. Instead, the Air Ministry decided to place contracts directly with Rover, and Power Jets relied on Rover and BTH for the provision of experimental engines and parts. From late 1940, Rolls-Royce also produced turbine blades, gear cases and other components for Power Jets without charge.[48]

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[44] Whittle, *Jet*, 135-136.

[45] Clark, *Tizard*, 299-300; Nahum, *Frank Whittle*, 170.

[46] NA AVIA 15/2987, 23.4.41, MAP meeting, discussion on PJ and Rovers

[47] NA AVIA 15/2305, 17.2.40, 4A, Letter Whyte to Tedder

[48] Hooker, *Not Much of an Engineer*, 63-67.

The next prototype built by BTH for Power Jets was the W.1A, which was meant to test the novel features of the W.2, Power Jets' first production engine.[49] The first W.2 engine was built by Rover and was delivered to Power Jets in February 1941.[50] By then, the latter firm had already redesigned the engine, however, because engine problems that would appear under some flight conditions had been revealed by additional calculations made possible by an increase in its staff.[51] Power Jets' revised design, the W.2B, was chosen to become the country's first production turbojet, and the drawings were given to Rover in March 1941.[52] Rover prepared its own drawings based on Power Jets', introducing in some places Rover designed components, which became a point of contention with Power Jets.[53]

During 1940, the assurance of increasing government support had allowed Power Jets to grow dramatically. The firm employed 5 people at the end of 1938, 15 at the end of 1939, 134 at the end of 1940, 329 at the end of 1941, 562 at the end of 1942 and 983 at the end of 1943. (See Figure 4.1.) By September 1940, the company had a well-defined organisation typical of an aero-engine firm, including a drawing office, a design office, an experimental workshop, combustion test and engine test sections, an inspection department, and a purchasing department. Nevertheless, with seventy staff members, the firm was still working in a subdivision of the Ladywood Works, Lutterworth (BTH having reoccupied the rest of the foundry with war work) and had no facilities for producing engine parts. In fact in August 1940, the factory at Lutterworth contained only one machine tool, a lathe, and its experimental shop was mostly staffed by skilled sheet-metal workers making combustion chambers, the chief problem plaguing the WU in 1939-1940.[54]

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[49] Whittle, *Jet*, 122-123.

[50] Whittle, *Jet*, 146.

[51] Whittle, *Jet*, 124.

[52] NA AVIA 15/1806, 24B, Rover Contracts (C/Eng/523)

[53] Brooks, *Vikings at Waterloo*, 47.

[54] Whittle, *Jet*, 88.

The firm's breakneck expansion was guided by a stringent recruitment policy that placed a high value on academic qualifications. In 1939, seven of the company's fifteen employees had scientific or technical qualifications. Applicants to the company were interviewed by Whittle and Whyte, the most technically accomplished of the firm's managers.[55] Whittle recalled that Daniel N. Walker, a senior engineer hired during 1939, was the only candidate accepted from 140 applicants. Soon Power Jets began inviting recent graduates to join the firm directly. A degree in engineering was the most common among the firm's highly qualified staff, but it also took on metallurgists, chemists, physicists, and mathematicians in addition to the personnel who supported the firm's engineers: general staff, machinists, draughtsmen and managers.[56]

Through selective recruitment, the company built up a loyal core engineering team of young men, who frequently had a first class honours degrees in Mechanical Science from Cambridge or London and who often came straight from academia. The team was united by their shared academic experience, their familiarity with mathematical analysis, their awe of Whittle and their dedication to the firm's goals. The disposition of the core engineering team imbued the firm with its 'definite character': that of a firm devoted to the development of an operational aero-engine.[57]

Despite its growth, Power Jets was still highly dependent on external expertise. This was illustrated by the problem of combustion, the part of the new engine that Whittle was least comfortable with. A reliable combustion system was ultimately created through collaboration with the Shell Company, which MAP had brought into the work in response to an appeal from Power Jets. Shell's Dr Lubbock developed an atomizing fuel burner in October 1940 that solved the problem of fuel dispersal for the time being.[58] Lubbock

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[55] Whittle, *Jet*, 92.

[56] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §13

[57] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §12

[58] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 319.

subsequently worked with all of the British turbojet firms.[59] Power Jets also benefited from the RAE's long-standing work on combustion. During 1940, the RAE seconded three qualified men to Power Jets to work on combustion: Dr William R. Hawthorne, R. F. Darling, and J. B. Bennett-Powell.[60] Hawthorne, who had a first from Cambridge, actually led Power Jets' combustion group for a time.[61] MAP helped by making a powerful compressor at Dartford available for combustion tests.[62]

The contradiction of Power Jets

At the time of its founding, Power Jets' only assets were patents, and the firm's management initially constructed a business model in which patents were central to their success as an independent firm as well as their only defence against stronger aero-engine manufacturers. The firm's aims were to build a turbojet aero-engine and to enter the aero-engine manufacturing industry. Because the war broke out before Power Jets had established itself, however, the firm's two 'inseparable' aims came into conflict.[63] Whittle, who came to view the company as his service command, was dedicated to its survival as an independent company.[64] Yet the necessity of sharing the firm's work widely in order to hasten wartime development, as demanded by MAP, clearly contradicted the firm's desire to protect its intellectual property, which would be central to its ability to become a successful firm.

Power Jets took a hard line on patenting by its collaborators and insisted on the paramount value of invention – its primary output. While Power Jets took out joint patents early on with Laidlaw, Drew and Company on combustion,[65] the firm contended that similar equality did not exist with BTH and Rover. In fact, Power Jets strongly objected to patent

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[59] NA AVIA 31/2, 18.7.42, GTCC Meeting Minutes #15

[60] Whittle, *Jet*, 117; Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 319.

[61] Hawthorne, 1991, 99.

[62] Whittle, *Jet*, 120.

[63] Whyte, *Jet*, 145.

[64] Farren quoted in Whittle, *Jet*, 101.

[65] BL Add 16931, 13.4.37

applications by the latter two companies, which it asserted could only come from 'information supplied by Power Jets'. Such patents, the firm argued, should properly be assigned to Power Jets, with BTH and Rover retaining non-exclusive licenses. Although Whittle admitted that it was often difficult to identify '[t]he true origin of any invention' when a problem was solved in conference, Power Jets consistently held that its claims to patents were greater than those of its collaborators.[66] Not only did Power Jets think BTH and Rover incapable of making useful contributions to work on the turbojet,[67] but the firm believed that its pioneering position entitled it to 'dominate design and development of the engines which the other two firms were to make' and to retain 'engineering control' over the W.2B.[68]

Power Jets' obsession with patents naturally aroused suspicion in the Air Ministry, which insisted that proprietary interests not be allowed to hinder the development of new weapons.[69] Just months after war broke out in 1939, the Air Ministry had deferred the question of rewards for patents until after the war, hoping that by promising to establish a mechanism for post-war settlement, it could 'remove any reluctance which [claimants] might have to giving their fullest cooperation [to others]... without a prior settlement of the terms for the use of their designs and patents.'[70] As MAP's Controller of Research and Development remarked with respect to an argument between Rover and Power Jets in late 1942, '[q]uestions of patent rights and petty jealousies are not to be allowed to cause one

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[66] Whittle, *Jet*, 104.

[67] Whittle, *Jet*, 96-113.

[68] Whittle, *Jet*, 105 and 126.

[69] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment; to its never-ending dismay, MAP gave Rover direct contracts without an agreement on patents being reached between Power Jets and Rover. (NA AVIA 10/412, 24.2.44, Tinling's talk); NA AIR 62/2, Whittle's comments on Keppel's narrative

[70] NA AVIA 22/1540, 4.11.39, 1a, Air Ministry (Supply)

day's delay in the supply of the best possible engine to the Royal Air Force'.[71] MAP, which held rights to Power Jets' patents, would dictate the best way to proceed.

The Ministry's insistence on cooperation was a premise of the Gas Turbine Collaboration Committee (GTCC), and the question of patenting work 'arising out of joint discussions' was considered by the GTCC early on.[72] Roxbee Cox, the chairman, opened the discussion of patents at the first meeting by emphasising the Ministry line that 'patents and commercial obligations' were less important than ensuring 'that there should be no obstacle to the free interchange of ideas.'[73] Ricardo's consultancy was in a similar position to Power Jets because it collaborated with all of the turbojet companies, but the consultancy decided to abstain from taking out patents on work done for members of the GTCC for which the company was a consultant. Ricardo's did not see a consulting agreement as compensation for 'renunciation of patent rights', however, it viewed this sacrifice as a contribution to the war effort.[74] Despite extensive discussion, neither the GTCC nor the Patents Sub-Committee, to which the question was deferred, reached a consensus about how to deal with patents. It was decided that firms should take out provisional patents to protect any new ideas before sharing them with other firms at the GTCC.[75] The lack of conflict over the issue during the war suggests that the collaboration of the GTCC did not necessarily lead to patentable results. Whittle remembered that GTCC meetings were relatively formal and 'people were a bit cautious'; it was at the cocktail parties afterwards that real discussion occurred.[76]

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[71] NA AVIA 15/1614, 15.10.42, 39, Minute Linnell

[72] Postan, Hay and Scott, *Design and Development of Weapons*, 205-206.

[73] NA AVIA 31/1, GTCC Meeting Minutes # 1

[74] Ricardo's had consulting relationships with Rolls-Royce, Napier and de Havilland, and Roxbee Cox offered to 'tactfully suggest' such agreements to Rover, Power Jets and Metrovick. (NA AVIA 46/237, Extracts from GTCC File; 11.11.41, Letter Roxbee Cox to Ricardo) The Ricardo barostat was used on all wartime British jet engines.

[75] NA AVIA 46/237, Extracts from GTCC File, 167a, letter from Roxbee Cox to Admiral Hoare

[76] Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 97. Schlaifer argued that the GTCC had contributed little to generating new ideas, which generally came from the work of individuals; the only exception was perhaps in combustion. (Schlaifer and Heron, *Development of Aircraft Engines*, 436-438.)

Power Jets' Board did not hesitate that the firm should 'collaborate to the fullest extent' with other firms as the Air Ministry required, but it wanted to make sure that the unique 'legal and contractual position' of the firm was appreciated by all concerned.[77] In January 1942, Whittle wrote a memo to the Secretary of the GTCC, Wing Commander Watt requesting the 'recognition of certain essential differences in the status of the various firms collaborating'.[78] In an attempt to indicate the many beneficiaries of Power Jets' work, Whittle's memo detailed which firms had had access to and those that had contributed to Power Jets' work – although he was more generous in the first than the second.[79] Reflecting the firm's patent policy, W.E.P. Johnson, an authority on patents at the firm, argued at a meeting of the GTCC's Patent Sub-committee that '[t]he question of ownership is often mixed, since the originator of the problem which may be the germ of the invention made have [sic] some claim to be called inventor as well as the solver of the problem.'[80] Under this broad interpretation of invention, Power Jets claimed not only ownership of turbojet designs based on its work but in effect also - quite in contradiction to patent practice – on all improvements made to Whittle's ideas. As the firm's commercial position was slowly undermined, its directors' claims for ownership became more and more broad.

Power Jets' work with Rolls-Royce took a slightly different track than its earlier collaboration with Rover. Collaboration on the WR.1 in 1941-1942 was cordial, in no small part because Rolls-Royce consented to take sub-contracts from Power Jets - the situation that Power Jets had formerly demanded with respect to Rover. The congenial relations between the two firms led Power Jets in late 1942 to approach Rolls-Royce to produce its new engine design, the Power Jets W.2/500. When it was soon after decided that Rolls-Royce should begin by taking over W.2B production, it at first seemed that Power Jets'

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[77] BL Add 61931, 8.1.42; NA AIR 62/1006, 23.1.42, Whittle, Gas Turbine Collaboration Committee

[78] NA AIR 62/1006, 23.1.42, Whittle, Gas Turbine Collaboration Committee

[79] This included Hawthorne's loan to Power Jets. (NA AIR 62/1006, 23.1.42, Whittle, Gas Turbine Collaboration Committee)

[80] NA AIR 62/994, 18.12.41, Letter W.E.P. Johnson to Watt

relationship with Rolls-Royce would continue to be friendly. Yet the combination of Rolls-Royce's growing confidence in turbojet design, supported increasingly by direct contracts from MAP, and Power Jets' prickly commercial concerns, including the insistence on the primacy of Power Jets' work, meant that relations between the two companies soon followed the same pattern as between Power Jets and Rover.

In the hopes of protecting their rights, Power Jets insisted that terms of reference that clearly defined each party's responsibilities (such as the firm had earlier failed to establish with Rover) be agreed between the two collaborators. Power Jets argued that patent arrangements would be the 'major difficulty' in close collaboration.[81] In a letter to Ernest Hives, Rolls-Royce's general manager, on 10 May 1943, Tinling sought to explain Power Jets' position:

> In regard to Patents which you may take out, we have not suggested anything like so severe a position as we contend applied to Rover in the past. Our purely tentative suggestion was that you might join us in Patent Applications which you may make arising out of development of our designs... we are largely dependent on Patent rights in the monopoly sense as a main asset, and therefore necessarily take a... view... that patents relating to designs of our parentage should not be freely available to parties not having a title in them.[82]

Tinling argued that Power Jets was the 'parent designer' of the entire W.2 series of turbojet engines. This extraordinary claim included the W.2/B, the W.2/500 and W.2/700 (three Power Jets developments of the W.2); the W.2/B26 (as Tinling referred to the Rover STX, a heavily revised version of the W.2B that had been designed by Rover to ease W.2B engine manufacture[83]); and the W.2/B37 (as Tinling referred to Rolls-Royce's B/37, which was based on the Rover's STX and included some features from Power Jets' W.2/500). Tinling

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[81] NA AIR 62/608, 21.4.43, Note W.E.P. Johnson

[82] NA AVIA 15/1806, 10.5.43, Letter Tinling to Hives

[83] Rover's B/26 entirely changed the architecture of the W.2B engine by replacing the reverse-flow combustion system of the W.2B (used in all Power Jets engines) with a straight-through system. Rather than derivative, the B/26 had been seen by some in MAP as a completely new private venture. (NA AVIA 13/937, 8.5.42, Rovers Brochure; NA AVIA 15/1614, 2.4.42, 15, Minute Linnell) In defence of its claim to the engine, Power Jets emphasised that it had previously designed a straight through engine, the W.3X. Yet Rover had built one without seeing Power Jets' drawings. (NA AVIA 13/937, 19.5.42, Whittle's Comments)

insisted that Rolls-Royce make its views known, for 'it is more likely that future difference of opinion may turn on the accuracy of this view than on any other single question we can envisage.'[84]

Despite Tinling's veiled threats, however, MAP sided with its trusted contractor. In February 1943, the Ministry's permanent secretary, Archibald Rowlands, assured Arthur Sidgreaves, Rolls-Royce's business manager, that 'there can be no question of Power Jets being able to restrain other Companies from performing [Government contracts] ... by the exercise of patent rights'.[85] The question of ownership, control, credit, survival and patents were connected for Power Jets, yet the firm had little success in establishing or defending its patent rights. It was seriously hampered in doing so by the extraordinary level of government funding that it received.[86] Patents, it became increasingly clear, were not enough to sustain a company as an independent inventive firm in a time of increasing state expenditure on research and development.

Rapid growth

Power Jets' unique character meant that it fitted uneasily into the Air Ministry's existing structure for the development and production of new aero-engines; firms that designed but did not produce aero-engines were, as an official historian later remarked, 'something of an anomaly in the field of Air Ministry R&D'.[87] The Ministry's standard arrangement for funding aero-engine research was to make progress payments based on hours of test-running or prototypes built, but as the early pre-war delays in funding Power Jets had demonstrated, such a model was inappropriate for a small company that needed working capital.[88] In 1941, the Air Ministry abandoned its attempt to fund Power Jets through development contracts altogether and began funding the company's work by the 'rather unorthodox procedure' of

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[84] NA AVIA 15/1806, 10.5.1943, Tinling to Hives

[85] NA AVIA 15/1806, 28.2.43 30B, Letter Rowlands to Sidgreaves

[86] Whittle, *Jet*, 104.

[87] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §10

[88] Ibid.

paying all of the firm's operating expenses.[89] Expenditure at Power Jets more than doubled each year between 1939 and 1942, when it exceeded £500,000.[90] (See Figure 4.1.)

The state paid directly for the firm's expansion. During the latter half of 1940, Power Jets had made some modest additions to its facilities after it was given a government authorization of £27,000 for equipment and building requirements (particularly test houses[91]). This allowed it to build a small workshop capable of making engine components by September 1940.

When the size of the factory at Lutterworth began to constrain the rapidly expanding company, the firm naturally appealed to the government. On 11 April 1941, Whyte submitted a request to MAP for an additional 49,000 square feet of factory and office space.[92] To ease its situation, the firm had already rented rooms for its design team in Brownsover Hall near Rugby, but otherwise, temporary extensions to the Ladywood works were the norm. The firm's desire to expand occasioned a Ministry meeting on 23 April 1941 to determine what should be done about the firm, and a range of possibilities were discussed. Roxbee Cox argued that a resolution had to be met quickly, for lack of space would soon interfere with Power Jets' 'vital research and development work'. He judged that the firm 'desperately' needed 13,000 square feet of additional space – a figure double the factory space that the firm had at Ladywood.[93]

At a subsequent meeting on 31 July 1941, the Ministry decided that Power Jets would get a new factory and, having failed to negotiate a satisfactory agreement to acquire a share in

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[89] Schlaifer and Heron, *Development of Aircraft Engines*, 346; The Treasury happily abandoned the pay-as-you-go scheme in 1944 when the firm was nationalised. (NA T 161/1240)

[90] The rapid rate of expansion of the firm led to internal disagreement between Whyte, with a more cautious approach to firm-building, and Whittle, whose desire for quick (and perhaps unsustainable) expansion to facilitate faster development was undoubtedly fuelled by his colleagues' well-publicised service during the Battle of Britain. Whyte resigned as managing director on 4 July 1941. (Whittle, *Jet*, 93; Whyte, 'Whittle and the Jet Adventure', 147.)

[91] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 319.

[92] NA AVIA 15/2987, 11.4.41 copy of 29.3.41, L.L. Whyte, Power Jets Ltd. Schedule of Factory Space

[93] NA AVIA 15/2987, 4.7.41, Roxbee Cox to Pye

the nominally private company, that the company's relationship with the state would carry on as before.[94] Power Jets would be maintained as an independent organisation to enable Whittle to keep working for MAP.[95] While Whittle's desire to expand 'his organisation' to include the production of engines was refused, the Ministry allowed that the firm's 'research work' could be extended to 'include the construction of prototype experimental engines'. As long as Power Jets continued to collaborate with 'any persons nominated by the department', it would be given facilities to produce twelve experimental engines per year.[96]

By July 1941, the proposal for Power Jets' factory expansion had meanwhile grown from 49,000 to 80,000 square feet. Of this, 27,000 feet were estimated for an office staff of about 180. Just under 47,000 square feet were allocated for key facilities: a sheet metal department, welding departments, machine shop, jig fixture and tool room, fitting shop, electrical department, various stores, auxiliary test rigs, inspection and viewing department, model and pattern shop, lofting room, carpenter's shop, five engine erection bays, heat treatment and metallurgical section, burner department, five combustion bays and combustion laboratories. The new factory would also require additional outbuildings for four test houses and two observation rooms, a building to house the Dartford Compressor (later abandoned in favour of two smaller Browett-Lindley compressors[97]), a canteen, a garage, a boiler house for heating apparatus, and a gate house in addition to service roads, fencing and a car park. An additional 25,000 square feet, bringing the total to more than 100,000, were allowed for the later installation of plant needed to produce twelve experimental engines per year.[98] Because a suitable existing factory building could not be found and Power Jets

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[94] Power Jets had been open to the state purchasing a bigger share in the company earlier, but earlier negotiations in July 1941 had foundered on the asking price - £300,000. Power Jets offered the state a share of up to 51%, including its existing 12% stake. The Treasury objected to MAP's involvement in a private business. (NA T 161/1240, 17.7.41, Letter to Gilbert)

[95] NA AVIA 46/237, 31.7.41, Doc 3a, Gas Turbine Collaboration

[96] NA AVIA 15/2987, 23.4.41, MAP meeting, discussion on PJ and Rovers

[97] NA AVIA 15/2987, 3.9.41, Letter Walker to Roxbee Cox

[98] NA AVIA 15/2987, 28.7.41, R.D. Williams, Proposed new works for Power Jets

threatened that the existing conditions at Lutterworth would 'delay production', MAP agreed to erect an entirely new factory for the firm at Whetstone, Leicestershire, despite the severe restrictions on building during the war.[99] (See Figure 4.2.) In the end, Power Jets' new 'development factory' cost £325,000 to build and equip.[100] In line with an existing model of MAP-company relations, the new factory remained government property, with Power Jets as its shadow management.[101] In October 1942, the Whetstone factory was capable of making about four engines per year,[102] but it wasn't yet quite clear what the factory would be used for.

The new facilities at Whetstone, accompanied by an influx of labour assigned by the Ministry of Labour, drastically changed Power Jets' identity. The company's labour force expanded from 330 employees at the end of 1941 to almost 1,000 by the end of 1943. Despite assurances that labour in Leicestershire would be well suited to the new factory because it was experienced in the 'batch production of hosiery machines... and the men therefore had the right mentality' for work at Power Jets,[103] Whittle complained about the quality of the new workforce. Power Jets' management struggled to instil a feeling of belonging in the larger organisation, which contrasted with the close-knit team at Lutterworth. They tried illustrating the importance of Power Jets' work to the war effort – the turbojet was still secret - through demonstrations of a turbojet engine, which most of the workers had never seen before.[104] Nevertheless, the workforce, whether containing

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[99] A move to Farnborough and Bedford, both future RAE sites were suggested but rejected in favour of something near to Lutterworth. The estimated cost was £237,930. (NA AVIA 15/2987, 17.10.41, Air Supply Board Meeting Conclusions)

[100] Estimate from second half of 1943. (NA T 161/1240)

[101] For the year to 30 June 1942 and 30 June 1943, the Treasury offered Power jets fixed profits according to the shadow scheme of £4,500. The firm's management declined the profits, offering to work without fees during the war. (NA T 161/1240) Power Jets had negotiated profits of £1,000 (roughly 5% on capital employed) and £1,500 for the year to 30 June 1940 and 30 June 1941. (NA T 161/1240, 16.1.41, Letter Graham to Fletcher)

[102] Whittle, *Jet*, 237.

[103] NA AVIA 15/2987, 28.7.41, Conference at MAP

[104] Whittle, *Jet*, 253-254.

communist sympathisers who staged strikes, as Whittle later alleged,[105] was certainly less loyal to the company, and denounced the competence of the company's leadership to the Minister of Aircraft Production, Stafford Cripps, when he visited in the latter half of 1943. This complaint occasioned an investigation by MAP that confirmed the leadership's inability to manage a large firm and questioned its freedom from Ministry oversight.[106]

Whittle, meanwhile, became more and more distanced from the day-to-day affairs of the larger company, in part because of problems with his health. In December 1941, Whittle suffered a nervous breakdown that kept him from the company for one month. In mid 1942, he spent about three months abroad working with companies in the United States. After attending a three-month course at the RAF Staff College in May 1943, Whittle returned to Power Jets with reduced duties, concerning himself primarily with long-range projects in the firm's new Special Projects Section at Brownsover Hall headed by L.J. Cheshire. It was by no means clear that Whittle would even return to Power Jets at that time, but the Ministry wanted to keep him involved in the programme and Whittle refused to take a position at MAP.[107] After the construction of the factory at Whetstone, the company's work was still dedicated to the design and development of turbojets, but its agenda was no longer driven by Whittle, but rather by the engineering team that he had recruited. It was now the company that was responsible for perpetuating his legacy.

Whetstone's production facilities meant that Power Jets was no longer reliant on Rover and BTH for engine parts.[108] The W.2/500, which Rolls-Royce declined to put into production, was the first engine that Power Jets had ever manufactured in its entirety. It was based on the W.2B but incorporated certain improvements, including ones suggested by the

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[105] Whittle, *Jet*, 252.

[106] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §49; Postan, Hay and Scott, *Design and Development of Weapons*, 228-229; Nahum, 'World War to Cold War', 99-100.

[107] Whittle, *Jet*, 258.

[108] Of the 32 development engines built by Rover at Barnoldswick, over twenty were used on development work at Barnoldswick and Clitheroe; Power Jets received just four of these engines. (Whittle, *Jet.*)

RAE. The engine ran a mere six months from when Power Jets started the design drawings, and it performed precisely as predicted, reaching its design thrust of 1,750 pounds on the first day of testing, 13 September 1942.[109]

Whittle's trip to the United States in June to August 1942 reinforced his view that pilot production, or the development of manufacturing technique through the production of small batches of engines, was an essential part of development. Whittle returned to Britain determined to redefine the divisions between 'design', 'research', 'development', and 'production' in Britain in order to extend Power Jets' activities.[110]

Thus in early 1943, Whittle proposed the extension of Power Jets' activities to include pilot production. Hives responded that Power Jets could 'best contribute at present' not by developing production technique but by 'producing improved designs'.[111] So although the firm did receive two MAP contracts for W.2/500 engines in January and February 1943, it retained a circumscribed role in design and development.[112] During 1943, Whetstone continued development of the W.2/500 and started on the design of its next engine, the W.2/700, which used the familiar Power Jets architecture. Neither engine went into production, however; over Power Jets' arguments, the Rolls-Royce B/37 was chosen instead of the Power Jets W.2/700.[113] The new, much more extensive Power Jets organisation thus failed where the smaller company had at least partially succeeded, for its W.2B was the first British turbojet engine to reach production.

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[109] Whittle, *Jet*, 227.

[110] Whittle, *Jet*, 216-217; NA AIR 62/2, Whittle's comments on Keppel's narrative

[111] NA AVIA 15/1806, 5.1.43, 12A, Notes of discussion held at Power Jets

[112] RRHT, A-Numbers List

[113] Whittle deployed many of the same arguments that he had used earlier against Rover's STX or B/26 design. (NA AIR 62/608, 19.8.43, Letter Whittle to Roxbee Cox)

A national resource

The large and growing investment of public funds in Power Jets without corresponding government control became of increasing concern to MAP over the course of the war.[114] The government's expenditure on Power Jets, including running costs, machinery and buildings came to almost £1.3M between the second half of 1939 and the end of 1943.[115] In late 1943, Minister of Aircraft Production Stafford Cripps started pushing outright for the purchase of Power Jets. He saw this as the best way to gain some benefit for the nation from the investment of public funds in the company as well as the way to secure an advanced technical base for the British aviation industry in the post war period.[116] Cripps, who was a qualified patent lawyer, also argued that purchasing Power Jets would clear up the convoluted patent situation 'very much to the country's advantage'.[117] MAP had declared that '[t]he patents position could not... be cleared up without an intensive enquiry lasting for about a year', so the validity of Power Jets' patents and their complicated relation to the work of other firms were by no means assured.[118]

Cripps' proposal for the formation of a government-owned company departed from all precedent. Like a Government Establishment, the firm was to do work for the Ministry, concern itself with the advance of knowledge, carry out research, and share information. It would be 'regarded as the recognised National authority in this field', investigating gas turbine applications not only to aero-engines, but also to marine engines, power stations and

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114 NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §50

115 Schlaifer and Heron, *Development of Aircraft Engines*, 346. The contemporary Treasury figures are approximate and cover different time periods. The Treasury calculated that total expenditure on Power Jets had been about £650,000 in the four years to 30 June 1943 plus an additional £325,000 spent on Whetstone (including plant). (NA T 161/1240)

116 Nahum, *Frank Whittle*, 112. Cripps' plans for a 'National Aeronautical Establishment' were realised, with Farren's active support, as RAE Bedford. See Nahum, *Frank Whittle*, 108-124 on Cripps' vision for British aviation.

117 NA T 161/1240, 13.12.43, Letter Cripps to Tobin; P. F. Clarke, *The Cripps Version: The Life of Sir Stafford Cripps, 1889-1952* (Allen Lane, 2002), 34-37.

118 NA T 161/1240, 29.11.43, Note on Power Jets

locomotives.[119] The company's role as a national centre also made it necessary to incorporate into the new company the section of the RAE that was working on gas turbines. The peculiar thing about Cripps' proposal was that the company was also to 'take all reasonable business measures to establish itself on as nearly a self-supporting a basis as possible by arranging profitable outlets for its intellectual or physical products'.[120] Because commercial disinterest was an essential attribute of government establishments, a commercial status seemed to threaten the organisation's primary role as a national research centre. Cripps nevertheless favoured giving the institution a commercial status in order to facilitate negotiation with other firms, allow the management a greater liberty of action, and most importantly, to make possible the retention of the best technical personnel through higher salaries.[121] Its new convoluted legal status notwithstanding, the arrangement required no immediate changes at Power Jets.

Cripps' proposal met with objections from all sides. The aero-engine industry objected vehemently to the firm's proposed engine design activities as unacceptable state supported design competition, and many civil servants agreed with the industry position that the best innovations emerged fastest from private enterprise.[122] Viscount Weir questioned the implications of the nationalisation for the government's role in development, which he thought should not be allowed to become a function of the state.[123] Power Jets' other

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[119] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §52

[120] NA AVIA 10/412, 'A suitable mandate for Power Jets (R&D) Ltd.'; NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §57

[121] NA T 161/1240, Note on the Future of Power Jets (Research and Development) Ltd; These were some of the very same reasons that Tizard had seen Power Jets' establishment as a private company advantageous despite the fact that the government would inevitably have to support it. (Nahum, *Frank Whittle*, 31-34.)

[122] Cf. David Edgerton, 'Technical Innovation, Industrial Capacity and Efficiency: Public Ownership and the British Military Aircraft Industry, 1935-1948,' *Business History* 26, no. 3 (1984): 247-279. During the inter-war and war period, government design capacity was viewed suspiciously both by civil servants and by industry. (NASM T, Box 1, Folder 1, 6.4.44, Letter Sidgreaves to Tinling)

[123] Weir and his brother used their profits on their Power Jets stock to create a fund for research. (NA T 161/1240, 11.4.44, Letter Weir to Cripps) Similar questions were raised by the nationalisation of Shorts Brothers in 1943. (Edgerton, 'Technical Innovation, Industrial Capacity and Efficiency'.)

shareholders were suspicious of the nationalisation because they suspected that it was an opportunistic use of war powers to cheat them of profits on a risky investment (the government ultimately paid £3.125 for each £1 share, which might be considered a generous return on a short investment that could not have succeeded without government support).[124]

The only way to overcome the strong Treasury opposition to the establishment of a long-term government-owned company was a compromise: the new company was agreed to be a temporary, war-time expedient, arranged to avoid disruption in gas turbine research during the war but up for review when it ended.[125] The government company was in this way more of an experiment than a departure in policy.[126] In this light, Cripps emerges as Power Jets' defender rather than its undoing, for he gave the firm a new purpose. Without Cripps' scheme, the company likely would have been converted to an Establishment even sooner than it was.[127]

Despite widespread resistance from industry, MAP, the Treasury, Power Jets, RAE, and even Downing Street, Cripps's plan went ahead. Despite disagreeing with the scheme (interestingly for fear of upsetting work at Farnborough), Cherwell later wrote to Churchill, 'I think it would be difficult to overrule [Cripps], as he has set his heart on this new government company.'[128] On 28 April 1944, Power Jets (Research & Development) Limited

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[124] NASM T, Box 1, Folder 1, 10.4.44, Letter Mrs Lubbock to Bonham-Carter; Tinling managed to engineer a unanimous vote to wind up the company in 1944 by convincing the company's shareholders of the real possibility that the company would be shut down completely if they refused to sell. (NASM T, Box 1, Folder 1, 13.4.44, Letter Tinling to Pettitt)

[125] NA T 161/1240, 10.2.44, Letter Lee to Tucker

[126] The immediate resistance raised to the formation of a government company goes against Edgerton's interpretation of the nationalisation as representing a new conception of the state's role in aero-engine design that was quickly reversed. Instead, the resistance to state design in aviation that Edgerton charts from the 1930s continued to be strong during the war, and war conditions led only to an apparent divergence of policy. (Edgerton, 'Technical Innovation, Industrial Capacity and Efficiency'.)

[127] Power Jets' relationship to MAP had already been moving towards those between an Establishment and its Ministry. (NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §41); Bulman had earlier argued that the company was in effect operating like a government research establishment and should be brought under MAP control. (Nahum, *Frank Whittle*, 110.)

[128] PREM 3/21/4, 2.6.44, 143, Memo Cherwell to Churchill

was founded as a government owned company, created from the combination of the nationalised Power Jets Ltd., which had about 1,000 employees in early 1944,[129] and the RAE's turbine section, numbering about fifty people.[130] The new company's capital was increased ten times, from Power Jets' £20,000 to £200,000. The new company's board of directors was nominated by MAP and included a number of powerful industrialists in addition to some of Power Jets' previous directors.[131] Over the first year of the government firm's existence, its staff and expenditure continued to increase, reaching 1,327 employees and about £600,000 pounds. [132] Whittle was disappointed at the nationalisation, but he hoped that the formation of the government company would still allow Power Jets to become a successful engine designing and developing firm, as he had always wanted.[133] He was made Chief Technical Advisor to the Board of the new company and a director in January 1945, although his ill health and frequent lecturing kept him away.[134]

During 1945, Power Jets (R&D) remained active. Whittle had deeply instilled in the firm his view that only 'one thing could save Power Jets from complete extinction -- superior technical competence.'[135] The firm continued its research work but increasingly without reference to the engines being produced at other firms. The firm worked further on thrust augmentation; created new turbojet designs including a supersonic engine and an axial engine, the LR.1, which Whittle participated in; tested German engines and confirmed their 'marked inferiority' to British engines; set up a training school at Lutterworth and trained

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129 Nahum, *Frank Whittle*, 124.

130 Postan, Hay and Scott, *Design and Development of Weapons*, 207; NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §50

131 NA T 161/1240; Schlaifer and Heron, *Development of Aircraft Engines*, 346; Nahum, 'World War to Cold War', 108.

132 Nahum, *Frank Whittle*, 124.

133 Whittle, *Jet*, 295.

134 During 1944, Whittle was in hospital for six months. (Golley, Whittle and Gunston, *Whittle, the True Story*, 221-229.)

135 Whittle, *Jet*, 108.

numerous visitors from Britain and abroad.[136] The new firm's terms of reference also gave it a chance to begin limited aero-engine production, and the factory achieved a new success in 1945: pilot producing engines for the first time. It began to manufacture W.2/700 engines at a rate of 30 engines per year, with spares equivalent to another 15 engines per year, although these engines were used for development.[137]

At the same time as founding Power Jets (R&D), Cripps established a 'Gas Turbine Technical Advisory and Co-ordinating Committee'[138] to reassure the aero-engine industry that the new government-owned company would not unfairly compete with it. The committee included members from MAP, the Admiralty, Power Jets (R&D), and from industry.[139] It was through this advisory committee, that the aero-engine industry agitated to restrict the firm's activities. Because of the 'imperative need to restore the confidence of the jet engine firms' and because the government felt that it needed to reassert control over the state-owned company, officials agreed in May 1945 to redraft Power Jets (R&D)'s terms of reference, eliminating manufacture. Such a move would make an important difference to the scale of the company, which weighed in its favour. Power Jets (R&D) was already 1,400 strong in May 1945; a national establishment, in contrast, would employ only 300-400 people.[140]

On 1 July 1946, Power Jets (R&D) was transformed into the National Gas Turbine Establishment. Power Jets' original engineering team saw this as a great injustice. Despite the similarity in some of the research work being done by Power Jets' former staff and the RAE turbine section's former staff, Whittle and his closest engineers felt very strongly that doing such work without also applying it to engine design was worse than useless. Whittle argued that his engineering team (his memoir made no reference to the rest of the Whetstone

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136 NASM T, Power Jets (R&D) Technical Report May-June 1945

137 Whittle, *Jet*, 287.

138 Postan, Hay and Scott, *Design and Development of Weapons*, 231.

139 Whittle, *Jet*, 283-284.

140 NA T 161/1240, Note on the future of Power Jets (Research and Development) Ltd.

organisation) was 'temperamentally unsuited' to 'pure research'.[141] Whittle resigned from the company in January 1946, complaining that 'I cannot arouse much interest in a myriad of small-scale and relatively unrelated experiments which end merely in a mass of reports' – a revealing description of his understanding of the work of research Establishments.[142] His objection went beyond the distasteful nature of 'pure research', however. In his memoir, Whittle later explained that he and his engineers 'would not tolerate a situation in which those *who had founded an industry were deprived of the right to design and make experimental engines.*'[143] But what was being denied to the engineers, whether or not they had founded an industry, was not 'the right to design and make experimental engines' – any of his engineers would have been taken on by the aero-engine industry - but rather the opportunity for the group to continue to design and produce experimental engines on particular terms that they themselves chose, rather than the terms that Power Jets' wartime expansion at government expense dictated. Whittle argued in his memoir that

> [t]here was nothing unreasonable in [trying to restore Power Jets' former lead in all branches of gas turbine technology]... Power Jets had clearly established a moral right to include [the development of manufacturing methods and limited engine production] as one of its functions because... not only had Power Jets pioneered engine development itself, but had also contributed more to the evolution of special production methods than all the rest of the firms put together.[144]

Whittle invoked the record of work at Power Jets to defend his team's special right to a privileged position. The entitlements due to technical pioneers, he argued, trumped the dues of public funding and the way in which design and production were commercially linked in the aero-engine industry. Despite its reliance on government support during the war, Whittle saw the firm's pioneering work and engineering excellence as giving it a moral right to pursue its work as it saw fit. Afterwards, Whittle argued that although Rolls-Royce and de Havilland

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[141] Whittle, *Jet*, 304-305.

[142] Quoted in Whittle, *Jet*, 296-8.

[143] Emphasis in the original. (Whittle, *Jet*, 283.)

[144] Whittle, *Jet*, 301.

had both 'put more jet engines into the air than Power Jets... no other firm had yet equalled Power Jets' record for the number of *types* of engine which had powered experimental aircraft (W.1, W.1A, W.2B, W.2/500, W.2/700).'[145] But as was demonstrated in Power Jets' nationalisation, the moral rights that had increasingly taken the place of patents in the firm's strategy during the war didn't obviously translate into commercial assets.

A focus on Whittle and his close team has obscured the fact that not all of the employees at Power Jets (R&D) felt as they did. It is well-known that Whittle and sixteen of his original engineers left Power Jets (R&D) in April 1946, but it is less advertised that some 100 'scientific and experimental officers' from the company stayed on,[146] a group who felt no strong aversion to the prospect of working for a national establishment. Although there was some public worry about the seriousness of the loss of the firm's most visible engineers for British competitiveness, Roxbee Cox and the Ministry of Supply were confident that they would be able to fill the vacancies at the new establishment from a large pool of applicants.[147]

After the formation of the National Gas Turbine Establishment, Power Jets (R&D) remained in existence to administer the British jet patents now owned outright by the Air Ministry. Between November 1949 and October 1951, the United States Government agreed to pay $4M (£1M) for the use of all of the British patents during the war and 'over the next 20 years'. No one undertook to unravel the many patent claims.[148] (The Treasury decided against using the patents in its Lend-Lease settlement and saw them instead as a legitimate contribution to the country's debt payments.) The total conceded by the United States for use of the British jet patents, much less than the amount that the British Government had

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[145] Emphasis in the original. (Whittle, *Jet*, 302.)

[146] *The Times*, 15.4.46, 'Jet-Propulsion Development Sixteen Engineers Resign.' Most did not return to aero-engine work; many worked on industrial and marine gas turbines. (Whittle, *Jet*, 300.); NA T 161/1240, 19.3.46, Letter Newton to Curtis

[147] KNA, File 2000.467, 14.4.46, Letter Roxbee Cox to Mother; NA AVIA 46/234, 15.4.46, Extract from Parliamentary Debates; *The Times*, 15.4.46

[148] *The Times*, 09.11.49; The amount originally suggested had been halved in light of payments already made by individual American firms for manufacturing licenses. ('U.S. Use of JET Patents Claim Settled For $4,000,000,' *The Times*, 13.10.51)

spent on the turbojet aero-engine during the war, was however quickly exceeded by the sale of production jet engines and airframes overseas.

The Royal Aircraft Establishment

The RAE is mentioned in many existing histories of the turbojet. Details of its experiments on axial compressors in the late 1930s were included in the studies by Schlaifer, Postan, Constant, Kay, for example.[149] Yet none of these studies, with the possible exception of Postan, assesses the importance of the RAE's work. The focus on the Establishment's pre-war research on axial gas turbines rather than its wartime work has hidden its activity during the war, apart from its well-known collaboration with Metrovick on the F.2 axial turbojet. The 1991 account by the engineer Sir William Hawthorne in *Notes and records of the Royal Society of London* suggested that the 'second strand' of British turbojet history at the RAE was of equal importance to that at Power Jets, but the article discussed only the period up to 1941.[150]

The changes in the RAE's status during the war are not clearly understood. The RAE's role in aircraft and engine development was discussed briefly in the official history by Scott and Hughes (1955), for example, but their account did not give an impression of how this changed during the war. In a buried remark, the official history by Postan hinted that the extent of the Establishment's role in gas turbine aero-engine designs during the war was notable: 'Certainly, it can be said that the position of the R.A.E. in the gas turbine field was more influential than it had ever been in the design of conventional aero-engines since the end of the 1914-18 war.'[151] Yet Postan gave little impression of how the Establishment's position came to be so.

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[149] Schlaifer and Heron, *Development of Aircraft Engines*, 348-350 and 355-357; Postan, Hay and Scott, *Design and Development of Weapons*, 182-185; Constant, *Origins of the Turbojet Revolution*, 214-215; Kay, *Turbojet History and Development*, 12-19.

[150] Hawthorne, 'The Early History of the Aircraft Gas Turbine in Britain'.

[151] Postan, Hay and Scott, *Design and Development of Weapons*, 207.

A few authors have offered an argument for the importance of the RAE's work in turbojet research and design. Despite the brevity of his account of the RAE's wartime work on gas turbines, Postan did argue that the Establishment was 'responsible for revolutionising in this country the prospects of the axial-flow compressor which from the point of view of future developments was perhaps a more desirable type,' although this praise was somewhat obscured by the subsequent assertion that 'the claim to have been the first to build and run a gas turbine was indisputably won by Air Commodore Whittle'.[152] Virtually the only account to make a strong case for the RAE's importance was a booklet prepared by an ex-RAE employee, Richard Dennis in 1999. Presenting the story of the RAE's work to a popular audience for the first time, Dennis argued that its pre-war and wartime research was hugely significant because it made the country a world-leader in axial-compressor design after the war.

In this section, I will demonstrate that the RAE's role in British turbojet engines is both more important and much richer than the axial compressor experiments that many authors have dwelled on. Both Postan and Dennis' conclusions can be amplified. I will argue that Griffith's work at the RAE was important, not because it pre-figured Whittle's work, but because of the influence of the research programme that it inspired at the RAE and the subsequent influence of the RAE that that programme inspired. A crucial figure in the RAE's programme was Griffith's assistant, Hayne Constant, who after Griffith's departure in 1939 promoted both Griffith's early research and the Engine Division's role in gas turbine aero-engine design and research.

In both Britain and Germany, research institutions were crucially important in the introduction of axial compressors. In Britain, the RAE, like the AVA in Germany, was the crucial centre for axial compressor expertise. Unlike the German research institution, however, the RAE was also an important source of advice for the Air Ministry and MAP.

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[152] Postan, Hay and Scott, *Design and Development of Weapons*, 185.

Moreover, the British Establishment took a leading role in shaping turbojet aero-engines in Britain, which extended beyond the end of the war.

This section offers the first account of the RAE as a turbojet design organisation. The creation of a devoted turbine section at the RAE in 1941 was not only a reflection of the Establishment's increasing work on gas turbines, as Postan asserted.[153] It was also part of a major reorganisation of the RAE during the Second World War, which increased its role in engine research generally. I will show that the RAE successfully established the development of axial gas turbine engines in Britain - a research programme that ultimately won out over the centrifugal compressors used by Power Jets, Rolls-Royce and De Havilland in the first generation of British jet engines – as well as supporting the hugely successful British manufacture of turbojet aero-engines after the war.

The Engine Department's gas turbine programme

The first serious research work on gas turbine aero-engines in Britain was inspired by Arnold A. Griffith, a senior scientist at the RAE. In a 1926 report and research proposal, he argued that an axial compressor could reach high enough efficiencies to be suitable for an aero-engine if it were designed according to aerodynamic theory. The paper's theoretical prediction was proven by experiments done at the RAE using a single stage axial test rig in 1929.[154] That same year, while working at the Air Ministry's Laboratory in South Kensington, Griffith wrote another report supporting the use of gas turbines in aero-engines. In it, he argued - against the 1920 report of W.J. Stern, an earlier scientist in the same Laboratory - that gas turbine aero-engines could be more efficient than reciprocating engines. In the same report, Griffith sketched out ideas for the design of a turboprop aero-engine and for a multi-stage, contra-rotating, contra-flow test rig to test his theoretical conclusions.[155]

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[153] Postan, Hay and Scott, *Design and Development of Weapons*, 207.

[154] NA AVIA 46/234, Griffith, RAE Report No H.1111; Constant, 1945b, 411

[155] NA AVIA 46/234, 9.20, 54, Stern Report; NA AVIA 43/234, 11.29, Griffith, AML 1050A 'The Present Position of the ICT as a power plant for aircraft'

The Aeronautical Research Committee (ARC), which advised the government on aeronautical research, followed Griffith's work closely from 1926 on, and its Engine Sub-committee formed a special panel to discuss Griffith's work on gas turbines. Despite the success of the scientist's early work, the panel was unconvinced in 1930 that gas turbine aero-engines were a practical proposition. Declining to support Griffith's aero-engine proposal, the panel recommended only the construction of the multi-stage compressor test rig. Because the rig's unconventional compressor was theoretically immune to stalling, which simple axial compressors were prone to, the ARC believed that Griffith's compressor could inspire industry to continue work on axial compressors if the 'conventional type' proved discouraging at first. The Committee simultaneously recommended related experiments, including on combustion - also because of their general applicability.[156]

Whether Griffith was put off by the panel's doubts about the internal combustion turbine or distracted by other work, the contra-rotating compressor rig was not designed and built until the late 1930s.[157] It was the dedication of Griffith's assistant, Hayne Constant, to his mentor's gas turbine ideas that led to the rig's eventual development. This was typical for Griffith, whose 'prolific brain' constantly produced many 'varied series of studies that he left to others to test, and he was always throwing out new suggestions', often impractically far in advance of practice.[158] In any case, as head of the RAE Engine Department between 1931 and 1939, Griffith had major responsibilities apart from his axial compressor research. When Constant returned to the RAE as Griffith's assistant in July 1936 after two years as a lecturer at Imperial College, he determinedly took up work on axial gas turbines.[159] In July 1936, Griffith and Constant received permission, as was necessary for research projects initiated at

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[156] NA AVIA 46/234, 4.30, Report of Panel HE1

[157] Hawthorne, 'Aircraft Propulsion from the Back Room', 96

[158] A. D. Baxter, *Professional Aero Engineer Novice Civil Servant* (Sussex: The Book Guild Ltd, 1988), 144-145.

[159] Constant did experiments at Imperial College that convinced him of the utility of Griffith's ideas. At Imperial, Tizard encouraged him to pursue the new type of aero-engines. (Hawthorne, 1978, 96.)

the government establishment, to build an eight-stage axial-flow compressor. This was several months before the ARC lent their full support to gas turbine aero-engine development in Britain, a decision based in no small part on the testimony of Griffth and Constant.[160]

In March 1937, at the ARC's request, Constant prepared a report on the potential of the ICT as an aircraft power plant. In it, he argued that advances in materials and compressor design had made it possible to construct an ICT using only components 'proved by past experience' that would have lower specific weight and specific fuel consumption than a contemporary piston engine.[161] Constant's report was reviewed by the ARC's Engine Sub-Committee on 16 March 1937 alongside a report prepared by Griffith on the Whittle 'jet propulsion system'.[162] It concluded that 'the time was ripe for departures in power plant design of this type and that a special effort should be made to foster them.'[163] Although it could not directly authorise work or disburse funds, the ARC's recommendation nevertheless resulted in increased government support for work on gas turbine aero-engines at both Power Jets and the RAE.[164] With the decision to support work at Power Jets in addition to work at the RAE, Britain now had two officially supported turbojet projects, one led by an RAF officer and the other by a civil servant, both Cambridge trained engineers.

Under Constant's leadership, the RAE's programme of axial gas turbine research began to push the bounds of its previously limited role in engine development. It built on the Establishment's research in the early 1930s on turbines operating in high temperature gas

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160 Roxbee Cox, 'British Aircraft Gas Turbines', 55.

161 NA AVIA 46/234, 3.37, Constant, RAE Note E #3546 'The ICT as a power plant for aircraft'. The thoroughness of Constant's report contrasts with the report prepared by Bramson for O.T. Falk in 1935. (Reprinted in Kay, *Turbojet History and Development.*)

162 NA AVIA 46/234, 2.37, Griffith, Report #3545 on Whittle Jet Propulsion System

163 NA AVIA 46/234, 87th Report of Engine Sub-Committee

164 Nahum, 'Two-Stroke or Turbine?', 315-319; Power Jets was promised government support in August 1937 and received its first payment in May 1938. (Schlaifer and Heron, *Development of Aircraft Engines*, 434-435.)

streams in turbo superchargers (although these were later abandoned in Britain),[165] and was shaped by Constant's effort to 'make new contacts and tap as much experience as possible' in gas turbines and new alloys in the academy, research institutions and industry in Britain and abroad.[166] British industry had not yet started work on axial compressors, so the Engine Department not only gathered data, as was usual for the Establishment, but also created gas turbine designs.[167] Between 1937 and the start of the war, the Engine Department designed six multi-stage axial compressors, including the contra-rotating compressor described by Griffith in 1929.[168]

In the late 1930s, Griffith successfully appealed to the Air Ministry to allow the RAE to place turbine contracts with outside firms. This enabled the Engine Department to circumvent the slow RAE tool room and get multiple gas turbine designs built quickly. Contracts were given in this way to Armstrong-Siddeley and Bristol and the steam turbine makers Fraser and Chalmers, Metrovick and Parsons.[169] After the war, Constant explained that like Power Jets, '[t]he R.A.E. … acted as a design and research group, the manufacture and testing being done mainly by outside contractors.'[170]

The ARC Engine Sub-Committee suggested in 1937 that work on gas turbines would 'probably require the cooperation of turbine builders' and recommended Metrovick, which became an important partner for the RAE.[171] Interestingly, BTH, the company that Whittle was working with, and Metrovick, working for the RAE, had a joint owner, Associated Electrical Industries. The RAE's representatives met with Metrovick on 3 June 1937 to discuss three possible design schemes, lettered A, B and C, which included a range of

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165 Hawthorne, 'Aircraft Propulsion from the Back Room', 96; Roxbee Cox, 'British Aircraft Gas Turbines', 55.

166 MOSI, 10.9.42, Eng/2038.R/HC/21, Report by Hayne Constant

167 Hawthorne, 'The Early History of the Aircraft Gas Turbine in Britain', 104.

168 Hawthorne, 'Aircraft Propulsion from the Back Room', 97.

169 Baxter, *Professional Aero Engineer*, 147.

170 Constant, 'The Development of the Internal Combustion Turbine', 409.

171 Hawthorne, 'Aircraft Propulsion from the Back Room', 96.

different compressor types: centrifugal, axial and contra-rotating. All were test units, with multiple separate rather than coaxial compressor-turbine units, avoiding the necessity for complicated mechanical design.[172] (See Figure 4.3.) In November 1938, the RAE went beyond its earlier dispersed designs to complete a new design, Scheme D, with co-axial high- and low-pressure compressor-turbine pairs. Scheme D.11 was completed on 29 August 1939, and Metrovick began detail design for the unit. The new scheme took precedence over schemes B and C, which Metrovick had already begun working on.[173] Griffith, as we have noted (in Chapter 3) left the RAE for Rolls-Royce in 1939, where he inaugurated work on axial compressors, which led on to the company's post-war axial engines.

The outbreak of war changed the RAE's research programme in two important ways. Firstly, it forced the RAE to give Metrovick more autonomy over the turbo-compressor units that they were building for the Establishment. Metrovick was now instructed to 'persevere on your own initiative' and to proceed without waiting 'for approval from RAE for every step', as they had before.[174] Secondly, the RAE saw that it could have a role designing flight engines rather than exclusively experimental bench units as its Schemes A through D had been. In April 1940, Metrovick, which was by now quite familiar with the details of axial compressors, started designing an axial compressor for the Crecy piston engine (Scheme E), while the RAE embarked on an axial compressor for a complete, flight-worthy turbojet, known as Scheme F. The RAE undertook to design, in addition to the axial compressor, the engine's combustion system and auxiliaries, and Power Jets was enlisted to design the engine's turbine. Eager to take advantage of the opportunity to put its research into a practical engine, the Chief Superintendent of the RAE, A.H. Hall, wrote a letter to MAP on 19 July 1940, asking for approval for the whole F.1 engine, rather than just the axial

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[172] The B10 unit was the high-pressure section of a dispersed compound turbine. (Hawthorne, 'Aircraft Propulsion from the Back Room', 96; Constant, 1945; MOSI, 16.12.37 Report by Rhoden)

[173] MOSI, Artus, Letters 3.11.38, 9.11.39 and 6.40.

[174] MOSI, Artus, 15.9.39, Letter RAE to Metrovick

compressor, which had already been approved. The Establishment's axial 'Jet Propelled Unit' was not expected to cost more than £10,000, and Hall argued that it would be superior to Power Jets' centrifugal engine.[175]

Power Jets soon withdrew from the RAE's F.1 project because of the pressure of other work.[176] The Establishment then approached Metrovick, which voiced its interest in building the engine in July 1940, although the firm's turbine team wanted to be allowed to 'check calculations and discuss modifications', rather than acting only as sub-contractors.[177] The two parties decided that the axial flight engine, now known as F.2, would use an RAE designed nine-stage axial compressor, while the combustion chamber, turbine and nozzle would be designed by Metrovick. The F.2 was to produce about 1,800 pounds thrust, slightly more than the W.2B.[178] The F.2 compressor blades were designed by the RAE based on the better part of a year's worth of detailed experiments using a low speed cascade tunnel and a single stage compressor – both typical of the RAE's meagre equipment for gas turbine research before mid-1941.[179] (For more details on the F.2 see Chapter 3.)

Constant boasted in a report in September 1942 that the F.2 was 'the first aero-engine design by RAE since the last war'.[180] The RAE became dedicated to the success of the F.2 aero-engine and emphasised to Metrovick that Scheme F took precedence over the research units, Schemes A, C, D and E, which the firm was working on.[181] In the interest of hastening the F.2's progress to flight status, Constant agreed, in autumn 1941, that

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175 NA AVIA 13/1403, 19.7.40, 31A, Letter Hall to DSR

176 NA AVIA 13/1403, 20.4.40, 2A, Roxbee Cox on behalf of Chief Superintendent RAE to Air Min RDE1; The decision to abandon the RAE's original plans to develop a turboprop for a simpler turbojet, as Power Jets was designing, was also a result of the war, which emphasised a scheme that could be developed quickly, rather than one that would meet the RAE's ultimate aim of bettering the fuel consumption and specific weight of a piston aero-engine – two things that a simple turbojet could not do. (MOSI, 10.9.42, Eng/2038.R/HC/21, Report by Hayne Constant)

177 MOSI, Artus, 25.7.40, Letter Smith to RAE

178 MOSI, Artus, 30.7.40, Report Smith to Baumann; 13.8.40, Memo Smith to Chief Draughtsman

179 MOSI 1999.39/1/68, 26.5.97, Letter from Bailey to Dennis

180 MOSI, 10.9.42, Constant, Engine Dept, RAE, Eng/2038.R/HC/21

181 NA AVIA 13/1403, 4.8.40, 42A, Hall to Metrovick

Armstrong-Siddeley should be brought into the project (as detailed in Chapter 3) to provide assistance on aero-engine design.[182]

Reorganisation at the RAE

In the summer of 1941, MAP made two decisions regarding jet engine development: first, that new research facilities would be provided for RAE turbine research (a new turbine section was created in August), and second, that a new factory would be built for Power Jets at Whetstone. In this way, MAP's Controller of Research and Development, Air Marshal Francis J. Linnell, wanted to continue to support work on multiple, competitive approaches to gas turbine aero-engines.[183]

The new facilities for the two jet teams were significantly different in both scale and purpose, however. The RAE's new turbine section at Pyestock included only an engine test house, a workshop, an office block and a laboratory. (See Figure 4.4.) These were facilities suited to a research establishment and very much in contrast to the extensive Power Jets facility at Whetstone, with its capacity to develop and manufacture aero-engines, if only on a small scale. The expenditure on buildings and research equipment at Pyestock was £150,000 – less than half of the £325,000 spent at Whetstone.[184]

The formation of the turbine section in 1941 was not the only change at the RAE that year. In fact, it was part of William Farren's efforts to restructure the entire Establishment. Farren made his acceptance of the leadership of the RAE in 1941 conditional on the unification of the two organisations then based at Farnborough, the RAE and the Airworthiness Department, which however answered to different officials in the Ministry. As the first Director of the newly unified RAE, he worked to expand and strengthen the Establishment. By the time that he left in December 1945, Farren was 'something of a

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[182] NA AVIA 15/1509, 38A, 15.1.42

[183] NA AVIA 46/237, 31.7.41, 3a, Gas Turbine Collaboration

[184] Hawthorne, 'Aircraft Propulsion from the Back Room', 98; NA T 161/1240, 7.12.43, Letter from Trend to Lee

legend', having virtually rebuilt Farnborough and having been a moving spirit behind Cripps' project to build a new RAE complex at Bedford.[185] By appointing Hayne Constant as head of the Engine Department in 1941, Farren placed an ambitious man with a particular interest in gas turbines in a position to revivify the Establishment's insufficient and deteriorating engine research facilities.[186] Although Constant assumed responsibility for all of the RAE's work on engines, he kept a particular interest in the turbine section that he had helped to create.[187] The turbine section continued to grow as an increasing number of personnel were diverted from piston engines to gas turbines. By 1944 it represented half of the RAE's Engine Department and had a staff of about fifty.[188]

Constant's ambition was for the Establishment's turbine section to become the main advisor to MAP on gas turbine aero-engines as well as the national research centre on the subject, carrying out experimental research, performance calculations, project studies, and flight trials.[189] This was a departure from the RAE's existing role in aero-engine design. For while the RAE was consulted on all new airframe designs, it had no control over piston aero-engine design. Farren's experience must have made him especially alive to the turbojet's potential for increasing the Establishment's influence.[190] He argued to MAP in January 1942 that the RAE's evaluative role should be extended from jet airframes to include jet engines. The new engines, unlike reciprocating engines, were particularly well suited to calculation, he argued, and thus to the RAE's particular expertise.[191] In an RAE report in September 1942, Constant argued that 'the RAE has been very largely responsible for the development of the

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185 George P. Thomson and Arnold A. Hall, 'William Scott Farren. 1892-1970', *Biographical Memoirs of Fellows of the Royal Society* 17 (1971): 229-230.

186 Thomson and Hall, 'William Scott Farren', 230; Postan, Hay and Scott, *Design and Development of Weapons*, 107 fn 1; Constant, 'The Early History of the Axial Type of Gas Turbine Engine', 412.

187 Hawthorne, Cohen and Howell, 'Hayne Constant', 275.

188 NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §30; Postan, Hay and Scott, *Design and Development of Weapons*, 207.

189 Hawthorne, 'The Early History of the Aircraft Gas Turbine in Britain', 104.

190 Farren's career had earlier brought him into contact with the first work on turbojet aero-engines and aircraft in Britain. (Thomson and Hall, 'William Scott Farren', 218-226.)

191 NA AVIA 15/1417, 27.1.42, 7A, Letter Farren to Pye

gas turbine as an aero engine... It is and will remain the responsibility of the turbine section, RAE, to affect this great revolution in power plant design.'[192]

Resistance to the RAE's growing influence came from George P. Bulman, who was head of Engine Development at MAP. Ever since he had taken charge of engine development in the Air Ministry at the beginning of 1928, Bulman had fought to curb the influence that the RAE had gained in aero-engine design during the First World War.[193] Bulman feared that an increased role for the RAE in gas turbines threatened both the role of his Directorate in guiding industry and the independence of the aero-engine industry's own design capability. He was particularly suspicious of arguments that emphasised the scientific nature of the new gas turbine aero-engines because he feared that they would be used to justify making the aero-engine industry subservient to the scientific power of the RAE.[194] MAP's Director of Scientific Research, David Pye, however, saw a legitimate role for the RAE in gas turbine aero-engine design, precisely because of its research capability. He argued that 'to design jet propulsion engines successfully, the designer must have at call certain fundamental aerodynamic knowledge. It is an art in which technical experience alone is not enough'.[195] Bulman continued to defend industry's initiative and his department's independence from the RAE until he left MAP's Directorate of Engine Development on 4 February 1944.[196]

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[192] MOSI, 10.9.42, Eng/2038.R/HC/21, Report by Hayne Constant

[193] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 54-57.

[194] NA AVIA 15/1417, Feb 1942, 9A, Memo Bulman; Bulman uses the same language in his discussion of the RAF's role during the first war in his memoir. (Cf. Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 127-128.)

[195] NA AVIA 15/1417, 22.2.42, 11, Minute Pye to Bulman and Rowe

[196] As Director for Construction of Research Facilities, Bulman worked with Farren to build the RAE complex at Bedford. (Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 350-352.)

Despite Bulman's opposition, it quickly became MAP practice to submit all new gas turbine aero-engine plans to the RAE for evaluation.[197] The RAE played an important role in evaluating all of Britain's early turbojet projects. Indeed (as discussed in Chapter 2), in November 1942, the future of the British jet engine programme was left to rest on a 'complete survey' by the RAE of the virtues of all of the several turbojet engines then under consideration for production: the W.2B, B/26, W.2/500 and H.1.[198]

In addition to judging industry proposals, the RAE remained closely involved in the design of axial engines. Like the F.2, Britain's first axial turbojet, the country's second axial engine was also influenced by the design work of the RAE. As discussed in Chapter 3, in 1942, the Establishment volunteered to help Armstrong-Siddeley (ASM) enter the field of axial gas turbine development by providing test data, research reports, advice, and an initial aerodynamic design for its first engine, the ASX.[199] The first ASX unit ran on 22 April 1943, and soon produced more than 2,000 pounds thrust.[200]

Government company and back again

In late 1943, when Cripps decided to nationalise Power Jets, Roxbee Cox, who was in charge of turbojet development at MAP, made the combination of Power Jets and the RAE's turbine section a condition for his accepting the directorship of Power Jets (R&D).[201] The director of the RAE, the head of its Engine Department and the head of its turbine section (Farren, Constant and Hawthorne) were all opposed, largely because such a change would interrupt Constant's 'plans and aspirations' for the turbine section at Pyestock as well as sever the section's particular relations to MAP, which Constant and Farren had done so

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[197] Hawthorne, 'Aircraft Propulsion from the Back Room', 98; Halford's suspicion about the RAE's input on the H1 demonstrated that the Establishment's work in the gas turbine field went beyond its role in piston engine work. (NA AVIA 13/935, 5.8.42, Letter Farren to Halford; 10.11.42, Letter Farren to Halford)

[198] NA AVIA 15/1708, 2.11.42, 15A, Meeting in Linnell's Office about 'the future of the W.2B design'

[199] NA AVIA 13/911, 14.8.42, ASM visit to RAE

[200] NA AVIA 31/3, 15.5.43, GTCC Minutes Meeting #9

[201] Postan, Hay and Scott, *Design and Development of Weapons*, 229-30.

much to promote during the war. [202] Roxbee Cox won out, however, and a single national centre was created from the two disparate parts. What Cherwell described as 'the Minister's new sociological experiment'[203] left the Power Jets organisation largely the same but required serious adjustments from the RAE staff, who were changed in a stroke from civil servants to private employees. Some members of the RAE decided to stay on in public service at MAP rather than join the new company.[204] Constant, however, chose to leave his many responsibilities at the RAE and remained with the turbine section as it became part of Power Jets (R&D).[205] He became head of the new company's engineering department, where he was influential in defining the firm's technical policy.[206]

After the new company was established, the former Power Jets and the RAE turbine section remained however physically separate, with Roxbee Cox spending half his time in Pyestock and half in Whetstone.[207] Despite having worked closely together since the late 1930s, Constant and Whittle found themselves leading competing factions at meetings of the Technical Policy Committee of the Gas Turbine Technical Advisory and Co-ordinating Committee. Constant thought the new company should emulate a national establishment by primarily supplying industry with research data. Whittle, as we have seen, wanted the company to remain the leading gas turbine design agency in Britain, which he argued required designing and developing prototype engines. Industry sided with Constant; what aero-engine manufacturing firms wanted from the government, according to Rolls-Royce, was not new engine designs, but 'to be supplied with more basic data on the many research

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[202] Hawthorne, 'Aircraft Propulsion from the Back Room', 100; Hawthorne, Cohen and Howell, 'Hayne Constant', 276; Postan, Hay and Scott, *Design and Development of Weapons*, 230.

[203] PREM 3/21/4, 26.5.44, 147, Memo Cherwell to Churchill

[204] Postan, Hay and Scott, *Design and Development of Weapons*, 230.

[205] Hawthorne, 'Aircraft Propulsion from the Back Room', 100.

[206] NA AVIA 46/174, Scott Narrative – the National Gas Turbine Establishment, §54

[207] KNA, File 2000.443, 30.4.44, Letter Roxbee Cox to Mother; In 1948, Roxbee Cox finished negotiations for a new site north of the RAE turbine section's existing site. (Roxbee Cox, 1948) The test facilities of the former Power Jets Whetstone factory were not fully combined with those of the original RAE turbine section until 1955.

and aerodynamics problems involved, and presented in a manner directed for specific application after confirmation by intensive testing.'[208] When it became clear that he would not be able to influence the company's engineering policy as he and Roxbee Cox had hoped, Whittle resigned from the Technical Policy Committee (but did not leave the company), sometime between 18 April 1945 and 8 May 1945.[209]

On 21 December 1945, it was decided that Power Jets (R&D) should be turned into the National Gas Turbine Establishment.[210] In its new form, its responsibilities were more akin to those of the former RAE turbine section than the former Power Jets. In fact, the decision to turn the company into an Establishment was met in full expectation that Whittle and Roxbee Cox would resign because of their earlier vocal insistence on the importance of aero-engine production to the company's function.[211] Whittle did resign, but although he hesitated at first, Roxbee Cox stayed on as the Director of the new Establishment. Hayne Constant became his Deputy.[212] In 1948, Constant ascended to the Directorship of the Establishment, where he remained until 1958. As Director, he oversaw the end of Power Jets' research programme on centrifugal gas turbines and the triumph of the axial compressor in British aero-engines.

The Ernst Heinkel Flugzeug Werke

The Ernst Heinkel Aircraft Company (EFHW) was unique in Germany for being the only company outside the aero-engine industry to develop a turbojet engine during the war. Because of the firm's record-making turbojet flights, it is almost as familiar in the story of the German turbojet as Power Jets is in the British. The firm's visibility is due to its many

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[208] RRHTHC, 17.4.45, Commentary by James E. Ellor

[209] Whittle, *Jet*, 282-284.

[210] Cripps, then President of the Board of Trade, was present. (NA T 161/1240, 21.12.45, Letter Flett to Bailey)

[211] NA T 161/1240, 19.3.46, Letter Newton to Curtis

[212] Roxbee Cox recalled that he had needed the job to earn a living, and the terms of his five-year contract were very favourable. (Nahum, *Frank Whittle*, 131; KNA, File 2000.443, 30.4.44, Letter Roxbee Cox to Mother) The Treasury described the terms of his engagement as 'at the extreme limit, but not over the limit of what is reasonable'. (NA T 161/1240, 7.2.44, Letter Fforde to Smith)

innovations, its importance as the second largest German aircraft company in the interwar and war years,[213] and the fame of its proprietor, Ernst Heinkel – indeed in the literature the company and the man are almost synonymous. Heinkel's visibility was reinforced by the publication of his ghost-written memoir in 1953 (released in English in 1956), although his account of the turbojet has been proven notoriously unreliable.[214] There have been several book-length studies of Heinkel and his firm by German authors H. J. Nowarra (1975), H. Dieter Köhler (1999), and most recently Volker Koos (2007), in which the jet features as one of the firm's many pioneering innovations.[215]

Accounts of the turbojet in Germany have taken two different approaches to EHFW's jet record. Accounts that focus on the first turbojet flight like Postan, Constant and Conner acclaim the company's success in turbojet development. The British official history argued that von Ohain's 'faster progress… was due very largely to the fact that he had the great good fortune to be able to develop his jet propulsion unit in surroundings which, if not exactly perfect, were considerably more propitious than those in which Air Commodore Whittle's unit was developed.'[216] Constant asserted that von Ohain's work advanced more quickly because of Heinkel's 'tremendous (compared to Power Jets) financial resources' and Heinkel's 'unrestrained' support.[217] In her biography of von Ohain, Conner too characterised

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213 Homze, *Arming the Luftwaffe*, 185.

214 Heinkel and Thorwald, *Stürmisches Leben* and *He 1000*; Michael J. Neufeld, 'Rocket Aircraft and the "Turbojet Revolution"', in *Innovation and the Development of Flight*, Roger Launius ed. (College Station, TX: Texas A & M University, 1999), 207-234; NASM VO, Box 4, 16.1.81, Letter Schelp to von Ohain

215 Heinz J. Nowarra, *Heinkel und seine Flugzeuge* (München: Lehmann, 1975); H. Dieter Köhler, *Ernst Heinkel: Pionier Der Schnellflugzeuge, Eine Biographie*, Second Edition (Bernard & Graefe, 1999); Volker Koos, *Ernst Heinkel: Vom Doppeldecker zum Strahltriebwerk* (Bielefeld, Delius Klasing, 2007).

216 Postan, Hay and Scott, *Design and Development of Weapons*, 190-192; Postan does not give an adequate account of EHFW. The official history used a very brief and flawed rendition of von Ohain's early story as a foil to emphasise Whittle's difficult path to support. (Postan, Hay and Scott, *Design and Development of Weapons*, 187-194.)

217 Constant, *Origins of the Turbojet Revolution*, 200-201.

the relationship between Heinkel and von Ohain as a constructive one.[218] These authors treated von Ohain as if he were an independent inventor, free to do as he chose after he secured funding. They depicted the relationship between EHFW and its turbojet designer, as a positive and enabling one, and argued that von Ohain was lucky to have found in Heinkel a willing sponsor for his work – especially in comparison with Whittle.

Such accounts that portray a mutually satisfactory turbojet programme at EHFW need to be drastically revised. Indeed, the second view of EHFW's turbojet work in the literature is a negative one. Authors who considered the firm's entire turbojet programme, such as Schlaifer, and aviation writers Köhler and Koos, judged the company's programme a failure, for although Heinkel was an important pioneer, no EFHW jet airframe or engine was ever produced in quantity. All three authors argued that the firm's resources were divided between too many projects. Köhler, however, maintained that Heinkel had a positive influence on the programme at his firm, interpreting the division of resources as a by-product of pioneering.[219] Schlaifer, in contrast, saw it as a product of the firm's research ethos and a crucial mistake given the airframe firm's lack of resources for and expertise in aero-engine manufacture.[220] Koos's excellent account of turbojet work at Heinkel went even farther, attributing the failure of EHFW's turbojet programme primarily to Heinkel's behaviour.[221]

Rather than focusing on Heinkel, as previous authors have done, this section will look in detail at the growth of EHFW's turbojet capability and specifically at how this influenced von Ohain's work. Instead of just looking at the time before the legendary flight of the world's first turbojet fighter, the He 280, it considers the entirety of von Ohain's work at the company. This section's conclusions support the more negative impressions of

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[218] Conner gives a detailed account of von Ohain's early work at EHFW, drawing on many sources; the details of his later work are somewhat confused. (Conner, *Elegance in Flight.*)

[219] Köhler, *Ernst Heinkel: Pionier Der Schnellflugzeuge,* 178 and 198.

[220] Schlaifer and Heron, *Development of Aircraft Engines*, 406-410

[221] Koos, *Ernst Heinkel*, 165.

Schlaifer and Koos. Building on comments about negative aspects of von Ohain's relationship to EHFW made by Schlaifer and later made publicly by von Ohain himself,[222] this section will argue that the reason that von Ohain's designs had no legacy was directly attributable to the nature of the company where he worked.

This section shows that although both von Ohain and Heinkel were dedicated to the development of the turbojet, their goals within that field were often opposed. As an employee, von Ohain was in the weaker position, and his work was in fact hugely disadvantaged through alliance with Heinkel, with whom he nevertheless remained on good terms. In this view, the flight of the He 280 was not an important accomplishment for von Ohain, but rather marked the culmination of Heinkel's – rather than von Ohain's - vision of turbojet development as a route to quick, inventive success. I will argue that it was only with developments at the firm in 1942-1943, including Heinkel losing control of EHFW's turbojet programme, that von Ohain finally got the propitious conditions and autonomy for development that he had desired since 1936, when he joined the company.

The beginning of EHFW's turbojet work

In 1936, the Ernst Heinkel Flugzeug Werke (EHFW) became the second German company to fund turbojet development after Junkers Aircraft Company.[223] This early start was the beginning of what became the most extensive – in terms of number of turbojet aero-engine and airframe projects – but also one of the least successful – in terms of production - turbojet programmes in Germany. Although EHFW had never produced an aero-engine before 1936, the high-speed turbojet fitted well into the company's image of itself as a pioneering, speed-record-breaking company, with design rather than production at the heart

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[222] Schlaifer and Heron, *Development of Aircraft Engines*, 410; Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 85.

[223] Koos, *Ernst Heinkel*, 132-135.

of its business.[224] When he received a letter introducing Dr Hans von Ohain and his design for a new aero-engine in March 1936, Ernst Heinkel jumped at the chance to develop a turbojet aero-engine, sensing an opportunity to secure another world-record for his company, enter the aero-engine industry and also gain an advantage over the established aero-engine firms, none of which were then working on a turbojet engine.[225]

Despite some scepticism from EHFW's engineers, von Ohain received a friendly reception at the company. The physicist had approached Heinkel, who had a reputation for being interested in high-speed flight and unorthodox ideas, because he feared a negative response from established aero-engine firms.[226] Von Ohain hoped to be able to develop his turbojet ideas at EHFW, yet in the end, he was hindered by the very things that had made the firm seem a good place for an inventor to work in 1936: Heinkel's rabid interest in new projects, his expansionist tendencies, his independence, and his firm's financial self-sufficiency. Because of the centrality of von Ohain's work to Heinkel's ambition to join the aero-engine industry, for the first seven (of nine) years of his employment at EHFW, von Ohain was never entirely free to develop a turbojet engine as he chose. By becoming part of a successful firm, von Ohain gained access to financial support, but his work was seriously obstructed by the inappropriate facilities and expertise available at the company as well as the firm's and its owner's ethos and demands.[227]

The terms of von Ohain's first contract with Heinkel, signed on 3 April 1936, made it clear that further support for his work was contingent on quick successes. If von Ohain successfully demonstrated the principle of jet propulsion, he was to be hired to continue work on the project for at least one year at a salary of 400 RM per month, in which case von

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[224] DM FA001/0258, 4.8.38, Letter Heinkel an Udet; EHFW was not the only German aviation firm to make a virtue of its design rather than production capability. (Overy, *Air War*, 179.) The huge number of German development projects is often interpreted as proof of German technical superiority, but they reflected rather an unfocussed procurement system.

[225] Koos, *Ernst Heinkel*, 141.

[226] Köhler, *Ernst Heinkel: Pionier Der Schnellflugzeuge*, 165.

[227] Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 16.

Ohain agreed to transfer his turbojet patents to EHFW.[228] The newcomer immediately felt the compulsion to quickly achieve results, the so-called 'Heinkel-tempo' that was de rigueur at the company. Heinkel's inexperience with aero-engines contributed to the pressure because, as von Ohain remembered, Heinkel was 'enormously impatient' and expected that a new engine could be finished in as short a time span as a new airframe.[229]

With his employment and the opportunity to further develop his turbojet ideas hanging in the balance, von Ohain sacrificed his systematic development plans (particularly for combustion) in favour of a design that could be built and run as soon as possible. Because centrifugal elements were better known and promised to be easy to build, von Ohain's first demonstrator unit at EHFW, the HeS 1, had a centrifugal compressor and turbine; von Ohain had employed the same elements in the turbojet model that he had personally paid for before coming to the firm. The fact that the engine had both a centrifugal compressor and centrifugal or radial-flow turbine was unique among all early turbojets and remained a feature of all of the engines that von Ohain designed up to 1942.[230] In the interest of speed, von Ohain decided to use hydrogen gas to power the engine, another unique feature. This meant that he could run the HeS 1 without the delay that would be incurred by developing a liquid fuel combustion system – indeed, problems with combustion delayed all of the early turbojets.[231]

The firm's existing facilities governed how the engine was built. A lack of aero-engine plant dictated that the demonstrator was made mostly from sheet metal. Systematic

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[228] NASM VO, Box 22, 3.4.36, Copy of contract signed by von Ohain and Heinkel; The level of von Ohain's salary in his next contract was not very large for an engineer with similar duties, but he was promised an immediate raise after the flight of the He 178. (Conner, *Elegance in Flight*, 80.) He was also promised a bonus as soon as each engine ran.

[229] Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 15.

[230] Including the HeS 1, 2, 3, 6, 8 and 10. (CIOS XXIII-14, 5.45, Turbine Activity at EHAG)

[231] Using hydrogen gas, which was gaseous and therefore easy to burn, avoided the problems of liquid fuels, which had somehow to be mixed with the incoming airstream. (Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 15.)

component testing, which was necessary to develop high performance aero-engine parts, was made impossible by the lack of equipment as well as Heinkel's constant pressure for speed.[232]

In March 1937, the HeS 1 secured von Ohain's job by demonstrating the possibility of a self-sustaining jet engine. His group's second demonstrator, the HeS 2, was built soon after. It produced more thrust than the HeS 1 and included the firm's first liquid fuel burning combustion system, which was designed with important insights from Max Hahn, one of von Ohain's chief assistants throughout.[233]

After von Ohain's first two demonstrator units had proved the possibility of the turbojet, Heinkel pushed the head of his turbojet programme to develop a flight engine as soon as possible, 'regardless of the quality of the engineering'. The engine just had to run; it didn't need to be a 'real mass production engine'.[234] At the same time, EHFW began designing an experimental airframe for the next engine. Taking advantage of von Ohain's work, Heinkel hoped to deploy the method that he had already successfully used in his airframe work to now enter the aero-engine field: using stopgap means to achieve a surprise success (rather than a production success) in order to gain commercial and political concessions. The proprietor's conception about the difference between demonstration and production prototypes was also drawn from airframe practice and proved to be similarly misguided in the aero-engine field.[235]

The RLM had initiated its own turbojet programme in 1938, inspired by the success of EHFW's work, yet the Ministry refused to grant the airframe firm an aero-engine contract.[236] By presenting the jet flight as a *fait accompli*, Heinkel hoped to force the RLM to support EHFW's aero-engine development activity, against the Ministry's avowed policy of

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[232] Like Whittle, von Ohain, was at first only able to test complete engines. (Ermenc, *Interviews with German Contributors*, 34-39; Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 93; Postan, Hay and Scott, *Design and Development of Weapons*, 190-191.)

[233] Hirschel, Prem and Madelung, Aeronautical Research in Germany, 236.

[234] Von Ohain quoted in Ermenc, *Interviews with German Contributors*, 37.

[235] Koos, *Ernst Heinkel*, 143-145.

[236] Ermenc, *Interviews with German Contributors*, 42.

only giving aero-engine contracts to manufacturers that had the facilities and expertise for aero-engine development.[237] Irrespective of von Ohain's intentions, his engine assumed a key place in Heinkel's business strategy. He could hardly refuse, for Heinkel presented this scheme as the surest way to get the resources that von Ohain needed for turbojet development.

Thus von Ohain found himself again working without tools or experienced aero-engine personnel and sacrificing systematic development plans for a quick result, but now in pursuit of resources for aero-engine development. His first flight engine, the HeS 3 and a second version, the HeS 3b, were, like the two demonstrator units before them, built quickly from materials that the firm had at hand. The new engine used the liquid combustion system of the HeS 2 demonstrator, for example, which was however still not fully developed. While the firm's experimental jet airframe, the He 178, was designed by Heinkel's best aerodynamicists, Siegfried Günter and Heinrich Helmbold,[238] von Ohain struggled to recruit competent engineers to his small engine team.[239]

Despite the rushed design and construction of the HeS 3b, the engine nevertheless propelled the He 178 airframe on the world's first turbojet flight on 27 August 1939. Von Ohain later recalled of this achievement, for which he would become famous: 'we flew the first time with many prayers.... that was *not* really a sincere engine business. It was simply a demonstration of the principle.'[240] The HeS 3b was only just sufficient for a first flight,[241] and went quite against von Ohain's notions of developing a functional turbojet.

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[237] CIOS XXIII-14, 5.45, Turbine Engine activity at EHAG

[238] Helmbold had earlier developed a two-stage contra-rotating compressor for a high-speed wind tunnel at EHFW. (Wagner and Cox, *First Jet Aircraft*, 52 fn 12; NASM VO); The He 178 was designed by the same division as the He 176 rocket plane and was made, like the 176, largely out of wood. (Koos, *Ernst Heinkel*, 140; DM FA001/0258, 6.2.39 Besprechung in Rostock 23.1.39; Reprint of Protokoll Nr S-017, end July/start August 1938 in Wagner and Cox, *First Jet Aircraft*, 17.)

[239] Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 95; He did however receive important help in learning how EHFW worked from Wilhelm Gundermann. (Conner, *Elegance in Flight*, 256.)

[240] Emphasis in the original. Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 16-17.

Although the engine secured a record for EHFW (on 13 February 1939, Heinkel decreed that a museum should be established at EHFW to house all of von Ohain's engines[242]), the practical results of the feat turned out to be less than Heinkel had hoped. Although the RLM acknowledged EHFW's work in the aero-engine field and granted the firm a contract for a twin-engined fighter prototype (later the He 280) and two engines (later the HeS 8),[243] these contracts didn't give EHFW access to aero-engine manufacturing facilities or engineers, both of which were in extremely short supply in Germany at the time.[244] Thus after the first flight of the He 178, von Ohain was little better-off in terms of resources than he had been before. At around the same time, however, Heinkel's acquisitive actions had dramatically expanded the firm's turbojet programme.

The inexorable expansion of EHFW's turbojet programme

While von Ohain was engaged in designing and building the HeS 3, Heinkel made his life dramatically more difficult by hiring a second turbojet team, led by Max Adolf Müller, which competed with von Ohain's group for the firm's already insufficient aero-engine development resources.[245] The same spirit that had made Heinkel welcome von Ohain and his centrifugal turbojet now made him open to Müller's offer of an axial turbojet design. EHFW's owner wanted to pursue as many variants of the new engines as possible, until enough information was available to choose definitively between them.[246] With the addition

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241 Conner, *Elegance in Flight*, 257.

242 Reproduction of Heinkel's museum directive in Conner, *Elegance in Flight*, 85.

243 Wagner and Cox, *First Jet Aircraft*, 30.

244 Schlaifer and Heron, *Development of Aircraft Engines*, 406; Koos, *Ernst Heinkel*, 156.

245 Schlaifer and Heron, *Development of Aircraft Engines*, 406-7.

246 In autumn 1938, Heinkel and von Ohain had initiated work on a turbojet (the HeS 9) based on an axial compressor designed by Walter Encke at the AVA. Von Ohain had attended Encke's lectures in Göttingen, and he recommended him to Heinkel as a consultant on axial compressors. Encke remained a consultant to EHFW until the end of the war. (Wagner and Cox, *First Jet Aircraft*, 31; NASM VO, Box 16, 463; Köhler, *Ernst Heinkel: Pionier Der Schnellflugzeuge*, 198; Koos, *Ernst Heinkel*, 154.) Work on the HeS 9 was soon abandoned in favour of Müller's axial engine.

of the Müller team, EFHW became the only company in Germany to have two turbojet teams working independently to develop centrifugal and axial engines.[247]

In addition to an advanced axial turbojet design influenced by Herbert Wagner, Müller brought with him something especially valuable to a firm lacking aero-engine resources: a dedicated group of about fourteen engineers, who had been working together at the Junkers Airframe Company for several years before they had been forced to leave by the RLM's turbojet policy.[248] The arrival of Müller's team more than doubled the size of the turbojet programme at EHFW, which had grown from a start of two men in 1936 to about ten in 1939. By 1940 it had reached about thirty (including Müller's team), which was, however, still far less than Power Jets' staff at the same time.[249]

Further exacerbating the shortage of resources for von Ohain, Müller indulged Heinkel's support for many projects by starting a range of jet engine developments. His group's most successful engine was the 'extremely advanced'[250] and impressively efficient axial engine[251] known internally as the HeS 30 (RLM number 109-006), which was based on the group's previous work at Junkers. In addition to the two HeS 30 units that were eventually completed at EHFW,[252] however, Müller and his engineers also devoted resources to work on a bypass axial turbojet, the HeS 30a; a constant volume combustion (as opposed to constant pressure) turbojet built from HeS 30 parts, the HeS 40; and a motorjet project begun at Junkers, which resulted in the HeS 50 and HeS 60.[253] None of these was ever

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247 They began work at EHFW on 1 September 1939. (Koos, *Ernst Heinkel*, 155.)

248 NASM VO, Box 16, 461-464; DM NL172/9, 7.8.83, Letter von Ohain an Knausenberger; Koos claimed it was 18 engineers. (Koos, *Ernst Heinkel*, 155.)

249 Ermence, *Interviews with German Contributors*, 47; Kay gives a figure of 120 for turbojet airframe and engine groups at the end of 1939, which implies that the group working on the airframe was far larger. (Kay, *Turbojet History and Development*, 178.)

250 Schlaifer and Heron, *Development of Aircraft Engines*, 402.

251 NASM VO, Copy of chapter for DGLR book by von Ohain

252 NA AVIA 15/2121, 25.5.45, 230, Report by Helmut Schelp

253 Wagner and Cox, *First Jet Aircraft*, 30-41; Kay, *German Jet Engine and Gas Turbine Development*, 35-37.

successful, and all were devised without regard for the existing production capacity.[254] Most of them were given up after Müller left the company in June 1942.[255]

An opportunity to gain both facilities and experienced aero-engine personnel presented itself, however, when the RLM put the small Hirth Motor Company of Stuttgart-Zuffenhausen (HMZ) up for sale in 1940. Several firms contested the sale.[256] Heinkel argued that HMZ would be especially useful to EHFW's important turbojet work because the piston engine maker built small in-line, air-cooled engines, which could be used in Müller's motorjets, and because it had recently begun making turbo superchargers under government ownership, which shared many elements with turbojets.[257] HMZ's development department at Zuffenhausen had a staff of about eighty-three, which easily exceeded the staff devoted to turbojet work at EHFW.[258] Once again, the importance of the piston aero-engine to the turbojet is evident.

Heinkel hoped to secure the sale for EHFW through the demonstration of the company's turbojet fighter prototype, the He 280, again relying on a spectacular first to get his way. This ambition for a flight increased pressure on turbojet development at the firm. The original choice for the He 280's engines was the promising, smaller-diameter HeS 30 axial engine. When this engine proved incapable of running under its own power, however, von Ohain was diverted from the systematic compressor research that his group had begun in order to finish an engine of the apparently proven centrifugal type that would enable the airframe to fly already in the spring of 1941.[259]

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254 NA AVIA 15/2121, 25.5.45, 230, Report by Helmut Schelp

255 Köhler, *Ernst Heinkel: Pionier Der Schnellflugzeuge*, 204; The exception was the HeS 50 motor jet engine, which Bentele continued work on at HMZ. (Bentele, *Engine Revolutions*, 63-64.)

256 DM FA001/0314, 12.6.40, Pfistermeister an Heinkel; Bentele of HMZ claimed to have received visits with regard to the sale from Daimler-Benz, Jumo, BMW, Messerschmitt, Heinkel, Dornier and several smaller aviation companies. (Bentele, *Engine Revolutions*, 33-34.)

257 DM FA001/0314, 11.6.40, Heinkel to Udet

258 Homze, *Arming the Luftwaffe*, 186.

259 Bentele, *Engine Revolutions*, 50.

Still struggling with a lack of resources and personnel, von Ohain now found himself building an engine in order to acquire an engine company. He was coming to see that aero-engine development at EHFW was not just about making turbojet engines; von Ohain later reflected that with the HeS 8 'again there was a string attached.'[260] The design and construction of the engines for the He 280 was hurried, but they successfully powered the world's first turbojet fighter on 30 March 1941. Von Ohain had achieved yet another turbojet record, yet it was in the service of Heinkel's agenda; the engine was a distraction from von Ohain's more systematic turbojet development programme, aimed at resolving the basic problems of the new engine type.

The flight of the He 280, unlike the flight of the He 178, seemed to have made a political difference, however. EHFW was allowed to purchase HMZ. In addition, the RLM gave the firm a production contract for 100 preproduction (apparently flight-worthy) HeS 8 engines (RLM number 109-001) and for the preparation of plant for HeS 8 manufacture.[261] Confident about the future of his turbojet programme and his achievements to that point, Heinkel wrote to a friend on 8 August 1941 that 'the start from the airframe field into the aero-engine field has so far been very promising.'[262]

The faults of the rushed design of the HeS 8 became apparent, however, for despite an additional year of development, the engine never reached suitability for production. Like the HeS 3b, the new engine had incorporated temporary solutions that were sufficient for a first flight but not for routine service, and von Ohain was unable to resolve them with his existing resources.[263] The first order for the HeS 8 was reduced to twenty-four engines for experimental work, and any notion of preparing for production of the engine was cancelled

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[260] Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 18.

[261] The contract was on Ernst Udet's orders. He was a friend of Heinkel, a supporter of EHFW's turbojet work, and known for unsuccessful guidance of the RLM's engine development programme. (NA AVIA 15/2121, 25.5.45, 230, Report by Helmut Schelp)

[262] FA001/0314, 8.8.41, Letter Heinkel an Herr Baron von le Fort

[263] Conner, *Elegance in Flight*, 257.

in March 1943, after the Jumo 004 was ordered into production.[264] Von Ohain attributed the HeS 8's failure to EHFW's lack of the 'fundamental prerequisites' for engine development: test stands, manufacturing equipment, and quality control specialists, all of which the company did not obtain until the purchase of HMZ in 1941, but which von Ohain, unlike Müller, did not gain access to until 1943.[265]

Heinkel boasted that the He 280 had been decisive in clearing the way for EHFW's acquisition of HMZ,[266] yet the reasons for the sale were more complicated. The decision to sell HMZ to EHFW was the product of a campaign by the firm's management during 1940, but more importantly, it relied on internal RLM support for EFHW's turbojet programme. Already in mid 1940, most of the RLM supported EHFW's bid to continue developing turbojet engines.[267] The last remaining contender for purchasing HMZ withdrew his bid in early 1941,[268] and by 6 March 1941 – some three weeks before the He 280's first turbojet flight - Heinkel had been given approval for the acquisition.[269]

A crucial factor that swung the sale for EHFW was the advocacy of Helmut Schelp, the leader of the RLM's turbojet development programme, who recognised that the lack of appropriate facilities was hindering the work of the skilled turbojet designers at the firm. For Schelp, the acquisition of an aero-engine manufacturing firm finally connected EHFW's development teams with facilities and personnel experienced in aero-engine production, which the RLM had always insisted was an essential prerequisite for effective turbojet

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264 NA AVIA 15/2121, 25.5.45, 230, Report by Helmut Schelp

265 Letter Von Ohain to Günther, 1.7.67 quoted in Wagner and Cox, *First Jet Aircraft*, 33.

266 DM FA001/0314, 27.6.41, Betriebsappell anlässlich der Übernahme von Hirth

267 Although Udet remained sceptical, Eisenlohr supported EHFW's bid for the firm. (DM FA001/0314, 12.6.40, Letter Pfistermeister an Heinkel) This support likely derived in large part from the firm's success with the He 178.

268 Koos, *Ernst Heinkel*, 156; Wagner and Cox, *First Jet Aircraft*, 55-6; DM FA001/0314, 10.3.41, Aktennotiz

269 DM FA001/0314, 10.3.41, Aktennotiz. The papers weren't signed by Heinkel until 4 June 1941. (DM FA001/0314, 4.6.41, Letter Heinkel an Steiger)

development.[270] The sale was also a gain of course for Schelp's programme; Schlaifer noted that the Hirth purchase represented a 'fairly large addition of manpower' to turbojet development at a time when the RLM's departments were competing for resources within the arms economy and within the Ministry.[271]

The sale was by no means a gift to EHFW, for Schelp undertook to steer the use of HMZ's facilities according to his own plans, rather than Heinkel's, whose impetuous management style had encouraged spreading the firm's resources too thinly among multiple aero-engine development projects.[272] A condition of the HMZ sale was that EHFW's turbojet work would move to HMZ.[273] Schelp forced Heinkel to concentrate his resources on a single engine by cancelling, during 1942, all of the firm's existing projects, including the HeS 30, which ran for the first time in May 1942, but which duplicated the performance of the Jumo 004 and BMW 003, both of which were closer to production at the time.[274]

Meanwhile, Schelp had initiated work at EHFW on the development of the HeS 11, a more powerful replacement for the BMW 003 and Jumo 004.[275] Von Ohain was put in charge of the engine design and with Schelp designed its unique diagonal compressor, a mixed centrifugal and axial element.[276] The design of the HeS 11 was completed by autumn 1942, but much remained to be ironed out during manufacture and testing.

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[270] Ermenc, *Interviews with German Contributors*, 116.

[271] Schlaifer and Heron, *Development of Aircraft Engines*, 398.

[272] EHFW was well-known for being more like a research facility than a production company. (Schlaifer and Heron, *Development of Aircraft Engines*, 410; Koos, *Ernst Heinkel*, 165); Heinkel bragged to Udet about the range of work going on at his firm. (DM FA001/0314, 11.6.40, Letter Heinkel to Udet)

[273] Ermenc, *Interviews with German Contributors*, 116.

[274] NA AVIA 15/2121, 25.5.45, 230, Report by Helmut Schelp

[275] Schlep remembered that the contract was granted in late 1941. (NA AVIA 15/2121, 25.5.45, Report by Helmut Schelp) Heinkel recorded that it was granted in late 1942. (DM FA001/050, HeS 11 contract)

[276] Wagner and Cox, *First Jet Aircraft*, 36; Schelp argued that the diagonal compressor was not vulnerable to icing up or stone-hits during take-off and landing and that it would allow the axial stages to run at a higher speed by heating the air before it reached them. (NA AVIA 15/2121, 25.5.45, 230, Report by Helmut Schelp)

New prospects for von Ohain

The benefit of the HMZ purchase was not uniformly felt by EHFW's different turbojet projects. In the course of 1941, Müller's group moved to Zuffenhausen, but von Ohain was left in Rostock. This state of affairs was finally altered through the actions of Dipl-Ing Harald Wolff, who took charge of turbojet engine development at Heinkel-Hirth on 1 August 1941.[277] Wolff, whom Schelp had suggested to Heinkel for the post, was an erstwhile director of Bramo and BMW and was, unlike Heinkel, an 'experienced and acknowledged specialist' of aero-engine development.[278] In June 1942, without consulting Heinkel, Wolff fired Müller, whose team refused to work with the men at HMZ. [279] Von Ohain became the leader of the firm's remaining turbojet work, which was focussed on the HeS 11. However Heinkel's irresolution continued to prevent the transfer of von Ohain's group to HMZ, even after the RLM insisted in July 1942 that Heinkel finish transferring all of EHFW's turbojet work to Stuttgart.[280] Heinkel was finally distanced from the programme by the intervention of the RLM. Wolff was made Kommissar of HMZ on 27 March 1943 in the hope of speeding up work on the HeS 11, which was considered 'decisive for the entirety of air armaments'.[281]

Wolff quickly moved von Ohain's work to Zuffenhausen, where von Ohain at last found himself at the head of a 'first class engineering staff', with access to testing and manufacturing equipment suited to aero-engine development. With Müller's group gone, about 150 engineers, designers and draughtsmen were available at HMZ for work on the

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[277] DM FA001/0322, 4.43, Draft letter to Milch

[278] Koos, *Ernst Heinkel*, 160.

[279] DM FA001/0322, 15.3.43, Letter Heinkel an Vorstand der EHAG; Müller continued to correspond with Heinkel after leaving the firm. (DM FA001/0322, 3.1.43, Letter Müller an Heinkel); DM FA001/0319, 7.7.41, Müller; Bentele, *Engine Revolutions*, 44; Müller was followed by most of his team. (Bentele, *Engine Revolutions*, 52.)

[280] Koos, *Ernst Heinkel*, 162.

[281] DM FA001/0322, 25.3.43, Letter Milch an Wolff; Wolff had tendered his resignation on 24 February 1943 in protest of Heinkel's intrusive second-guessing of his actions. (DM FA001/0322, 24.2.43, Letter Wolff an Heinkel)

HeS 11.[282] Key among HMZ's staff was its talented chief engineer, Max Bentele, who was put in charge of engine components.[283]

Even in his improved position at HMZ, however, von Ohain still had fewer resources than were available to Whittle and Power Jets. Power Jets had had 140 employees already at the end of 1940 and had also sub-contracted its construction work, which EHFW kept mostly in-house. The disparity continued to be marked, for von Ohain moved to HMZ about the same time that Power Jets' Whetstone factory opened. Hirth's production facilities, while a big improvement on those available at EHFW, were not however all immediately available to von Ohain's turbojet development because the small engine firm continued to manufacture turbo-superchargers.[284]

From mid-1943, the conditions for von Ohain's work were much more propitious than at any time before. Heinkel's pressure to speed up development of the HeS 11 continued, but von Ohain was now shielded from Heinkel's demands by Wolff. In contrast to the history-making HeS 1, HeS 3 and HeS 8 engines, the HeS 11 marked von Ohain's first real engine project. His team collaborated productively with HMZ's development personnel, and development of the engine moved ahead rapidly, especially on its advanced compressor and turbine. Although some problems with EHFW's earlier centrifugal engines could now be overcome,[285] the new engine was not without shortcomings. Bentele remembered that its sheet-metal-heavy annular combustor, which owed much to earlier turbojet development at EHFW, 'barely fulfilled its purpose'.[286]

Work on the HeS 11 was put under pressure by the war situation and the RLM's embrace of jets. In the first months of 1945, pressed from all sides to once again sacrifice

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[282] Schlaifer and Heron, *Development of Aircraft Engines*, 410.

[283] Ermenc, *Interviews with German Contributors*, 46; Whittle and von Ohain, *An Encounter between the Jet Engine Inventors*, 18; Bentele, *Engine Revolutions*, 51.

[284] DM FA001/0322, 22.2.43, Letter Heinkel an Wolff

[285] For example, engine lubrication. (Conner, *Elegance in Flight*, 257.)

[286] Bentele, *Engine Revolutions*, 57.

thorough development for speed, von Ohain's team worked to move the engine towards production.[287] Schelp's impatience with the HeS 11 was demonstrated by his plans late in the war to develop an engine for the Ar 234 jet bomber by scaling up an existing engine rather than developing the new engine to higher thrust.[288] The Jumo 004 and BMW 003, which Heinkel wanted the HeS 11 to catch up to, had been in development at least two years longer. Even with appropriate facilities and experienced personnel, one-and-a-half years were not enough to get the novel engine into quantity production.[289] The divergence between Heinkel and von Ohain's understanding of the HeS 11 revealed their fundamental disagreement about the firm's turbojet programme. While Heinkel later denounced the engine as a mistake ('Irrweg') because it was not the quick route to a production aero-engine that he had expected it to be, von Ohain (like Schelp) viewed the engine as the first step towards a new generation of high-powered turbojet engines.[290]

That the HeS 11 did not reach quantity production during the war was in no small part due to the nature of development at EHFW during the first seven years of von Ohain's turbojet work there. At the end of the war, EHFW[291] and HMZ stopped producing turbojets. Von Ohain emigrated to the United States, where he remained an active aero-propulsion engineer. When the remainder of Heinkel's firm (HMZ became an independent

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[287] DM FA001/0323, 9.11.44, Letter Heinkel an Frydag; By the end of 1943, the company was under political suspicion for unnecessary delays. (Koos, *Ernst Heinkel*, 187; FA001/0323, 9.11.44, Heinkel an Frydag) Such accusations were often based on the testimony of lay persons. (See for example: NS19/3652, 5.9.44, Letter Himmler an Speer)

[288] NA AVIA 15/2121, 25.5.45, 230, Report by Helmut Schlep

[289] von Ohain was very proud that HMZ produced 23 engines between April 1944 and April 1945. (Köhler, *Ernst Heinkel: Pionier Der Schnellflugzeuge*, 203); Budraß (2007) has argued that Wolff intentionally sabotaged production work on the HeS11, in part by encouraging von Ohain's scientific interests, but it seems unlikely that the engine could have reached production because of the short time of its development.

[290] Köhler, *Ernst Heinkel: Pionier Der Schnellflugzeuge*, 203.

[291] It was then known as the Ernst Heinkel Aktien-Gesellschaft (EHAG), for on 1 April 1943, financial emergency had forced Heinkel to reform his company.

firm again after the war[292]) was allowed to take up aviation production again in the mid-1950s, Heinkel's renewed efforts to get the HeS 11 into licence production in Spain failed.[293] Apart from some interest from American investigators in some HeS 11 elements (especially its air-cooled turbine),[294] von Ohain's turbojet work at EHFW had virtually no direct consequences. The firm never managed to become an aero-engine producer, and von Ohain's fame rests to this day on the records established with stunt turbojet engines rather than on turbojet development, as he would have preferred.

Conclusion

Despite their very different natures, Power Jets and EHFW had several things in common. Turbojet work at both firms began very early. In order to retain their independence of action both Whittle and von Ohain chose not to ally themselves with the established aero-engine industry, and both men began with centrifugal engines, which were simpler and faster to develop than axials. Both inventors were the first in their countries to put their engines into limited production, although these production engines were quickly dropped, and neither managed to get any further designs into production nor to get their work taken up by other firms. The lack of success of both men was less a comment on their inventive achievements, however, than on the nature of the institutions where they worked. Whittle's early work was shaped by the necessity of impressing the British Government with a viable production engine in order to gain resources. Von Ohain's first engines ran before Whittle's, but they were designed to meet a very different set of requirements, for Heinkel's first interest was in producing inventions, not engines.

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[292] In fact, in November 1944, Schelp had threatened EHAG's directors that the RLM would confiscate HMZ and give it to Daimler-Benz, where the job would be completed 'with greater élan and tenacity'. (DM FA001/0323, 9.11.44, Letter Heinkel an Frydag)

[293] Work began in 1951 and ended in 1956 after only three engines had been built under the Spanish designation, INI-11. (Wagner and Cox, *First Jet Aircraft*, 37.)

[294] Bentele, *Engine Revolutions*, 59.

Power Jets' later goals were shaped by its institutional insecurity (due to its reliance on government funding and the dissemination of its work to British and American industry) and by its strong belief in its own uniqueness and centrality to the British jet effort, which derived from Whittle's role as a pioneer. The effect of this peculiar mix, which was a product of the firm's patenting policy and the fact that government money flowed freely to the firm during the war with minimal oversight, was that the firm began to pursue excellence in turbojet design with little reference to the requirements of the market or the military. Power Jets had long been at a disadvantage because war had intervened before the firm had a chance to establish itself as a commercial enterprise. War accelerated and shaped the firm's evolution into a research and development company and largely negated the management's ability to establish a viable commercial position for the company after the war.

The fact that Power Jets received virtually a blank cheque to design and develop turbojets did not make it more successful than either the RAE or EHFW in the long run. Instead, this dependence made the company defensive and militated against the formation of deeper alliances with more established aero-engine companies, a distance that was mutually reinforced by manufacturers' increasing self-reliance in the new engines. This became particularly pronounced from 1943, when Whittle began to be more distant from the company's daily affairs and Rolls-Royce took over at Barnoldswick. The opening of the Whetstone factory in 1943 led the firm to reject the possibility of becoming a consultancy like Ricardo's, which had been formed earlier around a strong individual and never produced engines on a large scale.[295] In contrast to Power Jets, which ceased to exist in 1946, Ricardo's still designs and develops high-powered piston engines to this day. There were few supporters like Cripps left when Power Jets was turned into a national establishment, and its

[295] Nahum, *Frank Whittle*, 128; Frank Halford, another important British engine consultant, chose to ally himself with de Havilland, a production company, rather than continue to operate independently.

aspiration for pre-eminence in aero-engine design was lost, along with the centrifugal turbojet designs that it had supported throughout the war.

EHFW followed a different trajectory than Power Jets, but its turbojet work reached a similar, unproductive end. Unlike Power Jets, EHFW was an established airframe manufacturer, for which aero-engine manufacture was at best a secondary pursuit. Von Ohain was much less central at EHFW than Whittle at Power Jets, and unlike Whittle, von Ohain became part of an existing culture, which was largely defined by Heinkel. Because of Heinkel's strategy to attract resources to his firm through inventive success, EHFW did not pursue a production engine in the first five years of its turbojet work. The firm's goals, set under Heinkel's impetuous guidance, meant that von Ohain's systematic work was repeatedly sacrificed for stunt engines.

In contrast to Power Jets, which shifted from designing a production engine to doing research work quite apart from production engines, EHFW tried first to survive on turbojet design, and later shifted to focussing its efforts on production. Despite beginning to change its focus after its union with HMZ, EHFW remained much more research- than production-orientated to the end of the war.[296] Too little time remained for the HeS 11 to reach quantity production, when von Ohain was finally able to turn his attention to seriously developing an engine. When the engine, the last embodiment of von Ohain's early turbojet design work, failed to reach production, his legacy ended with it.

In some ways, Heinkel is a more appropriate comparison to Whittle than von Ohain. Heinkel exercised control over every aspect of his firm, deciding which engines and airframe projects were to be developed at EHFW. It was Heinkel rather than von Ohain who felt a paternalistic attachment to the firm and sought to extend its activities through claims to the

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[296] After the war, investigators at Zuffenhausen recorded that 'during the war years [HMZ was]... for all practical purposes a privately owned, state subsidised research and development laboratory.' (CIOS XXIII-14, 5.45, Turbine Engine activity at EHAG)

turbojet. The conviction of the centrality of inventors that was shared as much by Heinkel as Whittle was ultimately a disservice also to EHFW.

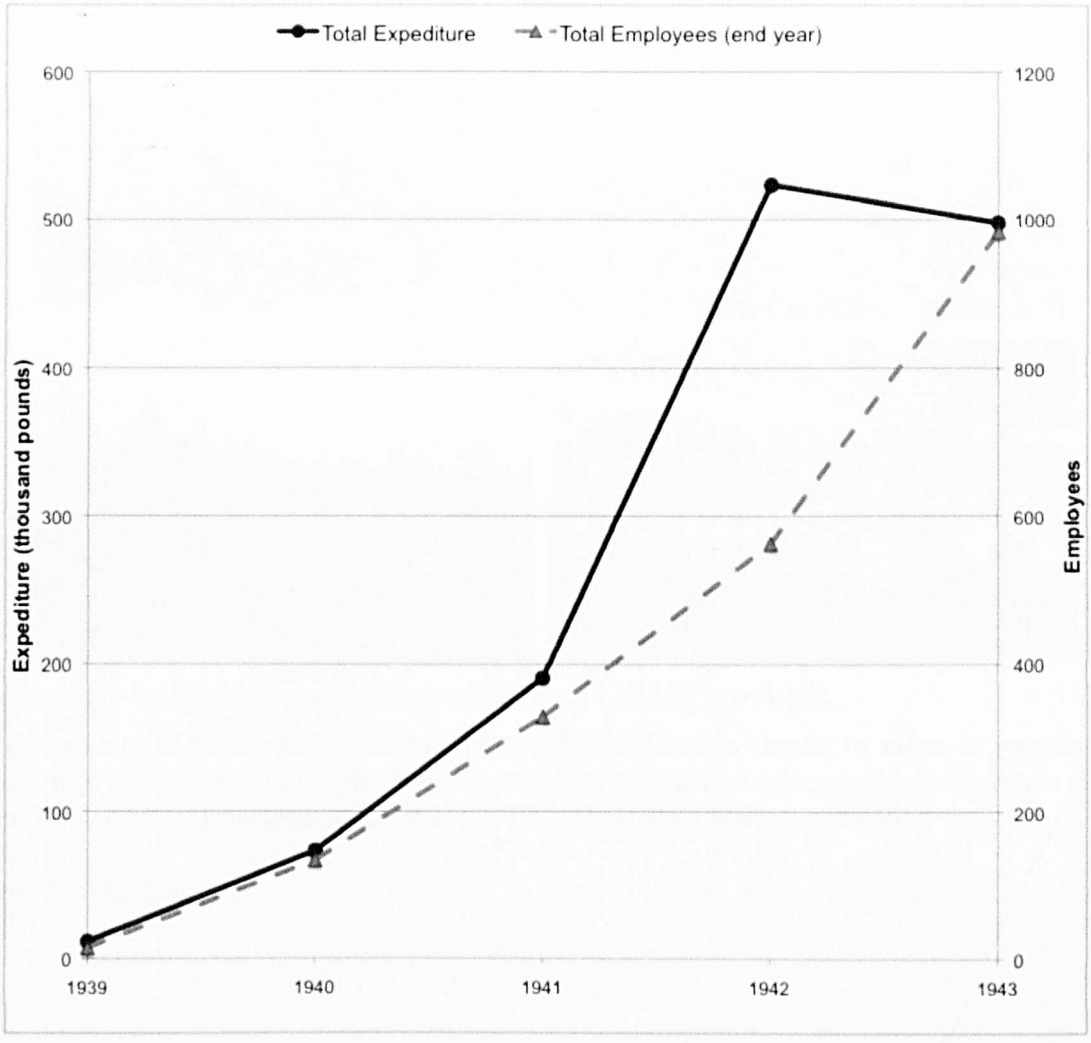
The RAE operated on a very different model than the two commercial turbojet developers. Although the institution expanded its role in aero-engine design and development during the war, it never lost sight of its core purpose: helping industry. It catered to the needs of industry while simultaneously increasing its claims to gas turbine expertise. Less known than Power Jets or EHFW, the RAE was in fact the most successful at getting its work into production, despite the fact that the Establishment, like Power Jets, relied on other firms for manufacture. In a roundabout way, Griffith's work was included through the RAE's work in the Metrovick F.2, which influenced the design of Metrovick's next engine, the F.9. The latter engine was further developed by ASM and was ultimately produced both in Britain and the United States. The axial gas turbine work of the RAE, through the F.2 and F.9., also influenced the design of the axial compressor of the successful Avon, which was designed by Griffith and Rolls-Royce.

The success of the axial compressor in British jet engines after the war was due in no small part to the institutional security of the axial gas turbine at the RAE. The structure of the British aero-engine industry dictated that a purely inventive institution could not continue to exist after the war as a competitive source of design, as Power Jets attempted. The RAE turbine section's more flexible vision of its advisory role as a government research institution prevailed over Power Jets' commercial ambitions and was carried forward in British practice. The opening of the National Gas Turbine Establishment on 1 July 1946 was the ultimate expression of the RAE's influence in the gas turbine field.

The institutional stories told in this chapter argue that the work of the RAE should get a more prominent role in the history of the turbojet than it has, while the work of Power Jets and EHFW should be correspondingly less prominent. Despite the visibility of Whittle and von Ohain in the literature as inventors of the turbojet, their work failed to have lasting

design consequences. Instead, it was the work of a relatively anonymous group at a Government research Establishment inspired by a relatively unknown scientist that proved most influential in shaping the future of the turbojet.

Figure 4.1. Expenditure and employment at Power Jets Ltd., 1939-1943



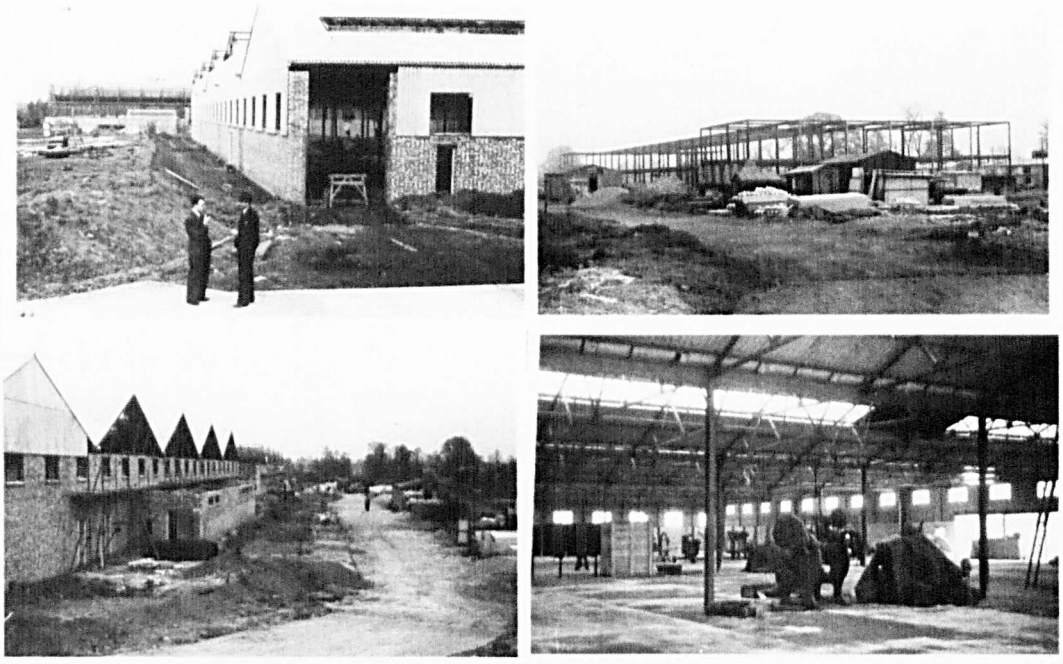
Total expenditure at the company grew even faster than its workforce, more than doubling each year between 1939 and 1942.

End year	1938	1939	1940	1941	1942	1943
Employees	5	15	134+	329	562	983

+ 53 joined during the last two months of the year

Source: Robert Schlaifer and S. D. Heron, *Development of Aircraft Engines* (Boston: Division of Research Graduate School of Business Administration Harvard University, 1950), 346; Lancelot L. Whyte, *Focus and Diversions* (London: Cresset Press, 1963), 145.

Figure 4.2. Power Jets' factory at Whetstone under construction, 15 May 1942



The factory's basic construction followed wartime building standards.

Hives wrote to MAP on 17 November 1942, '[s]ome decision should be taken as regards the Power Jets factory at Whetstone. I was astonished at the size of it, and the emptiness of it, when I visited it a short time ago.' (RRHC, 17.11.42, Letter Hives to MAP)

Source: NASM T Box 1.

Figure 4.3. Schematic of a dispersed compound turbine engine

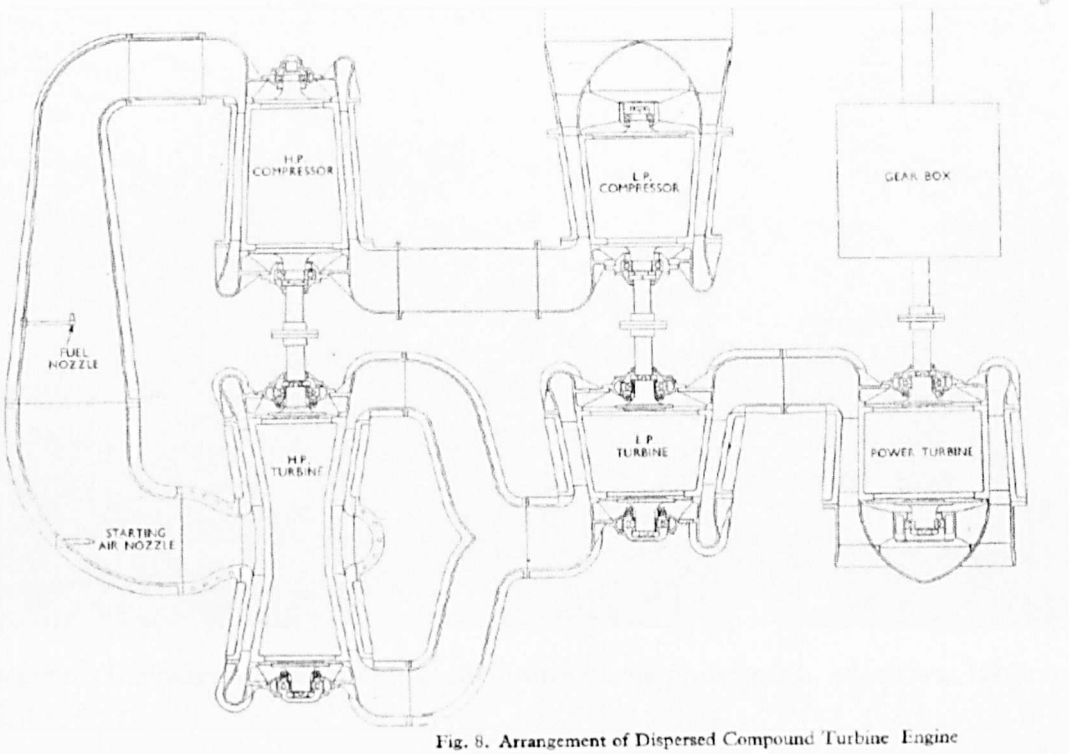


Fig. 8. Arrangement of Dispersed Compound Turbine Engine
Pressure ratio: 5/1.

Hayne Constant described the thinking behind the RAE's dispersed gas turbines: 'In this layout, the aerodynamic requirements were sacrificed in order to give a simple mechanical arrangement in which each compressor was directly driven by its own turbine so as to form a simple independent unit… In those days, we were supremely confident of our powers to control the working fluid but not so sure in our knowledge of mechanisms. The consequence was that we tried to evade the mechanical problems but gave ourselves some serious aerodynamic difficulties as a result.'

Source: Hayne Constant, 'The Early History of the Axial Type of Gas Turbine Engine,' *Proceedings of the Institution of Mechanical Engineers* 153 (1945): 416.

Figure 4.4. The RAE turbine section's new site at Pyestock



The section's buildings are just visible in the centre of the photograph, which was taken in 1947.

Source: Richard Dennis, *Farnborough's Jets* (Fleet, Hants: Footmark Publications, 1990), 31.

Chapter 5
Construction of a Hero and the Historiography of the Jet Engine

Whittle's role as a heroic-inventor was quickly established for both domestic and international audiences after 1944. The popular story of Whittle's jet work appeared in a wartime setting in which the spread of information was carefully controlled. Yet even with the gradual release of more information about jet development after the war, Whittle's heroic stature continued to be reinforced. Restrictions on the publication of information about the jet engine had left an opening for the story's presentation through a simple narrative of a lone, visionary inventor, which Whittle came to embody. The heroic conception of invention that made this story so plausible was rooted in earlier debates that linked patents, individuals and invention in the public mind.[1] Whittle himself never claimed to be the inventor of the jet engine, but he participated in its publicity in Britain and acted as a representative for the British jet community abroad. He was given these roles because he was regarded by others as *the* inventor of the jet engine.

Although public interests and values have shifted since the post-war period, the centre of the popular jet engine story – Whittle the inventor – has never seriously been challenged.[2] The foregoing chapters have served to sketch a picture of the world of activity that Whittle's work fit into, a world of many innovative engineers, firms and other institutions in many countries. Beside it, the heroic story of Whittle that was created in Britain looks distinctly peculiar. In this chapter, I will explain the origins of the Whittle story

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[1] Christine MacLeod, 'Concepts of Invention and the Patent Controversy in Victorian Britain,' in *Technological Change: Methods and Themes in the History of Technology*, Robert Fox ed. (Amsterdam: Harwood Academic, 1996), 137-153.

[2] If changes in the historiography of an event can be understood as evidence of the simultaneous production of new forms of understanding and new political forms in response to changing circumstances, as Dennis argued for the historiography of science, that a lack of change in the jet historiography suggests a disconnection between that understanding and more recent events. (Michael Aaron Dennis, 'Historiography of Science, an American Perspective', in *Companion to the History of Science in the Twentieth Century*, John Krige and Dominique Pestre ed. (London: Routledge, 2003), 1-26.)

that has become so well-known, and trace its influence through the post-war literature and even to professional history written in the late twentieth-century.

The jet story enters the public domain

The existence of the jet engine in Britain and America was first made public on 6 January 1944. A press release gave a first, abbreviated account of the secret project's history and reported impending jet production in both countries. In it, Frank Whittle was given full credit for the invention of the jet engine and for launching development in both Britain and America. Appended to the press release in Britain were notes on the careers of Frank Whittle, 'the inventor of the first successful jet propulsion engine for fighter aircraft', and P. E. Gerry Sayer, the test pilot at Gloster who flew the E.28/39 on its maiden flight.[3] The press lost no time in reproducing the release.[4] The public revelation of the British jet propelled Whittle into popular celebrity and claimed the invention for Britain.

This first press release about the jet was issued simultaneously by the British Air Ministry and American War Department on behalf of the Royal Air Force (RAF) and the United States Army Air Forces (USAAF) in accordance with an agreement between the Chief of the Air Staff, Air Marshal Sir Charles Portal, and the Commanding General of the USAAF, General Henry Arnold. Desiring to limit and control press attention to the new weapon, MAP had insisted on a complete ban on jet publicity, apart from releases of jointly agreed information made simultaneously in both countries.[5]

In addition to security concerns about the danger of revealing information to the enemy, assuring British credit for the invention was a key focus of MAP's jet publicity policy. The reason that MAP had originally requested a ban on jet publicity in November 1942 was largely for fear that credit for developing the jet would be contested, which might result in

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[3] The PR biography was supplemented by Roxbee-Cox in consultation with Whittle himself (NA AIR 2/7070, 30.12.43, 18B, Meeting about release)

[4] NA AIR 62/1023, 7.1.44, Extract from BBC News Bulletin, 7 am, and Home Service, 9 pm

[5] NA AIR 20/4235, 14.10.44, 39A, Cypher from RAFDEL to Air Ministry; 11.9.44, 26A, Extract from War Cabinet 122nd conclusions

the American press claiming the invention for America, as had happened earlier with radar. In a letter defending the need for a publicity ban, Air Chief Marshal Wilfrid Freeman, Chief Executive at MAP, had reminded the Air Ministry that American claims to have invented radar had created 'complete confusion in the minds of the American public' and had irreversibly damaged British credit for the invention.[6] In November 1943, the RAF Delegation in Washington, D.C. (RAFDEL) was instructed to try to get American agreement to a publicity ban because of security concerns and in language that made MAP's worries clear: 'premature publicity given to American developments might lead to world-wide misunderstanding' of British and American contributions to the jet.'[7] In late 1943, MAP would have preferred not to reveal publicly any information about the jet, but General Arnold urged that a press release had to be made as soon as possible in order to prevent unauthorised press speculation about the fighters that were then being tested throughout the United States. MAP acquiesced to Arnold's request rather than risk losing control of the story through unilateral publicity in the United States,[8] and the Ministry sought to use the release for their own purposes. A joint announcement, MAP hoped, could be used to ensure American recognition of Britain's pioneering role in the new technology.

Towards the end of December 1943, a joint statement began to be drafted via cypher between Washington and London. The text was traded back and forth, with each side proposing amendments, until it was approved at the very highest levels, by Arnold and Portal. RAFDEL objected to the first text sent from the American War Department because it did not give enough credit to Britain. This was rectified in a RAFDEL amendment, which added that the pioneering work on jet engines had been begun in Britain by Group Captain Frank Whittle, that the first engine had run in Britain in 1937, and that a Whittle engine had

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[6] NA AIR 2/7070, 22.11.43, 1A, Letter Freeman to Evill

[7] NA AIR 20/4235, 25.11.43, Letter Evill to Walsh

[8] NA AIR 2/7070, 3D, 22.12.43, Cypher from RAFDEL to Air Ministry; 12A, Cypher Portal to RAFDEL

been flown successfully in Britain in 1941. Furthermore, it mentioned that the Air Ministry had ordered a jet airframe from Gloster in 1939, a sign of foresight and an act of confidence in the new technology. The release made clear that that Britain's first engine design had been passed to the United States, and reported that the first American experimental jet aircraft had flown successfully on 1 October 1942.[9] (The full text is given in Appendix B.)

To make sure that it was acceptable to give Whittle full credit for the invention in the release, the Air Ministry passed the amended text to Freeman, who had been part of MAP when the jet programme began. The Air Ministry was cautious because it had earlier run into trouble over the attribution of the so-called Leigh Light to Wing Commander Leigh alone. Freeman saw no problem with the attribution to Whittle, however, because Whittle's jet patents had been granted at a time when the Air Ministry was, he claimed, uninterested in Whittle's work.[10] Thus it was that Freeman ensured that Whittle would be internationally publicised as the British inventor of the jet engine.

Whittle was taken aback by his dramatic rise to public prominence. On 11 January 1944, days after the first release, he made clear in his yearly address to the employees of Power Jets that he objected to the contents of the press release. Whittle assured the works that his remarks on the BBC, in which he apparently endorsed the government line, had been strictly circumscribed by the broadcasting company. He voiced his anger that the release gave a 'lopsided' view of jet development by mentioning only Whittle and Power Jets and neglecting the teamwork essential to the development of the first British jet engines. Not being a party to the agreement on jet publicity, Whittle found inexplicable that the press had not published the statement given to them by Power Jets, which explained Power Jets' collaboration with the British Thomson Houston Company (BTH).[11] The Air Ministry chose

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[9] NA AIR 2/7070, 22.12.43, RAFDEL to Air Ministry (for Evill from Welsh)

[10] NA AIR 2/7070, 28.12.43, Note by Caines; This same argument resurfaced later in the discussion of Power Jets' nationalisation and in the question of Whittle's right to an award for his work.

[11] NA AIR 62/1023, 7.1.44, Whittle address to Power Jets

not to officially rectify the mistake, although BTH had written to MAP in indignation about the omission since the release had named General Electric (GE).[12] Any recognition of the company would have gone against the official publicity policy, and the Air Ministry was afraid that acknowledging BTH would provoke more public attention at a time when public interest in the jet was dying down as well as endanger their ability to pressure the USAAF to keep its side of the bargain. BTH was consoled with a letter to *The Times* from Sir Maurice Bonham Carter, an erstwhile director of Power Jets Ltd., in February 1945.[13]

Publicity after the first press release

Giving Whittle credit for the invention was an effective weapon in technological rivalry between Britain and the United States.[14] The battle over jet publicity was a legitimate contest between the Allies during the war, and it was spirited because of the post-war stakes, when inventive genius presumably would be transfigured into commercial success.

The American press didn't foreground Whittle in the same way that the British press did, and even when the engine was acknowledged to have come from Britain, Bell and GE were as frequently featured. On 10 January 1944, *The New York Times* ran a Bell Aircraft advertisement that asserted that 'Bell Aircraft has built the first American fighter plans powered by jet propulsion engines. The engines, constructed by the General Electric Company, were developed from British designs... Like the Wright Brothers' flight at Kitty Hawk, we believe that the hundreds of successful flights made by Bell jet propelled ships open a new chapter in American Aviation history.' The ad raised worries in the Air Ministry of an Anglo-American publicity competition. Arnold was informed of the breach, and Portal instructed the Air Ministry that everything possible must be done to prevent similar lapses in

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[12] NA AIR 2/7070, 8.1.44, 29A, Letter Sporborg to Cripps

[13] NA AIR 2/7070, 17.2.44, Interdepartmental letter; Maurice Bonham Carter, 'Jet Propulsion (Letters to the Editor),' *The Times,* 15.2.44.

[14] NA AIR 2/7070, 22.11.43, 1A, Letter Freeman to Evill; The rivalry in aviation technology remained intense in the early post-war period. (Jeffrey Engel, *Cold War at 30,000 Feet: The Anglo-American Fight for Aviation Supremacy* (Cambridge, MA: Harvard UP, 2007).)

Britain. Because the British press was in a weaker position than its American counterpart, it was essential to avoid the charge that Britain wasn't playing by its own rules.[15] On 31 March 1944, all British manufacturers were instructed that their advertisements had to be submitted to censorship.[16]

Meanwhile, publicity for GE and Bell's work continued in the United States. In April 1944, the Minister of Aircraft Production, Stafford Cripps, wrote to Portal, quoting several articles in the American press that seemed to infringe the joint jet publicity policy. Cripps argued that the effect of American publicity was to give the impression that 'the origin of this revolutionary development is not British but American... Already there is considerable feeling in this country, particularly, of course, amongst those who played a part in early jet propulsion over here, that the United States are being allowed to walk away with a British Invention.'[17] Because, the American press was publishing images of the Italian Caproni-Campini motorjet aircraft, which had flown in August 1940 and provided an alternate invention story, Cripps suggested countering American claims by publishing an 'obsolete' photograph of the Gloster E.28/39. This modest request was turned down by the Air Ministry because it was unwilling to risk lifting the joint ban on publicity, which it felt was the only thing, however partially effective, protecting British interests from the active and nationalistic American press.[18]

MAP brought at least seven American articles to the Air Ministry's attention during the first half of 1944.[19] In July 1944, Freeman wrote to Portal about an article that had appeared in the *Evening Standard* that featured GE's jet engine production plans, which, he argued, proved that the publicity ban was not being enforced in the United States. He

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[15] NA AIR 2/7070, 21.1.44 – 31.1.44, 36A-36D

[16] NA AIR 2/7070, 31.3.44, 48A, Circular from J.E. Keel (MAP)

[17] NA AIR 2/7070, 19.4.44, 54A, Cripps to Portal

[18] NA AIR 2/7070, 19.4.44, 54A, Cripps to Portal; 21.4.44, Interdepartmental memo

[19] NA AIR 2/7070, 6.3.44, Letter Sorley; 5.5.44, 61a, Letter Freeman to Evill; 19.4.44, 54A, Letter Cripps to Portal

suggested further that the impending operational deployment of the Meteor offered an 'excuse' for some 'limited publicity' for British work in coordination with the United States. A release of information, he argued, might serve to motivate British workers in airframe and engine production, and would reassure the public that 'the Hun is not always ahead of us in secret weapons.'[20]

RAFDEL also felt that the Meteor's success should be publicised in order to douse American clamouring for permission to advertise their own research and development.[21] When on 14 August 1944, General Arnold suggested relaxing the publicity ban in order to respond to reports of the first German jets, the desirability of releasing some information on Allied jets was recognised by the British government.[22] The War Cabinet approved the release of a second joint statement, with some misgivings, on 11 September 1944.[23]

Much shorter than its predecessor and released on 27 September 1944, it reassured the public that the arrival of German jets had been expected, that the Allied jets had made progress since January, and that the British jet had already been 'employed with success against the flying bombs.' No manufacturers were mentioned.[24] (The full text is given in Appendix B.) The release was accompanied by photos of the first Allied jets - the single-engined British Gloster E.28/39 and the double-engined American Bell P-59 - which could be released because neither was to go into service. A caption explained that the E.28 was the first Allied jet to fly.[25] RAFDEL reported afterwards that a full American media frenzy about the P-59 had only been prevented by the 'wonderful co-operation and magnaminity [sic] of the War Department', which refused to allow the radio or film news to cover the story,

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[20] NA AIR 2/7070, 27.7.44, 76A, Freeman to Portal

[21] NA AIR 2/7070, 16.8.44, 81A, Letter Welsh to Evill

[22] NA AIR 2/7070, 14.8.44, 85A, Cypher Portal to Arnold; NA AIR 8/785, 14.8.44, Cypher from Arnold

[23] NA AIR 2/7070, 11.9.44, Extract from War Cabinet, 122nd conclusions

[24] NA AIR 2/7070, 27.9.44, 108a, Air Ministry, 'Progress of Jet-Propelled Aircraft'

[25] NA AIR 8/785, 27.9.44, 109c, Cypher Portal to Welsh; 27.9.44, 109d Cypher Welsh to Portal

'especially as their aircraft is a better looking job than the Gloster'. The cancellation of a trip by Whittle to New York was a relief to the Delegation, as the War Department 'would have gone up in smoke if he [Whittle] had come out with a fresh burst of publicity for British J.P. [jet propulsion]'. RAFDEL wanted to ensure that both sides respected the ban.[26]

British concern with 'keeping the British achievement before the American public' continued after the second release, and despite appeals from the War Department for additional publications, the Air Ministry refused to relax the Arnold-Portal agreement without a new publicity policy being agreed on in its place.[27] The enforcement of the ban made American jet manufacturers restive and had led them to put a conspiratorial interpretation on it. *Aviation News*, an American weekly,[28] published speculation on 13 November 1944 that the British authorities were forcing the jet publicity ban on the USAAF in order to repress reports of American progress that might 'possibly overshadow' Britain's work.[29] The British response to this provocation was quick; by the next day, the publisher, McGraw Hill had been asked to print a corrective statement in its next issue giving the true details of the ban, 'making clear that were it not for security considerations Britain would be the first to desire full publicity showing the scope of her whole achievement and current production in this field.'[30]

In February 1945, the British government conceded that it was time to revise the Arnold-Portal agreement.[31] Their hand was forced by the USAAF's determination to release a statement on the most promising American jet aircraft to date, the Lockheed P-80, in order, they said, to improve morale and attract workers to America's jet factories. After some debate, the British decided to release a detailed statement about the Meteor on 28 February

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[26] NA AIR 2/7070, 25.10.44, 123a, Extract from report by S/Ldr. Bown (RAFDEL)

[27] NA AIR 20/4235, 34-36A, 29.9.44-5.10.44

[28] *Aviation news* was published from 2 August 1943 to 30 June 1947.

[29] NA AIR 2/7070, Excerpt at 124B

[30] NA AIR 2/7070, 14.11.44, 126A, Letter Henderson to Air Ministry

[31] NA AIR 2/7070, 1.2.45, 148A, DCS Evill to Freeman

1945, simultaneously with the USAAF's announcement about the P-80. They also insisted that the USAAF's announcement mention that the first engine for the P-80 aircraft was built by de Havilland - a fact also included in the British release.[32] The British release gave details of the Meteor's operational role in the 'Battle of the Flying Bomb', went into considerable detail about the new aircraft, and gave specific details about British jet airframe and engine manufacturers. As the Meteor was already in active service, RAFDEL judged that the British announcement would certainly 'overshadow' the American release.[33] In the event, the Air Ministry's publication read like an extended advertisement for Whittle, the Meteor and for British jet engine manufacturers. It reported that:

> The first and so far the only jet propelled aircraft of the United Nations to go into action against the enemy is the Gloster "Meteor"... Like the Gloster E.28/39, the first turbine jet aircraft in the world to fly (in May 1941), the "Meteor" is also a product of the Gloster Aircraft Company (Hawker-Siddeley Group). The "Meteor" is powered with Rolls Royce engines manufactured to the basic design of Air Commodore Frank Whittle, R.A.F., in collaboration with Power Jets Ltd., and the British Thomson-Houston Co., Ltd. The first engine supplied to the U.S. Army Air Force in Oct., 1941 was built by Power Jets Ltd. Air Commodore Whittle visited the U.S.A. in order to assist our Allies to initiate their development programme.
>
> In addition to the "Meteor", Great Britain has another jet-propelled fighter in an advanced stage of development. This has been designed and engined by the De Havilland Aircraft Co. Ltd. These engines are also manufactured on the basic principles used by Air Commodore Whittle... It is known that the Rolls-Royce engine of this type is more efficient and of longer life than the Jumo engine of the German Messerschmitt Me 262.[34] (The full text is given in Appendix B.)

The Arnold-Portal agreement was replaced in June 1945 by a new policy that set out a list of items that could be publicly discussed without mutual consultation, which, however, explicitly prohibited the release of information or performance data on engines.[35] Unusually, the publicity agreement remained in force after the war until all British jet patents had been

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[32] NA AIR 2/7070, 20.2.45, 159B, Cypher Air Ministry to RAFDEL; 25.2.45, 168A, Cypher Air Ministry to RAFDEL

[33] NA AIR 2/7070, 22.2.45, 166A, RAFDEL to Air Ministry

[34] NA AIR 2/7070, 28.2.45, 177a, 'RAF "jet" fighters in action'

[35] NA AIR 2/7070, 26.6.45, 191A, Memo from Joint Security Control

secured; the release of additional information on jet engines was prevented until the policy was cancelled on 18 January 1946.[36]

That the release on the Meteor was complimentary to Rolls-Royce was clear when in April 1945, Rolls-Royce published an advertisement in *The Times* for its jet engines, which quoted the official press release exactly.[37] A few months later, Rolls-Royce ran an ad in the periodical *Flight,* that made no mention of Whittle, but did refer to jet propulsion as 'another British invention' – which in 1945, was as good as naming Whittle. Yet in contrast to the advertisement in *The Times*, the second ad focused not on the invention, but on Rolls-Royce's achievement: '[t]he first Jet-propulsion engines to be put into production in this country have been developed and produced by Rolls-Royce'.[38] (See Figure 5.1.)

After the end of the publicity ban, industry continued for some time to invoke its connection to Whittle. In 1950, de Havilland placed an ad for its jet engines in *The Times*, which boasted that when the authorities 'felt that we could afford to divert some serious engineering capacity from piston-engine design to concentrate upon Sir Frank Whittle's invention of the gas-turbine jet engine for aircraft', '[t]he de Havilland Company through Major Frank Halford was the first of the established engine builders to enter the new field with a jet intended for quantity production.' The advertisement closed on a nationalistic note, 'Britain holds the lead in jet-engine development, but to retain it will call for strong and sustained effort.'[39]

The government and its inventor-hero

From the time of the first press release, Whittle began receiving awards and honours from the government as well as academic and industrial bodies. Each public award was both a testament to and a reinforcement of Whittle's public profile. In January 1944, he was granted

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[36] NA AIR 2/7070, 18.1.46, 192A, Letter from Griffiths

[37] 'British Achievement in Jet Propulsion,' *The Times,* 19.4.45.

[38] *Flight*, 25.10.45.

[39] 'British Jet-engine Development; Rivalry with Co-operation,' *The Times,* 27.12.50.

a CBE and a Master's degree from Cambridge University. [40] In 1947, he was made a Fellow of the Royal Society,[41] and in 1948, he was knighted (like several other wartime inventors).[42] Whittle's recognition spread well beyond Britain. In 1946, he was made a Commander of the United States Legion of Merit and received the American Guggenheim Gold Medal for achievement in aeronautics.[43] In 1951, he was granted the Gold Medal of the Fédération Aeronautique.[44]

Contrary to Whittle's expectations, however, the rise of his public stature was accompanied by his decreasing importance to the British government as a technical expert. At the time of the government acquisition of Power Jets in 1944, as Chapter 4 illustrated, Whittle was already a marginal figure at the company. Whittle wanted to be involved in 'the counsels of the Ministry, especially on matters of policy', and complained to MAP that 'in my opinion, I have not carried anything like the weight I should have done in matters of policy.'[45] In late 1945, when it decided to turn Power Jets (R&D) into a national establishment, the Ministry of Supply (MoS, MAP's successor) did not see the loss of Whittle and his engineering team from the country's work on gas turbines as an insurmountable problem. In June 1946, a few months after Whittle's resignation from Power Jets (R&D),

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[40] In 1944 he also received in May: the 1943 James Alfred Ewing Medal from the Institutions of Civil and Mechanical Engineering, in October: the Freedom of Leamington (where he grew up), and lastly the Gold Medal of the Royal Aeronautical Society. (Feilden and Hawthorne, 'Sir Frank Whittle'; 'News in Brief,' *The Times,* 22.1.44, 9.5.44, 30.10.44) In 1946, he was awarded the 1945 Clayton Prize (£1,000) by the Institution of Mechanical Engineers, and granted an honorary doctorate by Manchester University. ('News in Brief,' *The Times,* 23.3.46; 'University Education,' *The Times,* 16.5.46.)

[41] Feilden and Hawthorne, 'Sir Frank Whittle.'

[42] 'The Birthday Honours,' *The Times,* 10.6.48; In 1948 he received the Kelvin Medal from the Institution of Electrical Engineers. ('The 600th Anniversary Of Caius College,' *The Times,* 8.10.48.) He was granted an honorary Doctorate at Oxford on the same day as Sir Stafford Cripps. ('Encaenia At Oxford Making Latin Fit The Atomic Age,' *The Times,* 23.6.49.) Also in 1949, he was presented the Melchett Medal for 1949 by the Institution of Fuel. ('News in Brief,' *The Times,* 14.10.49.) In 1953, he was awarded the Royal Society of Art's Albert Medal. (Feilden and Hawthorne, 'Sir Frank Whittle'.)

[43] The award was followed by a lecture tour, after which Whittle publicly reported that American engine development lagged two years behind that in Britain ('American Honour for Air Commodore Whittle,' *The Times,* 19.8.46; 'Jet-Propelled Aircraft Pioneer On American Development,' *The Times,* 19.9.46.)

[44] Feilden and Hawthorne, 'Sir Frank Whittle.'

[45] NA AVIA 10/412, 11.1.44, Letter Whittle to Cripps

however, the Ministry created a new position for him: Technical Advisor on Engine Design and Production to the Controller of Supplies (Air).[46] By retaining Whittle in a new marginal, advisory position, the Ministry could maintain its connection with the inventor-hero, ensuring that he was financially secure and using their connection to his continually growing renown to promote the British-ness of the jet engine. Whittle spent much of 1946 and 1947 on lecture tours around the world including in Holland, Belgium, France, the United States and Canada.[47]

Shortly after the first public revelation of the company's work, Whittle had given up his commercial interest in the company because he was convinced that a serving officer should not gain commercially from work that was part of his official duties.[48] Regardless of the financial implications of this principled action, MAP and MoS had always intended to give Whittle an *ex gratia* award after the war to recognise his wartime contribution. It was not unusual for an inventor to be rewarded *post hoc* for his work, and there was long-standing precedent for the Secretary of State for Air to pay remuneration to a company when its designs were used for government contracts.[49] MoS's generous treatment of Whittle after the war testified to the obligation that the government felt towards him. The Ministry made an interim payment to Whittle of £10,000 in April 1945, which was meant to support Whittle while it determined how much to award him for his service to the Crown.[50]

MoS decided that the Royal Commission on Awards to Inventors (RCAI) was best qualified to judge the magnitude of Whittle's ultimate award. Composed of government

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[46] 'News in Brief,' *The Times*, 6.6.46.

[47] Golley, Whittle and Gunston, *Whittle, the True Story*, 267-268.

[48] Whittle made the official endorsement of this interpretation a requirement of giving up his shares to avoid 'the risk of going down in history as a fool'. (Whittle, *Jet*, 274.)

[49] NA AVIA 22/1540, 4.11.39, 1A, Air Ministry (Supply)'s view on need for tribunal

[50] This sum was 'assessed on a conservative judgment' of the RCAI's future ruling, given the unusual nature of the case. (5.4.45, Letter Sir Harold Scott, Secretary of MoS, to Whittle reprinted in Whittle, *Jet*, 294.)

officials and senior engineering experts,[51] the RCAI had been set up in 1946 according to plans made during the war as the mechanism for making awards to inventors if their patents had been used by the Allied governments during the war.[52] Whittle made it clear that it would be 'extremely distasteful' to him to submit a case to the RCAI because he believed that 'the State should look after its own', so MoS applied to the RCAI on Whittle's behalf.[53] The Commission consented to hear the unique case, although an application by a government Ministry lay, strictly speaking, outside the RCAI's terms of reference.[54]

On 26 May 1948, MoS's case was presented formally before the Commission by E.L. Pickles, a member of the Ministry, who had been a party to the early turbojet programme at MAP.[55] The day before the hearing, the Commission visited the National Gas Turbine Establishment at Whetstone, where they saw 'various types of these devices' and heard from two leading figures in the country's wartime jet work, Harold Roxbee-Cox and Hayne Constant, about Whittle's contribution to jet propulsion and gas turbine development in Britain.

Pickles' argument had two parts: firstly, it sought to establish the degree to which Whittle, a serving officer, had been helped by government support and secondly, it attempted to demonstrate the contemporary importance of the aero-engines that Whittle's work had given rise to. Pickles began by presenting a brief history of the turbojet aero-

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[51] Whittle's case was heard by: Lord Justice Cohen (chairman), Mr K. Swan, K.C. (deputy chairman), Sir William Stanier and Sir George Lee (two well known engineers), Sir John Rae (representative of the Treasury) and Dr G.M. Bennett (Government Chemist) (NA T 166/5)

[52] NA AVIA 22/1540 and NA AVIA 65/446; The first RCAI was established in 1919. Interestingly, a similar number of cases were heard by the first and second Royal Commissions on Awards to Inventors (444 of 1834 claims over almost 15 years, versus 448 cases in about 8 years), yet significantly less money was paid out by the second commission. In 1954, the second RCAI granted about £600,000 in awards (paid for by the Treasury), while the first commission awarded about £1,500,000. ('Progress On Awards To Inventors Commission Nearing End Of Work,' *The Times*, 12.1.54.)

[53] NA T 166/5, Pickles' case to RCAI and Whittle, *Jet*, 276.

[54] NA AVIA 65/446, RCAI Progress report

[55] Pickles had been Director of Contracts in the MAP during the war and had served as a Chairman of Power Jets (R&D). In 1948, he was an Under Secretary at MoS. (NA T 166/5, 26.5.48, Transcript of RCAI hearing in the matter of 'Inventions made by Frank Whittle.')

engine, emphasising Whittle's service record, his selfless behaviour and the cost to him physically and mentally of his work on the turbojet during the war, and outlining the Ministry's involvement in Whittle's early work. That Whittle was an RAF officer was overlooked, for although serving officers were traditionally not entitled to any award for work that fell within their duties, the Commission felt that they could be awarded money in special cases such as 'extraordinary brilliancy of invention'.[56] Pickles defended the importance of the turbojet engine by highlighting its economic value. He quoted a value of approximately £7M for the 1,410 'Whittle-derived' engines that had been exported to date. Whittle's importance, Pickles argued, lay in the fact that his work had hastened and 'spectacularly advanced' the gas turbine industry in Great Britain.[57] The award did take into account the value of the Power Jets shares that Whittle had gifted to the Air Ministry, which was almost £48,000 - not in order to reimburse him, but in order to judge the importance of his work.[58] The RCAI ruled on Whittle's case on 28 May 1948, and both MoS and the Treasury agreed to the suggested sum of £100,000 to recognise Whittle's service to aeronautical science.[59] In 1948, Whittle also retired from the RAF on health grounds, but the handsome award alleviated any financial worries that he might have had.[60]

There was no more public affirmation of an inventor than an endorsement from the RCAI. Regardless of the Commission's process of evaluation or its grasp of the complexity of invention,[61] the values of the awards granted by the Commission were publicly understood to represent the relative value of different inventions and inventors. By this

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[56] NA AVIA 65/446, RCAI Progress report; Here the Commission departed from the precedent of the 1919 Commission. (RCAI Report, HMSO, 1953)

[57] NA T 166/5, 26.5.48, Transcript of RCAI hearing in the matter of 'Inventions made by Frank Whittle.'

[58] Whittle later emphasised that he had had not applied to the RCAI for an award and that the award was not meant as reimbursement for his shares. (Whittle, *Jet*, 306; 'Award To JET Engine Inventor, Sir Frank Whittle's Explanation,' *The Times*, 16.1.52.)

[59] Figures around £100,000 had been earlier proposed within MoS. (NA T 225/28, Whittle Case)

[60] Whittle, *Jet*, 304-306.

[61] The RCAI's notes on invention, arising from their work, are lengthy. (RCAI Report, HMSO, 1953)

measure, the award placed Whittle incontrovertibly among the small coterie of Britain's most exceptional engineers. Though the conditions of both invention and award varied widely, in the press, Whittle's award was compared to those of other great wartime inventors, including Sir Donald Bailey (£12,000 for the Bailey bridge) and later Sir Robert Watson-Watt (£50,000 for his work on radar) – the only single award that came close to Sir Frank's.[62] The largest amount that was awarded for a single invention was £120,000 for inventions to do with the undercarriage of the Halifax aircraft, but this was divided between several people.[63] Whittle's was the only award given for jet propulsion.

Unlike other well-known cases, however, in Whittle's case, the Commission was explicitly interested in the post-war rather than wartime value of his invention. The Treasury responded to a letter questioning the amount of Whittle's award with the statement: 'we were satisfied that an award was fully justified particularly in view of the fact that his invention has led up to a considerable volume of new export trade… This is, admittedly, a handsome sum but we do not regard it as too much to pay to a member of the community who has rendered such a service to the state as Whittle has done.'[64]

New medium, old story

Whittle's centrality to the British story was exemplified in an official government film about the jet engine, made in the late 1940s in response to demands in the national press.[65] Completed in December 1949 and entitled *The Wonder Jet,* it was envisaged as a contribution to a proposed series of eleven films on economic subjects that was to be made by the Central

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[62] '£100,000 For Air Cdre. Whittle JET Engine Inventor,' *The Times,* 28.5.48; '£94,600 Awards For Radar Sir R. Watson-Watt To Get £50,000,' *The Times,* 15.1.52; Pickles equated Whittle's achievement with that of Stephenson, Parsons and Watt. (NA T 166/5, 26.5.48, Transcript of RCAI hearing in the matter of 'Inventions made by Frank Whittle.')

[63] 'Progress On Awards To Inventors Commission Nearing End Of Work,' *The Times,* 12.1.54; In addition to Watson-Watt's award for the development of radar, almost £50,000 was granted to various other men for work on radar installations, bringing the total to £100,000. (NA AVIA 65/446)

[64] NA T 225/28, 18.6.48, letter from WC Pearce; reply from Glenvil Hall, MP, Treasury

[65] NA CAB 103/260, 22.10.47, Letter Williams-Thompson (CIO, MoS) to Luke (Cabinet Office)

Office of Information, the 1946 successor to the wartime Ministry of Information.[66] The Government hoped that the films would be distributed around the world. *The Wonder Jet* was longer than the other films, which underscored the importance attached to it. Almost twenty minutes in length, it ran onto two reels.[67]

Produced for the Central Office of Information by the Crown Film Unit, the film was an exemplar of the 'story documentary' tradition of documentary filmmaking, which had been pioneered in the interwar years by the Crown Film Unit's predecessor, the General Post Office Film Unit. The 'story documentary' style produced documentary films in which non-actors portrayed themselves in realistic narratives based on their own experiences.[68] Whittle not only contributed content but also appeared in the film. In *The Wonder Jet*'s segment on the 'inventor's long road of discouragement and danger', for example, Whittle featured in a re-enactment of one of his favourite stories about an early engine that ran alarmingly out of control when fuel that had collected in the engine caught fire. (See Figure 5.2.)

The film unabashedly promoted the jet engine and its British-ness: it explained the operation and safety of the new aero-engine (with the expansion of civil aviation in mind), the engine's invention ('a story of British pioneering'), and the engine's importance to Britain ('a vital factor in Britain's struggle for prosperity'). Its middle section told a familiar invention story supplemented by Whittle's own anecdotes. A film reviewer in *The Times* summed up the anodyne appeal of the heroic story that the film script adopted: even technically unconversant readers 'are ready to be interested by the story of small beginnings growing to great ends, of the long, tiring process of trial and error, and of the faith of the small body of men, with Sir Frank Whittle at their head, who finally brought about success.'[69]

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[66] INF 6/408, 8.2.50, Crown Job No. 118

[67] INF 6/408, 8.2.50, Crown Job No. 118

[68] The Unit was not a government department itself, although it was sponsored by several. 'Crown Film Unit', BFI Screenonline, accessed on 2 December 2007, http://www.screenonline.org.uk/film/id/469778/.

[69] 'Films of Fact "The Wonder Jet" (Reviews),' *The Times*, 3.12.49.

Given the film's message about the economic importance of the jet, the central place that patents assumed in the film was notable as well as familiar. *The Wonder Jet* made clear that revenue was generated not only from selling engines abroad but also from licensing patents. The jet engine was presented not as a secret, war-winning, military technology, but as an economic boon. The film made a strong link between the heroic inventor and his patents not as the symbol, but as the substance, of his invention. The patent was the mark of the inventor, the climax of invention, and the beginning of a new technology. Without a patent, it suggested, a man is not an inventor. Thus the film's selective view reproduced what was commonly understood about the process of invention and the types of valid claims to it.

Indeed, the film was used abroad using just such a claim to invention to promote British jet patents. Power Jets (R&D), which remained as a patent holding firm for the (government-owned) British jet patents after 1948, ordered a special edition of *The Wonder Jet.* It included an additional sequence depicting the shipment of the Power Jets W.1X to the USA in 1941, which was meant to refresh the connection between American engines and British jet patents in the American mind.[70] With the same goal, Power Jets (R&D) gifted the W.1X turbojet to the Smithsonian Institution in Washington, D.C. in 1949.[71] W.E.P. Johnson, patent agent and director of Power Jets (R&D), hoped that the presentation of the historic engine, like the film, would 'authoritatively put on record' the fact that the American jet industry owed the technology on which it was based to the UK, a fact too often overlooked, in his opinion, by the American industry.[72] The Whittle engine's induction into the museum would be an induction into the annals of American history.[73] In this way the

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[70] INF 6/408, 8.2.50, Crown Job No. 118

[71] 'First Jet Engine for U.S. Museum Gift Handed Over,' *The Times*, 9.11.49.

[72] FO 371/74280, 10.3.49, Letter Johnson to Secretary of State for Foreign Affairs (USA Division)

[73] It arrived at the Smithsonian not long after the original Wright flyer, which had since 1928 been housed in the Science Museum in London and which was put on display in the United States for the first time on 17 December 1948.

obsolete technical artefact would contribute historical authority to Whittle's pre-eminence and bolster Power Jets (R&D)'s patent sales.

Although a narrative of the jet engine, based on government records, had already been completed for the government's official historians by Cynthia Keppel, it was not used in the making of the film because the Cabinet Office refused, for reasons of confidentiality, to release it to the filmmakers.[74] According to one official,

> There are too many personalities involved, together with a very full and frank account of relations between Government departments and private firms, also of quarrels between individually named private firms. Quite apart from the differences of temperament and opinion revealed, which might well be seized by a film man to make a highly-coloured film in honour of Air Commodore Whittle, I think the Air Ministry would wish to have some say in how much of the pre-war story of official encouragement of jet propulsion development (or lack of it) is made public at this stage.[75]

The official who wrote this was clearly afraid that a 'full and frank' picture of government-industry relations might have a negative impact on the government's public image because it would tend to glorify Whittle and criticise the Air Ministry.

Historiographical success

It was only with Whittle's 1953 memoir, entitled *Jet, the Story of a Pioneer*, that a fuller version of the jet engine story appeared publicly. He did not intend *Jet* to be an autobiography,[76] and never in his book did Whittle refer to the jet as an invention nor to himself as an inventor. Nevertheless, Whittle's account of what he modestly referred to as his 'association with the development of the turbo-jet engine in Great Britain' was embraced by the public as the inventor's authoritative story. The memoir was first published for a popular audience by Frederick Muller. In 1954 it was republished in New York by Philosophical Library, and in 1957 as a trade paperback by Pan Books Ltd.

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[74] NA CAB 102/393, Keppel Narrative - Development of Jet Propulsion and Gas Turbine Engines in the UK

[75] NA CAB 103/260, 6.10.47, Hubback, Note for Record

[76] Whittle, *Jet*, Preface.

Jet was read by a wide public, and it transformed the public understanding of the development of the jet engine in Britain.[77] For Whittle publicised for the first time the intimate and messy relationships between the Air Ministry, industry and Power Jets – topics the government had studiously avoided. Whittle's narrative seemed to expand on a familiar and negative trope of the heroic inventor story: it was not just nature and technical caprice that the inventor had to combat, but also more modern problems: a lack of funds, the government's failure of foresight, industry's incompetence, and distrust from financiers at every minor technical setback. Given the atmosphere of disaster newly surrounding the Comet and the apparent failure of the second generation of British jet fighters, Whittle's account was understood as an indictment of government mismanagement of a seminal invention.

In the following decades, this interpretation of the Whittle story was seized on and furthered by declinist historians like Glyn Jones, who embraced Whittle's heroic status in their attempts to demonstrate the British Government's constant squandering of the nation's inventive resources.[78] Indeed, the story is still invoked today to show its lack of support for science and innovation.[79] That historians have used *Jet* as their primary source on the British jet story attests to its continuing influence. The first edition of the biography of Whittle, which was written by Golley in collaboration with Whittle, borrowed whole passages from *Jet*; it was published in a fifth revised edition in Britain in 2009, with a new supplement by Whittle's son.[80]

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[77] In a later edition, *Jet* was even marketed in this way. (Whittle, *Jet*, 1957 Edition, Back cover.)

[78] Glyn Jones, *The Jet Pioneers: The Birth of Jet-Powered Flight* (London: Methuen, 1989) used similar tropes to the author's earlier work on Barnes-Wallace. (Waqar Zaidi, 'The Janus-Face of Techno-Nationalism: Barnes Wallis and the "Strength of England"', *Technology and Culture* 49 (2008): 62-88.)

[79] 'Forgotten jet pioneer,' *Guardian*, 24.12.07; see also Dyson's article in *The Telegraph* quoted in the Introduction.

[80] John Golley and Bill Gunston, *Jet: Frank Whittle and the Invention of the Jet Engine*, Fifth (British) Edition. (Datum Publishing Limited, 2009); Golley's book was initially published after the fiftieth anniversary of the running of Whittle's first engine, in 1987. Another edition appeared after his death in 1996.

Alternatives to the Whittle story were known in Britain, but they never challenged Whittle's place as the jet inventor. As we saw in Chapter 1, immediately after the war many of the engineers involved in turbojet development gave public lectures and published papers in technical journals and the proceedings of professional societies. The war-time work of engineers who led jet engine development in industry such as Frank Halford, Hayne Constant and David Smith was thus known to the jet engine community, yet their efforts have hardly been written about since. In contrast to Whittle who was co-opted as a public figure and soon after left the jet field, all of these engineers remained little-known but active. A biography of Halford published in 1999 by the Rolls-Royce Heritage Trust, for example, devoted only a single chapter to his work on the turbojet.[81] All of these men had valid claims to being important turbojet pioneers but their promotion has relied on the support of fellow engineers and enthusiasts.

As discussed in Chapter 4, Arnold A. Griffith had perhaps the strongest claim to challenge Whittle's dominance in the British invention story because his work on gas turbines predated Whittle's. His work as well as the subsequent axial gas turbine research at the RAE was also publicised early on. On 17 December 1945, Roxbee Cox gave a lecture to the American Institute of the Aeronautical Sciences on 'British Aircraft Gas Turbines' in which he described Griffith and Whittle's work as the 'two distinct streams' of gas turbine work in Britain. Roxbee Cox saw his disclosure as part of the necessary publication of what had gone on in secrecy during the war. He began his lecture by commenting that '[t]he restrictions which, for reasons of military security, prevented the publication of such accounts a few months ago are now sufficiently relaxed for useful beginnings in the dissemination of the tremendous volume of material which has accumulated in the past few years to be made.'[82] Nevertheless, the descriptions of the work of Griffith and the RAE,

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[81] Taylor, *Boxkite to Jet.*

[82] Roxbee Cox, 'British Aircraft Gas Turbines', 53.

which appeared in the British press immediately after the war, were also eclipsed by Whittle. By 1951, an article on British turbojet and turboprop 'designs of a decade' could refer simply to Whittle's 'struggle' as an adequate story of the turbojet's early years in Britain.[83] While Griffith's work was acknowledged by aviation buffs and turbojet engineers, Whittle was being publicised as one of the world's great inventors, alongside Watt, Stephenson, Edison, Marconi and the Wright Brothers.[84] In 1999, an ex-RAE employee, Richard Dennis tried to match the popularisation that *Jet* had achieved for Power Jets' work by presenting the RAE's work for a popular audience for the first time.[85] Despite promotion by their supporters, however, the 'backroom boys' of the RAE never aroused much public interest in Britain.[86]

The only response from a government official to the dominance of Whittle's story and the lack of accounts of the jet engine from any other perspective was part of the memoir of George Bulman, which was written in the 1960s, but not published until 2002. Bulman had headed aero-engine development in the Air Ministry from 1928 to 1944, and in his memoir he responded explicitly to Whittle's portrayal of MAP's actions. He reacted to the canonical status of *Jet* by structuring his own story of the jet engine around a series of passages taken from Whittle's memoir, each of which he followed by his own re-interpretation. Before beginning his retelling of the jet story, Bulman explained, that

> [Whittle] leaves the reader in little doubt that in his view, I, in my capacity as DED [Director of Engine Development], and my staff continually thwarted him and must, therefore, be regarded as one of the prime factors in the frustrations and delays which dogged his endeavours. Now, for the first time, a little tardily perhaps, I offer my side of the story so that the basic facts may be laid bare in our respective apologia.[87]

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[83] 'Designs of a Decade,' *Flight*, 11.5.51.

[84] James Gerald Crowther, *Six Great Inventors: Watt, Stephenson, Edison, Marconi, Wright Brothers, Whittle*, (London: H. Hamilton, 1954).

[85] Richard Dennis, *Farnborough's Jets* (Fleet, Hants: Footmark Publications, 1999).

[86] Hawthorne, 'Aircraft Propulsion from the Back Room'.

[87] Bulman, *An Account of Partnership-Industry, Government and the Aero Engine*, 305.

Bulman did not expect to change entrenched public opinion with his memoir, and he appealed to the 'future judgment of historians' to vindicate his claims.

The centrality of Whittle in the story of the British turbojet was so well established by the end of the twentieth-century that even professional historians seeking to challenge the existing literature continue to reproduce it. Andrew Nahum's recent book, *Frank Whittle: Invention of the Jet*, was the first, after Bulman's autobiography, to offer a re-evaluation of the standard Whittle story that took the British Government's role in the turbojet story seriously. Yet Nahum too chose to structure his critique of the standard story around Whittle's engine. There is much to criticise in Whittle's account, yet as Nahum's title showed, his critique was less of Whittle's place in the historiography than of Whittle's one-sided interpretation of events. Nahum provided a valuable new perspective, but by virtue of his approach, ended up accepting Whittle's centrality in the jet story.

The German Challenge

The story of the German jets offered an obvious challenge to the Whittle story. Yet in the end, although it was known in Britain, the German story posed very little problem. Knowledge of 'German technical developments as revealed after the collapse', including the full gamut of German jet engines, was a point of interest to the readers of the aviation weekly *Flight*, for example, which published a series of articles on the topic by its editor G. Geoffrey Smith and Sir Roy Fedden in September to December 1945.[88] British jet publicity, however, paid little attention to the enemy's achievements. Whether or not they knew about the flight of the He 178 during the war, MAP ignored the fact that a German turbojet had been the first in the world to fly, even after Helmut Schelp, who was in London being

[88] G. Geoffrey Smith, *Flight*, 27.9.45 and 4.10.45; Roy Fedden, *Flight*, 29.11.45, 6.12.45, 13.12.45, and 20.12.45.

interrogated, brought it to their attention.[89] In their release on the Meteor in February 1945, the Air Ministry had claimed that honour for the E.28, and this was certainly never publicly modified. Wartime publicity's interest had been only to reassure the British public that the Meteor was superior to the Me 262; no invention story was associated with the German weapon.[90] The 1949 film *The Wonder Jet* told a British story, making no mention of American or German jet work. Any references to collaboration with 'our American Ally' from the Air Ministry's third press release were absent in the post-war film; the arrival of the W.1X in the United States was not depicted in the version of the film shown in Britain. The treatment of the jet story in Britain is a prime example of what Edgerton referred to as 'techno-nationalism'; non-British achievements in jet propulsion were simply not acknowledged.[91]

The official history of the jet prepared by Cynthia Keppel included references to the German jet programme in contrast to the British one, but did not offer anything remotely resembling a full account of German jet work. The details it included were gleaned from Schelp's interrogation and MAP reports. Keppel did mention von Ohain, but she spelled his name as 'von Chain'. Her mistake was reproduced in the published version (1964), suggesting that the German inventor's name was even then hardly well known in Britain. Heinkel's memoir, which included the jet among his other accomplishments, was published in English in 1956, but it downplayed von Ohain's role and emphasised Heinkel's.

Whittle's memoir mentioned German work, but did not emphasise it. His only reference to von Ohain work was a single sentence that noted: '[w]hile the B.T.-H. were building my engine, the aircraft firm of Heinkel were building a turbo-jet engine to the

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[89] Ermenc, *Interviews with German Contributors*, 112; The Air Ministry's release on the Meteor in January 1945 claimed that the E.28/39 was 'the first turbine jet aircraft in the world to fly (in May 1941)'. (NA AIR 2/7070, 28.2.45, 177a, 'RAF "jet" fighters in action')

[90] The Allies captured their first Me 262 in September 1944, and various British companies and establishments had carried out extensive tests on the aircraft's two Jumo 004 engines, which showed them to be inferior to the British jet engines, as the third release made known. (NA AVIA 15/2121, 13.9.44, 2A, Report on crashed enemy aircraft, first example of Me 262)

[91] Edgerton, *Shock of the Old*, 146.

design of a young engineer named von Ohain.'[92] Later in his book, Whittle devoted a chapter to German jet engines, in which his main argument was that they were much inferior to British engines. Further dismissing any notion that the German story might offer a challenge to his claims, he observed that although he could not make a 'definite claim' that the Germans had copied his 1930 patent, they had had every opportunity to, for several of his patent drawings were published in German technical journals before the war.[93] Thus in Britain, knowledge of German work (often quite technical) was widely available, but not much advertised to the general public.

In the United States the story was somewhat different. American authors presented German jet engines beside British and American work. Because of the early flight of the He 178, German work was usually acknowledged before British work. American work, despite its late date, was often taken to be inclusive of and superior to both of the earlier cases. In 1948, Leslie Neville and Nathaniel Silsbee, aviation writer and pilot respectively, published a book on jet propulsion that was meant to inform engineers, students and 'a rapidly increasing number of executives, businessmen, and professional men who are vitally interested in the problems of the air age that is now upon us.'[94] It included German, British and American developments under the chapter titles, 'How the Nazis Beat Us to It', 'The British Were Early, Too' and 'The AAF and American Industry Pull a Miracle'. The authors' story of German developments was derived largely from the published record of Schelp's interrogation.[95] Their British story was based on lectures by Whittle, Roxbee Cox, and Watt (Roxbee Cox's deputy), and began with the axial gas turbine (Griffith, Constant, Metrovick, ASM) before moving to Whittle's story.

Schlaifer's pioneering history, though including much information about Power Jets,

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[92] Whittle, *Jet*, 57.

[93] Whittle, *Jet*, 289.

[94] Neville and Silsbee, *Jet Propulsion Progress*, v.

[95] CIOS XXXII-46, 8.45, Interrogation of Dipl Ing Helmut Schelp

did not privilege either Britain or Whittle. His account covered the German story very thoroughly – based on publications and interviews with Germans who had moved to the United States after the war – and compared it to the British story. Schlaifer made no claims about invention, although his analysis acknowledged the difference between novel ideas and development. He juxtaposed the stories of Griffith, Constant, Whittle, von Ohain, Heinkel, Wagner, Müller, Oestrich, Franz and Schelp without significant analytical differentiation.

The tradition of trans-national histories of the jet was carried forward in the United States by a 1953 popular history, *Jet Pioneers*, by Grover Heiman. Heiman's first chapter was devoted to von Ohain and Heinkel, his second to Whittle, and the remainder of the book to American pioneers.[96] No equivalent popular, trans-national account was published in Britain or Germany.

It was in the United States that Whittle and von Ohain were first viewed as co-inventors. Whittle and von Ohain first met in January 1966, when they were jointly awarded the AIAA's Goddard Medal for the 'first successful application of turbojet propulsion to aircraft'.[97] Their status as jet inventors was cemented in the late 1970s and 1980s, as the two men, both then living in the United States, appeared together at numerous public events commemorating the jet engine. On 3 May 1978, for example, the Commander of Wright Field's Aero Propulsion Laboratory arranged for Whittle and von Ohain, then the Laboratory's chief scientist, to publicly recount the early history of the turbojet in an event entitled 'An Encounter between the Jet Engine Inventors'.[98] A symposium organised by the Smithsonian Institution's National Air and Space Museum in Washington, D.C. on 26 October 1979 to commemorate the fortieth anniversary of the He 178's flight, included

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[96] Heiman, *Jet Pioneers*.

[97] Conner, *Elegance in Flight*, 251.

[98] A transcript of their public, joint interview is given in Whittle and von Ohain, 1978. The two men also appeared together the following day at the US Air Force Museum in Dayton, Ohio. On 19 November 1986, the two inventors reprised their roles as part of the US Air Force Museum's Guest Lecture Series with a lecture entitled: 'The Birth of the jet engine in Britain and the development of the first turbo engine in Germany'.

lectures by Whittle, von Ohain and Franz (Jumo's leading turbojet engineer, then also living in the United States) as well as several figures from American jet history.[99] The museum's Jet Aviation Gallery, which opened in July 1981,[100] demonstrated their equal billing. In it, the W.1X was presented beside a re-construction of von Ohain's first flight engine, the HeS 3b. These were surrounded by later American jet engines. Opposite the row of engines was an Me 262 airframe and the prototype Lockheed XP-80. (See Figure 5.3) On 23 August 1989, the two inventors appeared once again together to celebrate the 'Golden Anniversary of Jet Powered Flight, 1939-1989' at an event organised by the American Institute of Aeronautics and Astronautics.[101] In 1991, von Ohain received the Guggenheim Medal 'for pioneering development of turbojet propulsion resulting in the first flight in 1939 and lifetime achievements in aeronautical propulsion dynamics', which Whittle had received in 1946. The men's shared status was again publicly recognised with the joint award in 1992 of the Charles Stark Draper Prize to both 'for engineering innovation and individual tenacity in developing and reduction to practice of the turbojet engine'.[102]

The American interest in German jet history began soon after the war, but the surge of public interest in the United States in the 1970s and 1980s was paralleled by increased German interest in the history of German aviation. In the 1980s, the Deutsches Museum in Munich, the German Aviation, Space and Supply Industries Association and the German Space Agency jointly began releasing a series on the history of German aviation. The second volume, published in 1981, was the technically rich history of German aero-engines edited by von Gersdorff and Grasmann, which included the first comprehensive German work on the

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[99] The proceedings were published, edited by Boyne and Lopez, *The Jet Age*.

[100] Conner, *Elegance in Flight*, 261.

[101] The unedited film footage of the event is available in the NASM Archive. An edited version was released publicly.

[102] Conner, 2001, 253; According to the website of the National Academy of Engineering, the joint award was given 'for their independent development of the turbojet engine.' ('NAE Website - Previous Recipients of the Charles Stark Draper Prize', National Academy of Engineering, accessed 26 October 1010, http://www.nae.edu/Activities/Projects20676/Awards/20681/PastWinners.aspx)

turbojet. Köhler's biography of Heinkel, Wagner's *The World's First Jet Aircraft*, Ebert et al.'s biography of Messerschmitt and Hirschel et al.'s volume on aviation research in Germany were all published in the same series.[103]

Simultaneously with the preparation of von Gersdorff and Grasmann's book, the Deutsches Museum made an effort to locate and collect an example of every important German aero-engine.[104] This led to the decision to commission a reconstruction of the German aero-engine that powered the world's first turbojet flight, which had been destroyed along with the He 178 airframe in a Berlin technical museum during the war.[105] The Deutsches Museum offered a second reconstructed engine to the Smithsonian Institution's National Air and Space Museum, where it was displayed beside the first British turbojet flight engine.

The appearance of the reconstruction of the HeS 3b in 1981 and the fiftieth anniversary of the engine's first flight in 1989, resulted in von Ohain being publicly recognised in Germany for the first time.[106] Von Ohain himself was a key figure in the reconstruction effort: he recreated the engine drawings from memory, supplied biographical information for the Museum's posted text and was the featured speaker on the occasion of the hand-over of the HeS 3b reconstruction to the Deutsches Museum on 15 May 1981.[107]

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[103] Volume 2: von Gersdorff and Grasmann, *Flugmotoren und Strahltriebwerke*; Volume 5: H. Dieter Köhler, *Ernst Heinkel: Pionier der Schnellflugzeuge, Eine Biographie* (Koblenz: Bernard & Graefe, 1983); Volume 14: Wagner, *Die Ersten Strahlflugzeuge*; Volume 17: Hans J. Ebert, Johann B. Kaiser and Klaus Peters, *Willy Messerschmitt: Pioneer der Luftfahrt und des Leichtbaues* (Koblenz: Bernard & Graefe, 1992); Volume 30: Ernst H. Hirschel, Horst Prem and Gero Madelung, *Luftfahrtforschung in Deutschland* (Koblenz: Bernard & Graefe, 2001)

[104] NASM Inventory Number: A19810039000, 'Heinkel (von Ohain) HeS 3B Turbojet Engine, Reproduction.', 29.5.78, Letter Walter Rathjen (Deutsches Museum) to Robert Meyer (NASM)

[105] Conner, *Elegance in Flight*, 254.

[106] DM FA001/1072, *Göttenberger Tagblatt*, 5.81; *Frankfurter Allgemeine*, 14.12.81; Fritz Janda, 'Oma finanzierte den ersten Jet,' *Abendzeitung*, 14.2.89.

[107] Von Ohain's speech was published with a brief introduction by Walter Rathjen in the Deutsches Museum publication, *Technik & Kultur*, in 1981. (Rathjen, "Weniger Gerausch, Keine Vibration!") Rathjen's introduction made clear that a copy of the engine would sit beside Whittle's engine in the Smithsonian Institution's National Air and Space Museum. In fact, von Ohain had already redrawn the engine – in part at his own expense - for an earlier, similar plan of the Smithsonian Institution, which was never realised. (Conner, *Elegance in Flight*, 254.)

Von Ohain was a key source for researchers; in the 1970s and 1980s he received inquires from von Gersdorff, Köhler, and Wagner, all of whom he continued to correspond with and whom he met later in Germany.[108]

At around the same time that this wave of interest in the jet engine's history swept the United States and Germany, the second trans-national history of the jet engine written by a professional historian appeared. Edward Constant's *Origins of the Turbojet Revolution* – an American contribution, like all professional trans-national histories of the jet engine thus far - was published in 1980 (after at least ten years of work[109]). Because the first German literature on the jet was only then being composed, Constant's account relied on Schlaifer's history, British literature on the British jet (including particularly Whittle's *Jet*), and accounts by the participants, including correspondence with Whittle, von Ohain, and Herbert Wagner. His book treated the German invention beside the British invention and did not privilege one or the other. Although he did discuss von Ohain first, Constant's story of the German jet engine did not single out von Ohain but rather gave the three German men discussed in Schlaifer's account, Hans von Ohain, Herbert Wagner and Helmut Schelp, equal credit for being jet revolutionaries.

Constant's account did not revise the existing British story. In fact, he contributed to its strength, by giving an explicit rebuttal of Griffith's claim to invention. Despite what he described as Griffith's 'intimate connection' with the turbojet revolution in Britain, Constant dismissed his claim to be a revolutionary because, while he had understood that a gas turbine could be used in an aero-engine, he had not grasped the importance of high-speed flight,

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[108] NASM VO Box 3, 4, and 12.

[109] Constant's book was published in 1980. It was based on his 1977 dissertation from Northwestern University. On 10 May 1970, he wrote to Whittle as a graduate student in history at Tulane asking for information for his 'history of the development of the turbo-jet engine'. (CAC WHTL A.325, 10.5.70, Letter Edward Constant to Sir Frank Whittle) He received responses from Whittle (20 May), von Ohain (31 July) and Wagner (18 Sept and 26 Oct) during 1970. (Constant, *Origins of the Turbojet Revolution*, 296-297.)

which made jet propulsion practicable.[110] Unlike Whittle, whom Constant asked in 1970 about the detailed steps in his thought process, Griffith, having died in 1963, was unavailable to explain his work. In making his judgement about the British turbojet revolutionaries, Constant had to rely on the British literature on the jet engine, which as we have seen, either supported the Whittle story or had failed to challenge it. In the end, he too concluded that Whittle was the key figure in the turbojet revolution in Britain, and his revisionist account remained in close agreement with the familiar story.

Conclusion

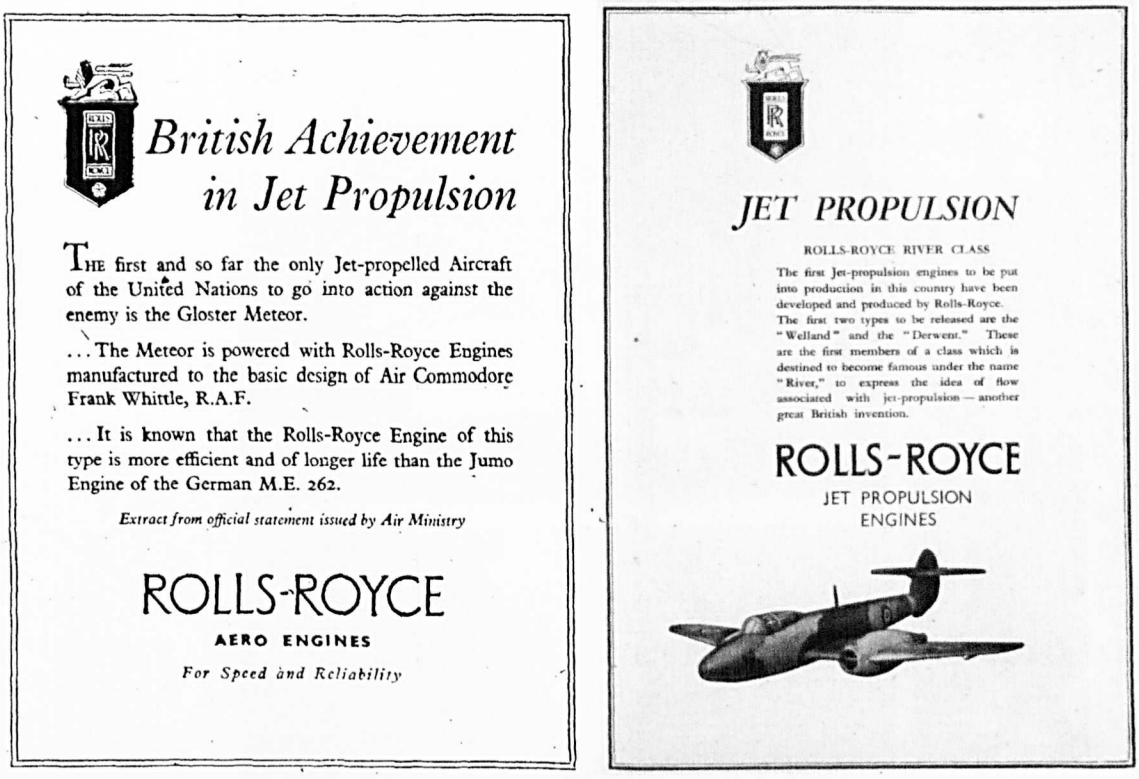
That Whittle made crucial contributions to the creation of the jet engine is uncontested. Nevertheless, it is revealing that he became famous after he ceased to be significant in British jet engine development. By 1944, when the first jet release was made, Whittle was already a shrinking figure at Power Jets, let alone in the turbojet field more generally. Despite this, the rich story of the jet's early years came to be dominated by a single story of Whittle's wartime work.

The construction of Whittle as an inventor-hero was an important means of buoying the post-war British economy because it allowed the Air Ministry to claim the jet engine for Britain. Yet the power of the Whittle story produced in the last years of the war, once released into a vacuum produced by the Ministry's jet publicity policy, was such that it obscured the stories of other important actors in the turbojet's early years. These included the crucial actors in the aero-engine industry, who had turned the jet engine into the viable commercial proposition that resulted in impressive post-war sales abroad. The power of the narrative of Whittle as the inventor of the jet engine has prevented a historical evaluation of the importance of his work and has hidden much of the story of the jet engine, even from revisionist historians. Whittle's achievement notwithstanding, his public visibility was a product of forces far removed from the jet engine. In light of the other jet activity of at least

[110] Constant, *Origins of the Turbojet Revolution*, 114 and 218.

equal importance described in this thesis, this demonstrates that the relationship between an inventor's work and his public visibility is by no means as obvious or as direct as the familiar heroic inventor story implies.

Figure 5.1. Early Rolls-Royce jet engine advertisements



British Achievement in Jet Propulsion

THE first and so far the only Jet-propelled Aircraft of the United Nations to go into action against the enemy is the Gloster Meteor.

... The Meteor is powered with Rolls-Royce Engines manufactured to the basic design of Air Commodore Frank Whittle, R.A.F.

... It is known that the Rolls-Royce Engine of this type is more efficient and of longer life than the Jumo Engine of the German M.E. 262.

Extract from official statement issued by Air Ministry

ROLLS-ROYCE

AERO ENGINES

For Speed and Reliability

JET PROPULSION

ROLLS-ROYCE RIVER CLASS

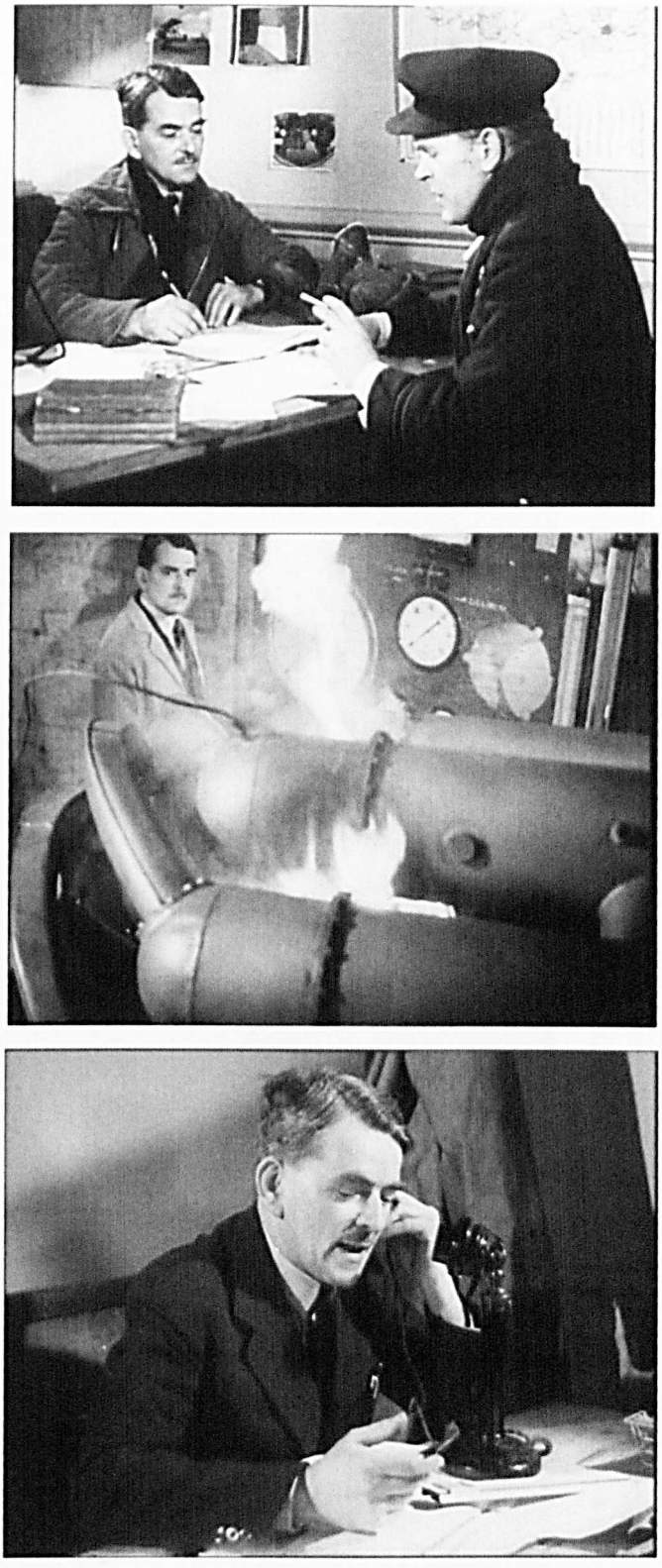
The first Jet-propulsion engines to be put into production in this country have been developed and produced by Rolls-Royce. The first two types to be released are the "Welland" and the "Derwent." These are the first members of a class which is destined to become famous under the name "River," to express the idea of flow associated with jet-propulsion — another great British invention.

ROLLS-ROYCE

JET PROPULSION ENGINES

Source: The Times, 19 April 1945; *Flight*, 25 October 1945.

Figure 5.2. Stills from *The Wonder Jet*



Frank Whittle and W.E.P. Johnson portrayed themselves in the film, which recreated several of Whittle's anecdotes from Power Jets.

Source: The Wonder Jet, 1949.

Figure 5.3. The Jet Aviation Gallery in the Smithsonian Institution's National Air and Space Museum, Washington, D.C.



The line of jet engines on the back wall of the gallery includes the Power Jets W1X (second engine from the left) and the recreation of the Heinkel HeS 3b (third from the left). The mural behind the engines depicts the first jet aircraft in the world. The Heinkel He 178 [A], Gloster E.28/39 [B] and Bell XP-59A [C] are depicted in the lower left of the mural. The noses of the Lockheed XP-80 (left) and Me 262 (right) are visible in the foreground.

Source: NASM.

Conclusion

When the Second World War broke out, one company in Britain and five in Germany were seriously designing jet engines. By the time that the war ended, six companies were producing jet engines: two each in Britain, Germany and the United States. In addition, seven companies in Britain, four in Germany and two in the United States were developing jet engines and on a larger scale than in 1939. The majority of these companies were aero-engine firms; all of the main aero-engine firms in Britain (five) and Germany (three) were developing jet engines. The two American companies developing jet engines were, in contrast, large manufacturing companies that had produced steam turbines before the war. Between 1939 and 1946, more than seven thousand jet engines were manufactured in the three leading jet engine countries. The overwhelming majority of these were built in Nazi Germany.

The standard story of the jet engine holds that the Germans were first and most successful with jets. Although Britain's early start is often recognised, the country is viewed as less successful than Germany, which is attributed to the reluctance, or even negligence, of the British Government in its support for jet engine development. The United States, the last of the three countries to begin work on jet engines during the war, is seen as the least successful, even a failure because it did not produce a significant number of jet engines during the war and its only viable engine was supposedly a copy of a British one.

This thesis has challenged all of these interpretations both in general and in detail. It did this using new material as well as reinterpretations of long-existing material, and its new perspective came from a focus on the frequently overlooked topics of production and development, as well as from a reconsideration of the process of invention and inventors. An important change that conceptually facilitated the new story told in this thesis was to reverse the familiar order of the story of the jet engine – an order indeed employed frequently in stories of new things. This key reversal changed the story's emphasis, placing

production rather than invention at its start and shifting attention toward the aero-engine industry, the centre of the history of the jet engine in terms of money, time and effort rather than public visibility or priority. Beginning with production, which in fact fundamentally shaped all three of the wartime jet programmes, subverted the tendency to think that novel ideas or inventors dictated the story of the jet engine. Indeed, Chapter 4 argued for the powerlessness of inventors in determining the impact of their work in some instances. By calling into question the very terms in which technical change is typically discussed, this thesis presented persuasive evidence for discarding the transition narrative and rethinking the history of the sources of change in the twentieth-century.

This thesis has made important changes to the story of the jet engine in all three countries. Firstly, it has shown that Britain was not behind, but rather ahead of Germany in its eagerness for the jet (even despite the larger number of projects in Germany in 1939). In fact, the Air Ministry's enthusiasm for the new engines led to the decision to produce jet engines in Britain already in 1940. This first impulse gave way to a pragmatic stay-the-course policy and ultimately a focus on development and post-war competitiveness, which explained the country's lower wartime production numbers. At the end of the war, Britain had the greatest number of developed jet engines types and the most wide-ranging jet engine development programme of any country, which included a range of engine designs and all of the country's aero-engine firms. The government's support for the development of the jet engine fits with historians' recent arguments for the central place of new weapons in British military strategy.[1] MAP's unfailing support for the attempts of many firms to begin developing ambitious gas turbine aero-engine designs may have been a costly side-effect of

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[1] Edgerton, *Warfare State: Britain*; Peden, *Arms, Economics and British Strategy*.

the government's enthusiasm for aviation, which contributed however to making Britain the world's leader in jet engines at the end of the war.[2]

The revision made in this thesis to the story of the German jet engine is no less dramatic. Traditionally the jet success story, Germany in fact had the least reliable jet engines at the end of the war, which sacrificed performance and safety for ease of production. Germany's engine production numbers were the highest of any country, but this was not because of its technical superiority nor because of an early commitment to jet engine production – indeed, Germany was the last of the three pioneering nations to decide to produce the new engines. Instead, the huge number of engines produced was achieved by turning the most authoritarian aspects of the Nazi state towards producing jet engines for the country's last desperate air offensive. Easier and cheaper to make than existing piston engines, as this thesis makes clear for the first time, German jet engines were produced in such large numbers because they could be adapted to the extreme conditions of scarcity that characterised German production in the last years of the war. In part because of the failure of the RLM's piston engine development and procurement policy, the jet became a crucial piece of Germany's final air armaments strategy, which, like its defence strategy more generally, relied on producing as many inferior weapons as cheaply as possible. The German jet engine was not a cutting-edge, game-changing weapon, but an ersatz piston engine. This strongly supports Adam Tooze's argument that the increases in German output at the end of the war should to be interpreted as the result of the brutal mass production of cheap, simple machines.[3]

The story of the United States, where the development of jet engines began after both Britain and Germany, is also revised in this work. The USAAF seized the opportunity

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[2] David Edgerton, *England and the Aeroplane: An Essay on a Militant and Technological Nation* (Basingstoke: M [i.e. Macmillan] in association with the Centre for the History of Science, Technology and Medicine, University of Manchester, 1991).

[3] Tooze, *Wages of Destruction.*

to take advantage of the British W.2B engine primarily because the engine appeared to offer a fast route to production. It was for this reason that GE ended up extensively developing a centrifugal jet engine. Although the United States produced few jet engines during the war, it nevertheless began to build a jet engine production infrastructure before Germany. Due to the decision to keep its aero-engine firms out of the jet engine field, the United States was not able to overtake Britain during the war, although American jet engine development progress was quick. Just as there was little pressing military need for jets in Britain, there was no reason for the USAAF to push for jet engine production at the cost of development. Indeed, GE used the war to build up an aero-engine development and production organisation that came into its own after 1945. This thesis has also highlighted the need to see the jet engine as an Anglo-American project, with intimate trans-Atlantic technical collaboration in development, as happened in other areas.

The dynamics of the production decisions that directly influenced the scope and goal of jet engine development programmes in all three countries reveals a range of different motivations and incentives for jet engine production that were political, commercial and military as well as technical. Indeed, the case for any superiority in performance for wartime jets over piston-engined aircraft is weak, whether in the case of Britain, the United States or Germany. In Germany, beginning to lose the war produced the necessary reason to favour jet engine production as a substitute for more expensive aircraft and ultimately to the exclusion of all else. Britain, meanwhile, could afford and chose to risk investing in new weapons, whether or not they were sure bets. British jet production was stimulated late in the war, not by military necessity, but by the need to justify early investments, reassure the British public of the country's military might, and influence the post-war world market. In the United States, a real stimulus to intensive production never really surfaced, although the country's resources allowed it to begin to build large manufacturing facilities during the war that were important just after it.

This thesis showed that output does not necessarily correlate with the success of a development programme. Indeed, studying development in its own right reveals an impressive amount of wartime activity that was not expressed in wartime production numbers. In Britain, MAP encouraged all of the country's aero-engine makers to take up the new engines, and so the British aero-engine industry was by far the most accomplished in jet engine design and development by the end of the war, with the American industry second and the German third.

In its focus on the aero-engine industry, my work on development has sought to highlight the previously unrecognised insights of Schlaifer's outstanding early account of the jet engine. I have shown that Schlaifer's contention that the aero-engine industry had a central role in new aero-engine development reflected a since neglected, yet fundamentally important, understanding of the crucial contributions made by this industry to the jet engine. In contrast to accounts that have used Schlaifer's narrative exclusively as a primary source, this study has used his arguments as its starting point. My work has allowed me to confirm and to elaborate many of the claims that his account did not prove in detail. A few of his interpretations should be revised in light of additional evidence, but the minor disagreements that I have with his account do not detract from the usefulness of the compelling framing of his early study.

As Schlaifer recognized, the aero-engine industry possessed experience optimised for the development and production of aero-engines that was hard to reproduce. He argued that the aero-engine industry was already familiar with and developing elements crucial to the jet, and I have gone farther to argue that the well-known centrifugal compressors, exhaust nozzles, high temperature alloys, fuel systems, turbines and (in Germany) turbine blade cooling of piston engine practice, like development methods more generally, were usefully

transferred to turbojet practice by aero-engine firms.[4] The ability to take advantage of such transfers dictated the speed and degree of a firm's success with turbojet engines. As firms increased their commitment to the new engine type, resources such as workshops, test equipment, production facilities and personnel were gradually moved from one engine type to the other, illustrating the continuity and competition between the two engine types. Edward Constant's characterisation of the jet engine as a radical break with piston engine practice is profoundly misguided.

Schlaifer's key arguments, which no other historian of the jet engine has engaged with, were about aero-engine development. I went beyond his analysis to look in detail at how aero-engine firms were successful at turbojet development, how they actually moved from one engine type to the other and how they turned expertise in piston engines into expertise in turbojets. In so doing, I emphasised, in contrast to Schlaifer, the centrality of company decisions rather than government decisions (as embodied in development and production contracts) to this switch. Furthermore, I recovered the little-known stories of the embrace of the turbojet by British aero-engine manufacturers during the war.

The outsider status of the jet engine's advocates is often emphasised, yet the story of the jet engine was largely a story of an industry deploying old expertise in a new task, as that industry's record of success as compared to steam turbine makers (Chapter 3) and outsiders (chapter 4) suggested. Although the jet engine altered the relations within the existing aero-engine industry in all three countries, it did not lead to the creation of a new industry, or new aero-engine firms (with the exception of GE), as was the case with the automobile industry, for example. Instead, it led to the transformation of an existing industry to a very substantial degree by its own actions. This is not to say that pioneers of the jet engine had no influence, but that their influence was not decisive. Rolls-Royce's long commitment to gas turbine

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[4] Constant, *Origins of the Turbojet Revolution*, 18.

engines, for example, was intensified and influenced but not created by the success of Power Jets. Griffith's first designs were not directly translated into a production aero-engine before he left the RAE, but his work was promoted by his assistant Hayne Constant. In Germany, von Ohain's work may have inspired others, but it was not the only jet project underway before the war, and no other firm used his engine design or created an engine similar to his.

Taking the contribution of industry to the jet engine seriously changes the standard story dramatically. Indeed, the historiography has already made a similar and important shift in the case of the atomic bomb, which has been transformed from a story of the radical invention of a small group of academic scientists to one of the extensive and costly industrial might that made the development of the bomb possible in the United States.[5] A similar shift remains to be made for the story of radar, another wartime technology known for its creation in an academic laboratory rather than for the industrial effort behind its development, production and perfection as a new machine.[6]

The role of the aero-engine industry in the development of the jet engine was enormously important. It is true that the industry did not immediately rush to develop the jet engine, though note must be made of the number of firms already working on jet engines before war broke out. The first and most important reason that firms were reluctant to take up jet engine development was the press of work on piston engine production and development. It was not the success of a group of revolutionaries dedicated to jet engines that converted the aero-engine industry, but rather the lessening pressures of piston engine production that freed firms to work on the new engines. Firms large enough to develop jet engines while also keeping up work on piston engines (Rolls-Royce, Jumo and BMW), those

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[5] Hughes, *American Genesis*, 381-421; Edgerton, *Shock of the Old*, 260.

[6] Brown spends little time on industry's contribution to radar, yet a glance at Smits' work suggests that industrial might was extremely important to its history. (Louis Brown, *A Radar History of World War II: Technical and Military Imperatives* (Philadelphia, PA: Institute of Physics, 1999); F. M. E. Smits, *A History of Engineering and Science in the Bell System. Electronics Technology, (1925-1975)* (Indianapolis, Indiana: AT&T Bell Laboratories, 1985).)

companies that saw their piston engine work disappear (de Havilland, ASM and Bramo), or those that had none (like the American steam turbine makers) were – tempered by the company's aero-engine competence - those firms that succeeded earliest. No firm abandoned a successful piston engine programme for a jet engine programme during the war.

Looking at the full story of wartime jet development in the aero-engine industry, with attention to both developmental successes and failures, reveals the shifting goals of industry as well as the changeability of the developmental timescales that industrial firms adapted to; both were defined by the uncertainty of novel development. Firms tried to reduce uncertainty by privileging existing experience and by pursuing multiple designs, including occasionally working on both axial and centrifugal engines. Rolls-Royce, for example, began with a long-term axial development programme, and added a second centrifugal line of development to their turbojet programme, which allowed the firm to secure a place in the market by making use of the government's generous wartime support for jet engine development and production. Its axial programme, meanwhile, fed into the firm's longer-term success. A similar story could be told for GE, although that firm's management wielded less influence over the firm's early jet engine development programme.

During the war, firms benefitted from seemingly unlimited development funds, yet at the same time, the war brought great urgency. The independence of aero-engine firms and their evaluation of the appropriate distribution of their resources between piston engines and jet engines was sometimes essential, such as at Rolls-Royce, Daimler-Benz, Jumo or BAC, whereas at other times it was problematic, for example at ASM, EHFW and BMW. In reducing the risk of the uncertain development of new aero-engine types, the government's financial support was essential, but not always decisive. Development could suffer because of pressure for production (particularly in Germany), and new designs were sometimes abandoned before their worth had been adequately tested (the B/26, HeS 30, and 109-007).

The war gave the governments in all three countries hugely increased executive power in addition to the power that they wielded in the interwar period: to replace managers and chief engineers, to move factories and sometimes workers, to cancel development projects, and especially to control resources. Government guidance sometimes served to return companies to better development paths. Yet the importance of Germany's centralised control over jet engine development has been exaggerated in the literature, for it was much more the authoritarian nature of the country's production system that was responsible for the remarkable number of jet aero-engines built during the last year of the war. While the role of the German government in development is overemphasised, the British government's early commitment to the engines is rarely appreciated. The lengths to which MAP improvised to keep its programme in being are rarely commented on, although Nahum's recent account of Whittle's work argued strongly for the extent of the British Government's accommodating approach to Power Jets.

Given the crucial role played by the aero-engine industry, it is astonishing that none of the three most prominent pioneering jet engine institutions in the literature, Power Jets, the Royal Aircraft Establishment and EHFW were part of the aero-engine industry either before the war or after it. For all three, jet engine invention or research, rather than production, was an institutional focus. Like steam turbine makers that developed jet engines, Power Jets and EHFW struggled to amass the expertise and resources to compete with established aero-engine companies. The story of both inventive firms illustrated that even in institutions isolated from production, production concerns made themselves felt during the war. Organisations that existed to invent products but not produce them were increasingly at a disadvantage because production brought political power. Without this, the two aspiring aero-engine firms became progressively more insecure, which impacted not only their attempts to enter the aero-engine industry but also the future of their inventive work. In contrast to Power Jets and EHFW, the RAE successfully adapted itself to the aero-engine

industry's needs. This is not surprising given that the RAE was a more stable, well-developed organisation than Power Jets or EHFW. Because of its institutional success, the RAE's inventive work on axial gas turbines was perpetuated in the National Gas Turbine Establishment and thence in the British aero-engine industry, whereas Power Jets' was not.

Chapter 4 argued that the process of invention, like development, can usefully be understood in terms of the nature and capability of organisations. Looking at the influence of inventive organisations on the work of individuals, whom the literature tends to portray as independent, showed how inventive institutions shaped inventors' agendas, the technical details of their engines, and the manner in which they executed their inventive work. To understand this, it was necessary to look at the longer-term relationships between these institutions and their particular turbojet designs. This countered the standard story's tendency to focus only on the earliest incarnations of a new machine, which has confused the reasons for and the evaluation of the ultimate success or failure of particular designs.

The prominence of Whittle's work early in the war reflected his role as the central figure in a rapidly growing institution, and the growth of his institution reflected the government's conviction of his importance. Nevertheless, his legacy was thrown into doubt in the last years of the war, as his institution became less secure. Meanwhile von Ohain's work was chained to the interests of an organisation primarily dedicated to airframe work, and he was only able to really develop aero-engines during the last years of war, after being freed from Heinkel's management. His work failed to influence later designs because the company where he worked failed to gain an influential position in aero-engine development. Griffith's work, in contrast, was successfully carried on by the RAE, although neither is as prominent in the jet literature as Whittle, Power Jets, von Ohain or EHFW. Despite the greater influence of the more effective institution, its work remains less visible in the history of the jet engine than either of the other two, a fact explained by the broad impact of the publicity discussed in Chapter 5.

Looking closely at work on jet engines both within the aero-engine industry and in inventive institutions supports Scranton's argument that our existing understanding of the relationship between scientific and technical knowledge does not explain the case of the jet engine. In his account, Edward Constant recognized the increasing importance of science, particularly aerodynamics, in aero-engine design, but he went too far by elevating it, in the form of his presumptive anomaly, to the definitive cause of technological revolution. Scranton, in contrast, used the case of the development of the jet engine to usefully challenge existing models of the relationship between technology and science in producing novelty when 'basic science remained too underdeveloped to offer guidance'.[7]

The development of jet engines emerged as a nexus for using and producing science, as historians like Vincenti have argued more generally by drawing attention to the systematic research and testing done by industry as a serious source of knowledge. The jet engine relied more on scientific inputs than piston engines. Yet the key expertise for making a new aero-engine was never the lab-based science so prominent in the history of the early twentieth-century, never chemistry or physics, but rather mathematics, projective geometry, mechanics and material science. As Chapter 3 demonstrated, despite the increasing importance of aerodynamics, expertise in development was far more important where the first jet engines were made, in part because the work of research establishments was made available to the aero-engine industry.

As a story of technical change, the jet story challenges the widely accepted transition narrative. The jet engine does not fit into nineteenth-century-style stories of independent inventors nor into the mould of twentieth century corporate laboratory invention. The jet is clearly not a case of individual invention, as chapter 4 showed. The invention of the jet engine was carried out with all of the trappings of twentieth-century business: from banking

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[7] Scranton, 'Technology-Led Innovation'.

houses to government contracts, from general and managerial staffs to huge production organisations. Indeed, the standard story's misleading notion of Whittle's independent-ness was part of a heroic story of invention that filled the void left by a Ministerial policy of information control, as argued in Chapter 5. For this reason alone, the jet story deserves to be revisited. Doing so, as this thesis has shown, reveals a world of activity obscured in Britain by a single dominant public narrative.

The jet engine not only relied on the tools of twentieth-century business, it could only have been produced by large engineering organisations. The new, high-powered aero-engines of the Second World War were not something that could be made by a small group of people in a mechanic's shop. Jet engines were the product of extensive and peculiarly twentieth-century systems that relied on a range of crucial skills, thousands of workers, extensive supply chains and tangles of interconnected sub-contracting companies. This thesis has demonstrated, furthermore, that novelty appeared during all stages of the jet engine's emergence and in a range of usefully interconnected industrial locations. The proximity of production, development, and invention in a single firm offered strong advantages as firm experts from one area influenced the work of others.

Quite in contrast to this picture, the transition narrative insists that invention in industry took place primarily in corporate laboratories. Chapters 3 and 4 described a variety of different types of organisations that were important to the jet engine. Some of them, which I labelled inventive institutions, understood their work as contributing directly to the emergence of technical novelty, yet none was a corporate laboratory. During the twentieth-century, streams of new products issued continuously from engineering industries without research laboratories in the academic sense. Instead they came from design offices and workshops, production lines and boardrooms, government laboratories and test stands. Technical novelty came from government experts, engineers, mathematicians, entrepreneurs, bankers and salaried inventors. An array of industries that were active and successful in the

mid-twentieth-century – trains, shipbuilding, automobiles, airframes, machine tools – similarly testify to the inadequacy of the transition narrative as an explanation of the sources of invention in the twentieth-century.

The sources of technical change in industry have not been adequately conceptualised by historians. The story of the jet engine demonstrates this, as Scranton's work has already argued for the post-war period, and this thesis has gone farther to argue that our understanding of the process of innovation needs to be dramatically revised in even the earliest phases of development, which the transition narrative focuses on. The inadequacy of our understanding extends well beyond the mechanical engineering industries, however. The stories of the atomic bomb and radar don't fit the dominant transition narrative either. These new machines were not produced by corporate research nor by academic science. The focus on academic ideas has had a similar effect on their analysis as the preoccupation with the independent inventor has had in the case of the jet. Brief reflection produces any number of other examples. In the same way that this thesis suggests the significance of revaluating which the important actors in the jet story were, it is useful to rethink other cases too, especially where their standard stories contradict what is already known.

As the review of the literature on technical change in Chapter 1 showed, the transition narrative's dominance is a product of the literature's failure to build on existing thought and its lack of subtlety and imagination. The narrative's pervasiveness today is a product of its conventionality rather than any positive analytical power. Its continued dominance in professional history is due in part to its hold over the historiography, for the narrative has encouraged historical research to be carried out within its strict limits. Its effectiveness in narrowing the view of historians has made itself felt; analysis of technical change has too often retreated into the unproductive dichotomy between individuals and corporate labs.

As important an asset for historians of technical change as openness to the stories of new sites and activities is attention to the specifics of each new machine. Through detailed attention to engine layouts and elements, this thesis has demonstrated the expository power of distinguishing between different machines which standard stories lump together under a single name. During the Second World War, 'the jet engine' was many things: different types of compressor and turbine, a variety of combustion systems, different metals and fuels, and the product of a range of industries, which embodied different engineering standards, goals and material circumstances. The great distance between the story told in this thesis and the standard story of the jet engine suggests the dangerous degree of simplification in popular accounts, in which what Whittle and von Ohain both invented was the 'jet engine', what Jumo and Rolls-Royce produced was the same power plant, and what the Luftwaffe and RAF flew were the same weapon. It is precisely at the early stages of a new machine, the moment with which so many accounts are obsessed, that this sacrifice of detail leads to the greatest loss of understanding of the complex story of how technical novelty emerges. What Whittle or von Ohain invented may be difficult to say, but the question is crucial. We have to be as careful about what is invented as about where, when, how and by whom.

Appendix A
Power Jets Ltd., Schedule of Shareholders, 1 November 1943

		Shares (£1)	
Mrs. Shelia Emmet	**Anscombe**	10	
Edward Robson	**Atkinson**	50	BTH draughtsman
Harry Edward	**Burgess**	300	
Miss Ethel Georgina	**Cox**	25	(Possible relation of Roxbee Cox)
V.E.	**Crompton**	20	Employee
I.D.	**Davidson**	50	
Bonamy	**Dobree**	100	
Messrs O.T.	**Falk Nominees Ltd**	5170	
G.B.R.	**Fielden**	50	Employee
Messrs.	**Gunn and Company, NY USA**	550	Includes 300 transferred from O.T. Falk and 250 from L.L. Whyte
Miss L.M.	**Herringshaw**	20	Secretary?
His Highness	**Yeshwant Ras Holkar, Maharaja of Indore**	600	Client of Whyte*
Her Highness	**Marguerite Holkar, Maharani of Indore**		
Denys Quinton	**Holland**	4500	For the British Thomson-Houston Company
James Dayton	**Imrie**	5000	For the Weir brothers
A.B.S.	**Laidlaw**	100	For services rendered
Messrs	**Laidlaw, Drew & Co Ltd**	370	
Mrs. S.	**Lees**	150	(Possible relation of W/C Lees)
H.B.	**Leney**	450	
Messrs.	**Lindsay, Long and Partners**	1200	Williams, Tinling Directors; appointment of Lindsay, Long and Partners for management services terminated on 31.12.41
Messrs.	**Lloyds Bank City Office Nominees Ltd.**	900	
Mrs L.	**Lubbock**	100	(Possible relation of Roy Lubbock)
	Mercantile Bank of India (Nominees)	600	Transferred from L.L.Whyte (Director), originally for service
R.D.	**van Milligen**	40	Employee
Ernest Kew	**Mills**	200	Employee
W.M.	**Ogston**	20	Employee
William Albert	**Randles**	150	BTH draughtsman
John D.	**Richardson**	50	
John Ryan	**Strugiss**	200	
T.A.	**Taylor**	50	Chief metallurgist
Mrs I.F.	**Taylor**	20	Reissued from I.F. Lucas (maiden name)
J.C.B.	**Tinling**	21	Director, A-Shares**
R.G.	**Voysey**	50	Employee
Reginald Newnham	**Waite**	200	Transferred from Mrs F.M. Chapman, (possible relation of chief draughtsman C.J. Chapman)

W.S.	**Wasserman**	125	Of New York, Whyte client*
Mrs. I.V.	**White**	200	Custodian of enemy property 1943
Frank	**Whittle**	56***	Honorary Chief Engineer, A-Shares**
Rolf Dudley	**Williams**	21	Director, A-Shares**
Guy Richard Charles	**Wyndham**	100	
	Total	**£21818**	

Held by O.T. Falk as a Nominee Company on behalf of the following beneficial owners:

A.J. Beamish	50	
Bonham Carter Pool	400	
Lady Charles Bonham Carter	300	
General Sir Charles Bonham Carter	100	
Gerard Bonham Carter	100	
Sir Maurice Bonham Carter	700	) 500 for services, Director
A.J. Bryant	20	
Durani Syndicate	250	
Oswald T. Falk	700	) 500 for services
H.M. Farrer (dead)	250	
Mrs E.J. Leney	150	Also invested in Napier
Sir Ronald C. Lindsay	800	Ambassador to USA
Mrs. H. M. Lubbock	400	(Possible relation of Roy Lubbock)
James Collingwood Burdett Tinling	250	Director
Mrs Vickery	200	
Rolf Dudley Williams	500	Director
Total	**£5170**	

* Whyte, *Focus and Diversions*, 115.

** The three 'A'-shareholders (Whittle, Tinling and Williams) held with 98 shares 49% of the voting rights in the company as well as the right to appoint the Chairman of the Board. The remainder of the shares was issued as 'B' shares.

*** Initially, Whittle held 42 shares for himself and 14 for the Crown (Air Ministry). After 1940, he held 32 for himself and 24 for the Crown.

Source: BL Add 61931; NASM T, Shareholder Lists in Box 1 and Box 2; Schlaifer and Heron, *Development of Aircraft Engines*, 340-342.

Appendix B
Air Ministry Jet Publicity (1944-1945)

First press release, 6 January 1944

NOTE.

THIS STORY IS BEING ISSUED SIMULTANEOUSLY IN U.S.A.

Not for publication or broadcast or use in club tapes before 2300 hours B.S.T., Thursday, 6th January.
Not to be transmitted before that time, except to the countries and in accordance with the conditions set out hereunder:
May be transmitted forthwith to the Dominions, India, U.S.A. and Egypt by cable only and endorsed: "Unpublishable, unbroadcastable and untransmissable (ex-country addressed) before 2200 hours G.M.T., Thursday, 6th January".

Air Ministry Bulletin No. 12544.

JET PROPELLED FIGHTER SUCCESSFULLY DEVELOPED.
FIRST FLIGHT IN BRITAIN IN 1941.

The following joint statement, which has been agreed with U.S. War Department in Washington, is placed at the disposal of the press by the Air Ministry and the Ministry of Aircraft Production:

According to a Joint U.S. Army Air Force - British Royal Air Force statement issued to-day by the War Department, Washington, Jet propelled fighter aircraft have successfully passed experimental tests and will soon be in production.

Originally to British design, the improved jet propulsion engines eliminate propellers on the new aircraft. Work was started on the engines in Great Britain in 1933 by Group Captain Frank Whittle. His first engine ran successfully in April 1937. The Air Ministry placed their first order in 1939 for an aircraft using jet propulsion engines with the ~~Gloucester~~ Gloster Aircraft Company Limited, Gloucester, England; the engines were to be built by Power Jets Limited, special factory in England, to whom Group Captain Whittle was loaned. The first successful flight of this aircraft was in May 1941. The pilot was the late Flight Lieutenant P.G. [Philip Gerry] Sayers, chief test pilot of the Gloucester Aircraft Company. The greatest credit should be given to Group Captain Whittle for this fine performance, for it was his genius and energy that made this possible.

[-2-]

Full information about this jet propulsion engine was disclosed in July 1941 to General Arnold who, like the British R.A.F. and M.A.P., had the foresight to appreciate the tremendous possibilities of this new form of aircraft power unit. He at once asked for an

engine to be sent over to U.S.A. The engine which had made the first flight was sent to General Electric Company in September 1941.

As the result of close cooperation between the U.S.A.A.F., R.A.F., A.A.F., Material Command and the Ministry of Aircraft Production and General Electric Company, a number of these engines were built. The first was ready for test in less than 6 months. At the same time the Bell Aircraft Company were given an order to build an aircraft suitable to take two of these engines and the first flight in the US was made in under twelve months. Several hundred successful flights have been carried out since then by British pilots in the U.S. and by British pilots with the British aircraft in England, many of them at high altitudes and extreme speed, all without a single mishap.

In view of this successful record and the obvious advantage of this new type of aircraft, General Arnold, commanding general of A.A.F. and the British Air Ministry and Ministry of Aircraft Production have directed that plans be made for the production of a sufficient quantity for training purposes both in the US and Great Britain.

The U.S.A.A.F. are allotting a number of these to the U.S. Navy for additional trials and experimentation. The maiden flight of the first experimental aircraft in U.S.A. took place on October 1st, 1942. This was the first successful operation of a combat plane using the jet propulsion principle. Robert M. Stanley, chief test pilot of the Bell Aircraft Company, was at the controls on the initial flight. The next day Brigadier-General (then Colonel) Lawrence C.D. Craigie, flew the aircraft, thus becoming the first army officer to fly a jet propelled

[-3-]

military aircraft in the United States. Among others who have tested the new aircraft are Brigadier B.W. Chidlaw, Chief of the Material Division, Office of Movement Control; Chief of Air Staff Material Maintenance and Distribution and Major-General William E. Kepner, an Air Corps fighter pilot formerly commanding 4th A.F.

In the United Kingdom the J.P. aircraft has been flown by a number of test pilots of aircraft firms and R.A.F. officers.

NOTES ON CAREERS.

Group Captain Frank Whittle.

Group Captain Frank Whittle is the inventor of the first successful jet propulsion engine for fighter aircraft. His first engine ran successfully in 1937, when he was placed on the Special Duty List for research work. Group Captain Whittle had been engaged in perfecting his invention through all its stages – except for a period at the R.A.F. Staff College in 1943 – whilst on loan to Power Jets Ltd. in a special factory in England.

He was born at Coventry on 1st June, 1907, and was educated at Leamington College, leaving there in 1923 to become a Royal Air Force apprentice. While an apprentice

he made a number of remarkable model aircraft, and at the end of his apprenticeship was awarded a cadetship.

From 1926 to 1928 he was a flight cadet at Cranwell, and at the end of his course he gained the Abdy-Gerrard-Fellowes Memorial Prize for aeronautical sciences.

After leaving Cranwell in 1928 he became a Pilot Officer in No.111 Fighter Squadron, and at the end of 1929 he took the instructors' course at the Central Flying School. During this period he began to work on his jet propulsion ideas.

Promotion to Flying Officer took place in January 1930, and in the same year he became a flying instructor at No.2 Flying Training School, Digby. It was during this period, that

[-4-]

with the late Flying Officer G.E. Campbell, he gave one of the most thrilling exhibitions of crazy flying at the Royal Air Force Display at Hendon.

He next became an experimental test pilot on float seaplanes at Felixstowe during 1931-2, specializing in catapult work. Following this he went tot Henlow on the Officers Engineering Course, 1932-3, being promoted to Flight Lieutenant in Jan, 1934.

He then spent three years at Cambridge University, obtaining a First Class Honours Mechanical Science Tripos in 1936, followed by a year's post graduate work at Cambridge, during which he was associated with Professor Sir Melville Jones. He became a Squadron Leader in December 1937, Wing Commander in June, 1940, and Group Captain on 1st July, 1937.

Group Captain Whittle married in 1930, and has two sons, aged 12 and 9 years.

Flight Lieutenant P.E.G. Sayer.

"One of the finest test pilots in the country", was the description applied to Phillip Edward Gerald Sayer, at the time of his death on October 22nd, 1942.

He was born on February 2nd, 1905 and was educated at Colchester Grammar School, obtaining a short service commission in the Royal Air Force on June 1924. After learning to fly in an Avre 504K, he flew Snipes and Gladiators, his outstanding qualities as a pilot resulting in an appointment as test pilot at Martlesham Heath.

Flight Lieutenant Sayer left the R.A.F. on the completion of his five-year commission to join the Hawker Company, and was appointed as assistant to Group Captain P.W.S. Bulman. Here he was engaged in testing Harts, Furies, and other aircraft, and on the acquisition of the Gloster Aircraft Company by the Hawker group, was appointed in 1935 chief test pilot of the Gloster Company. In this capacity he tested Gladiators, Hurricanes and Typhoons.

[-5-]

Flight Lieutenant Sayer was awarded the O.B.E. in the New Year's Honours List in 1942, for his work with the Gloster Company.

He has been described as a typical British test pilot, modest to a degree and disinclined to talk about his work. A tribute paid to him by Mr. Michael Daunt, one of his assistant test pilots stated:

"I have worked with 'Jerry' for five-and-a-half years and although he was virtually my boss he was the type of boss who was so much more a personal friend that one did every job of work as a piece of co-operation. As a test pilot he was one of the foremost in the country. He had a terrific ability of being able to fly extremely well and smoothly but he had also the type of orderly brain that never misses a detail. When he landed after an important test, the information he gave would always be of value to the future of that aeroplane and of help to its designer".

F/Lt. Sayer was a son of Wing Commander E.J. Sayer, Retired.

Directorate of Public Relations,

Air Ministry,
King Charles Street,
Whitehall, S.W.1.
6th January 1944.

Photographs of Group Captain Whittle are available at B.I.P.P.A. Reference Nos. CH 11867, 11868 and 11869.

Source: NA AIR 2/7070, 27B

Second press release, 27 September 1944

27.9.44 – No. 44

Air Ministry News Service — Air Ministry Bulletin No. 15768

THIS STORY IS BEING ISSUED SIMULTANEOUSLY IN U.S.A.
NOT FOR PUBLICATION OR BROADCAST OR USE ON CLUB TAPES
BEFORE 2000 HOURS B.S.T. WEDNESDAY, 27th SEPTEMBER
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PROGRESS OF JET-PROPELLED AIRCRAFT

The following joint statement, which has been agreed with U.S. War Department for issue in Washington, is placed at the disposal of the press by the Air Ministry and the Ministry of Aircraft Production:

The Press has already recorded that Allied aircraft in the European Theatre have been in action on several occasions with German jet-propelled fighters.

The appearance of these aircraft had been expected, and their design and operational characteristics appear to follow closely the estimates which had been formed of them.

In spite of their high speed and rate of climb, they have shown themselves to possess poor manoeuvrability, and our aircraft have had satisfactory exchanges with them in the engagements that have occurred.

It must however be expected that increased numbers of jet-propelled aircraft will appear in service and that they will become more effective as greater esperience [sic] is obtained.

Meanwhile, we are able to report that the development of British and American jet-propelled aircraft previously described in the announcement issued on January 6, 1944, has made progress.

Details of these aircraft and their engines must still remain secret but research scientists, aircraft technicians and workers in both Britain and America may take pride in their work.

British aircraft of this type have already been employed with success against the flying bombs.

Most valuable experience has thereby been gained.

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Source: NA AIR 2/7070, 108A

Third press release, 28 February 1945

Air Ministry News Service — Air Ministry Bulletin No. 17692.

Not for publication, broadcast or release on club tapes before 2000 hours B.S.T. on Wednesday, 28th February 1945.

A statement on jet-propelled aircraft is also being released in America.

R.A.F. "JET" FIGHTERS IN ACTION.

The first and so far the only jet propelled aircraft of the United Nations to go into action against the enemy is the Gloster "Meteor". These "Meteor" jet propelled fighters were first employed by a squadron of R.A.F. Fighter Command against flying-bombs launched by the Luftwaffe last summer from France so the first combats of British jets were not against conventional aircraft. The R.A.F. "Meteor" proved to possess a greatly superior speed to the pilotless German flying-bomb and many tactical lessons were learned from these early combats

Like the Gloster E.28/39, the first turbine jet aircraft in the world to fly (in May 1941), the "Meteor" is also a product of the Gloster Aircraft Company (Hawker-Siddeley Group). The "Meteor" is powered with Rolls Royce engines manufactured to the basic design of Air Commodore Frank Whittle, R.A.F., in collaboration with Power Jets Ltd., and the British Thomson-Houston Co., Ltd. The first engine supplied to the U.S. Army Air Force in Oct., 1941 was built by Power Jets Ltd. Air Commodore Whittle visited the U.S.A. in order to assist our Allies to initiate their development programme.

In addition to the "Meteor", Great Britain has another jet-propelled fighter in an advanced stage of development. This has been designed and engined by the De Havilland Aircraft Co. Ltd. These engines are also manufactured on the basic principles used by Air Commodore Whittle.

One built by this company was supplied to the U.S.A.A.F. in July 1943 and was used by the Lockheed Company as the power unit of a prototype aircraft which was built by that firm. This prototype later engined by a Unit of American construction [GEC Type I-40] was developed into the Lockheed P-80A.

Other research and development work is in active progress with a view to progressive increase of the performance of British built aircraft using jet propulsion units. These are of a highly secret nature.

Just as full information was provided to the United States Air Forces of the original Whittle design, so in conformity with the unswerving policy of the British Government to make all technical information immediately available to our American Ally, full details of the progress made by British Aircraft firms in developing jet aircraft and engines had been freely communicated to the United States. Information on American development progress is similarly being made available to us.

The original British turbine jet aircraft was a single-engined aeroplane but the "Meteor" is a twin-engined monoplane of very clean design. It first flew experimentally in March 1943, and since then the production types have been considerably improved.

The engines of the "Meteor" take in enormous quantities of air (hundredweights a minute) which are sucked in, compressed, heated with burning paraffin and ejected through the turbine and then through a large roar nozzle. There are several immediate advantages to be found in the jet engine or gas turbine. First and foremost it is simpler in almost every respect than the piston engine; it is lighter; it is far more easily serviced and it possesses a rotary as distinct from a reciprocating movement. It is known that the Rolls-Royce engine of this type is more efficient and of longer life than the Jumo engine of the German Messerschmitt Me 262.

[-2-]

The turbines emit no flame, as did the jet-propulsion units of flying-bombs, and only under certain rare conditions do they leave any smoke trails. The passage of a jet plane on the ground leaves in its wake the typical smell given off by a hot paraffin oil stove or a hurricane lamp.

The Gloster designers, chief of whom is Mr. W.G. Carter, had to take account of a new crop of aero-dynamic problems in order to achieve with safety the high speeds at which the "Meteor" flies, but in spite of this the aircraft is highly praised by the R.A.F. as being very manoeuvrable, easy to fly and with no such penalty as high landing speed. Its extreme smoothness of running, absence of the usual vibration, and simplicity of the engine controls are very much welcomed by pilots.

The first R.A.F. Squadron to be equipped with "squirts", as the pilots call their jet planes, was a squadron which had previously been flying Spitfires.

The squadron's pilots, not specially selected in any way and representing the average cross-section of any fighter unit in the Royal Air Force, began their jet training by converting from single-engine aircraft to "twins", learning the multi-engined technique in Oxfords' standard RAF twin-engined training aircraft.

Spurred on by the new job in prospect, they went solo on "twins" in record time, and after an average of six hours' solo multi-engine flying time they were judged ready to pass on to the next stage - the jet aircraft.

Travelling secretly, and in small batches, pilots and key ground staff went to an R.A.F. Experimental Establishment, where jet fighters fresh from the factory assembly line were awaiting collection.

While the pilots, fortified with a few hours' ground instruction from test pilots and experimental personnel, flew their first solo jet flights and did a few hours' practice flying on the new type, the ground crews learned the care and maintenance of the prototypes.

Then, after a few days, the pilots flew the jet aircraft back to their base, where the 'planes were guarded every minute of their earth-bound time by special security police.

The RAF's first operational jet patrol was flow during the Battle of the Flying Bomb and had its first success on August 4, 1944. Subsequently the Meteor shot down a substantial number of flying bombs.

"They are really beautiful aircraft, and I should hate to return to normal flying", said a pilot. "When they start up and taxi, our 'squirts' make a noise rather like an oversize vacuum cleaner, but when they take off, or fly at full throttle, they sound almost like a normal aircraft.

"The cockpit layout differs very little from the conventional type, and it is very comfortable with good visibility all round. There is plenty of armour to give one a sense of security, and a remarkable contrast to a normal type of aircraft is the almost complete absence of noise in the cockpit when one is flying, it is just like driving about on a cloud.

"The 'squirts' have plenty of power, and if you open the throttle suddenly you get a kick in the back from your seat. They go up like a lift, the faster the higher. They're sweet to handle even at high speed, and it's jets for me from now on".

Source: NA AIR 2/7070, 177A

Appendix C
Engine Comparison Table

This table is provided to help make sense of the many different engines mentioned in the text. It includes both piston engines and gas turbine engines (turbojets and turboprops). Piston engine powers have been converted to thrust to enable an order of magnitude comparison between the two different types. The rough conversion demonstrates that existing piston engines served as a reference point for early gas turbine engines and that the latter did not necessarily outperform the former. A variety of other measurements, which are not included here – including particularly fuel consumption – demonstrate the many compromises that occur in engine design and show that a given engine was rarely superior to all other engines in all of its characteristics; different engines were best suited to different applications.

Converting piston engine powers to thrust is an unnatural operation because the two engine types produce thrust in fundamentally different ways. The calculation of equivalent thrust done here is necessarily somewhat arbitrary. A reasonable speed for piston-engined aircraft, 300 mph, was chosen, and a reasonable propeller efficiency (for a variable pitch propeller) of 85% was assumed. Piston engine shaft power depends on speed and altitude, and piston engine specifications often list multiple values to reflect the use of superchargers at altitude. The shaft horsepower specifications used below reflect measurements for particular altitudes as indicated. A further complication is the fact that the thrusts and horse powers given are not readily converted into flight speeds; the performance of a piston engine / airframe combination depended on the match between the engine's output and the conditions of flight for which the airframe was designed. The calculations provided here should be viewed with these considerations in mind.

The figures given for engines in this table reflect mostly published figures (where engines became service engines, their model numbers are given in the chart), but output varied drastically for a given prototype over time, between different prototypes and between prototypes and service articles.

Equivalent power was calculated as follows:

Thrust = Power available / V_∞

V_∞ = cruising velocity

Assume V_∞ = 300 mph = 440 ft/sec

Power available (from a piston engine – propeller combination) = $\eta_{propeller} \bullet P_s$

P_s = shaft power in horsepower

1 HP = 550 ft•lbs/sec

Choose (optimistically) $\eta_{propeller} = 0.85$

Thrust = $\eta_{propeller} \bullet P_s \bullet$ 550 ft•lbs/sec/HP / V_∞

Thrust = $0.85 \bullet P_s \bullet 550 / 440$

Source: John Anderson, *Introduction to Flight* (McGraw-Hill, 2008), 416 and 421-424.

Description of values given in the comparison table

1. **T**: engine type, TJ = turbojet; TP = turboprop; PE = piston engine
2. **LAYOUT**: 3 columns
    a. For gas turbine engines: compressor (A = axial; CR = contra-rotating; C = centrifugal), combustion system (A = annular, for C = individual can combustors or ST = straight through - individual combustors the number of combustion chambers is given where known), turbine (giving the number of stages and the type, A= axial, C= centrifugal)
    b. For piston engine: number of cylinders and layout (either IL = in-line, R = radial, or V, X or H), displacement (L), and SC indicates the engine was supercharged
3. **PR**: highest pressure ratio of the supercharger or pressure ratio of the gas turbine
4. **TH lbs**: thrust of gas turbine engines and residual thrust of turboprops
5. **HP**: shaft horsepower for piston engines, a high cruising power was chosen rather than take-off power
6. **ALT 1000 ft**: altitude where given for piston engine powers in thousands of feet, otherwise assume sea-level
7. **EQ TH lbs**: equivalent thrust calculated for piston engines and turboprops, figures for turboprops this figure represents total engine power in thrust
8. **DRY lbs**: dry weight of unit; the weights of engines that drive propellers are generally given without propeller weights
9. **DESIGN / FIRST RUN**: gives the dates when designs were begun and when engines ran for the first time self-sustaining
10. **S**: Sources of data in chart – where no source is given the information was taken from the thesis text.

    (A) Paul H. Wilkinson, *Aircraft Engines of the World* (New York: Wilkinson, 1945)

    (B) 'British Power Units,' *Flight*, 4.9.47

    (C) Wagner, *Die Ersten Strahlflugzeuge*

    (D) Brooks, *Vikings at Waterloo*

    (E) Kay, *Turbojet History and Development*

	T	LAYOUT			PR	TH lbs	HP	ALT 1000 ft	EQ TH lbs	WT lbs	DESIGN / FIRST RUN	S
POWER JETS												
WU	TJ	1C	C	1A							1936/1937	
W.1	TJ	1C	C	1A							1939/1941	
W.1A	TJ	1C	C	1A		860			860		1941	(F)
W.2	TJ	1C	10C	1A		562			562		1941	(F)
W.2B	TJ	1C	10C	1A		1526			1526		1941	(F)
W.2/500	TJ	1C	C	1A		2485			2485		1942	(F)
W.2/700	TJ	1C	C	1A		2500			2500			(F)
LR.1	TJ	A		A								
ROVER												
STX/B26	TJ	1C	10ST	1A		1295			1295		1941-1942	(E)*
METROVICK												
F.2	TJ	9A	A	A		1800			1800		1941	(F)
F.2/4	TJ	A	A	A		3850			3850	1550		(B)
F.9	TJ	13A	A	2A		7000			7000		1945	(F)
DE HAVILLAND												
GIPSY KING	PE	12IL	18.37	SC			425		452	1056	/ 1937	(A)
GIPSY QUEEN 70	PE	6IL	10.18	SC			345	7.75	367	660		
H.1	TJ	1C	C	1A		3000			3000		1941/1942	
GOBLIN	TJ	1C	16ST	1A		3000			3000	c1550		(B)
GHOST	TJ	1C	10ST	1A		5000			5000	2011	1944	(B)
ROLLS-ROYCE												
VULTURE	PE	24X	42.4	SC	7.3		1845	5.0	1960	2450		(A)
MERLIN XX	PE	12V	27	SC	9.5		1480	6.0	1573	1385		(A)
MERLIN 61	PE	12V	27	SC	8.0		1570	11.5	1668	1640		(A)
MERLIN 140	PE	12V	27	SC			1780	4.5	1891	1780		(B)
GRIFFON 121	PE	12 V	36.7	SC			2300	15.75	2444	2150		(B)
CRECY	PE	12V	26	SC	7.0		2000		2125	2090		(A)
EAGLE	PE	24H	46	SC			3500	3.25	3719	4220		(B)
WR1	TJ	1C	10C	1A		1984			1984			(F)
WELLAND (W.2B/23)	TJ	1C	10C	1A		1698			1698			(F)
DERWENT (B/37)	TJ	1C	ST	1A		1984			1984			(F)
DERWENT V	TJ	1C	9ST	1A		3600			3600	1280		(B)
RB41 NENE	TJ	1C	9ST	1A		4500			4500	1640		(B)
CR.1	TJ	14A	A	14A								
AVON (AJ65)	TJ	15A	C	2A		5000			5000			(F)
RB/39 CLYDE	TP	1A 1C	9	2A		1225	3020		4434	2800		(B)
DART	TP	2C	7	2A			890		946	847		(F)
RCA1	TJ	A	C	A								
ARMSTRONG SIDDELEY												
CHEETAH 25	PE	7R	13.67	SC	6.5		405	4.0	430	805		(B)
DEERHOUND	PE	21R					1115		1185			
WOLFHOUND	PE	24R					3000		3188			
ASX	TJ	14A	C	2A		2551			2551		1942/1943	(F)
HEPPNER UNIT	TJ	CR										
ASP	TP	A	C	2A			3600		3825			
PYTHON	TP	14A	11	2A		1150	3670		3899	3190		(B)

	T	LAYOUT			PR	TH lbs	HP	ALT 1000 ft	EQ TH lbs	WT lbs	DESIGN / FIRST RUN	S
BRISTOL												
HERCULES 120	PE	14R	38.7	SC			1800	6.0	1913	2025		(B)
CENTAURUS XX	PE	2X18R	107.2	SC			5160	4.0	5483	c2900		(B)
THESEUS I	TP	1A1C	8			500	1950		2572	2310		(B)
NAPIER												
SABREVII	PE	24H	36.7	2S			3055	2.25	3246	2540		(B)
NAIAD	TP	A	5			241	1500		1835	1095		(B)
ELAND	TJ	10A	6	3A		825	2690		3683	1661		(C)
HEINKEL												
HeS 1	TJ	1C	A	1C							1936/1937	
HeS 2	TJ	1C	A	1		300			300			(F)
HeS 3b	TJ	1C	A	1A	2.8	1102			1102	792	1938/1939	(D)
HeS 8 (109-001)	TJ	1C	A	1A	2.7	1587			1587	836	1940/1941	
HeS 30 (109-006)	TJ	5A	9C	1A	3.2	1808			1808	836	1939/1942	
HeS 11	TJ	1D3A	A	1A	4.4	2866			2866	2090	1941/1945	
JUNKERS												
211-J	PE	12V	35	SC	11.4		1300	12.5	1381	1429		(A)
213-A	PE	12V	36.9	SC			1700	9.8	1806	1543		(A)
109-004A-0	TJ	8A	6	1		1852			1852	1870	1939/1940	(F)
109-004B-1	TJ	8A	6	1	3.1	1984			1984	1639		(D)
109-012	TJ	11A	6	2	5.5	6614			6614	3520	1945	(D)
109-022	TP	11A	A	3	5.5		6000		6375	6600	1945	(D)
BRAMO												
FAFNIR 323-P1	PE	9R	26.8	SC			810	8.5	861	1320		(A)
329	PE	14R					2000		2125			
109-002	TJ	CR	A									
WEINRICH SIMPLE AXIAL (P.3302)	TJ	6A	A	1A		330			330		1938/1940	
BMW												
132K	PE	9R	27.7	SC	12.4		960	9.8	1020	1168		(A)
139	PE	18R					1500		1594	1940		(A)
801	PE	14R	41.8	SC			1600	13.1	1700	1940		(A)
P.3303	TJ	2C		A							1938	
P.3302 (revised)	TJ	6A	A	1A		1323			1323		1940/1942	(F)
109-003A-0	TJ	7A	A	1A	3.1	1764			1764	1309		(D)
109-003A-2	TJ	7A	A	1A	3.4	1984			1984	1309		(D)
109-018	TJ	12A	A	3A	7.1	7716			7716	4840	1945	(D)
109-028	TP	12A	A	4A	7.0	2750	3100		6044	7040	1945	(D)
DAIMLER-BENZ												
601E	PE	12V	33.9	SC	10.0		1375	18.0	1461			(A)
603a	PE	12v	44.5	SC	9.2		1680	18.0	1785			(A)
605-A1	PE	12V	35.7	SC	10.0		1350	19.7	1434			(A)
109-007**	TJ	17CR	C	1A	8.0	2810			2810	2860	1939/1943	(F)
109-016	TJ	9A	A	2A		4400			4400		1943	(F)
109-021	TP	1D3A	A	2A	4.4	1741	2000		3866	2860	1944	(D)

Notes: * STX1 tested Feb 43; ** ducted fan

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DM FA001: Firmenarchiv Heinkel Werke

DM NL172: Nachlass Herbert Wagner (1900-1982)

Archives of the Deutsches Zentrum für Luft- und Raumfahrt (German Aerospace Center), Göttingen

Archive of the Manchester Museum of Science and Industry

Archives of the Rolls-Royce Heritage Trust

RR DMB: Directors Minute Books, Derby

RR HC: Hives Correspondence, Derby

RR L: Lappin files, Bristol

Archives of the Smithsonian Institution, National Air and Space Museum

NASM R: Registrar's Files

NASM T: Tinling Papers

NASM VO: Von Ohain Papers

British Library

BL Add 61931: Power Jets Limited, Minutes of directors' and shareholders' meetings

BMW Corporate Archive, Munich

Churchill Archives Centre, Churchill College Cambridge

CAC WHTL: Papers of Sir Frank Whittle

Daimler-Benz Corporate Archive, Stuttgart

Das Bundesarchiv (German National Archives)

Bundesarchiv, Lichterfelde

BA RL3: Generalluftzeugmeister

Bundesarchiv-Militärarchiv, Freiburg

BA MA N653: Nachlass Hertel, Walter (1898-1983)

BA MA NS19: Persönlicher Stab Reichsführer-SS

BA MA R3: Reichsministerium für Rüstung und Kriegsproduktion

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IWM FD: Speer / Foreign Documents Collection

Kings Norton Archive, Cranfield University

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NA AIR: Records created or inherited by the Air Ministry, the Royal Air Force, and related bodies

NA AIR 62: Air Commodore Sir Frank Whittle: Papers

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